Gerald Zamponi

Voltage-Gated Calcium Channels





Molecular Biology Intelligence Unit

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oltage-gated calcium channels are essential mediators of a range of physiological functions, including the communication between nerve cells, the regulation of heart beat, muscle contraction, and secretion of hormones such as insulin. Consequently, these channels are critical pharmacological targets in the treatment of a variety of disorders, such as epilepsy, hypertension, and pain. Voltage-gated calcium channels have therefore been subject to intense study by numerous investigators over the past few decades, and an immense body of work has accumulated. In this book, we provide the first comprehensive overview of our current state of knowledge concerning this exciting field of research. Leading off with a general review of calcium signaling and techniques to measure calcium channel activity, the book delves into a provocative overview of the history of the calcium channel field, contributed by one of the key pioneers in the field, Dr. Richard Tsien. This is followed by an in depth review of the biochemical and molecular biological characterization of calcium channel genes by Drs. Catterall and Snutch whose research has resulted in major advances in the calcium channel field. A number of chapters are dedicated towards various aspects of calcium channel structure and function, including channel gating, permeation, modulation and interactions with members of the exocytotic machinery-contributed by both established leaders and rising stars in the field. The next series of chapters is concerned with pharmacological and physiological aspects of voltage-gated calcium channels including genetic diseases linked to calcium channel genes. The book concludes with an overview of the effects of targeted calcium channel gene disruption in mice.

Over the past two decades, considerable progress has been made in terms of understanding the molecular physiology of voltage-gated calcium channels, yet, the work is far from complete. Identification of novel small organic calcium channel inhibitors remains a key priority towards treating diseases linked to these channels, and only recently has the first crystal structure of a calcium channel subunit been solved. Over the next decade, one may expect that current knowledge about the molecular structure of calcium channels will be used to understand, in detail, the function of these channels in their native cellular environment and in human physiology, and my fellow contributors and I look forward to being part of this effort.

Gerald W. Zamponi, Ph.D.

CHAPTER 1

Ca²⁺ Chemistry, Storage and Transport in Biologic Systems: An Overview

Tashi G. Kinjo and Paul P.M. Schnetkamp

Characteristics of the second state of the se

Why Ca²⁺: Unique Chemical and Physical Features

The chemical features and physical characteristics of the doubly charged Ca²⁺ contribute favorably to its role in biology. This has been extensively reviewed by Williams^{2,3} and a brief synopsis is provided here.

 Ca^{2+} displays a highly ionic character in its bonding. The covalent contribution in bond formation increases as one moves across the series from Ca^{2+} to Zn^{2+} . The highly ionic character of Ca^{2+} in bond formation restricts its interactions to liganding oxygen donating groups such as carbonyl, carboxyl, alcohols and ethers. Divalent cations that display highly covalent bond formations, such as Cd^{2+} , interact with stronger donating groups such as nitrogen and sulfur donors, and are thus removed from competing with Ca^{2+} for binding.

 Ca^{2+} is a rather large ion with a crystal ionic radius of 0.99 Å. This is larger than the majority of divalent cations including those in the third row of the periodic table from Mn^{2+} (radius of 0.80Å) across to Zn^{2+} (radius of 0.74Å). Cd^{2+} is very close in size with a radius of 0.97Å. Relative to the other ions in the second period, Ca^{2+} is larger than Mg^{2+} (radius of 0.66Å), however, smaller than Sr^{2+} (01.12Å) and Ba^{2+} (1.34Å).

In terms of the binding capability, ionic radius is an important determinant as to the strength and type of ligand that will bind to a particular ion. If this alone was the determining factor for the binding of potential ligands, then it would follow that smaller divalent cations would exhibit the strongest ligand binding due to a stronger electrostatic field. This, however, is not the

Voltage-Gated Calcium Channels, edited by Gerald Zamponi. ©2005 Eurekah.com and Kluwer Academic / Plenum Publishers. case. Smaller ions necessitate closer association of donor groups in three-dimensional space. This restricts the binding of ligands to smaller ions due to steric hindrance within the liganding molecule. However, if a divalent cation is too large, the reduction in electrostatic field causes a decrease in binding. Ca^{2+} provides the best balance between the two opposing forces; steric hindrance and electrostatic field intensity.

Ionic radius also determines the solubility of a particular ion with other ions. Mg^{2*} can pack tightly into the small holes created in the lattice of smaller anions such as hydroxide and fluoride ions. Ca^{2*} , however, is too large to fit into the holes in the lattice structure created by OH⁻ and F⁻ ions. Consequently, Mg^{2*} rather than Ca^{2*} , tends to precipitate out with small anions. Ca^{2*} precipitates out with larger anions such as phosphates and carbonates or polyanions such as nucleic acids and acidic proteins.

Ca²⁺ Evolution: A Rejection from Cytoplasm

An interesting theory on the evolution of the role of Ca^{2+} in biology has been presented by Williams,^{2,3} based on the ability for Ca^{2+} to precipitate organic anions. From life's very beginnings, it was essential that Ca^{2+} be separated from organic anions to avoid precipitation. Thus, Ca^{2+} had to be rejected from the cytoplasm of the earliest cells. This initial simple rejection of Ca^{2+} is still observed for all organisms, ranging from prokaryotes to multicellular eukaryotes, where intracellular free Ca^{2+} concentrations are maintained on the order of $10^{-7}M$. In the earliest forms of life, namely prokaryotes, Ca^{2+} is found in anaerobic bacteria to this day.

With the development of eukaryotes came the compartmentalization of the cytoplasm. It was then necessary for eukaryotic cells to develop intracellular signaling in order to coordinate function and placement of these organelles. The Ca^{2+} features outlined above makes Ca^{2+} an excellent second messenger, fast kinetics, and easy liganding ability. Therefore, eukaryotic cells started to use Ca^{2+} , and the previously set up Ca^{2+} electrochemical gradient from prokaryotes, for coordination of events within the cell. It is not until the development of unicellular eukaryotic cells, such as yeast, that we observe intracellular Ca^{2+} binding proteins. Emergence for the use of Ca^{2+} precipitates as external support and protective structures begin in eukaryotes with calcium carbonate shells. Multicellular eukaryotes then develop organized internal calcium phosphate precipitates in the form of bone, which act not only to provide structural support, but act as a Ca^{2+} reservoir for maintenance of circulating blood Ca^{2+} levels. The progression of the extensive use of Ca^{2+} is then based on its initial rejection from prokaryotic cells, creating a gradient for Ca^{2+} entry. This entry, in combination with the unique binding characteristics of Ca^{2+} , allowed eukaryotic cells to use this divalent cation as an essential element for the many processes in which it is used today.

Ca²⁺ Signaling and Storage: The Endoplasmic Recticulum

The endoplasmic recticulum is generally the predominant intracellular Ca^{2+} store. The ER is critical not only for Ca^{2+} storage, but release of Ca^{2+} from the ER is responsible for rapid transmission of Ca^{2+} signals from the periphery to the center of the cell and for local Ca^{2+} signaling.⁴ Interestingly, changes in ER Ca^{2+} handling is thought to be involved in neural ageing⁵ and improper ER Ca^{2+} control has pathogenic implications.⁶ Resting ER free Ca^{2+} concentration is thought to be on the order of several hundred μM ,⁷ in addition, lumenal ER Ca^{2+} is stored by high capacity-low affinity Ca^{2+} buffering proteins including calsequestrin and calreticulin.⁸

This resting level of lumenal ER free Ca^{2+} is the result of a balance between Ca^{2+} uptake via sarcoplasmic-endoplasmic type ATPases (SERCAs)⁹ and release. Ca^{2+} is released from the ER in either a stimulated or passive manner.

Stimulated release occurs through the activation of two receptor types; ryanodine receptors(RyR) and inositol 1,4,5-triphosphate(IP₃) receptors discussed in more detail later.⁸ In addition, other receptors may exist that release Ca²⁺ via cyclic-ADP-ribose and nicotinic

acid adenine dinucleotide phosphate (NAADP). Suprastimulation with high levels of Ca^{2+} releasing agonists reduce ER free Ca^{2+} to only the tens of μ M range.⁸ Inactivation of Ca^{2+} release channels by high cytosolic Ca^{2+} may contribute to this incomplete emptying. Interestingly, sustained submaximal levels of cytosolic IP₃ causes only partial transient release of calcium from the ER. Whereas additional levels of IP₃ induce more pulses of Ca^{2+} release. This is known as the quantal Ca^{2+} release phenonmenon.¹¹ The exact mechanism of this phenomenon, however, remains elusive.

Passive release is less well-defined and has been shown in many cell types to be remarkably dynamic as inhibition of the SERCA pump by thapsigargin often results in a rise in cytosolic free Ca^{2+} within a few seconds. This passive leak has been shown to be insensitive to inhibitors of both IP₃ and RyRs, but responsive to ATP levels.¹⁰ Recent evidence has implicated a protein involved in apoptosis, Bcl2, as having a possible role in passive Ca^{2+} leak from the ER.⁸

The Role of Ca²⁺ within the ER

 Ca^{2+} is fundamental for proper function of the ER. Indeed, evidence has accumulated that indicates that even ER structure and integrity are dependent upon lumenal free Ca^{2+} . Reports have indicated that loss of ER lumenal Ca^{2+} results in ER fragmentation.¹² Additionally, it has been shown that high levels of cytoplasmic Ca^{2+} can result in the loss of continuity of the ER membrane.¹³ Prevention of ER fragmentation has been observed upon protein kinase C(PKC) activation, which could possibly provide the ER with a protective mechanism upon store depletion with IP₃/DAG producing agonists.^{13,14} However, another group has since then observed that the protective effects of PKC activation occur only when fragmentation is caused by an increase in cytoplasmic Ca^{2+} and not when caused by ER Ca^{2+} depletion.¹⁵

In addition to Ca^{2+} handling, the ER is the site of protein processing, storage and transport. Interestingly, many Ca^{2+} binding proteins found within the ER also act as chaperone proteins. The two roles served by these proteins, chaperone and Ca^{2+} buffer, are not separate, but are intimately associated. Maturation and proper folding of proteins is affected by depletion of ER Ca^{2+} .⁸ The formation of chaperone complexes in the ER depends on Ca^{2+} concentration.¹⁶ Additionally, depletion of ER Ca^{2+} increases protein degradation.¹⁷

The ER alone is not responsible for correct trafficking and maturation of proteins. The ER is in constant communication with the Golgi network with proteins and vesicles being transported between the two. Ca^{2+} has been found to play an important role in this communication. Transport between the ER and Golgi has been shown to require certain levels of cytosolic free Ca^{2+} and may be dependent upon a local Ca^{2+} gradient in the cytoplasm separating these two organelles. In addition, transport of vesicles between the ER and Golgi depends on the presence of internal Ca^{2+} , within both the ER and Golgi, as transport did not occur following ER and Golgi emptying with Ca^{2+} ionophores and the SERCA pump inhibitor thapsigargin.⁸

Ca²⁺ also acts to control Ca²⁺ management within the ER as a feedback mechanism. There are several examples of this phenomenon, however, the most extensively studied is capacitative Ca²⁺ entry (CCE) through store-operated Ca²⁺ channels (SOCs). It has been found that depletion of lumenal ER free Ca²⁺ can stimulate the entry of extracellular Ca²⁺ into the cell in order to refill the ER(reviewed in ref. 18). CCE is discussed in later text. Passive Ca²⁺ leak out of the ER is also dependent on ER lumenal Ca²⁺. Observation have indicated that low levels of ER Ca²⁺ (100 μ M) greatly reduced this passive leak, additionally, ER Ca²⁺ affects IP₃R, SERCA activity and even expression of the ER Ca²⁺ binding protein calreticulin.⁸

ER Heterogeneity: Ca²⁺ Tunneling Versus Ca²⁺ Compartmentalization

Petersen provides an excellent discussion on the topic of ER calcium distribution.¹¹ An outline of this discussion is provided here. Classically, the endoplasmic recticulum has been thought of as one continuous membrane bound enclosure with equal protein expression and equilibrated ion concentrations throughout. ER protein expression, however, is not uniform but heterogeneous with specific localization of proteins into domains. Different SERCA

subtypes and Ca^{2+} release channels are found in different parts of the ER. This differential ER protein distribution is separate from, but related to the topic of ER calcium distribution. Recently, this topic has been the subject of debate. There have been many reports that IP₃ induced and Ry/caffeine induced Ca^{2+} release occur through separate calcium stores. Imaging experiments have indicated that IP₃ induced Ca^{2+} release is spatially distinct, and can be independently emptied, from release induced by Ry/caffeine.⁴ Currently, however, the classical view of an equilibrated ER Ca²⁺ distribution is accepted based on the results of diffusion using uncaged Ca^{2+} within the ER.

Ca²⁺ Signaling and Storage: Mitochondria

Since the 1960s, it has been known that mitochondria are capable of accumulating Ca²⁺. The importance of this uptake, however, was thought to be minimal as physiologic increases in cytosolic Ca²⁺ was seen as being insufficient to activate mitochondrial Ca²⁺ uptake mechanisms. Interest in mitochondrial Ca²⁺ uptake was then sparked by experiments using the Ca^{2+} -indicating protein aequorin, targeted to the mitochondrial matrix. These experiments indicated that mitochondrial matrix Ca²⁺ levels transiently increased following treatment with IP₃ liberating agonists.¹⁹ Mitochondria exhibit two mechanisms of Ca^{2+} uptake. Primarily, Ca^{2+} uptake occurs via a Ca^{2+} uniporter. The molecular characterization of this uniporter, however, remains elusive. Evidence has indicated that this uniporter functions like a channel with an increase in open probability associated with increased local Ca2+ concentrations(reviewed in 20). Ca²⁺ uptake through this uniporter is known as the Ruthenium Red (RuR)-sensitive pathway. The driving force for Ca²⁺ entry through the uniporter is provided by the mitochondrial membrane potential, reported to be -150 to -200mV with respect to the cytosol.²¹ The uniporter has a rather high Ca^{2+} dissociation constant (K_d>25 μ M),¹⁹ much greater than physiologic changes in net cytosolic Ca²⁺. Mitochondria, however, are subject to much higher cytoplasmic concentrations of Ca²⁺ in the form of microdomains that are released upon IP₃ receptor opening in the ER. In fact, the ER and mitochondria have been found to be very closely associated in space(<100nm), and in Ca²⁺ communication(see next section).²² A second form of mitochondrial Ca²⁺ uptake has also been reported and is known as the rapid uptake pathway.²³ Little is known about this mechanism of uptake. Mitochondrial Ca²⁺ uptake is balanced by Ca^{2+} extrusion through the mitochondrial Na⁺Ca²⁺ exchanger, which exhibits different characteristics than the plasma membrane exchanger.²¹

Mitochondrial Ca²⁺: Uptake Function and Effects

The main role of mitochondria has long been known to be oxidative phosphorylation.²⁴ Not surprisingly then, mitochondrial Ca^{2+} levels influence this process. The citric acid cycle is rate limited by levels of dehydrogenases. Expression of these enzymes is upregulated, with associated increase in ATP production, in response to accumulation of mitochondrial $Ca^{2+,25}$

A more unexpected role of Ca^{2+} uptake by mitochondria involves the fine tuning and shaping of intracellular Ca^{2+} signaling. A conventional view of Ca^{2+} signaling within a cell consists of a wave of Ca^{2+} propagating across the cytoplasm of the cell. This propagation is thought to occur by CICR through IP₃ receptors in the ER. The wave starts with a local increase in cytoplasmic Ca^{2+} . This sensitizes IP₃ receptors and enables their activation at lower levels of IP₃. The IP₃ receptor activates and releases Ca^{2+} , which acts to sensitize the IP₃ receptors on adjacent ER membrane. In this manner the wave of Ca^{2+} is released into the cytoplasm across the cell. The action of mitochondria in shaping of these signals is to restrict the rate of wave propagation and dampen its amplitude as it moves across the cell. Inhibition of mitochondrial Ca^{2+} uptake results in a constant rate of wave propagation and an increase in the rate of rise and amplitude of the signal.²² In pancreatic acinar cells, mitochondria found along the center line separating the apical and basal portions, has been shown to restrict the spread of Ca^{2+} waves from one end to the other.²⁶ Under certain conditions, (oxidative stress, adenine nucleotide depletion and increased inorganic phosphate levels) an increase in intra mitochondrial Ca^{2+} concentration will trigger the formation of a pore complex known as the permeability transition pore (mPTP). This complex is made up by several proteins located at the close contact points between the inner and outer mitochondrial membranes. The function of the mPTP, however, remains to be evaluated. Several theories have been put forward including Ca^{2+} signal modulation, apoptosis initiation, or Ca^{2+} release.²²

Ca²⁺ Buffering: Cytosolic and Lumenal

Protein bound calcium accounts for between 95% and 99% of the total Ca²⁺ load of a cell.²⁷ The proteins that are involved in this binding are collectively known as Ca²⁺ buffering proteins and belong to the EF-hand family of Ca²⁺ binding proteins.²⁸ Ca²⁺ buffering proteins serve several functions within cells. Besides their obvious function to buffer cytoplasmic/lumenal free Ca²⁺ levels, they can act as Ca²⁺ delivery proteins, signaling proteins, and chaperones. A soluble cytosolic protein that demonstrates two of these functions is parvalbumin(PV). This high affinity Ca^{2+} binding protein is found in high concentration in the sarcoplasm of vertebrate fast contracting muscles, where it is involved in muscle relaxation. The process of muscle relaxation occurs when Ca2+ dissociates from troponin C, moves towards, and is transported into the sarcoplasmic recticulum (SR). The sarcoplasm/cytoplasm of cells is not a free space in which Ca²⁺ can diffuse, but is instead filled with negatively charged proteins capable of binding to Ca^{2+} . Therefore, Ca^{2+} diffusion occurs rather slowly in these areas. In order to facilitate Ca^{2+} translocation, Ca²⁺ is taken up by PV, which moves freely to other locations in the cell. It is generally thought that after muscle contraction, Ca2+ is taken up by PV, which then relocates to deliver the Ca2+ to the SERCA pump of the SR. There has also been evidence for a direct interaction between PV and the SR through the binding of PV to an SR protein. This binding occurs in a Ca²⁺-dependent manner.²⁹

 Ca^{2+} buffering in intracellular organelles involves high binding capacity, low affinity (K_d.1mM) Ca²⁺ binding proteins including; calnexin, calreticulin, calsequestrin and endoplasmin.⁸ ER Ca²⁺ buffering in muscle cells is primarily a function of calsequestrin.³⁰ The ER of other cell types employs calreticulin, which acts not only in Ca²⁺ buffering, but as a molecular chaperone protein.³¹ Lumenal ER Ca²⁺ binding capacity has been reported to be quite low compared to that of the cytosol. In mouse pancreatic acinar cells, cytosolic Ca²⁺ binding capacity was observed to be two orders of magnitude greater than that of the ER.³² This high cytosolic binding capacity has been reported for some cell types, while found to be lower in others.¹¹ A complete picture of ER lumenal binding capacity and mobilities of the Ca²⁺ buffering proteins involved, in both the ER and the cytosol, needs further investigation.

Channels that Lead to an Increase in Cytosolic Ca²⁺

Temporal and spatial control of increases in cytosolic free Ca^{2+} is of paramount importance for proper functioning of most cells, and aberrant Ca^{2+} homeostasis can rapidly result in cell death. Therefore, it is not that surprising that members of several different gene families of Ca^{2+} permeable channels may contribute to Ca^{2+} influx into the cytosol. The first members of most of these gene families were discovered in the eighties and nineties, quickly followed by cloning of related gene products; by now with the human and mouse genomic sequencing projects nearing completion, a complete membership list is probably available for most gene families. Many of these channels contributing to Ca^{2+} influx into the cytosol can be found coexpressed in most cell types, especially in cells of excitable tissues. To reflect the diversity of specific cellular functions, most of the above gene families contain many different but related members, and this complexity is further increased by the presence of different splice variants. Although the occurrence of different splice variants is common, only in very few cases has a physiological significance been established with certainty.

Intracellular Ca²⁺ Release Channels

Two families of intracellular Ca^{2+} release channels have been found to date, the IP₃ receptor³³ and the Ryanodine receptor (RyR),³⁴ each family consisting of three distinct mammalian genes. The IP₃ and Ryanodine receptors are among the largest ion channel proteins and form functional tetramers with a MW of about 1.2 and 2 million daltons, respectively.

Ryanodine Receptors³⁴

Three isoforms of mammalian RyR have been cloned: RyR1 is expressed in skeletal muscle (5040 residues), RyR2 is expressed in cardiac muscle (4945 residues), and RyR3 is expressed in skeletal muscle (4871 residues) as well, but in lower amounts than RyR1. RyR1 and RyR2 are critical to proper functioning of the host tissue as knocking out these genes in mice is lethal; in contrast, the RyR3 knockout is relatively normal. The ryanodine receptor functions as an intracellular Ca²⁺ release channel responding to a depolarization of the plasmalemma, although the mechanism is quite different for the RyR1 and RyR2 isoforms, respectively. In skeletal muscle, membrane depolarization is directly mediated via protein-protein interactions involving the plasmalemma dihydropyridine receptor (i.e., voltage-gated calcium channel) and the RyR1 located in the sarcoplasmic reticulum. In heart muscle, membrane depolarization results in Ca^{2+} influx via voltage-gated calcium channels that is used as a trigger for further Ca²⁺ influx by opening RyR2 in the sarcoplasmic reticulum. The conductance properties of RyR channels are regulated by cytosolic Ca²⁺, Mg²⁺, ATP and phosphorylation. Channel opening is promoted by low cytosolic Ca²⁺ (1-10 µM) and inhibited by high Ca²⁺ (>1 mM); channel opening also appears regulated by luminal Ca²⁺, but this is less clearly defined. RyR1 is more sensitive to regulation by Mg²⁺ and free ATP compared with the other two isoforms: free Mg²⁺ is a potent inhibitor, while ATP activates RyR. In addition to cytosolic Ca²⁺, Ca²⁺ release from RyR can also be stimulated by cyclic-ADP-ribose, by caffeine, and by high concentrations of ryanodine. Ryanodine receptors have also been shown to associate with several other intracellular proteins including calmodulin, calsequestrin (the major soluble Ca2+ binding protein in the SR), and immunophilin FK-506 binding proteins. Of all of the effectors of RyR function, Ca²⁺ is clearly the most significant.

IP3 Receptors³³

Three isoforms of mammalian IP_3 receptors have been cloned containing around 2700 amino acids each. Isoforms show about 72% homology amongst each other, and, similar to the ryanodine receptor, functional channels are thought to be tetramers of identical subunits. For each subunit, three main domains can be distinguished: the N-terminal ligand binding domain (~500 residues), followed by a long regulatory domain (~1600 residues) containing among other things two consensus ATP-binding sites and the binding domains for calmodulin and FK-506 binding protein, and the C-terminal ion channel domain (~450 residues) that anchors the IP₃ receptor to the membrane. The C-terminal ion channel domain shows homology to the ion channel domain of the ryanodine receptor. IP3 opens channels in a cooperative fashion suggesting that each subunit requires IP3 to bind for channels to open; half of the channels are opened at <1 μ M IP₃. As with ryanodine receptors, cytosolic Ca²⁺ exerts biphasic effects with potentiation of IP3 effects at low Ca²⁺ concentration and inhibition of channel activity at high Ca²⁺ concentration. IP₃ receptors are also regulated by ATP in a biphasic manner with low ATP concentrations increasing channel activity and high ATP levels leading to a decrease in channel activity. IP3 receptors show tight interactions with two cytosolic proteins, calmodulin and immunophilin FK-506 binding protein, proteins that also have been shown to interact with ryanodine receptors. Both calmodulin and FK-506 binding protein appear to have inhibitory effects on channel activity. The IP3 receptor has also been suggested to directly interact with store-operated Ca²⁺ channels as will be discussed below.

As the three different IP₃ receptor subtypes are expressed to various degrees in different cell types, and can often be found in the same cell type, it has been of interest to characterize functional differences that might suggest distinct roles for different subtypes. Differences in

 Ca^{2+} sensitivity to open channels have been observed for the type-1 and type-3 receptors, respectively, which have led to the suggestion that the type-3 receptor is ideally suited for providing the first burst of Ca^{2+} at very low agonist concentrations, while the type-1 receptor may be better suited for regenerating Ca^{2+} waves.³⁵ Although oscillatory changes in Ca^{2+} were long known in such excitable tissues as neurons or cardiomyocytes, the advent of intracellular Ca^{2+} -indicating dyes revealed oscillatory Ca^{2+} waves in many nonexcitable cells. Differential regulation of IP₃ receptors by IP₃ and Ca^{2+} are likely to play key roles in generating and maintaining Ca^{2+} waves.³⁶

Plasma Membrane Ca²⁺ Channels

In addition to the voltage-gated Ca^{2+} channels that form the main focus of this volume, three main groups of other plasma membrane proteins allow Ca^{2+} entry into the cell:

- Most ligand-gated cation channels lead to membrane depolarization by providing relatively
 nonselective passage of both Na⁺ and K⁺. However, many of these channels including the
 neuronal acteylcholine receptors, ionotropic glutamate receptors (in particular the NMDA
 and AMPA subtypes), and cyclic nucleotide gated channels have significant permeabilities
 for Ca²⁺ as well, and Ca²⁺ influx via such channels has significant physiological effects. We
 will discuss this in more detail for the cyclic nucleotide-gated channels.
- 2. Extracellular ATP acts on cell surface receptors of the P2X and P2Y type. The P2Y type are G-protein coupled receptors and agonist binding often leads to a rise in intracellular Ca²⁺ via the IP₃ pathway. In contrast, P2X receptors are cation channels that lead directly to an increase in intracellular Ca²⁺.
- 3. Store-operated Ca^{2+} entry (SOCE), also referred to as capacitive Ca^{2+} entry, is a ubiquitous mechanism that opens a Ca^{2+} entry pathway in the plasma membrane after intracellular Ca^{2+} release has depleted intracellular Ca^{2+} stores. Members of the TRP gene family are considered to be the most likely candidate for SOCE.

Cyclic Nucleotide-Gated Channels

Cyclic nucleotide-gated channels were first described in vertebrate rod photoreceptors. They are found in the outer segment organelles of both rod and cone photoreceptors where the cGMP-gated channels carry the light-sensitive current. Cyclic nucleotide-gated channels have now been found in many different tissues, although their function has only been clearly delineated in sensory cells.³⁷ In retinal photoreceptors, 10-20% of the inward current is carried by Ca^{2+} under physiological conditions, leading to high sustained Ca^{2+} concentrations of about 500nM in darkness. Modulation of the cytosolic Ca^{2+} concentration by light-dependent changes in Ca^{2+} influx feeds into a powerful negative feedback loop, which involves guanylyl cyclase and mediates the process of light adaptation. Cyclic nucleotide-gated channels are heterotetramers consisting of CNGA and CNGB subunits.

P2X Receptors

P2X gene products are found in many tissues including motor neurons, sensory neurons, airway epithelia, bone, kidney and homopoietic tissue.³⁸ They form fast ATP-gated nonselective cation channels, some of which have a significant Ca²⁺ permeability. Seven genes coding for P2X receptor subunits have been identified. The P2X subunit proteins range from 384 to 595 residues, and contain 2 transmembrane spanning helices, separated by a large (-280 residues) extracellular domain. The extracellular domain contains ten conserved cysteine residues and fourteen conserved glycine residues, and two critical disulfide bonds contributing to the ATP binding pocket. Functional P2X receptors are thought to be homo- or heteromultimers, perhaps containing three or six subunits. Two main groups of P2X receptors can be distinguished, those that quickly desensitize (<300 ms) and those that do not or very slowly desensitize. Homomeric P2X7 proteins have the additional property of being permeable to small molecules with a MW of less than 900 kDa.

SOCE and the TRP Gene Family

Agonist-induced rise in intracellular free Ca²⁺ displays in most cases an initial transient phase due to Ca2+ release from intracellular stores, followed by a more sustained phase that requires the presence of extracellular Ca^{2+} . The latter was initially named capacitive Ca^{2+} entry, and is now often referred to as store-operated Ca²⁺ entry or SOCE. Unlike voltage-gated channels, SOCE often shows a high selectivity for Ca²⁺ over Ba²⁺ and Sr²⁺. SOCE has been most convincingly demonstrated with the use of fluorescent intracellular Ca²⁺-indicating dyes. Characterization of Ca²⁺ currents induced by store depletion has proven much more difficult, most likely due to the small currents involved and due to low single channel conductance. Such currents have now been described in a limited number of cell types and are referred to as ICRAC currents. Although the molecular entities underlying SOCE have not been resolved unambiguously, mounting evidence suggests that members of the TRP family are involved.³⁹ TRP stands for transient receptor potential referring to a protein in Drosophila photoreceptors that carries a light-activated inward Ca²⁺ current in the fly visual excitation process. The mammalian TRP gene family contains seven members, most containing about 860 residues. TRP topology is thought to consist of 6 transmembrane spanning helices with a poreforming reentrant loop located between the fifth and sixth helical segments, analogous to the topology of members of the superfamily of voltage-gated channels. The N-terminus is located in the cytoplasm and contains in most cases ankyrin-like repeats as well as a coiled-coiled domain, which may represent sites for interaction with other proteins. The C-terminus is quite variable in length and appears to be more specific for each individual TRP member. Heterologous expression of different members of the TRP gene family has become an important tool to investigate the molecular mechanism of SOCE as will be discussed below.

Mechanisms of Store-Operated Ca²⁺ Entry

One of the most scrutinized concepts in the study of Ca^{2+} homeostasis of the past decade is the mechanism by which store depletion leads to Ca^{2+} entry via the plasma membrane. Although much progress has been made, consensus on unambiguous identification of such a mechanism has remained elusive. Four different mechanisms have been proposed:⁴⁰⁻⁴²

- A diffusible Ca²⁺ Influx Factor (CIF) was the first mechanism considered and several partially purified fractions have been reported to activate Ca²⁺ influx in some cell systems. However, no clear identification has yet been made.
- 2. The Ca^{2+} regulation mechanism proposes that Ca^{2+} in a restricted space close to the release channel keeps it inhibited; emptying of Ca^{2+} stores removes the source of the inhibitory Ca^{2+} and opens the release channel.
- 3. The exocytosis model proposes that emptying Ca²⁺ stores promotes fusion of vesicles containing the Ca²⁺ release channels with the plasma membrane, thus introducing functional channels to the plasma membrane.
- 4. Conformational coupling between the IP₃ receptor in the ER with release channels in the plasma membrane.

The latter model has received a lot of attention recently, particularly in cellular systems after transfection with TRP3. Such experiments provide strong evidence for conformational coupling between TRP3 and IP₃ receptors. In contrast, elimination of all three IP₃ receptor sub-types from a preB-lymphocyte cell line eliminated agonist-induced Ca^{2+} release, but normal SOCE was observed after store depletion with thapsigargin. As suggested by Putney et al,⁴¹ this may indicate that multiple mechanisms exist that couple store depletion to Ca^{2+} entry, similar to the different mechanisms by which ryanodine receptors are activated in skeletal muscle compared with heart muscle.

Mechanisms to Lower Cytosolic Ca²⁺

Ca²⁺ extrusion from the cytoplasm is an energy-requiring process as Ca²⁺ needs to be moved against a large electrochemical gradient. Two classes of proteins contribute to Ca²⁺ extrusion

from the cytoplasm, those that move Ca^{2+} at the expense of ATP hydrolysis and those that utilize the energy provided by the inward Na⁺ gradient to couple Ca^{2+} extrusion to Na⁺ influx. Two gene families of ATP-dependent Ca^{2+} pumps have been identified: the PMCA gene family of pumps found in the plasma membrane and the SERCA gene family of pumps found in the endo- or sarcoplasmic reticulum. Likewise, two gene families of Na⁺/Ca²⁺ exchangers have been described: the NCX gene family operates at a stoichiometry of $3Na^+/1Ca^{2+}$, while the NCKX gene family operates at a stoichiometry of $4Na^+/1Ca^{2+}+1K^+$. Thus, members of the NCKX gene family use both the inward Na+ gradient and the outward K⁺ gradient for Ca^{2+} extrusion.

PMCA Gene Family

Four members of the mammalian PMCA gene family have been identified, each consisting of about 1200 residues.⁴³ PMCA belongs to the superfamily of P-type ATPases with particularly high expression levels in brain. PMCA operates as an electrogenic Ca^{2+}/H^+ exchanger with a 1:1 stoichiometry and a submicromolar affinity for Ca^{2+} . PMCA is thought to be regulated by calmodulin, acidic phospholipids, by neuroactive steroids, and by phosphorylation.

SERCA Gene Family

Three members of the mammalian SERCA gene family have been identified. SERCA1 represents the Ca²⁺ pump in the SR, expressed mainly in fast-twitched skeletal muscle, and serves the distinction of being the first Ca²⁺ transport protein for which the crystal structure has been obtained.^{44,45} Like PMCA, SERCA Ca²⁺ pumps belong to the P-type ATPases and also consist of a single polypeptide unlike most other P-type ATPases which are heterodimers. SERCA pumps contain ten membrane spanning alpha helices, and three distinct cytosolic domains, the activation domain, the phosphorylation domain and the nucleotide binding domain. SERCA pumps are regulated by a small protein called phospholamban; binding of phospholamban leads to a reduction in the apparent affinity for Ca²⁺.

NCX Gene Family

Three members of the mammalian NCX gene family have been identified.⁴⁶ NCX proteins contain about 940 residues and are thought to consist of sets of 5 and 4 transmembrane spanning helices separated by a large hydrophilic loop located in the cytosol. The second set of TM helices is also thought to contain a reentrant loop structure. NCX1 is the dominantly expressed isoform which plays a critical role in Ca^{2+} homeostasis in heart muscle. Several splice variants have been identified. NCX is a bidirectional Ca^{2+} transporter and the direction of Ca^{2+} flux is dependent on the electrochemical Na⁺ gradient. This exchanger is regulated by secondary interactions with both its substrates, named Na⁺-dependent inactivation and secondary activation by cytosolic Ca^{2+} . In addition, NCX is activated by phosphatidylinositol-4,5-bisphosphate; regulation by phosphatidylinositol-4,5-bisphosphate has now been shown for several other channels and transporters including the rod cGMP-gated channel, the PMCA Ca^{2+} pump and many others.⁴⁷ Very recently, voltage-gated Ca^{2+} channels were shown to be regulated by phosphatidylinositol-4,5-bisphosphate as well.³³

NCKX Gene Family

Four members of the mammalian NCKX gene family have been identified, which range in size from about 660 residues to 1210 residues.^{37,46,48} Like NCX, NCKX mediates bidirectional Ca²⁺ fluxes, dependent in this case on both the transmembrane Na⁺ and K⁺ gradients. Although some NCKX isoforms appear to enjoy widespread tissue distribution, very little is known about NCKX physiology outside of the vertebrate retina. In both rod and cone photoreceptors, the NCKX1 and NCKX2 isoforms, respectively, extrude Ca²⁺ that enters the outer segments of rod and cones via the cGMP-gated channels in darkness. Under bright illumination,

NCKX quickly lowers cytosolic Ca²⁺ and initiates a negative feedback loop that mediates the process of light adaptation. In bovine rod photoreceptors, a rod NCKX1 dimer has been shown to form a complex with the rod cGMP-gated channel heteromultimer.^{37,49}

In summary, calcium ions are of fundamental importance for cell function, and consequently, calcium concentrations are spatially and temporally controlled by a plethora of calcium handling proteins. The remainder of this book will focus in detail on one family of calcium permeant proteins—voltage-gated calcium channels.

Notes

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References

- 1. Bjorkman T, Cleland RE. The role of extracellular free-calcium gradients in gravitropic signaling in maize roots. Planta 1991; 185:379-384.
- 2. Williams RJ. Calcium. Methods Mol Biol 2002; 172:21-49.
- Williams RJ. Calcium: The Developing Role of its Chemistry in Biological Evolution. In: Carafoli E, Klee C, eds. Calcium as a Cellular Regulator. New York: Oxford University press, Inc., 1999:3-27.
- Blaustein MP, Golovina VA. Structural complexity and functional diversity of endoplasmic reticulum Ca(2+) stores. Trends Neurosci 2001; 24(10):602-608.
- 5. Verkhratsky A, Toescu EC. Calcium and neuronal ageing. Trends Neurosci 1998; 21(1):2-7.
- 6. Parekh AB. Calcium signaling and acute pancreatitis: specific response to a promiscuous messenger. Proc Natl Acad Sci USA 2000; 97(24):12933-12934.
- Miyawaki A, Llopis J, Heim R et al. Fluorescent indicators for Ca²⁺ based on green fluorescent proteins and calmodulin. Nature 1997; 388(6645):882-887.
- Ashby MC, Tepikin AV. ER calcium and the functions of intracellular organelles. Semin Cell Dev Biol 2001; 12(1):11-17.
- 9. Carafoli E, Brini M. Calcium pumps: Structural basis for and mechanism of calcium transmembrane transport. Curr Opin Chem Biol 2000; 4(2):152-161.
- 10. Hofer AM, Curci S, Machen TE et al. ATP regulates calcium leak from agonist-sensitive internal calcium stores. FASEB J 1996; 10(2):302-308.
- 11. Petersen OH, Tepikin A, Park MK. The endoplasmic reticulum: one continuous or several separate Ca(2+) stores? Trends Neurosci 2001; 24(5):271-276.
- 12. Terasaki M, Jaffe LA, Hunnicutt GR et al. Structural change of the endoplasmic reticulum during fertilization: Evidence for loss of membrane continuity using the green fluorescent protein. Dev Biol 1996; 179(2):320-328.
- 13. Putney Jr JW, Ribeiro CM. Signaling pathways between the plasma membrane and endoplasmic reticulum calcium stores. Cell Mol Life Sci 2000; 57(8-9):1272-1286.
- Ribeiro CM, Mckay RR, Hosoki E et al. Effects of elevated cytoplasmic calcium and protein kinase C on endoplasmic recticulum structure and function in HEK293 cells. Cell Calcium 2000; 27:175-185.
- 15. Subramanian K, Meyer T. Calcium-induced restructuring of nuclear envelope and endoplasmic reticulum calcium stores. Cell 1997; 89(6):963-971.
- Corbett EF, Oikawa K, Francois P et al. Ca²⁺ regulation of interactions between endoplasmic reticulum chaperones. J Biol Chem 1999; 274(10):6203-6211.
- Jeffery J, Kendall JM, Campbell AK. Apoaequorin monitors degradation of endoplasmic reticulum (ER) proteins initiated by loss of ER Ca(2+). Biochem Biophys Res Commun 2000; 268(3):711-715.
- 18. Warnat J, Philipp S, Zimmer S et al. Phenotype of a recombinant storeoperated channel: highly selective permeation of Ca^{2+} . J Physiol 1999; 518:631-638.
- 19. Pozzan T, Magalhaes P, Rizzuto R. The comeback of mitochondria to calcium signaling. Cell Calcium 2000; 28(5-6):279-283.
- 20. Rizzuto R, Bernardi P, Pozzan T. Mitochondria as all-round players of the calcium game. J Physiol 2000; 529:37-47.
- 21. Duchen MR. Mitochondria and calcium: from cell signalling to cell death. J Physiol 2000; 529:57-68.

- 22. Duchen MR. Mitochondria and Ca(2+)in cell physiology and pathophysiology. Cell Calcium 2000; 28(5-6):339-348.
- Sparagna GC, Gunter KK, Sheu SS et al. Mitochondrial calcium uptake from physiological-type pulses of calcium. A description of the rapid uptake mode. J Biol Chem 1995; 270(46):27510-27515.
- 24. Mitchell P, Moyle J. Chemiosmotic hypothesis of oxidative phosphorylation. Nature 1967; 213(72):137-139.
- 25. Maechler P, Wollheim CB. Mitochondrial signals in glucose-stimulated insulin secretion in the beta cell. J Physiol 2000; 529:49-56.
- 26. Tinel H, Cancela JM, Mogami H et al. Active mitochondria surrounding the pancreatic acinar granule region prevent spreading of inositol trisphosphate-evoked local cytosolic Ca(2+) signals. EMBO J 1999; 18(18):4999-5008.
- 27. Belan PV, Kostyuk PG, Snitsarev VA et al. Calcium clamp in single nerve cells. Cell Calcium 1993; 14(6):419-425.
- Pottorf WJ, Duckles SP, Buchholz JN. Mechanisms of calcium buffering in adrenergic neurones and effects of ageing: Testing the limits of homeostasis. J Auton Pharmacol 2000; 20(2):63-75.
- 29. Ushio H, Watabe S. Carp parvalbumin binds to and directly interacts with the sarcoplasmic reticulum for Ca²⁺ translocation. Biochem Biophys Res Commun 1994; 199(1):56-62.
- Mitchell RD, Simmerman HK, Jones LR. Ca²⁺ binding effects on protein conformation and protein interactions of canine cardiac calsequestrin. J Biol Chem 1988; 263(3):1376-1381.
- Michalak M, Corbett EF, Mesaeli N et al. Calreticulin: One protein, one gene, many functions. Biochem J 1999; 344:281-292.
- 32. Mogami H, Gardner J, Gerasimenko OV et al. Calcium binding capacity of the cytosol and endoplasmic reticulum of mouse pancreatic acinar cells. J Physiol 1999; 518:463-467.
- 33. Wu L, Bauer CS, Zhen XG et al. Dual regulation of voltage-gated calcium channels by PtdIns(4,5)P2. Nature 2002; 419(6910):947-952.
- 34. Fill M, Copello JA. Ryanodine receptor calcium release channels. Physiol Rev 2002; 82:893-922.
- 35. Yule DI. Subtype-specific regulation of inositol 1,4,5-trisphosphate receptors: controlling calcium signals in time and space. J Gen Physiol 2001; 117(5):431-434.
- Schuster S, Marhl M, Hofer T. Modelling of simple and complex calcium oscillations. From single-cell responses to intercellular signaling. Eur J Biochem 2002; 269(5):1333-1355.
- 37. Kaupp UB, Seifert R. Cyclic nucleotide-gated ion channels. Physiol Rev 2002; 82(3):769-824.
- 38. North RA. Molecular physiology of P2X receptors. Physiol Rev 2002; 82:1013-1067.
- 39. Zitt C, Halaszovich CR, Lückhoff A. The TRP family of cation channels: probing and advancing the concepts on receptor-activated calcium entry. Prog Neurobiol 2002; 66:243-264.
- 40. Vazquez G, Wedel BJ, St J Bird G et al. An inositol 1,4,5-trisphosphate receptor-dependent cation entry pathway in DT40 B lymphocytes. EMBO J 2002; 21(17):4531-4538.
- 41. Putney JWJ, Broad LM, Braun FJ et al. Mechanisms of capacitative calcium entry. J Cell Sci 2001; 114:2223-2229.
- Mikoshiba K, Hattori M. IP3 receptor-operated calcium entry. Science's STKE: Signal Transduction Knowledge Environment 2000; 2000(51):E1.
- Zylinska I., Soszynski M. Plasma membrane Ca²⁺-ATPase in excitable and nonexcitable cells. Acta Biochimica Polonica 2000; 47(3):529-539.
- Toyoshima C, Nakasako M, Nomura H et al. Crystal structure of the calcium pump of sarcoplasmic reticulum at 2.6 A resolution. Nature 2000; 405(6787):647-655.
- 45. Lee AG, East JM. What the structure of a calcium pump tells us about its mechanism. Biochem J 2001; 356:665-683.
- Blaustein MP, Lederer WJ. Sodium/Calcium Exchange: Its Physiological Implications. Physiol Rev 1999; 79(3):763-854.
- Hilgemann DW, Feng S, Nasuhoglu C. The complex and intriguing lives of PIP2 with ion channels and transporters. Science's STKE: Signal Transduction Knowledge Environment 2001; 2001(111):RE19.
- Prinsen CFM, Szerencsei RT, Schnetkamp PPM. Molecular cloning and functional expression the potassium-dependent sodium-calcium exchanger from human and chicken retinal cone photoreceptors. J Neurosci 2000; 20(4):1424-1434.
- Poetsch A, Molday LL, Molday RS. The cGMP-gated channel and related glutamic acid-rich proteins interact with peripherin-2 at the rim region of rod photoreceptor disc membranes. J Biol Chem 2001; 276(51):48009-48016.

Monitoring Intracellular Ca²⁺ in Brain Slices with Fluorescent Indicators

Sean J. Mulligan and Brian A. MacVicar

Introduction

I maging fluorescent chemical indicators specific for calcium (Ca^{2+}) has provided important insights into our current understanding of the many Ca^{2+} regulated cellular processes in the brain such as neurotransmitter release and synaptic plasticity. In this chapter we discuss the use of fluorescent Ca^{2+} indicators for the measurement of intracellular concentrations ($[Ca^{2+}]_i$) in brain slices. Single-wavelength intensity-modulating indicators are contrasted with dual-wavelength ratiometric indicators and high versus low-affinity indicators are described. The advantages and disadvantages of using a particular indicator form (free acid, AM-ester or dextran conjugate) for reliable Ca^{2+} imaging are outlined. Finally, we review calibration methods to estimate intracellular $[Ca^{2+}]$ from both nonratiometric and ratiometric indicators. This chapter should provide a guide to how and when to use various Ca^{2+} sensitive fluorescent indicators to map the spatio-temporal dynamics of intracellular $[Ca^{2+}]$ in brain slices.

Ca²⁺ Sensitive Fluorescent Chemical Indicators

Our current understanding of the numerous Ca^{2+} regulated physiological cellular phenomena in the brain has been greatly facilitated by the use of the Ca^{2+} sensitive fluorescent chemical probes developed by Tsien and colleagues.¹⁻¹⁰ The most widely used fluorescent indicators for intracellular measurement of free Ca^{2+} concentration ($[Ca^{2+}]_i$) are based on the Ca^{2+} chelator 1,2-bis-(2-aminophenoxy)ethane-*N*,*N*,*N*__,*N*__-tetraacetic acid (BAPTA) (Fig. 1). BAPTA has high selectivity for Ca^{2+} (K_d \approx 100nM at pH 7.0) over competing concentrations of Mg²⁺ and an extremely fast on rate (10^{8} - $10^{9}M^{-1}S^{-1}$) for Ca^{2+} binding. The main Ca^{2+} sensitive fluorescent indicators are obtained by coupling different fluorophores with varying spectral properties to the Ca^{2+} sensor BAPTA. The binding of Ca^{2+} to these Ca^{2+} sensitive indicators alters the excitation or emission spectra such that the fluorescence of the indicator that binds the Ca^{2+} can be easily distinguished from the fluorescence of the indicator that means Ca^{2+} free. The most useful fluorescent probes are those with large molar extinction coefficients and quantum yields that exhibit strong and stable fluorescence well above any background tissue autofluorescence. The wide range of Ca^{2+} sensitive indicators now available (www.probes.com) can be divided into several operational classes based on a number of criteria, the advantages and disadvantages of which should be considered when selecting a probe for a particular experiment; 1) single-wavelength intensity-modulating probes vs. dual-wavelength ratiometric probes, 2) Ca^{2+} binding affinity, and 3) indicator form (salt, AM ester or dextran conjugate).

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Figure 1. Chemical structures of the Ca²⁺ chelator BAPTA and the widely used BAPTA based fluorescent indicators quin-2, fura-2, indo-1, fluo-3, rhod-2, and Calcium Green-1. Adapted with permission from Tsien RY. Monitoring Cell Calcium. In: Carafoli E, Klee C, eds. Calcium as a Cellular Regulator. New York: Oxford University Press, 1999:28-54.

Single-Wavelength Probes

Increases in [Ca²⁺]_i result in dramatic increases in the quantum yield of single wavelength probes and hence the intensity of fluorescence emission, while the spectral maxima remain unchanged (i.e., no spectral shift). Fluo-3, rhod-2, and Calcium Green-1 and Calcium Green-2 are examples of commonly used single wavelength Ca^{2+} sensitive indicators that undergo an -100-fold increase in fluorescence emission upon binding Ca^{2+11} (Fig. 2). The high quantum yields characteristic of these single wavelength indicators, serves two important functions when attempting to image [Ca²⁺]; in the fine structures associated with neurons and glial cells in brain slices. First, because all Ca²⁺ indicators bind Ca²⁺, they act as additional buffers in the cell and can significantly alter Ca²⁺ dynamics.¹² In an attempt to measure undistorted changes in [Ca²⁺]; it is necessary to balance the relatively low indicator concentrations needed to best report unaltered dynamics of free [Ca²⁺]; with the need for sufficient fluorescence intensity that is gained with higher indicator concentrations. The high quantum yield of these indicators permits the use of lower dye concentrations to best report [Ca²⁺], dynamics while at the same time still achieving the necessary signal-to-noise for quantitative measurement. Secondly, laser intensity can be attenuated. The benefit of this is several-fold. First, fluorophores in the excited state are more prone to chemical reactions with other molecules and other fluorophores that can result in irreversible destruction or photobleaching, the final product being nonfluorescent.¹³ With laser attenuation, the lifetime of the fluorophore is prolonged. Secondly, fluorophores may not only undergo complete destruction and become nonfluorescent from photodamage, but may remain fluorescent, however unable to report Ca2+ changes. For example, basal fluorescence in the apical dendrites of neocortical neurons has been shown to increase linearly with



Figure 2. The Ca²⁺-dependent fluorescence emission spectra of the single wavelength Ca²⁺ sensitive indicators fluo-3 (A), rhod-2(B), Calcium Green-1(C), and Calcium Green-2(D). These indicators are excited by visible wavelengths of light and undergo dramatic increases in the intensity of fluorescence emission upon binding Ca²⁺ with no spectral shift. Adapted with permission from Molecular Probes.¹¹

cumulative photodamage.¹⁴ The increased basal fluorescence is thought to result from irreversible photo-induced changes in the fluorophores that bind them to the cellular matrix or membranes. The bound fluorophore is molecularly altered and no longer able to report changes but remains fluorescent. Further, laser attenuation increases cell viability by decreasing phototoxic effects to the cell, independent of photodamage to the fluorophore.

An important characteristic of single wavelength Ca^{2+} sensitive indicators is that they are excited by visible wavelengths of light. This makes this class of indicators well-matched for laser scanning microscopy because they are compatible with the standard fluorescein and rhodamine optical filter configurations common to most imaging system set-ups and they do not require the specialized chromatically corrected optical components necessary for use with UV excitation.¹⁵ Most laser-based systems are supplied with visible excitation lasers that are ideal for efficient excitation. The most common being the 488nm argon-ion laser that is optimal for excitation of the popular indicators fluo-3, Ca^{2+} Green-1, Ca^{2+} Green-2 and Oregon Green 488 BAPTA, and the 543 nm helium/neon-ion laser that is well suited to the excitation maxima of the common red-shifted wavelength probes rhod-2 and Ca^{2+} orange. In addition, visible wavelength light is



Figure 3. The Ca^{2+} -dependent fluorescence excitation spectra of fura-2 (left) and the emission spectra of indo-1 (right). Both of these common dual-wavelength ratiometric indicators are excited by UV wavelength light and show fluorescence intensity changes and spectral shifts in their excitation spectra (fura-2) or emission spectra (indo-1) with changing $[Ca^{2+}]$. Adapted with permission from Molecular Probes.¹¹

less cytotoxic than that of UV excitation¹⁶ and minimizes background scattering and the contribution of tissue autofluorescence, because in mammalian cells, intrinsic fluorescence is dominated by proteins and reduced nucleotides that exhibit strong fluorescence after ultraviolet (UV) excitation (for ex; NADH, NADPH; absorption maximum, 340nm; emission maximum, 460nm).¹³ Finally, visible wavelength excited indicators are compatible with photolabile 'caged' Ca^{2+} chelators used for rapidly changing $[Ca^{2+}]_i$ that require UV (-350nm) excitation.^{15,17,18}

Dual-Wavelength Ratiometric Probes

Like the single-wavelength probes, the ratiometric probes also show fluorescence intensity changes with changing $[Ca^{2+}]$. Unlike the single-wavelength probes however, the spectral maxima of the Ca^{2+} -free and the Ca^{2+} -bound forms of the ratiometric probes are at different wavelength locations (i.e.; they exhibit a spectral shift). The two most commonly used ratiometric indicators are fura-2 and indo-1.¹ Both these indicators are excited by UV wavelength light with resultant emission in the visible spectrum. They display Ca^{2+} dependent spectral shifts in either their excitation spectra in the case of fura-2, or emission spectra in the case of indo-1 (Fig. 3). The Ca^{2+} -free form of fura-2 displays high fluorescence emission intensity (collected at ~510 nm) when excited by 380nm wavelength light and low emission intensity upon binding Ca^{2+} . Reciprocal changes occur in fluorescence emission intensity when fura-2 is excited at 340nm wavelength light (i.e.; fluorescence emission intensity is low in the Ca^{2+} -free form and highest upon binding Ca^{2+}). In contrast, indo-1 is excited at a single wavelength of light (-340 nm) and the fluorescence intensity monitored at two emission wavelengths. The emission spectral maxima of indo-1 shifts from -480 nm in the Ca^{2+} -free form to -400 nm when the indicator is saturated with Ca^{2+} .

Because this class of indicators exhibit Ca^{2+} dependent spectral shifts, fluorescence intensity measurements can be made at two different wavelengths of the spectrum and a ratio calculated to determine $[Ca^{2+}]_i$ (see below). The ratiometric measurements are independent of the fluorescence intensity changes that arise from confounding factors unrelated to changes in $[Ca^{2+}]_i$ such as variations in indicator concentration, cell thickness, focal plane, cell volume or movement, and photobleaching effects to the probe. This fact makes the ratiometric indicators powerful tools for monitoring and quantifying Intracellular $[Ca^{2+}]$. Ratiometric imaging of $[Ca^{2+}]_i$ in brain slices using fura-2 has greatly increased our understanding of the spatio-temporal dynamics of $[Ca^{2+}]_i$ in fine neuronal structures such as dendrites¹⁹⁻²⁴ and presynaptic terminals.²⁵⁻³⁰

	Ca ²⁺ Free		Ca ²⁺ Bound		
Indicator	Excitation	Emisson	Excitation	Emisson	Κ _D μΜ
High-Affinity Indica	tors				
Fluo-3	503		506	526	0.39
Ca ²⁺ Green-1	506	531	506	531	0.19
Ca ²⁺ Green-2	506	536	503	536	0.55
Oregon Green 488 BAPTA-1	494	523	494	523	0.17
Rhod-2	548		552	578	0.57
Ca ²⁺ Orange	549	575	549	576	0.185
Fura-2	363	512	335	505	0.145
Indo-1	346	475	330	401	0.23
Low-Affinity Indicat	tors				
Mag-Fura-2	369	511	329	508	25
BTČ	464	533	401	52 9	7
Mag Fura-5	369	505	330	500	28
Magnesium Green	506	531	506	531	6
Ca Green-5N	506	532	506	532	14

Table 1. Properties of commonly used high- and low-affinity Ca²⁺ indicators

Ca²⁺ Binding Affinity

Fluorescent Ca^{2+} indicators bind Ca^{2+} in a reversible manner and as a result act as Ca^{2+} buffers once introduced into cells. These exogenous buffers can significantly alter Ca²⁺ dynamics.^{12,27,28,31-34} In order to reduce the buffering effects on Ca²⁺ signals, an important criterion for selecting an indicator is matching the Ca²⁺ binding affinity of the indicator to the range of interest over which [Ca²⁺]_i changes occur during a particular experiment. Ca²⁺ concentrations in astrocytes have been shown to be elevated to 3.5 μ M with dopamine application³⁵ and estimates of Ca²⁺ concentrations exceeding 200 µM have been reported at the inner membrane surface next to voltage-gated Ca²⁺ channel clusters (Ca²⁺ microdomains) in the presynaptic terminals of neurons during stimulation.³⁶ The common Ca²⁺ indicators mentioned above belong to the high-affinity class of fluorescent Ca²⁺ indicators, having KD's in the nanamolar range (Table 1). These high-affinity indicators greatly underestimate the increases in $[Ca^{2+}]_i$ during 'physiological' stimulation typically seen in neurons and astrocytes because Ca2+ concentrations above 1 µM produce almost complete binding saturation.¹¹ For example, in the apical dendrites of neocortical layer V and hippocampal CA1 pyramidal neurons in rat brain slices, the amplitude of a single action potential evoked fluorescence transient was reduced by a factor of about three with just 125µM Fura-2.12 The situation is equally dramatic at the presynaptic terminal. During trains of action potential evoked $[Ca^{2+}]_i$ increases, the fluorescence changes per spike decreased markedly during the train using high-affinity indicators such as Fura-2 and Calcium-Green-2^{27,28,33} (Fig. 4 top). The [Ca²⁺]; increases during the train saturate the responses of the indicators and thus the fluorescence transient is not linearly related to the changes in [Ca²⁺]; and accurate quantification is not possible (given that an equal amount of Ca^{2+} enters the presynaptic terminal with each stimulus in the train (300 nM₃).²⁷

Low-affinity Ca^{2+} indicators have been developed that have greatly improved our ability to more accurately follow and quantify the activity evoked $[Ca^{2+}]$; changes in neurons and astrocytes in brain slice preparations. Mag-fura-2,³⁷ mag fura-5,³⁸ BTC,³⁹ Magnesium Green,¹¹ and Calcium-Greeen-5N⁴⁰ are some of the most widely used low-affinity Ca²⁺ indicators that can detect $[Ca^{2+}]$; levels in the micromolar range (Table 1). The spectral shifts of the Fura-2



Figure 4. High-affinity Ca^{2+} indicators distort rapid Ca^{2+} changes. During trains of action potential evoked $[Ca^{2+}]_i$ increases (20Hz stimulus pulses indicated by double-arrows), the fluorescence changes per spike decrease markedly due to saturation of the high-affinity indicator Fura-2. The $[Ca^{2+}]_i$ increases do not saturate the response when the low-affinity indicator mag-fura-2 is used. Each stimulus in the train produces approximately the same change in fluorescence and thus the fluorescence transient is linearly related to the changes in $[Ca^{2+}]_i$. In addition, the decay time course of the Ca^{2+} transients using the low-affinity indicator mag-fura-2 is undistorted. Reprinted with permission from Molecular Probes¹¹ and Regehr WG, Atluri PP, Calcium transients in cerebellar granule cell presynaptic terminals. Biophys J 1995; 68(5):2156-70.

analogs mag-fura-2 and mag-fura-5 are very similar to those of fura-2 but occur at higher Ca²⁺ concentrations (K_D's \approx 25 µM and 28 µM respectively). BTC exhibits a shift in excitation maximum from ~480 nm to ~400 nm upon binding Ca²⁺ which makes it the only low-affinity ratiometric indicator (K_d \approx 7 µM) with visible excitation wavelengths. BTC thus permits ratiometric measurements of [Ca²⁺]_i while retaining the advantages associated with using longer wavelength excitation (outlined above). The spectral properties of the single-wavelength low-affinity Calcium-Green analoges Calcium Green-5N and Magnesium Green are the same as Calcium Green-1 but have K_D's \approx 14 µM and 6 µM respectively.

In addition to underestimating increases in $[Ca^{2+}]_i$, high-affinity Ca^{2+} indicators significantly distort the kinetics of rapid Ca^{2+} changes associated with the physiological processes that operate on millisecond time scales in neurons and astrocytes. Both the high- and low-affinity classes of fluorescent indicators have Ca^{2+} binding on-rates in the range of $10^8-10^9 M^{-1}s^{-1}$. They differ significantly however with respect to their off-rates. Low-affinity indicators have much faster Ca^{2+} dissociation rates that make them much more suitable for tracking the kinetics of rapid Ca^{2+} fluxes (the backward rate constants (k-) for Fura-2 and Mag-Fura2 are $-100s^{-1}$ and $26,000s^{-1}$ respectively). For example, the decay time constants of fluorescent transients evoked by single back-propagating action potentials in the apical dendrites of neocortical and hippocampal CA1 neurons increased dramatically with increasing concentrations of the high-affinity indicator Fura-2.^{12,41} Fura-2 concentrations of 20, 80 125, and 250 µM corresponded to decay time constants of 78, 117, 265 and 703 msec respectively.¹² In contrast, in a study with parallel experimental procedures, high concentrations (up to 2mM) of the low-affinity indicators Magnesium Green and Oregon green BAPTA-5N did not distort the decay time course of action potential evoked [Ca²⁺]_i transients, but in fact, were faster than the predicted 'physiological' [Ca²⁺]; transient (estimated from linear regression extrapolation to zero fura-2, during Fura-2 concentration dependence of decay time constant experiments).²⁴ At the presynaptic terminal the properties of the fluorescent transients also depend on the affinity of the indicator used. As discussed above, during trains of action potential evoked [Ca²⁺]_i increases, the fluorescence changes per spike decrease markedly during the trains using high-affinity indicators such as fura-2 and Calcium-Green-2 (Fig. 4 top). However, the [Ca²⁴]_i increases during trains did not saturate the response when low-affinity indicators were used. Each stimulus in the train produced approximately the same change in fluorescence and thus the fluorescence transient is linearly related to the changes in $[Ca^{2+}]_i$ and accurate quantification is possible.^{27,28,33} (Fig. 4 bottom) The slow Ca²⁺ binding off-rates of the high-affinity indicators make them unable to reliably track the decay time course of the Ca2+ transients in presynaptic terminals27,28,33,42 (Fig. 4 for qualitative decay comparison). At climbing fiber presynaptic terminals, single action potential evoked Calcium Green fluorescent transients decayed with a half decay time of 168 msec compared to only 33 msec with the novel low-affinity indicator Fluo-4 Dextran.⁴³

Ca²⁺ Indicator Form

Salts (Free Acids)

The common salt (or free acid) form of the Ca²⁺ indicators are negatively charged polycarboxylate anions that are membrane impermeant and so must be introduced into cells by microinjection. Because this form of the indicator is negatively charged, cells may be filled by iontophoretic injection using high resistance sharp electrodes (50-150 M Ω) that contain millimolar indicator concentrations.^{22,44,45} Cells are rapidly filled with indicator using this technique while the intracellular environment is not dialyzed with pipette solutions (hyperpolarizing at -0.2-0.5nA for 2-5 minutes loads an entire neocortical pyramidal cell with indicator).⁴⁶ Patch-clamping neurons and astrocytes in brain slices in the whole-cell configuration⁴⁷ with low resistance pipettes (3-10 M Ω) has become the preferred method for loading impermeant indicators into cells and simultaneously making electrophysilogical measurements. Micromolar concentrations of indicator (50-500 μ M) are loaded by the rapid diffusional exchange that takes place between the low resistance pipette tip and the intracellular cytoplasm.⁴⁸ This allows for defined intracellular indicator concentrations to be determined, which is a critical parameter in indicator calibrations (see below). The great advantage of using the free acid indicator form (in addition to avoiding the problems associated with using the AM-ester form -see below) is the remarkable fluorescence signal-to-noise achieved. Images from the finest neuronal structures are possible, including individual dendritic spines, axons and presynaptic terminals, and the Ca²⁺ transients in these structures can be reliably quantified (Fig. 5A,B).^{29,30,49-53}

Dextran Conjugates

Fluorescent Ca^{2+} indicators may be conjugated to dextrans, which are 3000 to 500,000 MW biologically inert hydrophilic polysaccharides. As with the salt forms, dextran conjugates are not membrane permeable and so must gain intracellular access by whole-cell patch pipette. Iontophoretic injection is not suitable because there is a reduction in the negative charge per unit mass. While the spectral characteristics of the dextran conjugates are similar to the free acid forms, the Ca²⁺ binding affinity is slightly reduced. For example, the K_D of the salt form of Fura-2 is 145 nM compared to 200-400 nM for Fura-2 dextran.¹¹ Molecular probes (Eugene,



Figure 5. Neurons and astrocytes in the brain slice preparation loaded with the free acid, dextran conjugate, or AM-ester forms of Ca2+ sensitive indicators. A) Two-photon image of a pyramidal neuron dendrite with spines from mouse visual cortex filled with 200 µM of the free acid form of Calcium Green-1 by whole cell patch pipette. (scale=5 µm) Reprinted with permission from Holthoff K, Tsay D, Yuste R. Calcium dynamics of spines depend on their dendritic location. Neuron. 2002 Jan 31;33(3):425-37. B) Two-photon image of an axonal arbor of a layer 2/3 neocortical pyramidal neuron filled with 100 µM of the free acid form of Oregon BAPTA-1 via patch pipette. (scale=1 µm) Reprinted with permission from Cox CL, Denk W, Tank DW, Svoboda K. Action potentials reliably invade axonal arbors of rat neocortical neurons. Proc Natl Acad Sci U S A 2000; 97(17):9724-8. C) An overlay of two confocal image stacks in a sagital cerebellar slice showing a Calcium Green Dextran-labeled climbing fiber incoming axon (white) innervating the thick proximal dendrites of a Purkinje neuron (grey) labeled with the fluorescent dye Alexa Fluor 568 hydrazide (Molecular Probes). (scale=20 µm) Reprinted with permission from Kreitzer AC, Gee KR, Archer EA, Regehr WG. Monitoring presynaptic calcium dynamics in projection fibers by in vivo loading of a novel calcium indicator. Neuron. 2000; 27(1):25-32. D) Dozens of neurons in layer 2/3 somatosensory cortex are labeled with the AM-ester form of Fura-2. The brain slice was taken from an 18 day old rat. (scale=100 μ m) Reprinted with permission from Smetters D, Majewska A, Yuste R. Detecting action potentials in neuronal populations with calcium imaging. Methods. 1999;18(2):215-21. E) Two-photon image stack f GFP labeled astrocytes (left) loaded with Ca^{2+} Orange-AM (right). (scale=20 μ m). Mulligan and MacVicor unpublished observations.

OR) offers a 70,00MW dextran simultaneously conjugated to Calcium Green-1 and the Ca^{2+} -insensitive dye Texas Red that provides ratiometric Ca^{2+} measurements with visible wavelength excitation. Dextran-conjugated Ca^{2+} indicators retain all the advantages the salt form indicators have over AM-ester forms, and in addition, are much less likely to bind to cellular proteins and are better retained in cells and less resistant to extrusion.¹¹ The fact that they do not leak out of cells makes them ideally suited for long-term Ca^{2+} measurements and excellent retrograde and anterograde tracers.^{54,55} Krietzer et al (2000)⁴³ have loaded dextrans in to the cellular nuclei of the inferior olive in vivo, and monitored Ca^{2+} dynamics days later in presynaptic terminals at the cerebellar climbing fiber to Purkinje cell synapse (Fig. 5C).

AM-Esters

Loading neurons and astrocytes in brain slices can be achieved without the use of micropipettes for indicator injection and disruption to cell membranes. The negative charged carboxylate groups of the salt and dextran-conjugated forms of Ca^{2+} indicators that render them hydrophilic and cell impermeant, may be derivatized as acetoxymethyl (AM) –esters.⁵ The AM-ester form of the Ca^{2+} indicator is lipophilic, membrane-permeant and insensitive to ions. Incubation of brain slices in a solution of the AM-ester form results in cellular loading by diffusion through the cell membrane. Once inside the cells, the acetyl-ester linkages are then hydrolyzed by intracellular esterases to release the active Ca^{2+} sensitive indicator, which is now membrane-impermeant and trapped in the cytoplasm.

The advantage of using the AM-ester form of indicator, is that it facilitates the bulk loading of many cells or many specific cellular structures, while avoiding delicate intracellular microelectrode techniques required for loading the salt and dextran-conjugate forms. This method then, provides a way of monitoring intracellular Ca²⁺ dynamics in many neurons (or neuronal processes) and astrocytes in a brain slice. For example, Yuste and colleagues have been able to bulk load AM-ester forms of Ca²⁺ indicators into populations of neurons in brain slices and image somatic Ca²⁺ transients (Fig. 5D).⁵⁶⁻⁵⁸ By stimulating one excitatory neuron while imaging hundreds of others they are able to identify connected neurons and begin to explore cortical microcircuitry. Regehr and Tank (1991)⁵⁹ developed a method for selectively filling presynaptic terminals in adult brain slices by localized perfusion with the AM-ester form of Fura-2. They and others have used this method to image presynaptic Ca²⁺ transients and have greatly contributed to our current understanding of the role of Ca²⁺ in synaptic transmission at central synapses.^{26-28,42,60-67} Astrocytes in brain slices are readily loaded with AM-esters (Fig. 5E). Results from studies monitoring Ca²⁺ transients in AM-ester loaded astrocytes has forced us to expand our current view of the functional roles astrocytes play in theø central nervous system. For example, it is now believed that astrocytes are involved in activity-dependent modulation of synaptic transmission and that spontaneous intrinsic Ca^{2+} oscillations in astrocytes can propagate and act as a primary source for generating neuronal activity.^{68,69}

There are a number of pitfalls of using AM-ester Ca^{2+} indicators. First and foremost there is a dramatic reduction in the cellular fluorescence signal-to-noise over background compared with the intracellular injected forms due to nonspecific loading and indicator that remains extracellular but fluorescent. Another major problem is incomplete hydrolysis of the esters. The fully esterfied form of Fura-2 for example contains five AM groups linked to the carboxylate groups.¹¹ If there is not complete hydrolysis of all five groups a new form that is Ca^{2+} insensitive yet highly fluorescent remains.⁷⁰ Incomplete hydrolysis can also result in sequestering or compartmentalization inside the cell.^{71,72} If the cell has low esterase activity and slow de-esterification results, the indicator is able to move freely from the cytoplasm and into intracellular organelles such as mitochondria, sarcoplamic reticulum, lysosomes and the nucleus where it then becomes cleaved and remains trapped there but unable to report cytoplasmic Ca^{2+} changes.⁷³ Extrusion across the plasma membrane by the multidrug resistance transporter is also a problem that is specific to the AM form but not the free acid or dextran forms.⁷⁴ The above problems make it virtually impossible to perform quantitative indicator calibrations in vivo (see below). A final complication of the AM-ester form is that the successful loading of neurons is highly age dependent. Indeed, few labs have been able to load any neurons in adult brain slices (but esee ref. 56).

Quantitative Measurement of [Ca²⁺]_i

Ratiometric Calibration

The best quantitative descriptions of $[Ca^{2+}]_i$ can be achieved when using dual-wavelength ratiometric dyes, such as fura-2, because fluorescence measurements can be made at two different wavelengths and a ratio calculated to determine $[Ca^{2+}]_i$ independent of the fluorescence intensity changes that arise from confounding factors unrelated to changes in $[Ca^{2+}]_i$, such as variations in indicator concentration, cell thickness, focal plane, cell volume or movement, photobleaching effects to the probe, and instrument sensitivity. The relationship between $[Ca^{2+}]_i$ and the experimentally measured fluorescence is described in the calibration equation given by Grynkiewicz et al (1985);

$$[Ca^{2+}]_i = K_D (R-R_{min}/R_{max}-R) (S_{f2}/S_{b2})$$

For Fura-2, K_D is the dissociation constant of Fura-2, R is the background corrected experimentally measured ratio of fluorescence intensity produced by 340 nm and 380 nm excitation, R_{min} is the ratio at 0 [Ca²⁺]_i, R_{max} is the ratio at a saturating [Ca²⁺], and S_{f2}/S_{b2} is the ratio of the fluorescence intensities in 0 [Ca²⁺] and saturating [Ca²⁺]. To determine R_{min} , R_{max} , and S_{f2}/S_{b2} , in vitro or in vivo calibrations must be performed and requires that the K_D for the indicator be known. These calibrations entail using a set of buffer solutions of known [Ca²⁺], and are available in 'Kit' form from Molecular Probes. When doing calibrations, it is again important to consider the Ca²⁺ binding affinity of the indicator. Kits for high-affinity Ca²⁺ indicators contain 10 mM K₂EGTA and 10 mM CaEGTA buffered solutions that provide a range of "zero" free Ca²⁺ to 40 μ M free Ca²⁺. Solutions for low-Affinity Ca²⁺ Indicator calibration provide a range from 1 μ M to 1 mM free Ca²⁺. The choice of whether to do an in vitro or in vivo calibration will depend on the indicator loading technique used during the experiment, i.e.; bulk loading with AM-esters or whole-cell patch pipette.

AM ester-loading indicators require calibrations to be performed in vitro, under conditions that closely mimic experimental conditions. Incomplete hydrolysis of the AM-ester, indicator compartmentalization, and ineffective access of ionophores (used to equilibrate $[Ca^{2+}]_i$ with buffers of known Ca^{2+} concentrations) into regions within brain slices, as well as indicator leakage from the cells when permeabilized all make in vivo calibration impractical.^{26,11} In vitro calibrations suffer however, from the fact that the spectral properties of the indicator are altered by the pH, ionic strength, intracellular binding and uptake and viscosity of the cytoplasmic environment and thus do not represent in vivo conditions.^{72,75} In an attempt to correct viscosity, a viscosity correction (0.7-0.85) may be applied.⁷⁶ In vivo calibrations are possible when indicator loading with whole-cell patch pipettes because the pipette has direct access to the intracellular environment and thus circumvents the problems associated with using ionophores for the equilibration of internal and external $[Ca^{2+}]$.⁴⁸ During these calibrations, standard intracellular patch solutions are loaded to different known $[Ca^{2+}]$ levels, the fluorescence ratios experimentally measured and the parameters R_{min} , R_{max} , and S_{12}/S_{b2} determined.

Single-Wavelength Calibration

Single-wavelength indicators are fluorescence intensity modulating probes and so do not allow for wavelength ratioing. As an alternative, when imaging $[Ca^{2+}]_i$ in neurons and astrocytes in brain slices it is typical to report $[Ca^{2+}]_i$ changes in normalized terms of relative florescence changes over the baseline fluorescence level, commonly known as $\Delta F/F.^{51,50,69,77-80}$

Defined as;

$$\Delta F/F = ((F_1 - B_1) - (F_0 - B_0))/(F_0 - B_0)$$
where F_1 and F_0 are fluorescence in the imaged region of interest at any given time point and at the beginning of the experiment respectively, and B_1 and B_0 are the background fluorescence at any given time point and at the beginning of the experiment respectively. Background values are taken from an adjacent area distant to any indicator-containing structures. Although reporting $[Ca^{2+}]_i$ changes in terms of $\Delta F/F$ does not allow for quantitative molar measurement of $[Ca^{2+}]_i$, it is independent of indicator concentration, optical path and imaging sensitivity and is useful for reporting relative changes, induced for example by drug application. To accurately assess relative $[Ca^{2+}]_i$ changes however, it is necessary to show that the fluorescent transients are linearly related to the changes in $[Ca^{2+}]_i$. This condition is best met by using low-affinity indicators, as saturation of high-affinity indicators occurs during most physiological increases in $[Ca^{2+}]_i$ at typical indicator concentrations used and results in nonlinear changes.^{12,27,28,51,56,81,82}

In theory, fluorescence signals from single wavelength indicators can be converted to $[Ca^{2+}]_i$ by the equation given by Grynkiewicz et al (1985);

$$[Ca^{2+}]_i = K_D (F - F_{\min}/F_{\max} - F)$$

where K_D is the dissociation constant of the indicator, F is the background subtracted experimentally measured fluorescence intensity, F_{min} is the fluorescence intensity at 0 $[Ca^{2+}]_i$, and F_{max} is the fluorescence intensity at a saturating a $[Ca^{2+}]$. Analogous to the situation using ratiometric indicators, the indicator K_D must be known and F_{min} and F_{max} determined from calibrations with solutions of known $[Ca^{2+}]$. F_{min} and F_{max} can only be reliably established in an in vitro setting at the same indicator concentration, optical pathlength and without any photobleaching or change in instrument sensitivity because the great variability in these requirements makes performing in vivo calibrations not practical. Quantitative measurements of intracellular Ca^{2+} concentrations may be determined from single wavelength indicators in vivo however, if coloaded with another indicator of a differing wavelength. For example, because the single-wavelength indicators Fluo-3 and Fura Red exhibit reciprocal shifts in fluorescence intensity upon binding Ca^{2+} , ratiometric measurements of $[Ca^{2+}]_i$ are possible.^{83,84} Simply coloading single-wavelength Ca^{2+} indicators with Ca^{2+} -insensitive indicators that are excited at the same wavelengths, but detected at much longer wavelengths can also be done to make ratiometric measurements possible.

Changes in calcium concentration $(\Delta[Ca^{2+}]_i)$ can be quantified by two methods with single-wavelength indicators, one method for use with low-affinity Ca²⁺ indicators and the other for use with high-affinity indicators. The method appropriate for use with low-affinity indicators is based on the relative florescence changes over baseline fluorescence levels ($\Delta F/F$). Fluorescence intensity changes can be converted to changes in $[Ca^{2+}]_i$ using the following formula;⁸⁵

$$(\Delta [Ca^{2+}]_i = (K_D / (\Delta F/F)_{max}) (\Delta F/F) (\Delta F/F << (\Delta F/F)_{max})$$

where, the parameters are the same as above and $(\Delta F/F)_{max}$ is the maximal change in fluorescence upon indicator saturation, which can be estimated in neurons using strong stimulation. The formula is only applicable if the indicator is far from saturation during evoked changes in $[Ca^{2+}]_i$, a condition met with low-affinity Ca^{2+} indicators. The method appropriate for use with high-affinity indicators is derived from the nonlinear dependence of fluorescence on $[Ca^{2+}]_i$ caused by high-affinity indicator saturation. Two closely timed stimulation pulses produces fluorescent transients (for example, action potential evoked Ca^{2+} influx into dendritic spines⁷⁷ or presynaptic terminals,^{55,85} the second of which is smaller than the first when loaded with high-affinity Ca^{2+} indicators but not low-affinity indicators.^{27,33,55,77,85} This indicates that partial saturation of the high-affinity indicators is responsible for the $\Delta F/F$ decrements and enable quantification of changes in intracellular Ca^{2+} influx ($\Delta [Ca^{2+}]_i$) per action potential using the following formula;

$$\Delta [Ca^{2+}]_{i} = ([Ca^{2+}]_{0} + K_{D}) (1 - \alpha) / 2\alpha$$





Figure 6. Quantification of changes in intracellular Ca^{2+} influx per action potential is possible using high-affinity indicators. Two closely timed stimulation pulses produces fluorescent transients in a CA1 neuron, the second of which is smaller than the first when loaded with the high-affinity Ca^{2+} indicator Calcium Green-1 (500 μ M)(left), but not with the low-affinity indicator Magnesium Green (500 μ M)(right). See accompanying text for explanation of symbols. Reprinted with permission from Yuste R, Majewska A, Cash SS, Denk W. Mechanisms of calcium influx into hippocampal spines: heterogeneity among spines, coincidence detection by NMDA receptors, and optical quantal analysis. J Neurosci 1999; 19(6):1976-87.

where $\alpha = (F_3 - F_2) / (F_1 - F_0)$ and $[Ca^{2+}]_0$ is the estimated resting Ca^{2+} concentration, K_D is the dissociation constant of the indicator, F_0 is the indicator fluorescence at resting $[Ca^{2+}]_0$, F_1 is the peak fluorescence produced by the first action potential, F_2 is the fluorescence immediately before the second action potential, and F_3 is the peak fluorescence produced by the second action potential (Fig. 6 left). Use of this equation to estimate $\Delta[Ca^{2+}]_i$ assumes that the influxes produced by each action potential are the same (as confirmed by low affinity indicators (Fig. 6 right)^{27,33,55,77,85} and that the decay in $[Ca^{2+}]_i$ between action potentials is small compared with the peak $[Ca^{2+}]_i$.

Conclusion

The use of Ca^{2+} sensitive fluorescent indicators has proven to be an indispensable tool for studying the spatio-temporal dynamics of intracellular $[Ca^{2+}]$, which plays a critical role in many cellular processes. In this chapter we have discussed commonly used fluorescent Ca^{2+} indicators for the measurement of intracellular $[Ca^{2+}]$ in neurons and astrocytes in brain slice preparations. By reviewing the properties of the several operational indicator classes and discussing the experimental advantages and disadvantages of each, it is hoped that many of the experimental pitfalls may be avoided when attempting to accurately follow and quantify intracellular $[Ca^{2+}]$ changes.

References

- 1. Grynkiewicz G, Poenie M, Tsien RY. A new generation of Ca^{2+} indicators with greatly improved fluorescence properties. J Biol Chem 1985; 260:3440-3450.
- 2. Minta A, Kao JP, Tsien RY. Fluorescent indicators for cytosolic calcium based on rhodamine and fluorescein chromophores. J Biol Chem 1989; 264:8171-8178.
- Poenie M, Tsien R. Fura-2: A powerful new tool for measuring and imaging [Ca²⁺]i in single cells. Prog Clin Biol Res 1986; 210:53-56.
- Tsien RY. New calcium indicators and buffers with high selectivity against magnesium and protons: design, synthesis, and properties of prototype structures. Biochemistry 1980; 19:2396-2404.
- 5. Tsien RY. A nondisruptive technique for loading calcium buffers and indicators into cells. Nature 1981; 290:527-528.
- Tsien RY, Pozzan T, Rink TJ. Calcium homeostasis in intact lymphocytes: Cytoplasmic free calcium monitored with a new, intracellularly trapped fluorescent indicator. J Cell Biol 1982; 94:325-334.
- 7. Tsien RY. Intracellular measurements of ion activities. Annu Rev Biophys Bioeng 1983; 12:91-116.

- Tsien RY. Measuring and manipulating cytosolic Ca²⁺ with trapped indicators. Kroc Found Ser 1984; 17:147-155.
- Tsien RY, Rink TJ, Poenie M. Measurement of cytosolic free Ca²⁺ in individual small cells using fluorescence microscopy with dual excitation wavelengths. Cell Calcium 1985; 6:145-157.
- 10. Tsien RY. Fluorescent indicators of ion concentrations. Methods Cell Biol 1989; 30:127-156.
- 11. Haugland RP. Handbook of fluorescent probes and research products. In: Oregon E, ed. Molecular Probes, 9th ed. 2002:984 pages.
- 12. Helmchen F, Imoto K, Sakmann B. Ca²⁺ buffering and action potential-evoked Ca²⁺ signaling in dendrites of pyramidal neurons. Biophys J 1996; 70:1069-1081.
- 13. Slavik J. Fluorescent probes in cellular and molecular biology. Boca Ratan: CRC Press, 1994.
- 14. Koester HJ, Baur D, Uhl R et al. Ca²⁺ fluorescence imaging with pico and femtosecond two-photon excitation: signal and photodamage. Biophys J 1999; 77:2226-2236.
- Niggli E, Piston DW, Kirby MS et al. A confocal laser scanning microscope designed for indicators with ultraviolet excitation wavelengths. Am J Physiol 1994; 266:C303-310.
- Brakenhoff GJ, Muller M, Ghauharali RI. Analysis of efficiency of two-photon versus single-photon absorption of fluorescence generation in biological objects. J Microsc 1996; 183:140-144.
- van Koeveringe GA, van Mastrigt R. Photolysis of caged calcium using a low-cost flash unit. Methods Mol Biol 1999; 114:209-220.
- Parpura V, Haydon PG. "Uncaging" using optical fibers to deliver UV light directly to the sample. Croat Med J 1999; 40:340-345.
- 19. Regehr WG, Connor JA, Tank DW. Optical imaging of calcium accumulation in hippocampal pyramidal cells during synaptic activation. Nature 1989; 341:533-536.
- Regehr WG, Tank DW. Postsynaptic NMDA receptor-mediated calcium accumulation in hippocampal CA1 pyramidal cell dendrites. Nature 1990; 345:807-810.
- Larkum ME, Kaiser KM, Sakmann B. Calcium electrogenesis in distal apical dendrites of layer 5 pyramidal cells at a critical frequency of back-propagating action potentials. Proc Natl Acad Sci USA 1999; 96:14600-14604.
- 22. Yuste R, Gutnick MJ, Saar D et al. Ca²⁺ accumulations in dendrites of neocortical pyramidal neurons: an apical band and evidence for two functional compartments. Neuron 1994; 13:23-43.
- Schiller J, Helmchen F, Sakmann B. Spatial profile of dendritic calcium transients evoked by action potentials in rat neocortical pyramidal neurones. J Physiol 1995; 487:583-600.
- Kaiser KM, Zilberter Y, Sakmann B. Back-propagating action potentials mediate calcium signalling in dendrites of bitufted interneurons in layer 2/3 of rat somatosensory cortex. J Physiol 2001; 535:17-31.
- 25. Regehr WG, Tank DW. The maintenance of LTP at hippocampal mossy fiber synapses is independent of sustained presynaptic calcium. Neuron 1991; 7:451-459.
- Regehr WG, Delaney KR, Tank DW. The role of presynaptic calcium in short-term enhancement at the hippocampal mossy fiber synapse. J Neurosci 1994; 14:523-537.
- 27. Regehr WG, Atluri PP. Calcium transients in cerebellar granule cell presynaptic terminals. Biophys J 1995; 68:2156-2170.
- Mintz IM, Sabatini BL, Regehr WG. Calcium control of transmitter release at a cerebellar synapse. Neuron 1995; 15:675-688.
- 29. Wu LG, Borst JG, Sakmann B. R-type Ca²⁺ currents evoke transmitter release at a rat central synapse. Proc Natl Acad Sci USA 1998; 95:4720-4725.
- Wu LG, Westenbroek RE, Borst JG et al. Calcium channel types with distinct presynaptic localization couple differentially to transmitter release in single calyx-type synapses. J Neurosci 1999; 19:726-736.
- Eilers J, Callewaert G, Armstrong C et al. Calcium signaling in a narrow somatic submembrane shell during synaptic activity in cerebellar Purkinje neurons. Proc Natl Acad Sci USA 1995; 92:10272-10276.
- Stout AK, Reynolds IJ. High-affinity calcium indicators underestimate increases in intracellular calcium concentrations associated with excitotoxic glutamate stimulations. Neuroscience 1999; 89:91-100.
- 33. Sinha SR, Wu LG, Saggau P. Presynaptic calcium dynamics and transmitter release evoked by single action potentials at mammalian central synapses. Biophys J 1997; 72:637-651.
- Maravall M, Mainen ZF, Sabatini BL et al. Estimating intracellular calcium concentrations and buffering without wavelength ratioing. Biophys J 2000; 78:2655-2667.
- 35. Parpura V, Haydon PG. Physiological astrocytic calcium levels stimulate glutamate release to modulate adjacent neurons. Proc Natl Acad Sci USA 2000; 97:8629-8634.
- 36. Simon SM, Llinas RR. Compartmentalization of the submembrane calcium activity during calcium influx and its significance in transmitter release. Biophys J 1985; 48:485-498.

- 37. Raju B, Murphy E, Levy LA et al. A fluorescent indicator for measuring cytosolic free magnesium. Am J Physiol 1989; 256:C540-548.
- Illner H, McGuigan JA, Luthi D. Evaluation of mag-fura-5, the new fluorescent indicator for free magnesium measurements. Pflugers Arch 1992; 422:179-184.
- 39. Iatridou H, Foukaraki E, Kuhn MA et al. The development of a new family of intracellular calcium probes. Cell Calcium 1994; 15:190-198.
- Rajdev S, Reynolds IJ. Calcium green-5N, a novel fluorescent probe for monitoring high intracellular free Ca²⁺ concentrations associated with glutamate excitotoxicity in cultured rat brain neurons. Neurosci Lett 1993; 162:149-152.
- Regehr WG, Tank DW. Calcium concentration dynamics produced by synaptic activation of CA1 hippocampal pyramidal cells. J Neurosci 1992; 12:4202-4223.
- Sabatini BL, Regehr WG. Optical measurement of presynaptic calcium currents. Biophys J 1998; 74:1549-1563.
- 43. Kreitzer AC, Gee KR, Archer EA et al. Monitoring presynaptic calcium dynamics in projection fibers by in vivo loading of a novel calcium indicator. Neuron 2000; 27:25-32.
- 44. Helmchen F, Svoboda K, Denk W et al. In vivo dendritic calcium dynamics in deep-layer cortical pyramidal neurons. Nat Neurosci 1999; 2:989-996.
- 45. Svoboda K, Helmchen F, Denk W et al. Spread of dendritic excitation in layer 2/3 pyramidal neurons in rat barrel cortex in vivo. Nat Neurosci 1999; 2:65-73.
- 46. Svoboda KT DW, Stepnoski RA, Denk W. Two-photon imaging of neuronal function in the neocortex in vivo. Imaging neurons: A laboratory manual. R. Yuste, F. Lanni, A. Konnerth ed. New York: Cold Spring Harbor Laboratory Press, 2000: 22.1-22.11.
- 47. Hamill OP, Marty A, Neher E et al. Improved patch-clamp techniques for high-resolution current recording from cells and cell-free membrane patches. Pflugers Arch 1981; 391:85-100.
- Pusch M, Neher E. Rates of diffusional exchange between small cells and a measuring patch pipette. Pflugers Arch 1988; 411:204-211.
- 49. Cox CL, Denk W, Tank DW et al. Action potentials reliably invade axonal arbors of rat neocortical neurons. Proc Natl Acad Sci USA 2000; 97:9724-9728.
- 50. Sabatini BL, Svoboda K. Analysis of calcium channels in single spines using optical fluctuation analysis. Nature 2000; 408:589-593.
- 51. Koester HJ, Sakmann B. Calcium dynamics in single spines during coincident pre and postsynaptic activity depend on relative timing of back-propagating action potentials and subthreshold excitatory postsynaptic potentials. Proc Natl Acad Sci USA 1998; 95:9596-9601.
- 52. Schiller J, Schiller Y, Clapham DE. NMDA receptors amplify calcium influx into dendritic spines during associative pre and postsynaptic activation. Nat Neurosci 1998; 1:114-118.
- 53. Majewska A, Brown E, Ross J et al. Mechanisms of calcium decay kinetics in hippocampal spines: role of spine calcium pumps and calcium diffusion through the spine neck in biochemical compartmentalization. J Neurosci 2000; 20:1722-1734.
- 54. O'Donovan MJ, Ho S, Sholomenko G et al. Real-time imaging of neurons retrogradely and anterogradely labelled with calcium-sensitive dyes. J Neurosci Methods 1993; 46:91-106.
- Mulligan SJ, Davison I, Delaney KR. Mitral cell presynaptic Ca(2+) influx and synaptic transmission in frog amygdala. Neuroscience 2001; 104:137-151.
- Peterlin ZA, Kozłoski J, Mao BQ et al. Optical probing of neuronal circuits with calcium indicators. Proc Natl Acad Sci USA 2000; 97:3619-3624.
- 57. Mao BQ, Hamzei-Sichani F, Aronov D et al. Dynamics of spontaneous activity in neocortical slices. Neuron 2001; 32:883-898.
- Smetters D, Majewska A, Yuste R. Detecting action potentials in neuronal populations with calcium imaging. Methods 1999; 18:215-221.
- 59. Regehr WG, Tank DW. Selective fura-2 loading of presynaptic terminals and nerve cell processes by local perfusion in mammalian brain slice. J Neurosci Methods 1991; 37:111-119.
- 60. Atluri PP, Regehr WG. Determinants of the time course of facilitation at the granule cell to Purkinje cell synapse. J Neurosci 1996; 16:5661-5671.
- 61. Dittman JS, Regehr WG. Contributions of calcium-dependent and calcium-independent mechanisms to presynaptic inhibition at a cerebellar synapse. J Neurosci 1996; 16:1623-1633.
- 62. Chen C, Regehr WG. The mechanism of cAMP-mediated enhancement at a cerebellar synapse. J Neurosci 1997; 17:8687-8694.
- 63. Sabatini BL, Regehr WG. Timing of neurotransmission at fast synapses in the mammalian brain. Nature 1996; 384:170-172.
- 64. Sabatini BL, Regehr WG. Control of neurotransmitter release by presynaptic waveform at the granule cell to purkinje cell synapse. J Neurosci 1997; 17:3425-3435.

- 65. Wu LG, Saggau P. Pharmacological identification of two types of presynaptic voltage- dependent calcium channels at CA3-CA1 synapses of the hippocampus. J Neurosci 1994; 14:5613-5622.
- 66. Wu LG, Saggau P. Adenosine inhibits evoked synaptic transmission primarily by reducing presynaptic calcium influx in area CA1 of hippocampus. Neuron 1994; 12:1139-1148.
- 67. Wu LG, Saggau P. Presynaptic calcium is increased during normal synaptic transmission and paired-pulse facilitation, but not in long-term potentiation in area CA1 of hippocampus. J Neurosci 1994; 14:645-654.
- 68. Parri HR, Gould TM, Crunelli V. Spontaneous astrocytic Ca²⁺ oscillations in situ drive NMDAR-mediated neuronal excitation. Nat Neurosci 2001; 4:803-812.
- 69. Kang J, Jiang L, Goldman SA et al. Astrocyte-mediated potentiation of inhibitory synaptic transmission. Nat Neurosci 1998; 1:683-692.
- Scanlon M, Williams DA, Fay FS. A Ca²⁺-insensitive form of fura-2 associated with polymorphonuclear leukocytes. Assessment and accurate Ca²⁺ measurement. J Biol Chem 1987; 262:6308-6312.
- 71. Williams DA, Fay FS. Intracellular calibration of the fluorescent calcium indicator Fura-2. Cell Calcium 1990; 11:75-83.
- Moore ED, Becker PL, Fogarty KE et al. Ca²⁺ imaging in single living cells: theoretical and practical issues. Cell Calcium 1990; 11:157-179.
- 73. Blatter LA, Wier WG. Intracellular diffusion, binding, and compartmentalization of the fluorescent calcium indicators indo-1 and fura-2. Biophys J 1990; 58:1491-1499.
- Homolya L, Hollo Z, Germann UA et al. Fluorescent cellular indicators are extruded by the multidrug resistance protein. J Biol Chem 1993; 268:21493-21496.
- Konishi M, Olson A, Hollingworth S et al. Myoplasmic binding of fura-2 investigated by steady-state fluorescence and absorbance measurements. Biophys J 1988; 54:1089-1104.
- Poenie M. Alteration of intracellular Fura-2 fluorescence by viscosity: A simple correction. Cell Calcium 1990; 11:85-91.
- 77. Yuste R, Majewska A, Cash SS et al. Mechanisms of calcium influx into hippocampal spines: heterogeneity among spines, coincidence detection by NMDA receptors, and optical quantal analysis. J Neurosci 1999; 19:1976-1987.
- Nett WJ, Oloff SH, McCarthy KD. Hippocampal astrocytes in situ exhibit calcium oscillations that occur independent of neuronal activity. J Neurophysiol 2002; 87:528-537.
- 79. Holthoff K, Tsay D, Yuste R. Calcium dynamics of spines depend on their dendritic location. Neuron 2002; 33:425-437.
- Carter AG, Regehr WG. Prolonged synaptic currents and glutamate spillover at the parallel fiber to stellate cell synapse. J Neurosci 2000; 20:4423-4434.
- Helmchen F, Borst JG, Sakmann B. Calcium dynamics associated with a single action potential in a CNS presynaptic terminal. Biophys J 1997; 72:1458-1471.
- Basarsky TA, Duffy SN, Andrew RD et al. Imaging spreading depression and associated intracellular calcium waves in brain slices. J Neurosci 1998; 18:7189-7199.
- Grondahl TO, Hablitz JJ, Langmoen IA. Depletion of intracellular Ca²⁺ stores or lowering extracellular calcium alters intracellular Ca²⁺ changes during cerebral energy deprivation. Brain Res 1998; 796:125-131.
- 84. Grondahl T, Langmoen IA. Confocal laser scanning microscopy used to monitor intracellular Ca²⁺ changes in hippocampal CA 1 neurons during energy deprivation. Brain Res 1998; 785:58-65.
- Feller MB, Delaney KR, Tank DW. Presynaptic calcium dynamics at the frog retinotectal synapse. J Neurophysiol 1996; 76:381-400.

CHAPTER 3

A Brief History of Calcium Channel Discovery

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The Key Role of Ca²⁺ Channels in Cellular Signaling

The Stretch Reflex Exemplifies the Importance of Electrical-to-Chemical Transduction

The stretch reflex represents the best-known and longest studied neural circuit. Unlike sensory circuits, for example in the visual system, the stretch reflex connects an external input to a behavioral output, both mechanical in nature, and is thus easily demonstrable without technical equipment. It provides an extremely reliable input-output relationship—hence, our view of the "knee-jerk" reaction as the epitome of automatic behavior. Yet, the underlying physiology of this stretch reflex is not so simple. Indeed, it consists of an extensive chain of events, characterized by many conversions between mechanical, electrical and chemical forms of energy, complex enough to rival a contraption by Rube Goldberg (Fig. 1). The stretch reflex invokes the burgeoning fields of excitation-secretion coupling and excitation-contraction coupling. Fortunately, after decades of study (and several Nobel Prizes, the most recent in 2003), the chain of causality between a tap on the tendon and the subsequent knee jerk is now understood in considerable detail. At three stages—two electro-chemical synapses and one electro-mechanical transducer—electrical impulse spread is linked to the flow of calcium ions, and, in one way or another, that flow of Ca2+ is controlled by Ca2+ channels. These Ca2+ channels do not function in isolation-rather, they work in coordination with other varieties of ion channels, notably, voltage-gated sodium and potassium channels, as well as ligand-gated channels controlled by the neurotransmitters glutamate and acetylcholine. But the critical and specific role of Ca^{2+} channels in signal transduction is unique: in every instance, the conversion of an electrical signal to a chemical message requires the activation of Ca²⁺ channels. This is a nearly universal rule in excitable cells.

Why Are Calcium Channels So Powerful, Pervasive and Fascinating?

Let us begin with the issue of how Ca^{2+} channels are generically well suited to their unique task, and return later to the issue of Ca^{2+} channel types and their specialization for specific roles. The chemistry of calcium puts it into a different category than alkali metal elements such as sodium or potassium, or other alkaline earth elements such as magnesium.^{1.4} It has been suggested that once cells opted to use high-energy phosphate compounds as metabolic currency, they faced great evolutionary pressure to maintain an unusually low intracellular Ca^{2+} concentration ([Ca^{2+}]_i < 100 nM). Otherwise, salts of calcium and phosphate would precipitate, turning the cytosol into a bone-like solid.¹ Accordingly, special homeostatic mechanisms such as calcium pumps evolved. In turn, the low [Ca^{2+}]_i made it possible to produce a significant change in concentration with only a small Ca^{2+} flux across the cell membrane; this kind of



Figure 1. The classical "knee-jerk" stretch reflex illustrates the critical role of voltage-gated Ca²⁺ channels in converting electrical signals to biochemical and mechanical signals. Upper panel, sequence of events in the stretch reflex depicted schematically. Lower panel, corresponding mechanical, electrical and chemical steps in the pathway, with the participating channel types, ions and transmitters indicated. Note that Ca²⁺ channels are required in every case of conversion from membrane electrical activity (ELEC) to intracellular biochemical signaling (CHEM). A, actin (thin filament); ACh, acetylcholine; AChR, acetylcholine receptor; Ca, calcium; glu, glutamate; GluR, glutamate receptor; K, potassium; M, myosin (thick filament); MF, muscle fiber; MN, motoneuron; MS, muscle spindle; Na, sodium; NT, nerve terminal; SR, sarcoplasmic reticulum; T, transverse tubule.

leverage for signaling is not shared by sodium or potassium ions. In a typical cell, the concentrations of Na⁺ and K⁺ on both sides of the membrane are in the millimolar range, so a much larger flux of ions would be needed to produce a proportional change in concentration; thus, the ion fluxes that generate Na⁺ and K⁺ spikes are not sufficient to deliver an ion-encoded message. Moreover, calcium has an additional advantage for signaling, in that receptor proteins that respond efficiently to Ca²⁺ ions could be readily utilized because calcium's divalent charge provides the energy needed to help drive large conformational changes. Finally, inasmuch as Ca²⁺ is a "hard" ion, it satisfies a more sharply defined set of requirements for high-affinity binding than a soft ion such as Mg²⁺, thereby favoring highly specific interactions.

Why is it so significant that Ca^{2+} channels are highly sensitive to membrane voltage? Coupling membrane potential to second-messenger signaling greatly expands cellular capability. Electrical events have intrinsic advantages in cell signaling, including the ability of action potentials to spread quickly and faithfully, and the possibility of summation of synaptic inputs. Finally, voltage-dependence offers a means of linking the activity of one channel (e.g., Na⁺) to that of another (e.g., K⁺ or Ca²⁺ channels), even if the channels are not in close physical proximity.

Combining the ideas of Ca^{2+} as a chemical messenger and change in membrane as an initiator of Ca^{2+} influx brings us to the essence of the advantages offered by voltage-gated Ca^{2+} channels. The opening of a voltage-gated Ca^{2+} channel is a powerful mechanism for delivering the second messenger (Ca^{2+}) very quickly, as there is no lack of Ca^{2+} in the external milieu, and the concentration gradient for generating a large net flux is provided by the same processes that keep cytosolic Ca^{2+} low. Consequently, large fluxes translate to a rapid rise in intracellular Ca^{2+} . In addition, Ca^{2+} channels in the plasma membrane have an added advantage relative to channels in intracellular membranes, in that they have access to the plasma membrane's voltage potential, a global indicator of cellular activity. A rapid, voltage-dependent closing of the channel allows for dissipation of the message by diffusion and strong, rapid local buffering, thereby



Figure 2. A) Ca^{2+} channels can be modeled as key signal transducers, analogous to G protein–coupled receptors and other famous membrane-associated signaling systems. In this pathway, the stimulus (e.g., a sensory input) leads to a change in membrane voltage (e.g., an invading action potential), which in turn activates voltage-gated Ca^{2+} channels. Ca^{2+} influx through these channels serves as a diffusible second messenger to trigger cellular events. B) Ca^{2+} forms the link between the classical Hodgkin cycle³² and synaptic vesicle recycling of the kind envisioned by Heuser and Reese. AP, action potential at the presynaptic terminal; V_m , membrane potential.

achieving spatio-temporally precise signaling. In fact, Ca^{2+} channels can be thought of as playing much the same role as other sources of second messengers in signaling cascades. Thus, Ca^{2+} channel activity can be likened to renowned signaling systems like G protein–coupled receptors and adenylyl cyclase (Fig. 2A). In contrast, such a comparison would not be appropriate for Na⁺, K⁺ and Cl⁻ channels.

To capitalize on all of these advantages, Ca^{2+} channels must satisfy a number of structural and biochemical requirements. First, they should be highly voltage-dependent, making them quick to both open and close in response to changes in membrane potential (e.g., action potentials and excitatory postsynaptic potentials). Second, they must be highly permeable to Ca^{2+} , but not to other ions such as Na⁺, or K⁺. Calcium channels must also be properly localized near the relevant targets of Ca^{2+} regulation, allowing for local increases in Ca^{2+} concentration. Finally, they must be subject to modulation, and diverse enough to allow for selective regulation of different classes of calcium channels. All of these requirements seem to have been fulfilled by the Ca^{2+} channels one finds in excitable cells. It is thus perhaps no wonder that calcium channels are critical for so many cellular processes.

Nevertheless, Ca²⁺ Channels Were Relative Latecomers to Cellular Electrophysiology

Considering the pivotal role of Ca^{2+} channels in so many cellular processes, as well as the near-ubiquitous presence of difference types of Ca^{2+} channels in excitable cells, it would seem that they would have been intensely studied from the very beginning of the era of intracellular recording and channel biophysics. But this was hardly the case. Why was the calcium channel nearly overlooked at first, and why did it receive relatively little attention even after it was first discovered? Neural circuits like the stretch reflex were very much on the minds of Alan Hodgkin, Andrew Huxley, and John Eccles, the winners of the first Nobel Prize in modern electrophysiology. However, they focused primarily on electrogenesis by sodium channels and the postsynaptic manifestations of neurotransmission, indisputably important elements of neuronal communication. In the case of Hodgkin, Huxley and Bernard Katz, a sensible preference for large preparations and large currents, attributes suitable for propagation over long distances, led them to study the squid giant axon. Here, the electrophysiological study of excitability became rightfully synonymous with the Sodium Theory. In the case of Eccles, the focus was on postsynaptic recordings and the nature of excitatory and inhibitory transmission, questions passed down from Charles Sherrington.

One glimpse of the central focus of the era can be obtained by revisiting a thick compendium of classical literature, gathered in 1972 by Ian Cooke and Mack Lipkin. Their *Cellular Neurophysiology* ⁵ offered a generation of neuroscience students easy access to the original classic studies. Reflective of the ethos of the time, there was a huge disparity in Cooke and Lipkin's choice between amounts of space devoted to Na⁺ versus Ca²⁺ entry; indeed, not a single paper is devoted to Ca²⁺ channels as such. Today, however, it is apparent that Ca²⁺ channels have reached the forefront of the field of ion channel research, as judged by the number of abstracts, meetings and publications devoted to Ca²⁺ channels as opposed to Na⁺ channels. Indeed, entire international symposia are now dedicated exclusively to current research on calcium channels; due to their vital role in cellular signaling, their diversity, and great susceptibility to modulation, Ca²⁺ channels have attracted considerable interest. It may be satisfying for some of us to see such fervent attention to the molecular object of our affections, but the question still remains: how did we get from there to here?

The Winding Road of Calcium Channel Discovery

Bernard Katz and Colleagues: Early Beginnings at University College London

Where did the notion of a calcium channel first start? Clearly, it was in the Biophysics Department at University College London, founded by A.V. Hill and later led by Bernard Katz (Fig. 3A). Most investigators would credit Katz, Paul Fatt and Bernard Ginsborg for pioneering the calcium channel field with their work in large muscle cells of crab⁶ and crayfish.⁷ These three were charter members of a small group of electrophysiologists who clarified many aspects of nerve propagation and synaptic transmission. But despite the pedigree of these investigators, calcium channels were not a major source of attention in the early 1950s, despite their now clearly critical role in even the simplest neuromuscular circuit. Indeed, the discovery of Ca²⁺ spikes aroused no great excitement in the 1950s, nor even many years later, when the accumulated triumphs of electrophysiology were reviewed.

Given their functional importance, why were Ca^{2*} channels so slow to catch on? Several reasons come to mind.

The First Paper Drew Little Attention because the Investigators Themselves Were Unsure of What They Had Found

Fatt and Katz entitled their 1953 paper "The Electrical Properties of Crustacean Muscle Fibres", not exactly a title destined to be a Citation Classic! In fact, the discovery itself was merely an accident. Fatt and Katz were after bigger game—the electrical properties of inhibi-



Figure 3. Three of the principal founders of the field of voltage-gated calcium channels. A) Sir Bernard Katz. B) Susumu Hagiwara. C) Harald Reuter.

tory transmission—and were proceeding through a checklist of resting potential, membrane resistance and capacitance, the current–voltage relationship, and the basis of electrogenesis. They were not expecting to find electrical responses that persisted in sodium-free media, for example when Na⁺ was replaced by tetrabutylammonium (TBA). The data at hand were limited, so their conclusions were suitably cautious. They discussed in considerable detail the "choline action potential" and the "tetrabutylammonium action potential", but were quite circumspect about concluding that Ca²⁺ was the charge carrier: "The mechanism of the action potential, and the species of ions involved in the movement of charge across the membrane, remain a puzzling problem...(i) it may be that TBA remains adsorbed to the fibre surface, but is mobilized during excitation and temporarily transferred into the cell interior; (ii) alternatively, influx of calcium or magnesium, or outflux of some internal anion may be responsible for transport of charge."

The Next Advance in Understanding Was Slow in Coming

It took a full five years before Fatt, now working with Ginsborg, published a follow-up study, showing that full-blown action potentials could be generated in the absence of Na⁺, even without quaternary ammonium ions, provided the external solution contained strontium or barium ions.⁷ After soaking the preparation in tetraethylammonium-containing solution and subsequent washout of TEA, Ca²⁺ could serve as a charge carrier (later, it was found that the quaternary ammonium compounds entered the fiber and served to dampen outward potassium currents). This led to a cautious but clear statement that the movement of Sr²⁺, Ba²⁺ or even Ca²⁺ itself could support action potentials across the membrane.

Interest in Excitability Revolved around Proposed Mechanisms in Squid Axons

At the time, the results in crustacean muscle were of interest mainly because they seemed so unusual. The "Sodium Theory" had already been proven in myelinated nerve, ⁸ skeletal muscle⁹ and heart tissue.¹⁰ The behavior of all tissues was judged against the standard of squid axons, where the recordings were most reliable. Exceptions were therefore of growing importance, if for no other reason than an ongoing debate with Ichiji Tasaki, who opposed the Sodium Theory of Hodgkin and colleagues. Since most of the 1953 Fatt & Katz paper was devoted to nailing down the fact that the action potential was not due to sodium entry, spikes dependent on Ca²⁺ entry were seen mainly as a curious variant on the dominant Na⁺ entry mechanism.

The Studies in Crustacean Muscle Focused on Electrogenesis Only, without Reference to Muscle Contraction

A direct relationship between Ca^{2+} entry and muscle contraction was not mentioned. In those days, the role of Ca^{2+} in contractile activation was not fully appreciated. This was despite

Heilbrunn and Wiercinski's experiments with Ca^{2+} injection,¹¹ as well as the much earlier work of Sydney Ringer, who showed the critical dependence of cardiac contraction on external Ca^{2+} . Even the discovery of troponin-C as a Ca^{2+} sensor for muscle contraction ¹² didn't bring to full light the importance of Ca^{2+} in contractile activation.

The Uncovering of Ca²⁺ Spikes Appeared Amidst a Crowded Field of Discovery

Even at its publication, Fatt and Katz's paper on the electrical properties of crab muscle was unfortunately but understandably overshadowed by its companion paper,¹³ their classic work on inhibitory transmission, a study establishing that inhibitory impulses can increase the post-junctional membrane conductance, thereby shunting excitatory neurotransmission whether or not the membrane actually hyperpolarizes. Bernard Katz himself was partway along a marvelous intellectual trajectory, ranging from excitability¹⁴ to mechanisms of excitatory transmission¹⁵ and the quantal basis of transmitter release.¹⁶

Each of the above factors contributed to the slow entrance of calcium channels into the burgeoning field of ion channel electrophysiology. However, despite their relative lateness entering the field, once their importance became clear, calcium channels quickly assumed a prominent position in the arena of ion channel electrophysiology.

The Inescapable Influence of Alan Hodgkin and Squid Axons

As an aside to the story of Katz and his associates in the Department of Biophysics, it is interesting to ask the question of whether Alan Hodgkin and Andrew Huxley, the principal pioneers in the field of membrane excitability, ever actually studied Ca²⁺ channels. As co-founders of the Sodium Theory (together with Katz), Hodgkin and Huxley never directly worked on calcium channels, although they came much closer than people usually think. Limitations on availability of squid to certain seasons and certain locations, and perhaps restlessness while the rest of the world caught up to the 1952 papers, spurred their interest in solving other problems. Thus, Hodgkin and Huxley turned eventually to excitation-contraction coupling, the terminal step in the stretch reflex, in vertebrate skeletal muscle. In classic experiments performed with Bob Taylor, Huxley used focal stimulation to demonstrate that voltage-dependence of contraction arose at regularly spaced "hot-spots" within the Z-line of frog skeletal muscle, corresponding to the openings of transverse tubules. Concurrently, working with Paul Horowicz, Hodgkin applied K*-rich solutions to depolarize single muscle fibers and described the very steep voltage-dependence of contraction. We now know that E-C coupling is critically dependent on voltage-gated Ca²⁺ channels (comprised of the α_{1S} (Ca_v1.1) subunit along with ancillary subunits) in the transverse tubules. So in fact Hodgkin and Huxley both implicitly studied Ca2+ channels.

While we are on the subject of Ca^{2*} channels and muscle contraction, it is worth noting that several scientific heirs of Hodgkin and Huxley's have made vital contributions to the field of E–C coupling, some directly or indirectly involving Ca^{2*} channels. Knox Chandler (a postdoc of Hodgkin's) and Martin Schneider (a graduate student with Horowicz, thereby Hodgkin's scientific "grandson") are good examples. They co-discovered a charge movement in the transverse tubules that mediated the voltage-dependence of contraction.¹⁷ That charge movement was really a form of gating current, now known to be critical for controlling the gating of almost all voltage-dependent channels. What wasn't clear then, and was only shown much later by Eduardo Rios, a postdoc of Schneider's, was that the charge movement observed by Schneider and Chandler actually originates in the skeletal L-type (α_{1S}) Ca^{2*} channel.¹⁸

Certainly one of the most fascinating parts of the story of Alan Hodgkin and calcium channels is as follows. Hodgkin and Keynes used squid axons to make the first measurements of activity-dependent $^{45}Ca^{2+}$ flux.¹⁹ They found that the net entry of tracer calcium was 600-fold less than the entry of sodium, making Ca^{2+} unlikely to contribute to the spike. However, they included this prophetic statement in their discussion:

"The finding of a greater uptake of calcium by stimulated nerve may be relevant in considering the mode of release of chemical transmitters by nerve endings. In addition to its action in dispersing squid axoplasm, calcium has been found to have a disruptive effect on other intracellular structures, such as the sarcosomes of heart muscle, and it is interesting to speculate whether a penetration of calcium at the nerve ending might not be one of the factors involved in breaking up the intracellular vesicles near the membrane²⁰ and releasing acetylcholine from them. There is some indication that Mg^{2+} ions do not have the same action as Ca^{2+} on intracellular structures, so that a competition between them to enter the nerve terminals, together with a failure of Mg^{2+} to disrupt the vesicles, might help to explain the inhibitory effect of magnesium." This was a clear (and accurate) assessment of the importance of Ca^{2+} entry in mediating many cellular processes, such as transmitter release and E–C coupling.

Katz's group was also very familiar with the importance of Ca^{2+} in transmission²¹ and the antagonistic effect of $Mg^{2+,22}$ Although in Katz's department, these authors did not mention Fatt and Katz's 1953 paper; after all, at that time the working hypothesis, (del Castillo and Katz and later, Jenkinson)^{23,24} was to envision Ca^{2+} and Mg^{2+} competing for an unidentified surface receptor X, which upon binding ligand converted to an active form X', allowing release of acetylcholine. So Hodgkin and Keynes were breaking new ground by suggesting that neurosecretion might be triggered by Ca^{2+} influx. They further suggested that Fatt and Katz might have been studying excitability that depended on some kind of divalent cation influx. So the first insight into the notion of the calcium channel's role in excitation-response coupling may actually have originated with Hodgkin and Keynes in 1957; the follow year, Fatt and Ginsborg nicely credited this paper in their study of divalent cation spikes,⁷ thereby adding favor to the notion of Ca^{2+} -dependent excitability.

Katz and Miledi Re-Enter the Fray by Focusing on the Squid Giant Synapse

So when did it become accepted that Ca²⁺ entry through voltage-gated calcium channels triggers transmitter release? Katz's classic text *Nerve, Muscle, and Synapse*²⁵ provided a retrospective snapshot of his views more than a dozen years after his 1953 paper on crab muscle electrophysiology. Katz quoted Fatt and Ginsborg's evidence in crustacean muscle for "entry of a divalent cation like Ca", but only as a curious exception to the generalization of Na⁺ influx as the inward current during excitation. With characteristic modesty, there was no reference to Fatt and Katz.⁶ The birth of calcium channels was tucked away in a short paragraph alongside the efflux of an internal anion in the impulse-conducting plant cell *Nitella*, both deemed illustrative exceptions. It appears that the provocation from Hodgkin and Keynes¹⁹ about synaptic transmission had not yet taken effect. However, something was clearly brewing, because there is a forward-looking statement in the very last paragraph of Katz's book:

It is interesting to note certain features that the initiation of muscle contraction shares with the initiation of an action potential and with the release of a transmitter substance at a nerve terminal. In all three cases, the primary event is a depolarization of the cell membrane. Depolarization, however, is not a sufficient stimulus; it becomes effective in producing its diverse results only if calcium is present, whether the final result be increase of sodium permeability.²⁶ the facilitated release of acetylcholine quanta,²⁷ or the activation of myosin molecules.²⁸

The germ of an idea about a messenger role for Ca^{2+} was there, but Katz continued to focus on the presence of calcium, not on Ca^{2+} flux per se.

Of course, in the long run, Katz made further giant contributions to understanding the significance of Ca^{2+} influx for triggering downstream cellular events. This was revisited in 1967, after the momentous period of clarifying the quantal nature of neurotransmission and the key role of calcium. Working with Ricardo Miledi at the Marine Station in Naples, Katz returned to the subject of Ca^{2+} entry, but now looking in nerve terminals. Using the squid giant synapse, Katz and Miledi showed: that transmission required membrane depolarization, but not sodium channels; that Ca^{2+} spikes could be generated at the terminal if outward K⁺ currents were blocked; and that transmitter release required repolarization when initiated by strong depolarization, consistent with the requirement for both channel opening and a strong electrical driving force for Ca^{2+} influx. Interestingly, in his papers describing his work on the squid synapse, Katz refers back to the work on crustacean muscle, but once again only to the

paper of Fatt & Ginsborg,⁷ and not his own earlier work.⁶ Nevertheless, the studies of Katz and Miledi were to provide a foundation for elegant studies in the 1970s by Llinás and colleagues²⁹ and later by Augustine, Charlton and Smith.³⁰

Susumu Hagiwara: Ca²⁺-Based Electrogenesis in Full Bloom

Another significant contributor to the birth of the field of calcium channels was Susumu Hagiwara (Fig. 3B). Known affectionately as "Hagi", Hagiwara was a zoologist whose roots were in Japan, but who worked mainly in the States. Although he held an M.D. (as well as a Ph.D.), Hagiwara was not particularly obsessed about working strictly with mammals or even vertebrates; nowadays he might be classified a comparative neuroethologist. His interests were extremely broad, ranging from the singing of cicadas to echolocation in bats, from the electrical properties of eggs to taste sensation in cats. Within this expansive range of topics, Hagiwara is best known for his studies on "calcium spikes", first in barnacle giant muscle fibers, then later in many other preparations.

Interestingly, the Chilean barnacle was actually a substitute for the squid at the Monte Mar marine station on the Chilean coast. The squid were displaced from their usual territory by a large storm, forcing Hagi and his colleagues Alan Grinnell and Jared Diamond to find another preparation. As described earlier by Hoyle, the giant muscle fibers of the barnacle were up to a millimeter in diameter and five centimeters in length. So here was a large preparation in which Ca²⁺ channels could be brought to center stage under appropriate experimental conditions (even though these fibers don't have full-blown spikes under physiological conditions).

Hagiwara is often credited with helping to establish the ubiquity of Ca²⁺ channels because of his work on so many different preparations. Ted Bullock and Alan Grinnell, two of Hagiwara's long-time colleagues, provided this quote from Bertil Hille:³¹ "Hagi [was] a research scientist of peerless distinction... He is remembered as the champion who brought the calcium channel to its rightful respected place and in the process discovered blocking ions, flux saturation, inactivation dependent on internal calcium, and many other unanticipated phenomena."

This well-deserved praise for Hagiwara does not change the history of the calcium channel itself, or its slow emergence from obscurity. Once again, Bullock and Grinnell on Hagiwara: "He recounts, with characteristically self-deprecating humor, how, during this period when 'the calcium channel was only found in miserable animals like crustaceans and was thought to play no important function in the mammalian brain... I suffered tremendously from a minority [*sic*] complex."

Along with its humble position in the phylogenetic tree, the barnacle had an additional handicap: the complicated morphological cable properties of its giant muscle fiber made it very difficult to study in a rigorously biophysical way. As Hagiwara and Byerly stated, "At first it appeared that barnacle giant muscle fibers might become the 'squid axon' of Ca currents... however, there are deep, long invaginations of the sarcolemma in all crustacean muscle fibers...[which] cause barnacle muscle to fail to satisfy criteria about reliability and speed of voltage control." In his classic book on ion channels,³² Hille judiciously skips over these cable complications, but chooses instead to introduce the gigaohm seal (patch-clamp) recording methods of Neher and Sakmann and Sigworth,³³ right in the middle of the chapter on calcium channels. This seems fair enough, as this was one field that benefited enormously from patch-clamp techniques.

Despite the obscure idiosyncrasies of the invertebrate preparations of those early days, the interactions between investigators were typified by collegiality. Alan Grinnell described the relationship between Katz and Hagiwara as follows: "Hagi and BK met several times, and I know they admired each others' work. One of the reasons I went to UCLA after my postdoc in London was Katz's strong recommendation of Hagi. And in 1967, when Hagi and I went to Chile to study the giant synapse in squids there—which proved abortive because a major storm came up, following which the squid were unobtainable for several years, so we worked on giant barnacles instead—we were later grateful for the storm, since that fall Katz & Miledi published

their beautiful J Physiol paper on Naples squid establishing the role of Ca²⁺ in synaptic transmission. As Hagi said at the time, we would have been scooped by the best."

Around the same time, Hagiwara and Nakajima³⁴ published a fundamental paper describing the pharmacology of Ca^{2+} spikes, neatly combining work on both barnacle muscle and heart muscle. The agents tetrodotoxin (TTX) and procaine, normally effective on Na⁺ spikes of other tissues, failed to block the barnacle Ca^{2+} spike. On the other hand, manganese acted as an inhibitor, competing with Ca^{2+} to block the Ca^{2+} spike. In heart, TTX and procaine suppressed the initial rate of the rising phase, but spared the plateau; in contrast, manganese acted primarily on the plateau phase. As Hagiwara and Nakajima recognized, the heart provides a clear example of a setting where Ca^{2+} channels are absolutely essential for maintaining life; we know now that all heart cells use Ca^{2+} channels for one or more aspects of their electrical activity. Ca^{2+} channels are critical for pacemaker activity in the sino-atrial node, whose depolarization is aided in its last stages by an increasing permeability to Ca^{2+} ions. Slow propagation in the atrio-ventricular node absolutely requires Ca^{2+} channels. Finally, in the atria and ventricles, where the pumping action of the heart takes place, both the action potential plateau and contraction rely on Ca^{2+} channels.

Harald Reuter: First Ca²⁺ Currents under Voltage Clamp

Enter the next major father figure in this saga, Harald Reuter (Fig. 3C). Born in Germany, Reuter has spent the bulk of his illustrious scientific career in Bern, Switzerland, but with brief and sometimes nearly annual peregrinations to the States. Reuter first came to calcium channel research as an M.D., with a non-quantitative training in cardiac pharmacology and an abiding interest in how adrenaline affects the heart. Reuter's voltage-clamp recordings of shortened Purkinje fibers, using the method of Trautwein and associates, were the first to provide evidence for a Ca²⁺ current.³⁵ Interestingly, the same Journal of Physiology volume that featured Reuter's paper on the putative Ca²⁺ current also contained Katz and Miledi's study of synaptic transmission in the absence of nerve impulses, using TTX to block Na⁺ channels.³⁶ One year following his presentation of Ca²⁺ currents, Reuter, together with Seitz, found evidence linking external Na⁺ to Ca²⁺ efflux, now known as the Na⁺–Ca²⁺ exchange.³⁷

The work in cardiac Purkinje fibers was later followed by recordings from bundles of ventricular or atrial heart muscle,^{38,39} which also showed inward currents supported by Ca²⁺ influx. In magnitude and kinetics, the putative Ca²⁺ channel currents were smaller and slower than sodium currents. This conclusion soon came under attack on technical grounds, mainly from Ted Johnson and Mel Lieberman, who suggested that the "calcium current" or "slow inward current" might be an artifact arising from the methodologies that needed to be applied to try controlling the membrane potential while the membrane current was generated.⁴⁰ The multi-cellular cardiac preparations were regarded as far inferior to experimental systems such as the squid giant axon, where techniques for uniformly controlling the membrane potential were more rigorously applicable. For example, narrow extracellular spaces in the cardiac tissue could support unwanted and immeasurable voltage drops in series with the excitable membrane of interest, invalidating the voltage clamp. The next few years were particularly confusing for the study of cardiac Ca²⁺ channels, which was a world unto itself for a while, with little crossover from those interested in nerve or skeletal muscle. The controversy about the very existence of Ca^{2+} currents began to resolve with cardiac preparations with more favorable geometries, such as the rabbit Purkinje fiber (wide clefts)⁴¹ combined with three-microelectrode voltage clamp, which measured and capitalized on cable non-uniformity but nevertheless verified the existence of bona fide Ca²⁺ currents.⁴² The ultimate resolution came with the advent of methods for studying single cells, first with large suction electrodes and later with modern patch-clamp methodology. The ability to alter the intracellular ionic composition, first tediously developed in multicellular preparations,⁴³ became much easier at the level of single cells.⁴⁴ Interestingly, Harald Reuter was very active in the use of both suction and patch-clamp electrodes, and made many additional contributions to the field of cardiac electrophysiology and Ca²⁺ channels using these newer techniques.

In hindsight, most would agree that the first sets of voltage-clamp experiments had not paid sufficient attention to possible technical difficulties, but were nevertheless correct in uncovering a new component of inward excitatory current. It is clear now that the problems of spatio-temporal control of membrane potential were actually less serious than originally thought, whereas issues of overlapping currents were more severe. An experiment in which extracellular $[Ca^{2+}]$ varied could undoubtedly evoke changes in Ca^{2+} -dependent currents as well as in the flux through Ca^{2+} channels themselves.

The mid-1960s also marked the advent of pharmacological approaches to identifying Ca^{2+} currents using channel blockers such as verapamil, nifedipine and diltiazem, thanks to the efforts of Albrecht Fleckenstein and others (for review, see ref. 45). Application of such agents buttressed emergent ideas about the distinct nature of sodium and calcium channels in cardiac cells. Today, Ca^{2+} channel blockers are effective in a number of cardiovascular syndromes and represent a multibillion-dollar business; who would have thought that good could result from channel blockade that could in principle reduce the strength of cardiac contraction? In fact, the main therapeutic target for the Ca^{2+} channel blockers is the L-type Ca^{2+} channel in vascular smooth muscle, where relaxation favors blood flow and lowers blood pressure; this arises from the ability of the blockers to act more potently on vascular smooth muscle than on heart (a piece of good fortune for both the patient and the drug industry).

The Diversity of Native Ca²⁺ Channel Currents

Early Studies on the Diversity of Ca²⁺ Channel Types

In the early days of Ca^{2+} channel electrophysiology using morphologically simple preparations, the original presumption (with or without credit to Gertrude Stein) was that "a Ca^{2+} channel is a Ca^{2+} channel is a Ca^{2+} channel", with little regard for the possibility of multiple Ca^{2+} channel types. Peter Baker, one of the leading scientists in the study of squid axon excitability, was an example of someone with little patience for studies of multiple Ca^{2+} channels. To him, the important issues were whether Ca^{2+} channels truly existed, how they were linked to the process of vesicle exocytosis, and how vesicle fusion itself took place. This was fair enough, and perhaps fitting for someone who began his career at a time when the very nature of excitability and the role of Na⁺ influx were still under fire.

However, Hagiwara was ahead of his time in recognizing the multiplicity of channels and their possible importance in excitability. Working with starfish eggs, he and his colleagues Ozawa and Sand described two inward currents, labeled I and II, both supported by Ca^{2+} influx;⁴⁶ (see also Fox and Krasne⁴⁷ for their work on egg cells of a marine worm). Today, their "I" and "II" would be more descriptively termed low-voltage activated (LVA) and high-voltage activated (HVA), respectively. As Hagiwara and Byerly stated in 1981: "...at present it seems most objective to give up the prejudice that the Ca channel is like the Na channel and allow that there may be various types of Ca channels." But not everyone was convinced: Lux's group⁴⁸ summarized their patch-clamp recordings of unitary Ca²⁺ channel activity from bird, snail and rat by saying "...we conclude that Ca^{2+} channels everywhere are basically the same."

The distinction between LVA and HVA channels gained momentum through several studies in the early 1980s, mostly in biological systems less obscure than starfish eggs. In beautiful recordings of action potentials in inferior olivary neurons, Llinás and Yarom⁴⁹ discovered low-threshold Ca²⁺ spikes that depended on an underlying conductance; this conductance required strongly negative potentials to become de-inactivated. This was the current-clamp equivalent of LVA channels, later termed T-type channels. Carbone and Lux,⁵⁰ as well as Fedulova, Kostyuk and colleagues,⁵¹ provided further evidence of LVA Ca²⁺ channels in the form of single-channel recordings of chick and rat sensory neurons. Finally, Matteson and Armstrong^{52,53} demonstrated slow deactivation of T-type channels upon sudden repolarization, a key property of these channels. In 1985, Bean obtained similar evidence for the distinctiveness of T-type channels in atrial myocytes, showing that only the HVA population of channels was responsive to Ca^{2+} channel blockers and β -adrenergic stimulation.⁵⁴

In that period, the evidence supporting the separation of voltage-gated Ca^{2+} channels into LVA and HVA channels was mostly biophysical. This evidence included voltage-dependence of gating (LVA channels require a more negative holding potential, and activate at much more negative test potentials than HVA channels), speed of deactivation (LVA channels deactivate slowly compared to HVA channels), resistance to run-down (loss of activity) following patch excision or dialysis of the cytosol (LVA channels are more resistant to run-down), and differential sensitivity to Cd^{2+} (LVA channels are much less sensitive to Cd^{2+}). Taken together, it became increasingly evident that voltage-gated calcium channels could be accurately separated into two broad categories on the basis of biophysical properties.

A Tripartite Classification of Native Ca²⁺ Channels

Our group's own interest in multiple types of Ca²⁺ channels took an interesting turn when Martha Nowycky and Aaron Fox teamed up to examine the properties of single Ca^{2+} channels in cell bodies of chick sensory neurons.⁵⁵ Based on published research, for example Aaron's previous work on marine worm egg Ca2+ channels, we fully expected to find two categories of Ca²⁺ channels, LVA and HVA. However, the observed pattern of unitary channel properties their slope conductances and activation and inactivation properties-fit more neatly into three distinct categories, leading Martha to postulate that there must be a third category. Upon closer examination of our whole-cell and single-channel recordings, it became clear that she was correct, and we soon found other criteria for distinguishing the three channel types, which we then called T-type (LVA) and N- and L-type (both HVA). The L-type channels were so named because they had a large unitary conductance to Ba²⁺, supported a long-lasting Ba²⁺ current (different properties were found with Ca²⁺ as the charge carrier, but the Ba²⁺ currents provided the most distinctive channel profiles) and were similar to single channels found in heart cells.⁵⁶ The T-type channels generated tiny unitary Ba²⁺ currents, gave rise to a transient average current, showed characteristically slow deactivation following sudden repolarization,⁵⁷ and were also found in heart cells.^{54,58} Finally, the N-type channels were largely specific to neurons, had an intermediate conductance to Ba²⁺, and, although they required negative holding potentials to be available for opening, they were activated at high voltages, indicating that they were neither T- nor L-type. Contrary to recurrent rumors, the N-type channel was not named by or for Martha Nowycky, although there would have been some justice had this been the case.

In coming up with this tripartite classification, the trickiest distinction was between L-type and N-type channels. Their profiles of unitary Ba²⁺ conductance and voltage-dependent gating were distinctive enough, but the most decisive evidence came from experiments with the drug Bay K8644; this dihydropyridine compound acts as a stimulator (agonist) of L-type Ca²⁺ channels, greatly increasing divalent cation influx by promoting a mode of activity with very long openings (Fig. 4A). Indeed, the behavior and pharmacology of neuronal L-type channels⁵⁹ were very similar to those of cardiac L-type channels.⁶⁰ In contrast, N-type channel activity was not affected by Bay K8644 (Fig. 4B). Once again, pharmacology provided essential tools for studying Ca²⁺ channels, and confirmed distinctions derived from biophysical comparisons.

Shortly after the first presentation of the tripartite classification of voltage-gated calcium channels, a peptide toxin derived from marine snail venom, ω-conotoxin-GVIA, became available through the excellent work of Baldomero Olivera and Doju Yoshikami. Working together with them, we found that this peptide blocks HVA channel activity, particularly that of N-type channels.⁶¹ We then used this peptide in collaboration with Richard Miller's group to demonstrate that N-type channels play an important role in the release of norepinephrine from sympathetic neurons.⁶² Soon thereafter, the groups of Peter Hess and Bruce Bean showed that ω-conotoxin-GVIA was actually quite selective for N-type channels and thus completely spared L-type channels,^{63,64} providing further evidence to support distinctions between N- and L-type Ca²⁺ channels.



Figure 4. Distinguishing between three classes of Ca^{2+} channel activity in sensory neurons with distinct biophysical and pharmacological profiles. Use of the dihydropyridine BayK8644 as a selective stimulator of L-type voltage-gated Ca^{2+} channels. A) unitary L-type Ca^{2+} channel activity recorded from a cell-attached patch of a guinea pig ventricular cell, using the voltage protocol indicated. By convention, downward deflections represent inward current through the channel. Left panel, in control solution, the channel displays brief openings (mode 1 activity), with occasional null (mode 0) activity. Right panel, application of 5 μ M BayK8644 greatly increases open probability by inducing long-lasting openings (mode 2). Adapted from Hess et al (1984).⁶⁰ B) In recordings of macroscopic currents, 5 μ M BayK8644 dramatically increases the activity of L-type Ca^{2+} channels, but not N- or T-type channels. Left panel, control single-channel current averages recorded from cell-attached patches of chick dorsal root ganglion neurons. Right panel, the same patches recorded after application of 5 μ M BayK8644. Adapted from Nowycky et al (1985).⁵⁵

The Tripartite Classification of Neuronal Ca²⁺ Channels Was Not Universally Accepted

Some of the experts in the field, including Richard Miller and Harald Reuter, embraced the distinction between T-, N-, and L-type channels, noting that it resolved many puzzling aspects of findings on neurotransmitter release.^{65,66} However, the idea of three categories of voltage-gated Ca²⁺ channels was slow to catch on with the groups that had contributed to the original LVA–HVA distinction. The greatest resistance to the tripartite classification came from Swandulla and Armstrong,⁶⁷ who found the separation between L-type and N-type channels unconvincing, based on their favorite criterion, the speed of tail deactivation.⁶⁷ Carbone and Lux also found it difficult initially to accept the pharmacological separation between L- and N-type channels, in part because they were unable to elicit convincing responses to dihydropyridine

	Table	1. А fev	v significant	events in the	brief history	∕ of N-ty	pe Ca ²⁺	channels
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1985	N-type Ca ²⁺ channels discovered
1987	Specific block by ω-conopeptide first described
1987	N-type channel identified as target of modulation by G proteins
1988	Role of N-type channels in norepinephrine release established
1992	Isolation of the cDNA clone for the α_{1B} subunit
1993	N-type channels found to play key role in CNS transmission
1995	Block of N-type channels as therapeutic intervention for intractable pain

antagonists such as nifedipine, and even the agonist Bay K8644, despite these compounds' carefully-verified effectiveness in heart cells.⁶⁸ In contrast, the Kiev group of Platon Kostyuk and colleagues were rather receptive to the idea that the HVA channels could indeed be split into two groups; they confirmed the specificity of Bay K8644 for one of those groups, and even proposed a distinction between high-threshold, inactivating (HTI) and high-threshold, non-inactivating (HTN) channels, in keeping with the N- and L-type subdivisions, respectively.

It is interesting to look back over the rapid progression of developments in the study of the N-type channel (Table 1). In the decade following its initial discovery, we witnessed the emergence of a specific blocker (ω -conotoxin-GVIA) as well as the cloning of the underlying α_1 subunit, α_{1B} (Ca_v2.2; for a review of voltage-gated calcium channel nomenclature) (see refs. 69 and 70). Other highlights include the recognition of the key role of N-type channels in neurotransmitter release in peripheral and central neurons, and their susceptibility to modulation by G-protein–coupled receptors. More recently, the N-type channel has been examined as a possible therapeutic target for treatment of intractable pain, though this has yet to receive full FDA approval.

Beyond T, N and L: The Identification of P/Q-Type Channels

Not long after the debut of N-type channels, Rodolfo Llinás and colleagues discovered a non-inactivating, DHP-insensitive current in the cell bodies of cerebellar Purkinje neurons; because of this localization, they named these channels P-type Ca²⁺ channels.^{71,72} Bruce Bean, Michael Adams and colleagues then demonstrated that these P-type channels were exquisitely sensitive to the funnel web spider toxin peptides ω -Aga-IVA and ω -Aga-IVB. Around the same time, a full-length brain Ca²⁺ channel gene called BI (for brain-1) was cloned and expressed by Yasuo Mori and Shoshaku Numa in Kyoto.⁷³ Many call this α_{1A} , following the general classification of brain Ca²⁺ channels from Terry Snutch, Henry Lester and Norman Davidson. Because the message for this Ca²⁺ channel was abundant in cerebellum, and specifically in cerebellar Purkinje cells, Rudolfo Llinás felt sure that it encoded the P-type channel. However, Numa was reluctant to commit to this, as the properties of the cloned α_{1A} subunits, when expressed in Xenopus oocytes, deviated greatly from those of native P-type channels recorded from cerebellar Purkinje neurons. Rather, the behavior of the cloned α_{1A} subunit in oocytes was much more similar to a current component labeled Q-type by our group.⁷⁴ Several lines of evidence, including antibodies, antisense techniques⁷⁵ and gene knockout have now convincingly established that both P- and Q-type currents both arise from α_{1A} . For example, both current types are completely eliminated in cerebellar Purkinje and granule neurons of α_{1A}^{-1-1} mice.⁷⁶ Thus, the currently accepted terminology of "P/Q-type" channel seems appropriate, as the original distinctions between the P and Q components have been mostly accounted for by splice variation in the α_{1A} gene.⁷⁷

This is an appropriate point to acknowledge the enormous contributions of those who have provided the molecular tools that played a critical role in identifying diverse Ca^{2+} channels and dissecting their contributions to neuronal function (see later chapters in this book). Baldomero Olivera has been widely recognized as a pioneer in discovering the ω -conotoxins, but what is not

commonly known is that he came to the field as a molecular biologist and adapted to the limited resources available in his native Philippines by studying a local menace, the deadly marine snails. His careful and thorough examination of these snails led to the discovery of a large number of invaluable neurotoxins.⁷⁸ Michael Adams, who discovered the peptide ω -Aga-IVA, began his work as an entomologist, not a neuroscientist. The availability of ω -conotoxin GVIA and ω -Aga-IVA helped settle debates over the distinctiveness of N- and P/Q-type channels, clarified their relationship to their respective α_1 subunits, and greatly accelerated our examination of these channels' roles in neuronal processes such as Ca²⁺ signaling and neurotransmission.

The Uncovering of Yet another Kind of HVA Neuronal Ca²⁺ Channel: R-Type

By the early 1990s, the actions and specificity of the newly available toxins and pharmacological compounds were understood sufficiently to allow a separation of current components based primarily on pharmacology. Andy Randall used a combination of nimodipine (L-typespecific), ω -conotoxin-GVIA (N-type-specific) and ω -Aga-IVA (P/Q-type-specific) to tease apart the various Ca²⁺ current types in cerebellar granule neurons.⁷⁴ Because of the homogeneous nature of the neurons in this preparation, as well as their favorable passive properties, a clean, reproducible dissection of HVA Ca²⁺ current types was obtained (Fig. 5). Present were currents carried by the three usual suspects, L-, N- and P/Q-type channels. However, a fourth current type, displaying properties distinct from the other three, was revealed upon application of inhibitors of the three known channel types. Because this current was resistant to the three inhibitors (making it residual after inhibition of the other three current types), it was named R-type. This current type showed unique properties, including very rapid decay and an unusual sensitivity to block by Ni²⁺. Moreover, there was a strong resemblance to the properties of a novel α_1 subunit (*doe*-1) cloned from a marine ray by our group in collaboration with Tom Schwarz and his colleagues.⁷⁹

The designation of another channel type seemed problematic to several experts in the field, who initially dismissed the notion of a fourth HVA Ca²⁺ channel type, suggesting that the residual current might result from incomplete block of L-, N- or P/Q-type channels. Even the distinct kinetics of this R-type current might have been explained by alternative splicing of one of the other channel type's message (as was the case with P- and Q-type channels), or perhaps by associating with a different accessory subunit. Lacking a mammalian homolog for the α_1 gene encoding this current, the smoking gun we needed was a specific inhibitor of this residual current, ideally one selective enough to spare L-, N- and P/Q-type currents. Fortunately, this was provided by Robert Newcomb, George Miljanich and colleagues, who isolated another spider toxin peptide, designated SNX-482.⁸⁰ This inhibitor blocks R-type currents in several neuronal systems.

Issues Surrounding α_{1E} and Its Initial Identification with T-Type Channels

Another interesting episode in the unveiling of the Ca²⁺ channel family occurred when matching α_{1E} , the most recent member of the Ca_v2 subfamily to be cloned, with a Ca²⁺ channel phenotype defined by electrophysiological properties. When Tuck-Wah Soong, Terry Snutch, and their colleagues first isolated α_{1E} , they suggested somewhat provocatively that this gene might encode low-voltage-activated T-type channels.^{81,82} Of all the voltage-gated Ca²⁺ channels, T-type currents were the easiest to isolate biophysically, yet the hardest to study biochemically (perhaps their role in generating relatively slow pacemaker depolarizations required only small currents and thus low levels of protein in the membrane); therefore, successfully cloning this channel would represent a major step forward in the study of T-type calcium channels. On the other hand, our group^{74,83} favored the notion that α_{1E} encodes the R-type current that remained after blockade of neuronal L-, N-, and P/Q-type channels. This controversy was ultimately laid to rest by the cloning of novel α_1 subunits by Edward Perez-Reyes, LeAnn Cribbs and their colleagues.⁸⁴⁻⁸⁶ These genes were classified α_{1G} , α_{1H} and α_{1J} , in keeping with the convention of the time (these genes comprise their own subfamily, called Ca, 3). The isolation of these clones stands as a testament to the persistence of the researchers and their willingness to try in silico approaches. When these three genes were expressed and recorded, the currents matched nicely with native T-type



Figure 5. Pharmacological dissection of high-voltage–activated (HVA) whole-cell Ca²⁺ current types in rat cerebellar granule neurons. A) L- and N-type currents were isolated by application of 10 μ M nimodipine or 1 μ M ω -conotoxin-GVIA (ω -CTx-GVIA), respectively. P- and Q-type currents were isolated by application of 1.5 nM or 1–3 μ M ω -agatoxin-IVA (ω -Aga-IVA), respectively. R-type current was isolated by combined application of nimodipine, ω -CTx-GVIA and ω -Aga-IVA. B) summary of the current densities and relative contributions of each current type, determined from the data in A. Adapted from Randall and Tsien (1995).⁷⁴

(LVA) currents; none of these three clones gave rise to R-type currents. On the other hand, it is now generally accepted that α_{1E} is the major contributor to R-type current. Recently, the interest in R-type channels has sharply increased due to their ability to support neurotransmitter release^{87,88} and their contribution to dendritic Ca²⁺ homeostasis⁸⁹ and synaptic plasticity.⁹⁰ In the discovery of the R-type channel, one sees repeated the familiar history of an initial distinction of a Ca²⁺ channel type based on biophysical and pharmacological criteria, followed by an emerging consensus about its molecular basis, driven in part by cloning. What began as a curiosity or anomaly (and to many investigators, an artifact) rapidly transitioned from controversy to general acceptance, proving to be more interesting than its discoverers could have anticipated.



Figure 6. Convergence of physiological and molecular biological evidence for a tripartite classification of voltage-gated Ca²⁺ channels. A) unitary activity of three voltage-gated Ca²⁺ channel types, recorded from cell-attached patches of chick dorsal root ganglion neurons. Activity was elicited by stepping from a given holding potential (HP) to the appropriate test potential (TP), as follows: L-type, -20 mV to +20 mV; N-type, -80 mV to +20 mV; T-type, -80 mV to -20 mV. Adapted from Nowycky et al (1985).⁵⁵ B) tripartite classification of voltage-gated Ca²⁺ channels, based on biophysical properties, pharmacological sensitivity and sequence homology. The Ca_v1 and Ca_v2 subfamilies comprise the high-voltage-activated channels, while the Ca_v3 subfamily contains low-voltage-activated (T-type) channels.

The Current State of the Three-Branched Calcium Channel Family Tree

A new set of questions comes to mind now that the diverse nature of the Ca^{2+} channel family, first proposed on the basis of patch-clamp recordings, has received corroboration from molecular biology. Sequence analysis has confirmed and extended our original tripartite classification (Fig. 6). The members of the Ca_v2 subfamily, first typified by N-type channels (N-type = α_{1B} ; P/Q-type = α_{1A} ; R-type = α_{1E}), appear functionally quite distinct from the Ca_v1 subfamily of L-type channels (α_{1S} , α_{1C} , α_{1D} and α_{1F}) and the Ca_v3 subfamily of T-type channels (α_{1G} , α_{1H} and α_{1I}). Each of the cloned channels shows a steep voltage-dependence, highly similar to a first approximation, and a strong selectivity for Ca²⁺ and Ba²⁺ rather than Na⁺. In this regard, truly "a Ca^{2+} channel is a Ca^{2+} channel is a Ca^{2+} channel". If so, why might such diversity have evolved? The most obvious answer is that the individual family members evolved to fill distinct physiological or cell biological niches. The employment of more than one type of channel allows greater flexibility with regard to time- and voltage-dependence, cellular localization, and responsiveness to different forms of modulatory regulation. Diverse as they are, Ca^{2+} channel types are far less numerous than the signaling roles for voltage-gated Ca^{2+} entry itself.

Conclusions: Some Lessons and Ironies

The history of calcium channel discovery offers many insights and a few interesting ironies. Although first identified in the heyday of classical neurophysiology, Ca2+ channels did not receive much initial attention, despite their now-evident importance in processes such as chemical neurotransmission and excitation-contraction coupling. The timeline of Ca²⁺ channel discovery is remarkable when one considers the extraordinarily long gestation period from first sighting (1953/1958) to full-blown focus (1970s for multicellular approaches, 1980s for patch-clamp recordings). The circuitous path to understanding how Ca2+ entry triggers neurosecretion, reviewed in this chapter, is indicative of a more general disconnect between the participation of Ca2+ in electrogenesis and the role of Ca2+ as a second messenger. Squid giant axons, the preeminent preparation for studying axonal conduction, do not express high levels of Ca2+ channels. Despite pioneering work by Reuter and others, this paucity of Ca^{2+} channels in squid axons had a strong influence: Johnson and Lieberman were not alone in asking why the heart should use calcium channels to make action potentials when the reigning preparation, the squid giant axon, did not. The course of scientific discovery might have been quite different if physiologists had focused on crustacean muscles, which appear to lack sodium channels, rather than squid giant axons. Another irony is that full-blown Ca²⁺ spikes, the first indication of the presence of Ca²⁺ channels, are not actually critical for excitation-contraction coupling in the muscle fibers of crab, crayfish or barnacle, and are evident only when K⁺ channels are blocked or Ca²⁺ channel inactivation is suppressed.

In mammalian preparations, the sino-atrial and atrio-ventricular nodes offer the clearest examples of Ca^{2+} channel-dependent electrogenesis, but these systems are rather difficult to study, even today. On the other hand, skeletal muscle is one of the richest sources of homogeneous Ca^{2+} channels, and thereby facilitated the early biochemical characterization of $Ca_v1.1$ (α_{15}) subunits by William Catterall, Kevin Campbell, Michel Lazdunski and others, as well as the first cloning of a Ca^{2+} channel by Shoshaku Numa and colleagues. Yet, despite much elegant work,⁹¹ the steps between Ca^{2+} channel activation and subsequent internal Ca^{2+} release from the sarcoplasmic reticulum remain incompletely understood even a decade later.

In recent years, rapid progress in the fields of Ca²⁺ channel structure, function, diversity and regulation can be attributed to several key factors. First, investigators have approached the study of calcium channels from many angles, ranging from hardcore biophysics and biochemistry to clinical perspectives—recall that Harald Reuter and Albrecht Fleckenstein both began their careers as cardiac pharmacologists. Second, even with the advent of improved patch-clamp technologies, and the availability of a veritable cornucopia of potent, selective Ca^{2+} channel drugs, the field would not have experienced such a rapid rate of progress without a shift in the prevailing attitudes of the individual investigators. The sharing of information and resources between scientists has greatly contributed to the speed of new discoveries. In earlier times, compartmentalization stood as a barrier to collaborative discovery. For example, an early paper about Ca²⁺ channels in cardiac preparations would credit Hagiwara and Nakajima as well as Niedergerke and Orkand for circumstantial evidence of such channels in heart, but not cite Fatt and Katz or Fatt and Ginsborg's work! On the other hand, working from an invertebrate vantage point, Hagiwara and Byerly entitled their 1981 review "Calcium Channel", but stated disarmingly that they were not familiar with the literature in vertebrate heart or smooth muscle. As Rodolfo Llinás put it in a 1983 letter: "We need to unify our fields a bit more. Nature seems to be trying to tell us something and we continue stubbornly to think that muscles and nerve cells are not next of kin." Thankfully, this wish for unification has now largely been realized, and we now understand a great deal more about what nature can tell us about Ca²⁺ channels, their diversity, and their critical roles in cellular processes.

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References

- 1. Williams RJ. Cation distributions and the energy status of cells. J Bioenerg 1970; 1:215-225.
- 2. Falke JJ, Drake SK, Hazard AL et al. Molecular tuning of ion binding to calcium signaling proteins. Q Rev Biophys 1994; 27:219-290.
- 3. Carafoli E, Santella L, Branca D et al. Generation, control, and processing of cellular calcium signals. Crit Rev Biochem Mol Biol 2001; 36:107-260.
- 4. Carafoli E. Calcium signaling: a tale for all seasons. P Natl Acad Sci USA 2002; 99:1115-1122.
- 5. Cooke IM, Lipkin M. Cellular Neurophysiology. New York: Holt, Rinehart and Winston 1972.
- 6. Fatt P, Katz B. The electrical properties of crustacean muscle fibres. J Physiol-London 1953a; 120:171-204.
- 7. Fatt P, Ginsborg BL. The ionic requirements for the production of action potentials in crustacean muscle fibres. J Physiol-London 1958; 142:516-543.
- 8. Huxley AF, Stampfli R. Effect of potassium and sodium on resting and action potentials of single myelinated nerve fibres. J Physiol-London 1951; 112:496-508.
- 9. Nastuk WL, Hodgkin AL. The electrical activity of single muscle fibres. J Cell Comp Physl 1950; 35:39-73.
- 10. Draper MH, Weidmann S. Cardica resting and action potentials recorded with an intracellular electrode. J Physiol-London 1951; 115:74-79.
- 11. Heilbrunn LV, Wiercinski FJ. The action of various cations on muscle protoplasm. J Cell Compar Physl 1947; 29:15-32.
- 12. Ebashi S, Endo M. Calcium ion and muscle contraction. Prog Biophys Mol Bio 1968; 18:123-183.
- 13. Fatt P, Katz B. The effect of inhibitory nerve impulses on a crustacean muscle fibre. J Physiol-London 1953b; 121.
- 14. Hodgkin AL, Katz B. The effect of sodium ions on the electrical activity of the giant axon of the squid. J Physiol-London 1949; 108:37-77.
- 15. Fatt P, Katz V. An analysis of the end-plate potential recorded with an intra-cellular electrode. J Physiol-London 1951; 115.
- 16. del Castillo J, Katz B. Quantal components of the end plate potential. J Physiol-London 1954b; 560-573.
- 17. Schneider MF, Chandler WK. Voltage dependent charge movement of skeletal muscle: a possible step in excitation-contraction coupling. Nature 1973; 242:244-246.
- 18. Rios E, Brum G. Involvement of dihydropyridine receptors in excitation-contraction coupling in skeletal muscle. Nature 1987; 325:717-720.
- 19. Hodgkin AL, Keynes RD. Movements of labelled calcium in squid giant axons. J Physiol-London 1957; 138:253-281.
- 20. del Castillo J, Katz B. Biophysical aspects of neuro-muscular transmission. Prog Biophys Mol Bio 1956; 6:122-.
- 21. del Castillo J, Stark L. The effect of calcium ions on the motor end-plate potentials. J Physiol-London 1952; 116:507-515.
- 22. del Castillo J, Engbaek L. The nature of the neuromuscular block produced by magnesium. J Physiol-London 1954; 124:370-384.
- 23. del Castillo J, Katz B. The effect of magnesium on the activity of motor nerve endings. J Physiol-London 1954a; 124:553-559.
- 24. Jenkinson DH. The nature of the antagonism between calcium and magnesium ions at the neuromuscular junction. J Physiol-London 1957; 138:434-444.
- 25. Katz B. Nerve, Muscle, and Synapse. New York: McGraw-Hill, 1966.
- 26. Hodgkin AL. The Croonian Lecture: Ionic movements and electrical activity in giant nerve fibres. Proc Roy Soc (London) ser B, 1958; 148:1-37.
- 27. Katz B. The Croonian Lecture: The transmission of impulses from nerve to muscle, and the subcellular unit of synaptic action. Proc Roy Soc (London) ser B, 1962; 155:455-477.
- 28. Huxley AF. Muscle. Annu Rev Physiol. 1964; 26:131-152.

- 29. Llinás R, Steinberg IZ, Walton K. Presynaptic calcium currents and their relation to synaptic transmission: voltage clamp study in squid giant synapse and theoretical model for the calcium gate. P Natl Acad Sci USA 1976; 73:2913-2922.
- Augustine GJ, Charlton MP, Smith SJ. Calcium action in synaptic transmitter release. Annu Rev Neurosci 1987; 10:633-693.
- Bullock TH, Grinnell AD. Susumu Hagiwara November 6, 1922-April 1, 1989. Biogr Mem Natl Acad Sci 1996; 69:59-85.
- 32. Hille B. Ionic Channels of Excitable Membranes, Second Edition. Sunderland, MA: Sinauer Associates, 1992.
- Hamill OP, Marty A, Neher E et al. Improved patch-clamp techniques for high-resolution current recording from cells and cell-free membrane patches. Pflügers Arch 1981; 391:85-100.
- Hagiwara S, Nakajima S. Differences in Na and Ca spikes as examined by application of tetrodotoxin, procaine, and manganese ions. J Gen Physiol 1966; 49:793-806.
- 35. Reuter H. The dependence of slow inward current in Purkinje fibres on the extracellular calcium-concentration. J Physiol-London 1967; 192:479-492.
- 36. Katz B, Miledi R. A study of synaptic transmission in the absence of nerve impulses. J Physiol-London 1967; 192:407-436.
- 37. Reuter H, Seitz N. The dependence of calcium efflux from cardiac muscle on temperature and external ion composition. J Physiol-London 1968; 195:451-470.
- 38. Rougier O, Vassort G, Garnier D et al. Existence and role of a slow inward current during the frog atrial action potential. Pflügers Arch 1969; 308:91-110.
- Beeler GW, Jr., Reuter H. Membrane calcium current in ventricular myocardial fibres. J Physiol-London 1970; 207:191-209.
- 40. Johnson EA, Lieberman M. Heart: excitation and contraction. Ann Rev Physiol 1971; 33:479-532.
- 41. Colatsky TJ, Tsien RW. Electrical properties associated with wide intercellular clefts in rabbit Purkinje fibres. J Physiol-London 1979; 290:227-252.
- Kass RS, Siegelbaum SA, Tsien RW. Three-micro-electrode voltage clamp experiments in calf cardiac Purkinje fibres: is slow inward current adequately measured? J Physiol-London 1979; 290:201-225.
- 43. Marban E, Tsien RW. Effects of nystatin-mediated intracellular ion substitution on membrane currents in calf purkinje fibres. J Physiol-London 1982; 329:569-587.
- 44. Lee KS, Akaike N, Brown AM. The suction pipette method for internal perfusion and voltage clamp of small excitable cells. J Neurosci Meth 1980; 2:51-78.
- 45. Fleckenstein A. History of calcium antagonists. Circ Res 1983; 52:I3-16.
- 46. Hagiwara S, Ozawa S, Sand O. Voltage clamp analysis of two inward current mechanisms in the egg cell membrane of a starfish. J Gen Physiol 1975; 65:617-644.
- 47. Fox AP, Krasne S. Two calcium currents in Neanthes arenaceodentatus egg cell membranes. J Physiol-London 1984; 356:491-505.
- Brown AM, Camerer H, Kunze DL et al. Similarity of unitary Ca²⁺ currents in three different species. Nature 1982; 299:156-158.
- 49. Llinás R, Yarom Y. Electrophysiology of mammalian inferior olivary neurones in vitro. Different types of voltage-dependent ionic conductances. J Physiol-London 1981; 315:549-567.
- Carbone E, Lux HD. A low voltage-activated calcium conductance in embryonic chick sensory neurons. Biophys J 1984; 46:413-418.
- Fedulova SA, Kostyuk PG, Veselovsky NS. Two types of calcium channels in the somatic membrane of new-born rat dorsal root ganglion neurones. J Physiol-London 1985; 359:431-446.
- 52. Armstrong CM, Matteson DR. Two distinct populations of calcium channels in a clonal line of pituitary cells. Science 1985; 4682:65-67.
- 53. Matteson DR, Armstrong CM. Properties of two types of calcium channels in clonal pituitary cells. J Gen Physiol 1986; 87:161-182.
- 54. Bean BP. Two kinds of calcium channels in canine atrial cells. Differences in kinetics, selectivity, and pharmacology. J Gen Physiol 1985; 86:1-30.
- 55. Nowycky MC, Fox AP, Tsien RW. Three types of neuronal calcium channel with different calcium agonist sensitivity. Nature 1985; 316:440-443.
- 56. Reuter H, Stevens CF, Tsien RW et al. Properties of single calcium channels in cardiac cell culture. Nature 1982; 297:501-504.
- Armstrong CM, Matteson DR. Two distinct populations of calcium channels in a clonal line of pituitary cells. Science 1985; 227:65-67.
- 58. Nilius B, Hess P, Lansman JB et al. A novel type of cardiac calcium channel in ventricular cells. Nature 1985; 316:443-446.

- 59. Nowycky MC, Fox AP, Tsien RW. Long-opening mode of gating of neuronal calcium channels and its promotion by the dihydropyridine calcium agonist Bay K 8644. P Natl Acad Sci USA 1985; 82:2178-2182.
- 60. Hess P, Lansman JB, Tsien RW. Different modes of Ca channel gating behaviour favoured by dihydropyridine Ca agonists and antagonists. Nature 1984; 311:538-544.
- McCleskey EW, Fox AP, Feldman DH et al. ω-Conotoxin: direct and persistent blockade of specific types of calcium channels in neurons but not muscle. P Natl Acad Sci USA 1987; 84:4327-4331.
- 62. Hirning LD, Fox AP, McCleskey EW et al. Dominant role of N-type Ca2+ channels in evoked release of norepinephrine from sympathetic neurons. Science 1988; 239:57-61.
- 63. Plummer MR, Logothetis DE, Hess P. Elementary properties and pharmacological sensitivities of calcium channels in mammalian peripheral neurons. Neuron 1989; 2:1453-1463.
- Boland LM, Morrill JA, Bean BP. ω-Conotoxin block of N-type calcium channels in frog and rat sympathetic neurons. J Neurosci 1994; 14:5011-5027.
- 65. Reuter H. A variety of calcium channels. Nature 1985; 316:391.
- 66. Miller RJ. Multiple calcium channels and neuronal function. Science 1987; 235:46-52.
- 67. Swandulla D, Armstrong CM. Fast-deactivating calcium channels in chick sensory neurons. J Gen Physiol 1988; 92:197-218.
- 68. Lux HD. Studies on the development of voltage-activated calcium channels in vertebrate neurons. In: Calcium and Ion Channel Modulation (Grinnell AD, Armstrong D, Jackson MB, eds), New York: Plenum Press, 1988:p 313324^c.
- 69. Birnbaumer L, Campbell KP, Catterall WA et al. The naming of voltage-gated calcium channels. Neuron 1994; 13:505-506.
- Ertel EA, Campbell KP, Harpold MM et al. Nomenclature of voltage-gated calcium channels. Neuron 2000; 25:533-535.
- 71. Llinás R, Sugimori M, Lin JW et al. Blocking and isolation of a calcium channel from neurons in mammals and cephalopods utilizing a toxin fraction (FTX) from funnel-web spider poison. P Natl Acad Sci USA 1989; 86:1689-1693.
- 72. Llinás R, Sugimori M, Hillman DE et al. Distribution and functional significance of the P-type, voltage-dependent Ca²⁺ channels in the mammalian central nervous system. Trends Neurosci 1992; 15:351-355.
- 73. Mori Y, Friedrich T, Kim MS et al. Primary structure and functional expression from complementary DNA of a brain calcium channel. Nature 1991; 350:398-402.
- 74. Randall A, Tsien RW. Pharmacological dissection of multiple types of Ca2+ channel currents in rat cerebellar granule neurons. J Neurosci 1995; 15:2995-3012.
- 75. Gillard SE, Volsen SG, Smith W et al. Identification of pore-forming subunit of P-type calcium channels: an antisense study on rat cerebellar Purkinje cells in culture. Neuropharmacology 1997; 36:405-409.
- 76. Jun K-S, Piedras-Rentería ES, Smith SM et al. Ablation of P/Q-type Ca²⁺ channel currents and progressive, fatal ataxia in mice lacking the a1A subunit. P Natl Acad Sci USA 1999.
- 77. Bourinet E, Soong TW, Sutton K et al. Splicing of alpha 1A subunit gene generates phenotypic variants of P- and Q-type calcium channels. Nat Neurosci 1999; 2:407-415.
- 78. Olivera BM, Rivier J, Scott JK et al. Conotoxins. J Biol Chem 1991; 266:22067-22070.
- 79. Ellinor PT, Zhang J-F, Randall AD et al. Functional expression of a rapidly inactivating neuronal calcium channel. Nature 1993; 63:455-458.
- 80. Newcomb R, Szoke B, Palma A et al. Selective peptide antagonist of the class E calcium channel from the venom of the tarantula Hysterocrates gigas. Biochemistry 1998; 37:15353-15362.
- Soong TW, Stea A, Hodson CD et al. Structure and functional expression of a member of the low voltage-activated calcium channel family. Science 1993; 260:1133-1136.
- 82. Niidome T, Mori Y. Primary structure and tissue distribution of a novel calcium channel from rabbit brain. Ann NY Acad Sci 1993; 707:368-372.
- 83. Zhang J-F, Randall AD, Ellinor PT et al. Distinctive pharmacology and kinetics of cloned neuronal Ca²⁺ channels and their possible counterparts in mammalian CNS neurons. Neuropharmacology 1993; 32:1075-1088
- 84. Cribbs LL, Lee JH, Yang J et al. Cloning and characterization of alpha1H from human heart, a member of the T-type Ca²⁺ channel gene family. Circ Res 1998; 83:103-109.
- Perez-Reyes E, Cribbs LL, Daud A et al. Molecular characterization of a neuronal low-voltage-activated T-type calcium channel. Nature 1998; 391:896-900.
- 86. Lee JH, Daud AN, Cribbs LL et al. Cloning and expression of a novel member of the low voltage-activated T-type calcium channel family. J Neurosci 1999; 19:1912-1921.

- Wu LG, Borst JG, Sakmann B. R-type Ca²⁺ currents evoke transmitter release at a rat central synapse. P Natl Acad Sci USA 1998; 95:4720-4725.
- Albillos, A, Neher E, Moser T. R-Type Ca²⁺ channels are coupled to the rapid component of secretion in mouse adrenal slice chromaffin cells. J Neurosci 2000; 20:8323-8330.
- 89. Yasuda R, Sabatini BL, Svoboda K. Plasticity of calcium channels in dendritic spines. Nat Neurosci 2003; 6:948-955.
- 90. Breustedt J, Vogt KE, Miller RJ et al. Alpha1E-containing Ca2+ channels are involved in synaptic plasticity. P Natl Acad Sci USA 2003; 100:12450-12455.
- 91. Tanabe T, Beam KG, Adams BA et al. Regions of the skeletal muscle dihydropyridine receptor critical for excitation-contraction coupling. Nature 1990; 346:567-569.

Biochemical Studies of Voltage-Gated Ca²⁺ Channels

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Abstract

 $\label{eq:solution} V_{1} = \sum_{i=1}^{2^{+}} \frac{1}{i} \sum_{i=1}^{2^{+}} \frac{1}{i}$

Introduction

 Ca^{2+} channels have been studied intensively by electrophysiological methods since the initial recordings of Ca^{2+} currents by Reuter in 1967.¹ In the early 1980's, stimulated in part by success at purification and reconstitution of sodium channels,² a new focus of Ca^{2+} channel research developed aimed at identification of the Ca^{2+} channel proteins and analysis of their biochemical properties. In this chapter, I briefly review the biochemical studies that led to the first identification of the Ca^{2+} channel proteins and provided the foundation for the subsequent analysis of the structure and function of the channel subunits by molecular biological methods. I have restricted consideration here primarily to experiments in which biochemical methods were applied to purified protein preparations. For this reason, only the Ca^{2+} channels of the Ca_v^{2} families are considered. Readers are directed to subsequent chapters in this book for consideration of more recent studies that have employed a combination of molecular biological and protein expression methods to further analyze these questions.

Purification and Biochemical Characterization of Skeletal Muscle Ca²⁺ Channels

The Ca²⁺ channels in the transverse tubule membranes of skeletal muscle have served as a primary biochemical preparation for studies of Ca²⁺ channels because of their abundance. These channels serve two critical physiological roles. Like other Ca²⁺ channels, they mediate Ca²⁺ entry in response to depolarization. The primary voltage-gated Ca²⁺ currents in skeletal muscle



Figure 1. Biochemical properties of skeletal muscle Ca^{2+} channels. A. Summary of the biochemical properties of purified skeletal muscle Ca^{2+} channels. Lanes 1 and 2, silver stain of polypeptides; lane 3, staining with an antibody against the α_1 subunit; lane 4, staining with concanavalin A, a lectin binding high mannose N-linked carbohydrate chains; lane 5, staining with wheat germ agglutinin, a lectin staining N-linked complex carbohydrate chains; lane 6, photoaffinity labeling with azidopine, a photoreactive dihydropyridine; lane 7, photoaffinity labeling with TID, a hydrophobic probe of the transmembrane regions of proteins; lane 8, phosphorylation by cAMP-dependent protein kinase (adapted from ref. 14). B) The subunit structure of Ca^{2+} channels purified from skeletal muscle Ca^{2+} channels.¹⁴ This model also fits biochemical and molecular biological results for neuronal Ca^{2+} channels. P, sites of phosphorylation by cAMP-dependent protein kinase and protein kinase $C. \Psi$, sites of N-linked glycosylation.

are L-type,³⁻⁵ characterized by slow voltage-dependent inactivation, large single channel conductance (about 25 pS), high voltage of activation, and specific inhibition by dihydropyridine Ca^{2+} channel antagonists. These channels activate very slowly, and the Ca^{2+} entering vertebrate skeletal muscle through voltage-gated Ca^{2+} channels is not required for muscle contraction. It appears to replenish cellular Ca^{2+} during periods of rapid activity and to increase intracellular Ca^{2+} in response to tetanic stimulation, leading to increased contractile force. The primary physiological role for the skeletal muscle Ca^{2+} channels is to serve as a voltage sensor in excitation-contraction coupling. Voltage-gated Ca^{2+} channels in the transverse tubule membranes are thought to interact physically with the Ca^{2+} release channels located in the sarcoplasmic reticulum membrane. Voltage-driven conformational changes in the voltage-gated Ca^{2+} channels then activate the Ca^{2+} release from the sarcoplasmic reticulum by protein-protein interactions.⁶⁻⁸

Purification of Ca^{2+} channels from skeletal muscle began with isolation of the transverse tubule membranes, which are highly enriched in Ca^{2+} channel protein, and specific labeling by high affinity binding to dihydropyridine Ca^{2+} channel antagonists to identify the channel protein.^{9,10} Ca^{2+} channels were solubilized in the mild detergent digitonin to retain native subunit associations and purified by a combination of ion exchange chromatography, affinity chromatography on wheat germ agglutinin-Sepharose, and sedimentation through sucrose gradients.¹⁰ A heterogeous α subunit band^{9,10} and associated β subunits of 50 kD and γ subunits of 33 kD¹⁰ were identified as components of the Ca^{2+} channel in the initial purification studies, as assessed by comigration during column chromatography and sucrose gradient sedimentation. Subsequent experiments demonstrated that the heterogenous α subunit band contained not only the principal α_1 subunits with an apparent molecular masses of 143 kD and 27 kD, respectively, as illustrated in the SDS-PAGE results in Figure 1A.¹¹⁻¹⁵ The specific association



Figure 2. Structures of the Subunits of Ca_{*} Channels. Transmembrane folding models and site of regulation of the Ca²⁺ channel subunits. Predicted alpha helices are depicted as cylinders. The lengths of lines correspond approximately to the lengths of the polypeptide segments represented.

of these proteins as a multisubunit complex was supported by the copurification of each subunit with the dihyropyridine binding activity and Ca²⁺ conductance activity of the Ca²⁺ channel,^{10,14,16,17} by coimmunoprecipitation of all these proteins by antibodies directed against the α_1 subunits,^{12,14,18} and by co-immunoprecipitation of the Ca²⁺ channel complex by antibodies against each auxiliary subunit.¹⁹⁻²¹ Estimates of stoichiometry indicated that each mol of Ca²⁺ channel complex contains approximately 1 mol of each of the 5 subunits. The biochemical and molecular properties of each of the subunits of skeletal muscle Ca²⁺ channels are considered below.

α_I Subunit

The α_1 subunit of skeletal muscle Ca²⁺ channels was cloned by library screening based on amino acid sequence²² (Fig. 2). The cDNA predicts a protein of 1873 amino acids with a molecular weight of 212 kD, considerably larger than the estimate of 175 kD for the α_1 subunits of purified Ca²⁺ channels. Analysis of the α_1 subunits of purified Ca²⁺ channels and Ca²⁺ channels in transverse tubule membranes using sequence-directed antibodies showed that most (>90%) contained α_1 subunits that were truncated in their carboxyl terminal domain between residues 1685 and 1699 resulting in a 190 kD form that runs anomalously in SDS gels at 175 kD.^{23,24} Only a small fraction (<10%) of skeletal muscle Ca²⁺ channels contained the full length α_1 subunit encoded by the cDNA. Both forms were detected in rat skeletal muscle cells in culture suggesting that both may be present in vivo.²⁵ Since no mRNA encoding the more abundant, truncated form has been identified, the truncated form is probably produced by specific proteolytic processing in vivo. A similar cleavage product can be produced by calpain treatment, suggesting calpain as a candidate for in vivo processing of the α_1 subunits.²⁶

α_2 Subunit

The α_2 subunit of skeletal muscle Ca²⁺ channels is a hydrophobic glycoprotein with an apparent molecular mass of 143 kD before deglycosylation and 105 kD after deglycosylation (Fig. 1A, lanes 1 and 2).^{14,27,28} It contains both high mannose and complex carbohydrate chains (Fig. 1A, lanes 4 and 5). Cloning and sequencing cDNAs encoding the α_2 subunit defined a protein of 1106 amino acids with a molecular mass of 125 kD, multiple potential

transmembrane segments, and multiple consensus sites for N-linked glycosylation²⁹ (Fig. 2). The predicted α_2 protein was 20 kD larger than the apparent molecular mass of the deglycosylated α_2 subunit suggesting that a portion of the protein encoded by the α_2 cDNAs may not be present in the mature α_2 subunit that had been characterized biochemically. Subsequent studies showed that both α_2 - δ subunits are encoded by the same mRNA (see below).

β Subunit

The β subunits are hydrophilic proteins that are not glycosylated and therefore are likely to be located on the intracellular side of the membrane (Fig. 1).^{14,20} cDNA cloning and sequencing revealed a protein of 524 amino acids with a predicted molecular mass of 58 kD.³⁰ In agreement with biochemical data, the primary structure does not include any potential transmembrane segments but contains multiple consensus sites for phosphorylation by different protein kinases (Fig. 2B).

y Subunit

The γ subunit of skeletal muscle Ca²⁺ channels is a hydrophobic glycoprotein with an apparent molecular mass of 30 kD without deglycosylation and 20 kD following deglycosylation.^{14,21} Cloning and sequencing cDNAs encoding γ subunits revealed a protein of 222 amino acid residues with a molecular mass of 25 kD.^{31,32} The deduced primary structure contained four predicted hydrophobic transmembrane segments and multiple sites for N-linked glycosylation.

δ Subunit

The δ subunit appears on SDS gels as a doublet of 24 and 27 kD proteins, which are both hydrophobic and glycosylated.^{14,28} Determination of the amino acid sequences of peptides derived from the δ subunit showed that it was encoded by the same mRNA as the α_2 subunit.^{33,34} The mature α_2 subunit is truncated at alanine 934 of the $\alpha_2\delta$ precursor protein; residues 935-1106 constitute the disulfide-linked δ subunit. This sequence comprises a protein of 16 kD and contains a single transmembrane segment and three consensus sequences for N-linked glycosylation. The doublet on SDS gels represents two differently glycosylated forms of the δ subunit.

Membrane Association of Subunits

The transmembrane organization of the Ca²⁺ channel complex was initially investigated by labeling of potential transmembrane segments with a hydrophobic photoaffinity probe.¹⁴ By this criterion, the α_1 , $\alpha_2\delta$ complex, and γ subunits were identified as probable integral membrane proteins, with the labeling of the α_2 subunits the weakest despite its large size (Fig. 1A, lane 7, and B).¹⁴ Subsequent hydropathy analysis of the primary structures revealed 24 transmembrane segments in the α_1 subunit, four in the γ subunit, and one in the δ subunit (Fig. 2), but the prediction of transmembrane alpha helices in the α_2 subunits has been uncertain.²⁹ Analysis of association of the α_2 subunit with the membrane by expression and biochemical extraction procedures led to the conclusion that the α_2 subunit does not have a true transmembrane segment.³⁵ Instead, it is likely to be associated with the membrane primarily by virtue of its disulfide linkage to the δ subunit and perhaps also by superficial ionic and hydrophobic interactions with the membrane bilayer (Fig. 1B).

Sites of Protein Phosphorylation

Activation of skeletal muscle L-type Ca²⁺ channels is enhanced by phosphorylation by cAMP-dependent protein kinase.^{36,37} In cultured skeletal muscle cells, repetitive depolarization causes a dramatic enhancement of Ca²⁺ currents,^{38,39} up to 10-fold in the critical membrane potential range near -20 mV. This potentiation of Ca²⁺ currents is strongly voltage-dependent and also is dependent on the activity of cAMP-dependent protein kinase.³⁹ This may result from interaction between voltage-dependent gating and phosphorylation of the Ca²⁺

channel itself. This novel regulatory mechanism greatly increases Ca²⁺ channel activity during tetanic stimulation of skeletal muscle cells and may play a critical role in the regulation of contractile force of skeletal muscle in response to hormones and to the frequency of stimulation of the motor nerve.

The α_1 subunit and the β subunit of skeletal muscle Ca²⁺ channels are substrates for phosphorylation by cAMP-dependent protein kinase and a number of other protein kinases (Fig. 1A, lane 8).^{14,40-44} Ca²⁺ flux through the purified skeletal muscle Ca²⁺ channel is regulated by cAMP-dependent protein phosphorylation.^{17,45-47} Ion flux studies in reconstituted phospholipid vesicles show that phosphorylation of the α_1 and β subunits can greatly increase the number of functional Ca²⁺ channels in purified preparations.^{46,47} Single channel recording experiments in planar bilayer membranes detect both increases in the number of functional Ca²⁺ channels and increases in the activity of single Ca²⁺ channels after phosphorylation by cAMP-dependent protein kinase.^{17,45} Thus, the α_1 and β subunits of the purified Ca²⁺ channel function in vitro.

Two size forms of the α_1 subunit of approximately 190 kDa and 212 kDa are present in purified preparations of skeletal muscle Ca²⁺ channels, T-tubule membranes, and intact skeletal muscle cells in culture, and both are phosphorylated by PKA in intact cells.²³⁻²⁵ Antibody mapping of the C-terminal region of α_{1190} placed the C-terminus between residues 1685 and 1699.²⁴ The most rapidly phosphorylated site in the truncated form of the α_1 subunit in purified Ca²⁺ channel preparations is Ser 687, located in the intracellular loop between domains II and III.^{48,49} In contrast, time course experiments indicated that Ser 1854 near the C-terminal portion of full-length α_{1212} is the most intensely and rapidly phosphorylated.^{49,50} To date, the site(s) of phosphorylation that regulate skeletal muscle Ca²⁺ channel activity have not been directly identified.

Phosphorylation of the β Subunit of Skeletal Muscle Ca²⁺ Channels

Like the α_1 subunit of the skeletal muscle Ca²⁺ channel, the β subunit is stoichiometrically phosphorylated by cAMP-dependent protein kinase in purified preparations⁴⁰ and in reconstituted Ca²⁺ channels that are regulated by cAMP-dependent protein kinase.^{17,47} Both serine 182 and threonine 205 have been shown to be phosphorylated in vitro.^{23,30} Since phosphorylation of both α_1 - β subunits have been shown to be correlated with regulation of the ion conductance activity of skeletal muscle Ca²⁺ channels, both are candidates for sites of channel modulation by phosphorylation.

Sites of Drug Binding

A defining feature of Ca_v1 channels and the L-type Ca^{2+} currents they conduct is block by dihydropyridines, phenylalkylamines, and other Ca^{2+} channel antagonist drugs. Photoaffinity labeling studies established that the binding sites of dihydropyridines, ^{13-15,21} phenylalkylamines,⁵¹ and benzothiazepines⁵² are located in the α_1 subunits. Detailed mapping of the dihydropyridine receptor site by proteolytic digestion and mapping of the digested fragments with sequence-directed antibodies identified the IIIS6 and IVS6 segments as important components of the binding site.⁵³ These results led to a **domain interface** model of drug binding of dihydropyridines, in which these drugs bind at the interface between domain III and IV at the point of interaction of the S6 segments.⁵⁴ Subsequent extensive mapping of the dihydropyridine receptor site by mutagenesis and functional analysis has given a detailed view of this important receptor in non-L-type Ca^{2+} channels.⁵⁵⁻⁵⁷ Similarly, the receptor sites of phenylalkylamines and benzothiazepines have been extensively mapped by photoaffininty labeling and peptide mapping^{58,59} and subsequently by mutagenesis and functional analysis (see Chapter 17). All three receptor sites are close in the expected three-dimensional structure of the channel and have both distinct and overlapping molecular determinants of their binding.

Biochemical Properties of Other Carl Channels

Subunits of Purified Cardiac Ca²⁺ Channels

Like the skeletal muscle Ca²⁺ channel, the principal cardiac Ca²⁺ channel conducts L-type Ca^{2+} currents.^{60,61} Antibodies against $\alpha_2\delta$ subunits of skeletal muscle Ca^{2+} channels detect corresponding subunits in cardiac preparations.^{62,63} Partially purified cardiac Ca²⁺ channels contain α_1 , $\alpha_2\delta$, and β subunits.⁶⁴⁻⁶⁸ However, the relatively low abundance of Ca²⁺ channels in cardiac tissue and the difficulty of controlling proteolysis during lengthy purification procedures have frustrated attempts at complete purification of an intact cardiac Ca2+ channel complex. The α_1 subunit with an apparent mass of 165 kD to 190 kD has been directly identified by photoaffinity labeling with photoreactive dihydropyridines.^{64,66,69} As in skeletal muscle, most of the α_1 subunits of cardiac Ca²⁺ channels are truncated at the C-terminus by proteolytic processing.⁷⁰ The primary site for phosphorylation by PKA in vitro and in cultured cells is Ser1928 (in rabbit Ca, 1.2 sequence numbering), which is located in the distal C-terminus beyond the site of proteolytic cleavage,⁷⁰ as observed for the skeletal muscle Ca²⁺ channel.^{49,50} Therefore, it is possible that there is a functional relationship between proteolytic cleavage of the C-terminal domain and regulation of the cardiac Ca^{2+} channel by protein phosphorylation. Consistent with this idea, truncation of the C-terminal domain by expression of cDNAs with appropriate deletions yields increased Ca2+ channel activity,71 and perfusion of C-terminal peptides into the cells expressing truncated channels inhibits the increase in Ca²⁺ channel activity.72

Molecular Basis for Modulation of Cardiac Ca^{2+} Channels by PKA Although regulation of the cardiac Ca^{2+} channels by the cAMP pathway was the first example of ion channel regulation through second messenger pathways, 73,74 the molecular basis for this regulation is still not clearly resolved. Early biochemical studies of the cardiac Ca²⁺ channel resulted in purification of a short, 160 to 195 kDa form of the α_1 subunit that was not a substrate for cAMP-dependent protein kinase.^{64,66} As for skeletal muscle Ca²⁺ channels, more recent results on cardiac Ca^{2+} channels have revealed a full-length $\alpha 1$ subunit form with a molecular mass of approximately 220 kDa, as expected from the cDNA sequence.⁷⁰ This full-length α_1 subunit is phosphorylated on a single serine residue (Ser1928) in the C-terminal domain.⁷⁰ Similarly, expression of the C-terminal domain in bacteria yields a protein that is phosphorylated primarily on Ser1928.⁷⁵ This site is missing in the truncated from of the α_1 subunit isolated in early biochemical preparations. Primarily the full-length form of Ca, 1.2 is present in cardiac tissue.^{76,77} Both β_1 and β_2 isoforms are expressed in cardiac tissue.⁷⁶⁻⁷⁹ and likely are both associated in Ca_v1.2 channels.

 Ca^{2+} channels in a CHO cell line that expresses only the full-length form of the $Ca_{1.2} \alpha_{1.2}$ subunit can be regulated by activation of endogenous PKA, by intracellular perfusion of PKA, and by voltage-dependent potentiation, which requires the activity of PKA.^{80,81} These results indicate that at least part of the regulation of Ca2+ channel activity is due to phosphorylation of the α_1 subunit. Since the α_1 subunit is only phosphorylated on Ser1928 in vitro or in transfected cells,⁷⁰ this regulation likely involves phosphorylation of this site. In support of this conclusion, mutation of this serine residue to alanine reduces the regulation of Ca²⁺ channel activity caused by activation of PKA with 8-Br-cAMP in transiently transfected human embryonic kidney cells from a 35% increase to a 7% increase.^{76,77} Although these results are promising, the extent of regulation of Ca²⁺ channel activity in these experiments in transfected cells falls well short of the magnitude recorded in native cardiac cells (2- to 4-fold increase), and regulation of cloned Ca²⁺ channels analyzed in this way is not observed in some of the major laboratories in the field.⁸² Therefore, it seems likely that additional regulatory influences that have not yet been reproduced and characterized in transfected cells are important for control of the activity of cardiac Ca²⁺ channels in vivo.

Phosphorylation of the β Subunit of Cardiac Ca²⁺ Channels by PKA

The β subunits of cardiac Ca²⁺ channels are phosphorylated by PKA in intact hearts treated with β -adrenergic agonists.⁸³ Bunemann et al⁸⁴ have reported substantial (greater than 2-fold) regulation of a C-terminal truncated form of Ca_v1.2 lacking Ser1928 by intracellular perfusion of activated PKA in human embryonic kidney cells co-transfected with Ca_v1.2 and β_{2a} subunits. This regulation required phosphorylation of Ser 478 and/or Ser 479, two serine residues in non-classical PKA phosphorylation sites that are specific to the β_{2a} subunit. These results provide the best evidence to date for an important role of the β subunits in regulation of cardiac Ca²⁺ channels. It will be important to further analyze Ca²⁺ channel regulation when full-length α 1 subunits are co-expressed with β_{2a} and other β subunits expressed in cardiac myocytes and to restore regulation by physiological stimulus procedures rather than intracellular perfusion of activated PKA.

Subunits of Purified Neuronal Cav1 Channels

Because the concentration of Ca^{2+} channels in skeletal muscle transverse tubules is much higher than in neuronal membranes, the biochemical properties of these channels in neurons are not as well established. Immunoprecipitation of Ca^{2+} channel complexes labeled with dihydropyridines using specific antibodies against $\alpha_2\delta$ subunits revealed a complex of polypeptides with sizes corresponding to α_1 , $\alpha_2\delta$, and β subunits of dihydropyridine-sensitive L-type Ca^{2+} channels in the brain.^{19,85,86} A potentially novel 100 kD protein was also identified as a specifically associated component of the L-type Ca^{2+} channel complex from brain.¹⁹ Further biochemical characterization of brain Ca_v 1 channels will require development of a method for purification of larger quantities of channel protein.

Biochemical Properties of the Cav2 Family of Ca²⁺ Channels

Multiple types of Ca^{2+} channels, which differ in physiological and pharmacological properties, are expressed in neurons. At least three types of high-voltage-activated Ca^{2+} channels have been distinguished in addition to L-type (see Chapter 3).⁸⁷⁻⁵⁰ N-type, P-type, and Q-type channels all have intermediate single channel conductances (about 15 pS) and can mediate Ca^{2+} currents with varying rates of voltage-dependent inactivation depending on their subunit composition and on other factors (see below). They are best distinguished by their pharmacological properties: N-type channels are specifically inhibited by ω -conotoxin GVIA whereas P/ Q-type are most sensitive to ω -agatoxin IVA and ω -conotoxin MVIIC. These specific peptide toxins have provided experimental tools for analysis of the protein subunits of neuronal Ca^{2+} channels.

Ca_v2.2 Channels

The ω -conotoxin-sensitive N-type Ca²⁺ channels purified from rat brain contain an α_1 subunit, a 140 kD α_2 -like subunit, and β subunits of 60 kDa to 70 kD as identified by antibodies against the skeletal muscle forms of these subunits.^{19,91-94} Both L-type and N-type Ca²⁺ channels from brain appear to lack a γ subunit, but a protein of approximately 100 kD is specifically associated with N-type Ca²⁺ channels as well as L-type Ca²⁺ channels from brain and may be an additional, brain-specific associated protein.^{19,91,92,94} The α_1 subunit of N-type Ca²⁺ channels was identified as Ca₂2.2 by homology cDNA cloning, co-immunoprecipitation, and functional expression.^{95,96} As for the Ca₂1 family channels, analysis of the Ca₂2.2 α_1 subunit using sequence-specific antibodies revealed two size forms (240 kD and 210 kD) that differ in their C-termini and in their phosphorylation by specific protein kinases.^{97,98} It is unknown at present whether these Ca₂2.2 α_1 subunits are derived from proteolytic truncation, alternatively spliced mRNAs or both (see Chapter 5).

Ca_v2.1 Channels

Agatoxin-sensitive P/Q-type Ca^{2+} channels purified from brain are also composed of α_1 , $\alpha_2\delta$, and β subunits.^{99,100,101} In addition, recent experiments have unexpectedly revealed a novel γ subunit, which is the target of the *stargazer* mutation in mice.¹⁰² This γ -subunit-like protein can modulate the voltage dependence of expressed Ca^{2+} channels containing $Ca_{\nu}2.1$ subunits, so they may be associated with these Ca^{2+} channels in vivo.¹⁰² If this new γ subunit is indeed associated with neuronal Ca^{2+} channels, their subunit composition would be identical to that of skeletal muscle Ca^{2+} channels defined in biochemical experiments.¹⁴ The cDNA encoding the $Ca_{\nu}2.1$ subunit was isolated by homology cloning and identified by functional expression.^{103,104} Analysis of the α_1 subunit peptides present in brain has revealed a wide range of size forms, including C-terminal truncations and internal deletions, and these isoforms are differentially phosphorylated by protein kinases.^{105,106} These results continue the theme that all Ca^{2+} channels studied to date have multiple forms due to varying C-terminal domains and that they are differentially phosphorylated by protein kinases.

Interactions of Ca²⁺ Channels with Intracellular Regulatory Proteins

 Ca^{2+} entering cells through voltage-gated Ca^{2+} channels initiates many intracellular processes through activation of effector mechanisms. Often these effector mechanisms are highly localized to respond to high local concentrations of Ca^{2+} . In addition, local regulation of Ca^{2+} channel function is also modulated by specifically bound regulatory proteins. The interactions of these intracellular effector and regulatory proteins with Ca^{2+} channels have been studied by biochemical approaches as outlined here and by molecular biological methods as described in Chapters 8, 9 and 11. These studies show that a functional Ca^{2+} channel complex not only has four auxiliary subunits but also contains multiple associated regulatory proteins that modify its activity.

Ryanodine Receptors

In skeletal muscle fibers, excitation-contraction coupling involves direct conformational coupling of the voltage-gated Ca²⁺ channel in the transverse tubule membrane to the ryanodine-sensitive Ca²⁺ release channel (RyR) of the sarcoplasmic reticulum at the transverse tubule/sarcoplasmic reticulum junction.^{6,7,107} Conformational coupling is mediated by the intracellular loop connecting domains II and III of the α_1 subunit.^{105,109} Depolarization of the transverse tubules by the conducted action potential activates L-type voltage-gated Ca²⁺ channels. A complex of ryanodine receptor and Ca²⁺ channels can be identified by detergent extraction and resolution by sucrose gradient sedimentation and antibody labeling.¹¹⁰ This complex is required for excitation/contraction coupling and for feedback regulation of Ca²⁺ channel function.^{109,111} and Chapter 21.

SNARE Proteins

 Ca^{2+} entry through voltage-gated Ca^{2+} channels is thought to initiate exocytosis by triggering the fusion of secretory vesicle membranes with the plasma membrane through actions on the SNARE protein complex of syntaxin, SNAP-25, and VAMP/synaptobrevin (reviewed in refs. 112,113). The function of the SNARE protein complex is regulated by interactions with numerous proteins, including the synaptic vesicle Ca^{2+} -binding protein synaptotagmin. The SNARE proteins syntaxin and SNAP-25 are associated with N-type and P/Q-type Ca^{2+} channels and can be co-purified and co-immunoprecipitated from brain.^{91,100,114,115} Presynaptic N-type and P/Q-type Ca^{2+} channels interact directly with the SNARE proteins through a specific synaptic protein interaction (synprint) site in the large intracellular loop connecting domains II and III.^{116,117} and Chapter 8. This binding interaction is regulated by Ca^{2+} and protein phosphorylation.^{117,118} Synaptotagmin also binds to the synprint site of Ca_v2 Ca^{2+} channels.¹¹⁹⁻¹²¹ Injection of peptide inhibitors of this SNARE protein interaction into pre-synaptic neurons inhibits synaptic transmission, consistent with the conclusion that this interaction is required to position docked synaptic vesicles near Ca^{2+} channels for effective fast exocytosis.^{116,122,123} SNARE protein interaction at this site is also important for G protein regulation of Ca^{2+} channels (see Chapter 9).

Kinase Anchoring Proteins

cAMP-dependent protein kinase is often anchored to specific subcellular compartments or specific kinase substrates by A Kinase Anchoring Proteins (AKAPs).^{124,125} These proteins contain a targeting domain that directs the AKAP to a specific cellular site and a kinase anchoring domain containing an amphipathic alpha helix that binds the regulatory subunit dimer of cAMP-dependent protein kinase. Because regulation of the skeletal muscle Ca²⁺ channel by membrane depolarization and cAMP-dependent protein kinase is very rapid, with observable effects in 50 ms, it was an attractive candidate for regulation through PKA bound to AKAPs. Biochemical studies of skeletal muscle Ca²⁺ channels revealed a novel 15-kDa AKAP (AKAP-15) associated with purified Ca²⁺ channels and with specifically immunoprecipitated Ca²⁺ channels.¹²⁶ This AKAP is an 81-residue protein with N-terminal palmitoyl and myristoyl moieties that serve as membrane anchors and an amphipathic helix that binds PKA¹²⁷ (also designated AKAP-18).¹²⁸ AKAP-15, PKA, and Ca²⁺ channels are co-localized in the specialized junctions formed between sarcoplasmic reticulum and transverse tubule membranes, where excitation-contraction coupling takes place.^{127,129} AKAP-15 binds to the skeletal muscle Ca²⁺ channel through a specific modified leucine zipper motif in the distal C-terminal domain.¹³⁰ In this way, the bound AKAP directly targets PKA to its sites of phosphorylation in the C-terminal of the full-length α_1 subunit.

Ca²⁺ Binding Proteins

 Ca^{2+} entering cells through Ca^{2+} channels is involved in initiation of intracellular signaling processes, and these often involve Ca^{2+} binding proteins like calmodulin, which is expressed ubiquitously, and neuro-specific Ca^{2+} binding proteins, which are expressed in specific neurons and in distinct subcellular locations. Research reviewed in Chapter 11 shows that both calmodulin and neuro-specific Ca^{2+} binding proteins interact with Ca^{2+} channels at specific binding sites in the C-terminal domains and modulate their function.

Conclusion

Voltage-gated Ca²⁺ channels are complex proteins containing five distinct protein subunits, α , α , β , γ , and δ , that specifically associate with each other. In addition to subunit assembly, their biosynthesis involves extensive glycosylation as well as proteolytic processing and disulfide linkage of subunits. Each α 1 subunit that has been studied is present in multiple isoforms that differ in their C-terminal domains and in phosphorylation by specific kinases. Ca²⁺ channels provide intracellular Ca²⁺ to initiate local signaling events, and they are directly associated with both effector proteins that initiate Ca²⁺ -dependent processes and with regulatory proteins that control their activity. Ca²⁺ channel signaling complexes are a crucial element of local regulation of cellular events.

References

- 1. Reuter H. The dependence of slow inward current in Purkinje fibres on the extracellular calcium-concentration. J Physiol (Lond) 1967; 192:479-492.
- 2. Catterall WA. The molecular basis of neuronal excitability. Science 1984; 223:653-661.
- 3. Almers W, Fink R, Palade PT. Calcium depletion in frog muscle tubules: the decline of calcium current under maintained depolarization. J Physiol (Lond) 1981; 312:177-217.
- Rosenberg RL, Hess P, Reeves JP et al. Calcium channels in planar lipid bilayers: Insights into mechanisms of ion permeation and gating. Science 1986; 231:1564-1566.
- 5. Sanchez JA, Stefani E. Inward calcium current in twitch muscle fibers of the frog. J Physiol1978; 283:197-209.

- 6. Adams BA, Beam KG. Muscular dysgenesis in mice: A model system for studying excitation-contraction coupling. FASEB J 1990; 4:2809-2816.
- 7. Catterall WA. Excitation-contraction coupling in vertebrate skeletal muscle: A tale of two calcium channels. Cell 1991; 64:871-874.
- 8. Rios E, Brum G. Involvement of dihydropyridine receptors in excitation-contraction coupling in skeletal muscle. Nature (London) 1987; 325:717-720.
- 9. Borsotto M, Barhanin J, Fosset M et al. The 1,4-dihydropyridine receptor associated with the skeletal muscle voltage-dependent Ca⁺⁺. J Biol Chem1985; 260:14255-14263.
- 10. Curtis BM, Catterall WA. Purification of the calcium antagonist receptor of the voltage-sensitive calcium channel from skeletal muscle transverse tubules. Biochem 1984; 23:2113-2118.
- Hosey MM, Barhanin J, Schmid A et al. Photoaffinity labelling and phosphorylation of a 165 kilodalton peptide associated with dihydropyridine and phenylalkylamine-sensitive calcium channels. Biochem Biophys Res Commun 1987; 147:1137-1145.
- 12. Leung AT, Imagawa T, Campbell KP. Structural characterization of the 1,4-dihydropyridine receptor of the voltage-dependent Ca²⁺ channel from rabbit skeletal muscle. Evidence for two distinct high molecular weight subunits. J Biol Chem 1987; 262:7943-7946.
- 13. Sieber M, Nastainczyk W, Zubor V et al. The 165-kDa peptide of the purified skeletal muscle dihydropyridine receptor contains the known regulatory sites of the calcium channel. Eur J Biochem 1987; 167:117-122.
- 14. Takahashi M, Seagar MJ, Jones JF et al. Subunit structure of dihydropyridine-sensitive calcium channels from skeletal muscle. Proc Natl Acad Sci USA 1987; 84:5478-5482.
- Vaghy PL, Striessnig J, Miwa K et al. Identification of a novel 1,4-dihydropyridine- and phenylalkylamine-binding polypeptide in calcium channel preparations. J Biol Chem 1987; 262:14337-14342.
- 16. Curtis BM, Catterall WA. Reconstitution of the voltage-sensitive calcium channel purified from skeletal muscle transverse tubules. Biochemistry 1986; 25:3077-3083.
- 17. Flockerzi V, Oeken H-J, Hofmann F et al. Purified dihydropyridine-binding site from skeletal muscle t-tubules is a functional calcium channel. Nature 1986; 323:66-68.
- Morton ME, Froehner SC. Monoclonal antibody identifies a 200-kDa subunit of the dihydropyridine-sensitive calcium channel. J Biol Chem 1987; 262:11904-11907.
- 19. Ahlijanian MK, Westenbroek RE, Catterall WA. Subunit structure and localization of dihydropyridine-sensitive calcium channels in mammalian brain, spinal cord, and retina. Neuron 1990; 4:819-832.
- Leung AT, Imagawa T, Block B et al. Biochemical and ultrastructural characterization of the 1,4-dihydropyridine receptor from rabbit skeletal muscle Evidence for a 52,000 Da subunit. J Biol Chem 1988; 263:994-1001.
- Sharp AH, Campbell KP. Characterization of the 1,4-dihydropyridine receptor using subunit-specific polyclonal antibodies. Evidence for a 32,000-Da subunit. J Biol Chem 1989; 264:2816-2825.
- 22. Tanabe T, Takeshima H, Mikami A et al. Primary structure of the receptor for calcium channel blockers from skeletal muscle. Nature 1987; 328:313-318.
- 23. De Jongh KS, Merrick DK, Catterall WA. Subunits of purified calcium channels: a 212-kDa form of α 1 and partial amino acid sequence of a phosphorylation site of an independent β subunit. Proc Natl Acad Sci USA 1989; 86:8585-8589.
- 24. De Jongh KS, Warner C, Colvin AA et al. Characterization of the two size forms of the α_1 subunit of skeletal muscle L-type calcium channels. Proc Natl Acad Sci USA 1991; 88:10778-10782.
- 25. Lai Y, Seagar MJ, Takahashi M et al. Cyclic AMP-dependent phosphorylation of two size forms of α₁ subunits of L-type calcium channels in rat skeletal muscle cells. J Biol Chem 1990; 265:20839-20848.
- 26. De Jongh KS, Colvin AA, Wang KKW et al. Differential proteolysis of the full-length form of the L-type calcium channel α_1 subunit by calpain. J Neurochem 1994; 63:1558-1564.
- 27. Burgess AJ, Norman RI. The large glycoprotein subunit of the skeletal muscle voltage-sensitive calcium channel. Eur J Biochem 1988; 178:527-533.
- Vandaele S, Fosset M, Galizzi J-P et al. Monoclonal antibodies that coimmunoprecipitate the 1,4-dihydropyridine and phenylalkylamine receptors and reveal the Ca²⁺ channel structure. Biochemistry 1987; 26:5-9.
- 29. Ellis SB, Williams ME, Ways NR et al. Sequence and expression of mRNAs encoding the alpha 1 and alpha 2 subunits of a DHP-sensitive calcium channel. Science 1988; 241:1661-1664.
- 30. Ruth P, Röhrkasten A, Biel M et al. Primary structure of the beta subunit of the DHP-sensitive calcium channel from skeletal muscle. Science 1989; 245:1115-1118.
- 31. Bosse E, Regulla S, Biel M et al. The cDNA and deduced amino acid sequence of the gamma subunit of the L-type calcium channel from rabbit skeletal muscle. FEBS Lett 1990; 267:153-156.
- 32. Jay SD, Ellis SB, McCue AF et al. Primary structure of the gamma subunit of the DHP-sensitive calcium channel from skeletal muscle. Science 1990; 248:490-492.
- 33. De Jongh KS, Warner C, Catterall WA. Subunits of purified calcium channels. α2 and δ are encoded by the same gene. J Biol Chem 1990; 265:14738-14741.
- 34. Jay SD, Sharp AH, Kahl SD et al. Structural characterization of the dihydropyridine-sensitive calcium channel α_2 -subunit and the associated δ peptides. J Biol Chem 1991; 266:3287-3293.
- 35. Gurnett CA, De Waard M, Campbell KP. Dual function of the voltage-dependent Ca²⁺ channel $\alpha_2\delta$ subunit in current stimulation and subunit interaction. Neuron 1996; 16:431-440.
- 36. Arreola J, Calvo J, Garcia MC et al. Modulation of calcium channels of twitch skeletal muscle fibres of the frog by adrenaline and cyclic adenosine monophosphate. J Physiol (Lond) 1987; 393:307-330.
- 37. Schmid A, Renaud J, Lazdunski M. Short term and long term effects of beta-adrenergic effectors and cyclic AMP on nitrendipine-sensitive voltage-dependent Ca²⁺ channels of skeletal muscle. J Biol Chem 1985; 260:13041-13046.
- 38. Fleig A, Penner R. Silent calcium channels generate excessive tail currents and facilitation of calcium currents in rat skeletal myoballs. J Physiol (Lond) 1996; 494:141-153.
- Sculptoreanu A, Scheuer T, Catterall WA. Voltage-dependent potentiation of L-type Ca²⁺ channels due to phosphorylation by cAMP-dependent protein kinase. Nature 1993a; 364:240-243.
- Curtis BM, Catterall WA. Phosphorylation of the calcium antagonist receptor of the voltage-sensitive calcium channel by cAMP-dependent protein kinase. Proc Natl Acad Sci USA 1985; 82:2528-2532.
- Haase H, Podzuweit T, Lutsch G et al. Signaling from beta-adrenoceptor to L-type calcium channel: identification of a novel cardiac protein kinase A target possessing similarities to AHNAK. FASEB J 1999; 13:2161-2172.
- 42. Jahn H, Nastainczyk W, Röhrkasten A et al. Site-specific phosphorylation of the purified receptor for calcium-channel blockers by cAMP- and cGMP-dependent protein kinases, protein kinase C, calmodulin-dependent protein kinase II and casein kinase II. Eur J Biochem 1988; 178:535-542.
- Nastainczyk W, Röhrkasten A, Sieber M et al. Phosphorylation of the purified receptor for calcium channel blockers by cAMP kinase and protein kinase C. Eur J Biochem 1987; 169:137-142.
- 44. O'Callahan CM, Hosey MM. Multiple phosphorylation sites in the 165-kilodalton peptide associated with dihydropyridine-sensitive calcium channels. Biochemistry 1988; 27:6071-6077.
- 45. Hymel L, Striessnig J, Glossmann H et al. Purified skeletal muscle 1,4-dihydropyridine receptor forms phosphorylation-dependent oligomeric calcium channels in planar bilayers. Proc Natl Acad Sci USA 1988; 85:4290-4294.
- 46. Mundiña-Weilenmann C, Chang CF, Gutierrez LM et al. Demonstration of the phosphorylation of dihydropyridine-sensitive calcium channels in chick skeletal muscle and the resultant activation of the channels after reconstitution. J Biol Chem 1991; 266:4067-4073.
- Nunoki K, Florio V, Catterall WA. Activation of purified calcium channels by stoichiometric protein phosphorylation. Proc Natl Acad Sci USA 1989; 86:6816-6820.
- Röhrkasten A, Meyer HE, Nastainczyk W et al. cAMP-dependent protein kinase rapidly phosphorylates serine- 687 of the skeletal muscle receptor for calcium channel blockers. J Biol Chem 1988; 263:15325-15329.
- Rotman EI, De Jongh KS, Florio V et al. Specific phosphorylation of a COOH-terminal site on the full-length form of the α1 subunit of the skeletal muscle calcium channel by cAMP-dependent protein kinase. J Biol Chem 1992; 267:16100-16105.
- Rotman EI, Murphy BJ, Catterall WA. Sites of selective cAMP-dependent phosphorylation of the L-type calcium channel α₁ subunit from intact rabbit skeletal muscle myotubes. J Biol Chem 1995; 270:16371-16377.
- Striessnig J, Knaus HG, Grabner M et al. Photoaffinity labelling of the phenylalkylamine receptor of the skeletal muscle transverse-tubule calcium channel. FEBS Lett 1987; 212:247-253.
- 52. Striessnig J, Scheffauer F, Mitterdorfer J et al. Identification of the benzothiazepine-binding polypeptide of skeletal muscle calcium channels with (+)-cis-azidodiltiazem and anti-ligand antibodies. J Biol Chem 1990b; 265:363-370.
- 53. Striessnig J, Murphy BJ, Catterall WA. The dihydropyridine receptor of L-type Ca²⁺ channels: Identification of binding domains for (+)-[³H]PN200-110 and [³H]azidopine within the α -1 subunit. Proc Natl Acad Sci USA 1991; 88:10769-10773.
- Catterall WA, Striessnig J. Receptor sites for Ca²⁺ channel antagonists. Trends Pharmacol Sci 1992; 13:256-262.
- 55. Hockerman GH, Peterson BZ, Sharp E et al. Construction of a high-affinity receptor site for dihydropyridine agonists and antagonists by single amino acid substitutions in a non-L-type Ca²⁺ channel. Proc Natl Acad Sci USA 1997; 94:14906-14911.

- 56. Ito H, Klugbauer N, Hofmann F. Transfer of the high affinity dihydropyridine sensitivity from L-type to non-L-type calcium channel. Mol Pharmacol 1997; 52:735-740.
- 57. Sinnegger MJ, Wang ZY, Grabner M et al. Nine L-type amino acid residues confer full 1,4-dihydropyridine sensitivity to the neuronal calcium channel α_{1A} subunit - Role of L-type MET. J Biol Chem 1997; 272:27686-27693.
- 58. Kraus R, Reichl B, Kimball SD et al. Identification of benz(othi)azepine-binding regions within L-type calcium channel α₁ subunits. J Biol Chem 1996; 271:20113-20118.
- 59. Striessnig J, Glossmann H, Catterall WA. Identification of a phenylalkylamine binding region within the α_1 subunit of skeletal muscle Ca²⁺ channels. Proc Natl Acad Sci USA 1990a; 87:9108-9112.
- 60. Reuter H. Calcium channel modulation by neurotransmitters, enzymes and drugs. Nature 1983; 301:569-574.
- 61. Tsien RW. Calcium channels in excitable cell membranes. Annu Rev Physiol 1983; 45:341-358.
- 62. Schmid A, Barhanin J, Coppola T et al. Immunochemical analysis of subunit structures of 1,4-dihydropyridine receptors associated with voltage dependent Ca⁺⁺ channels in skeletal, cardiac and smooth muscle. Biochemistry 1986; 25:3492-3495.
- 63. Takahashi M, Catterall WA. Dihydropyridine-sensitive calcium channels in cardiac and skeletal muscle membranes: studies with antibodies against the alpha subunits. Biochemistry 1987a; 26:5518-5526.
- Chang FC, Hosey MM. Dihydropyridine and phenylalkylamine receptors associated with cardiac and skeletal muscle calcium channels are structurally different. J Biol Chem 1988; 263:18929-18937.
- 65. Kuniyasu A, Oka K, Ide-Yamada T et al. Structural characterization of the dihydropyridine receptor-linked calcium channel from porcine heart. J Biochem(Tokyo) 1992; 112:235-242.
- Schneider T, Hofmann F. The bovine cardiac receptor for calcium channel blockers is a 195-kDa protein. Eur J Biochem 1988; 174:369-375.
- 67. Tokumaru H, Anzai K, Abe T et al. Purification of the cardiac 1,4-dihydropyridine receptor using immunoaffinity chromatography with a monoclonal antibody against the $\alpha_2\delta$ subunit of the skeletal muscle dihydropyridine receptor. Eur J Pharmacol Mol Pharmacol 1992; 227:363-370.
- 68. Tuana BS, Murphy BJ, Yi Q. Subcellular distribution and isolation of the Ca²⁺ antagonist receptor associated with the voltage regulated Ca²⁺ channel from rabbit heart muscle. Mol Cell Biochem 1987; 76:173-184.
- 69. Ferry DR, Goll A, Glossmann H. Photoaffinity labelling of the cardiac calcium channel. (-)-[3H]azidopine labels a 165 kDa polypeptide, and evidence against a [3H]=1,4-dihydropyridineisothiocyanate being a calcium-channel-specific affinity ligand. Biochem J 1987; 243:127-135.
- 70. De Jongh KS, Murphy BJ, Colvin AA et al. Specific phosphorylation of a site in the full-length form of the α_1 subunit of the cardiac L-type calcium channel by cAMP-dependent protein kinase. Biochemistry 1996; 35:10392-10402.
- 71. Wei XNA, Lacerda AE, Olcese R et al. Modification of Ca²⁺ channel activity by deletions at the carboxyl terminus of the cardiac α1 subunit. J Biol Chem 1994; 269:1635-1640.
- 72. Gao T, Cuadra AE, Ma H et al. C-terminal fragments of the alpha 1C (Cav1.2) subunit associate with and regulate L-type calcium channels containing C-terminal-truncated alpha 1C subunits. J Biol Chem 2001; 276:21089-21097.
- 73. Armstrong DL, Rossier MF, Scherbatko AD et al. Enzymatic gating of voltage-activated calcium channels. Ann NY Acad Sci 1991; 635:26-34.
- 74. McDonald TF, Pelzer S, Trautwein W et al. Regulation and modulation of calcium channels in cardiac, skeletal, and smooth muscle cells. Physiol Rev 1994; 74:365-507.
- 75. Mitterdorfer J, Froschmayr M, Grabner M et al. Identification of PK-A phosphorylation sites in the carboxyl terminus of L-type calcium channel α_1 subunits. Biochemistry 1996; 35:9400-9406.
- 76. Gao T, Yatani A, Dell'Acqua ML et al. cAMP-dependent regulation of cardiac L-type Ca²⁺ channels requires membrane targeting of PKA and phosphorylation of channel subunits. Neuron 1997; 19:185-196.
- 77. Gao TY, Puri TS, Gerhardstein BL et al. Identification and subcellular localization of the subunits of L-type calcium channels and adenylyl cyclase in cardiac myocytes. J Biol Chem 1997; 272:19401-19407.
- 78. Biel M, Hullin R, Freundner S et al. Tissue-specific expression of high-voltage-activated dihydropyridine-sensitive L-type calcium channels. Eur J Biochem 1991; 200:81-88.
- 79. Hullin R, Singer-Lahat D, Freichel M et al. Calcium channel beta subunit heterogeneity: Functional expression of cloned cDNA from heart, aorta and brain. EMBO J 1992; 11:885-890.
- Sculptoreanu A, Rotman E, Takahashi M et al. Voltage-dependent potentiation of the activity of cardiac L-type calcium channel α₁ subunits due to phosphorylation by cAMP-dependent protein kinase. Proc Natl Acad Sci USA 1993; 90:10135-10139.

- Yoshida A, Takahashi M, Nishimura S et al. Cyclic AMP-dependent phosphorylation and regulation of the cardiac dihydropyridine-sensitive Ca channel. FEBS Lett 1992a; 309:343-349.
- 82. Zong X, Schreieck J, Mehrke G et al. On the regulation of the expressed L-type calcium channel by cAMP-dependent phosphorylation. Pflugers Arch 1995; 430:340-347.
- 83. Haase H, Bartel S, Karczewski P et al. In-vivo phosphorylation of the cardiac L-type calcium channel beta-subunit in response to catecholamines. Mol Cell Biochem 1996; 163-164:99-106.
- Bunemann M, Gerhardstein BL, Gao TY et al. Functional regulation of L-type calcium channels via protein kianse A-mediated phosphorylation of the beta-2 subunit. J Biol Chem 1999; 274:33851-33854.
- 85. Takahashi M, Catterall WA. Identification of an alpha subunit of dihydropyridine-sensitive brain calcium channels. Science 1987b; 236:88-91.
- 86. Takahashi M, Fujimoto Y. Identification of a dihydropyridine-sensitive calcium channel in chick brain by a monoclonal antibody. Biochem Biophys Res Comm 1989; 163:1182-1188.
- 87. Tsien RW, Lipscombe D, Madison DV et al. Multiple types of neuronal calcium channels and their selective modulation. Trends Neurosci 1988; 11:431-438.
- 88. Bean BP. Classes of calcium channels in vertebrate cells. Annu Rev Physiol 1989; 51:367-384.
- Llinas R, Sugimori M, Hillman DE et al. Distribution and functional significance of the P-type, voltage-dependent Ca²⁺ channels in the mammalian central nervous system. Trends Neurosci 1992; 15:351-355.
- 90. Zhang J-F, Randall AD, Ellinor PT et al. Distinctive pharmacology and kinetics of cloned neuronal Ca²⁺ channels and their possible counterparts in mammalian CNS neurons. Neuropharma-cology 1993; 32:1075-1088.
- 91. Leveque C, El Far O, Martin-Moutot N et al. Purification of the N-type calcium channel associated with syntaxin and synaptotagmin: a complex implicated in synaptic vesicle exocytosis. J Biol Chem 1994; 269:6306-6312.
- McEnery MW, Snowman AM, Sharp AH et al. Purified ω-conotoxin GVIA receptor of rat brain resembles a dihydropyridine-sensitive L-type calcium channel. Proc Natl Acad Sci USA 1991; 88:11095-11099.
- 93. Sakamoto J, Campbell KP. A monoclonal antibody to the β subunit of the skeletal muscle dihydropyridine receptor immunoprecipitates the brain ω-conotoxin GVIA receptor. J Biol Chem 1991; 266:18914-18919.
- 94. Witcher DR, De Waard M, Sakamoto J et al. Subunit identification and reconstitution of the N-type Ca²⁺ channel complex purified from brain. Science 1993; 261:486-489.
- Dubel SJ, Starr TVB, Hell J et al. Molecular cloning of the α-1 subunit of an ω-conotoxin-sensitive calcium channel. Proc Natl Acad Sci USA 1992; 89:5058-5062.
- Williams ME, Brust PF, Feldman DH et al. Structure and functional expression of an omega-conotoxin-sensitive human N-type calcium channel. Science 1992; 257:389-395.
- 97. Hell JW, Appleyard SM, Yokoyama CT et al. Differential phosphorylation of two size forms of the N-type calcium channel α_1 subunit which have different COOH-termini. J Biol Chem 1993; 269:7390-7396.
- 98. Westenbroek RE, Hell JW, Warner C et al. Biochemical properties and subcellular distribution of an N-type calcium channel α₁ subunit. Neuron 1992; 9:1099-1115.
- 99. Liu H, De Waard M, Scott VES et al. Identification of three subunits of the high affinity ω-conotoxin MVIIC-sensitive Ca²⁺ channel. J Biol Chem 1996; 271:13804-13810.
- 100. Martin-Moutot N, Charvin N, Leveque C et al. Interaction of SNARE complexes with P/Q-type calcium channels in rat cerebellar synaptosomes. J Biol Chem 1996; 271:6567-6570.
- 101. Martin-Moutot N, Leveque C, Sato K et al. Properties of omega conotoxin MVIIC receptors associated with α_{1A} calcium channel subunits in rat brain. FEBS Lett 1995; 366:21-25.
- 102. Letts VA, Felix R, Biddlecome GH et al. The mouse stargazer gene encodes a neuronal Ca^{2+} -channel γ subunit. Nature Genet 1998; 19:340-347.
- 103. Mori Y, Friedrich T, Kim M-S et al. Primary structure and functional expression from complementary DNA of a brain calcium channel. Nature 1991; 350:398-402.
- 104. Starr TVB, Prystay W, Snutch TP. Primary structure of a calcium channel that is highly expressed in the rat cerebellum. Proc Natl Acad Sci USA 1991; 88:5621-5625.
- 105. Sakurai T, Hell JW, Woppmann A et al. Immunochemical identification and differential phosphorylation of alternatively spliced forms of the α_{1A} subunit of brain calcium channels. J Biol Chem 1995; 270:21234-21242.

Molecular Properties of Voltage-Gated Calcium Channels

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Native Voltage-Gated Ca²⁺ Channels

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High Voltage-Activated Ca²⁺ Channels

L-Type Channels

L-type Ca^{2+} channels were initially described in peripheral neurons and cardiac cells, but appear to be present in all excitable as well as many types of non-excitable cells.⁴ In certain cells, L-type channels have been shown to be preferentially localized to specific subcellular regions. For example, the L-type channels responsible for skeletal muscle contraction are concentrated on the transverse tubule membrane,⁵ while neuronal L-type channels are located primarily on cell bodies and proximal dendrites.⁶ The L-type channel is the primary route for Ca^{2+} entry into cardiac, skeletal, and smooth muscles.² The skeletal muscle L-type channel acts as a voltage sensor for excitation-contraction (E-C) coupling in skeletal muscle, presumably linking membrane depolarization to Ca^{2+} release from intracellular stores. While Ca^{2+} entry through this channel is not required for the initiation of contraction in skeletal muscle, it may provide a source of Ca^{2+} to replenish internal stores.^{2,4,7,8} There is some evidence that L-type channels are involved in exocytotic release from endocrine cells and some neurons⁹⁻¹³ and the localization of L-type channels on the cell soma⁶ has also implicated these channels in the regulation of gene expression.¹⁴⁻¹⁶

Much is known about the pharmacological properties of L-type Ca²⁺ channels. The three main classes of organic L-type channel blockers are the phenylalkylamines (verapamil), benzothiazapines (diltiazem), and 1,4-dihydropyridines (DHPs) (e.g., nitrendipine, nifedipine, nimodipine). The DHP antagonists bind preferentially to channels in the active conformation, a state favored by depolarization (producing more potent inhibition at depolarized potentials). A number of DHP agonists have also been developed, the most highly utilized of which is

(-)-Bay K 8644 which increases both the open time and the single channel conductance (see chapter by Striessnig for more detail). L-type channels are also blocked by certain native peptide toxins such as ω -agatoxin IIIA (ω -Aga IIIA), isolated from the venom of the funnel web spider *Agelenopsis aperta*.^{17,18} ω -Aga IIIA reduces the current amplitude without affecting the time course and unlike the DHPs, ω -Aga IIIA inhibition is voltage-independent and blocks L-type channels at all potentials² (see chapter by Adams and Lewis for more detail).

L-type channels have a unitary conductance ranging from 20 and 27 pS using 110 mM barium (Ba²⁺) as the charge carrier. L-type channels require large departures from resting potential to become activated and typically begin to open at potentials positive to -10 mV, although they can activate at significantly more negative potentials in chromaffin cells, sensory neurons, and cardiac cells. In the presence of Ba²⁺ as the charge carrier, once open, L-type channels do not inactivate significantly during depolarizations of hundreds of milliseconds.^{2,3,19} Compared to Ba²⁺ currents, using Ca²⁺ as the charge carrier L-type currents are smaller and inactivate rapidly. This Ca²⁺-dependent inactivation has a number of characteristic properties and inactivation attributable to Ca²⁺ influx is greatest at depolarizations at which Ca²⁺ entry through the channel is maximal.²⁰ While the degree of inactivation is slowed by the addition of BAPTA and other Ca²⁺ chelators, it is not completely abolished. Ca²⁺-dependent inactivation can however be eliminated by intracellular applications of trypsin, suggesting that the mechanism through which Ca^{2+} acts to inactivate the channel is in close proximity to, if not part of, the channel complex itself.^{2,3,21,22} Because the rate of Ca^{2+} -dependent inactivation does not change with channel density, Neely et al (1994)²² proposed a "local domain" hypothesis, in which Ca²⁺ affects only the channel through which it enters (see Chapter 11 for more detail). Moreover, current models view calmodulin to be constitutively bound to the C-terminus forming part of the Ca²⁺ sensing machinery, ultimately leading to the signal transduction of Ca²⁺-dependent inactivation.²³

N-Type Channels

In addition to L- and T-type Ca^{2+} channels, recordings from chick dorsal root ganglion (DRG) cells revealed a third type of single channel Ca^{2+} conductance of 13 pS (in 110 mM Ba^{2+}), intermediate between that of the T- (8 pS) and L- (25 pS) type channels.^{1,2,19,24,25} Although this conductance shares some general electrophysiological characteristics with currents through both T- and L-type channels, it could not be attributed to either. Consequently, the corresponding channel was designated as N (neither)-type.

Although first identified in chick DRG neurons, N-type channels have also been detected in mammalian DRG cells,²⁶⁻²⁹ mammalian and amphibian sympathetic neurons,³⁰⁻³³ and other cells of the peripheral and central nervous systems.³⁴⁻³⁹ N-type channels appear to be expressed only in neuronal tissues,^{31,40} although an N-type current has been reported in rat thyroid C-cell line.⁴¹ Electrophysiologically, N-type channels are most easily distinguished from L-type channels by their inactivation properties. Unlike L-type channels, N-type channels display time-dependent inactivation (with Ba2+ as the charge carrier). N-type currents decay with a time constant (τ) ranging from 50 to 110 ms, significantly slower than the rapid ($\tau = 20-50$ ms) inactivation of the LVA T-type channels, but much faster than the non-inactivating L-type channels. In chick DRG neurons, the N-type current decays almost completely during a test depolarization of 140 ms, while L-type current shows little inactivation over the same period of time.¹ However, N-type currents do not always inactivate rapidly. In sympathetic neurons, the decay rate of N-type currents is much slower ($\tau = 500$ to 800 ms) and can be incomplete, even over depolarizations lasting longer than one second.^{2,41-42} Thus, there appears to be at least two distinct components to N-type current inactivation. These differences in inactivation kinetics could reflect different subtypes of N-type channel. Alternatively, a single N-type channel could support both currents by switching between the slow- and fast-inactivating states. 40,43

In addition to the time-dependence parameter, there is also a voltage-dependent aspect to N-type channel inactivation.^{1,24,25,29} Holding the cell membrane at potentials between -60

and -40 mV results in significant inactivation of the N-type current, and strongly negative potentials are required to reprime the channels. N-type channels are markedly more sensitive to the effects of holding potential on inactivation than are L-type channels. At resting membrane potentials of -20 mV, N-type channels are completely inactivated while L-type channels remain available for opening.

Theoretically, the different inactivation properties of N- and L-type channels provides two parameters that can be used to dissect the relative contributions of the two channel types to the whole cell HVA current.^{2,24} One method takes advantage of the different inactivation rates. The component of whole cell current that decays during a prolonged depolarization can be attributed to the inactivating N-type channels, while the non-inactivating portion is identified as L-type current. The second approach exploits the different ranges over which voltage-dependent inactivation takes place. The contribution of each type to the whole cell current may be determined by analyzing the differences in whole cell currents elicited by depolarizations from resting potentials of -40 and -90 mV. Because L-type channels are relatively resistant to the effects of holding potential on inactivation while N-type channels inactivate at depolarized membrane potentials, the difference under these two conditions should reflect the contribution of N-type channels to the whole-cell current. However, neither method may be adequate to properly distinguish these currents. Some N-type channels can inactivate quite slowly and inactivation may not be complete. In addition, voltage-dependent inactivation of N-type channels can be highly variable and takes place over a wide range of holding potentials between -80 to -20 mV.^{24,25} If N-type channels predominate in a cell, the residual current through incompletely inactivated N-type channels may be significant. Thus definitions of Nand L-type current based solely on these criteria may not be valid.

Pharmacologically, N-type channels are sensitive to inhibition by a class of native peptide toxins called the ω -conotoxins, which are a family of small (13-29 amino acid) peptides found in the venom of predatory marine snails of the genus *Conus.*^{44,45} All known ω -conotoxins inhibit N-type Ca²⁺ channels, although their specificities and blocking affinities for this particular channel vary significantly. To date, ω -conotoxin GVIA (ω -CgTx), a 27-amino acid peptide from *Conus geographus*⁴⁶ is the most specific ω -conotoxin peptide for N-type channel inhibition. ω -CgTx produces complete and irreversible inhibition of N-type currents in DRG, hippocampal, sympathetic, and sensory neurons at concentrations of approximately 100 nM to 1 μ M.⁴⁷⁻⁴⁹ At higher concentrations (5-15 μ M), ω -CgTx also inhibits L- and T-type currents, although unlike N-type channels, the effects are incomplete and reversible⁴⁷⁻⁵² (see chapter by Adams and Lewis for more detail).

 ω -CgTx binding sites (and by extension N-type Ca²⁺ channels) are distributed throughout the PNS and CNS, including the cortex, hippocampus, olfactory bulb, and cerebellar cortex, and appear especially concentrated in regions of high synaptic density.^{2,53-58} Although N-type channels were first identified by single channel recordings from the cell bodies of DRG neurons,¹ they appear to be more abundantly localized on dendrites and axon terminals. In muscle, ω -CgTx binding occurs at the active zones of presynaptic cells in spatial register with the postsynaptic acetylcholine (ACh) receptors on the muscle. Labeling is rarely found between active zones, nor is it localized to areas of the presynaptic membrane that do not face the muscle. N-type channels have also been observed to cluster in areas of synaptic contact on hippocampal CA1 neurons.⁵⁴

The presence of N-type channels on the presynaptic membrane suggests that Ca^{2+} entry through these channels is responsible for triggering neurotransmitter release. An early study⁵⁹ demonstrated that ω -CgTx blocks electrically-induced release from the frog NMJ and numerous subsequent studies have demonstrated that the application of ω -CgTx inhibits neurotransmitter release in the central and peripheral nervous system.⁶⁰⁻⁶⁷ Furthermore, biochemical studies indicate that N-type channels are physically associated with proteins such as synaptotagmin and syntaxin which are part of the exocytotic machinery.⁶⁸⁻⁷⁰ There appear to be species- and cell-specific differences in N-type-channel-regulated neurotransmission. For example, while ω -CgTx completely abolishes neurotransmission at the avian and amphibian NMJ, it has no effect on the mammalian motor nervous system.^{59,65,71-73} The ability of this toxin to inhibit neurotransmission also varies depending on the type of synapse within a given species.^{52,65-67} For example, inhibitory synaptic transmission in hippocampal CA1 neurons is strongly reduced by the application of ω -CgTx, whereas the toxin blocks excitatory transmissions to a much lesser extent. In addition, while ω -CgTx inhibits release of ACh from both autonomic and central neurons in the rat, release from central neurons is approximately 20-fold less sensitive.⁶⁵

In spite of the complete and irreversible inhibition of N-type channels produced by ω -CgTx, application of the toxin to many types of neurons only partially inhibits neurotransmitter release, suggesting that other types of Ca²⁺ channels contribute to neurotransmitter release from both central and peripheral neurons.^{58,74,75} In fact, while regulation of transmitter release from peripheral neurons appears to predominantly involve N-type channels, release in the central nervous system appears to be controlled primarily by other types of Ca²⁺ channels that are insensitive to both ω -CgTx and DHPs.^{76,77}

The presence of N-type channels in regions other than the synapse indicates that these channels have other functions in addition to neurotransmitter release. N-type channels localized to dendritic branch points may be involved in integration or amplification of neural inputs.⁵⁶ N-type channels may also play a role in nervous system development as evidenced by the expression of N-type channels on postmitotic cerebellar granule cells. These cells only begin migration after the appearance of N-type channels and ω -CgTx causes a cessation of migration.⁷⁸

Other HVA Ca²⁺ Channels: P-, Q-, and O-Types

The original classification system of Ca^{2+} channels, which was expanded from the simple LVA/ HVA dichotomy to encompass T-, L- and N-channels, was subsequently found to be too restrictive to adequately describe all types of Ca^{2+} conductances. The availability of blocking agents that target L- and N-type channels revealed other HVA currents that could not be defined according to this scheme.^{36,37,45,79,81} These novel channel types, variously named P-, Q-, O-, and R-, have primarily been defined on the basis of their distinctive pharmacological properties rather than electrophysiological characteristics.

The P-type current was originally identified as an HVA current in Purkinje cells that is insensitive to the agents typically used to inhibit L- and N-type channels.⁸² These channels are thought to support the Ca²⁺-dependent action potentials in the dendrites of cerebellar Purkinje cells, which are unaffected by DHPs and ω -CgTx, but are potently blocked by components of the venom of the funnel web spider *Agelenopsis aperta*.⁸²⁻⁸⁵

Whole cell recordings from Purkinje cells reveal an HVA current that peaks at voltages between -30 and -20 mV and inactivates slowly over the duration of the depolarization.^{37,52,81,86} Single channel analysis of P-type channels reveals conductances in ranges similar to those of Nand L-type channels. Multiple unitary conductance levels of 9, 14, 19 pS in 110 mM Ba have been reported for P-type channels in the Purkinje cell soma and dendrites,⁸⁷ and a P-type current in hypoglossal motorneurons has a unitary conductance of 20 pS.³⁹

The venom of the funnel web spider, like that of the cone snail, is a cocktail of toxins that target different elements of the synaptic machinery. FTX, a non-peptide component of the venom (arginine polyamine and a synthetic analog of FTX, sFTX), was initially reported to be specific blockers of P-type channels,^{3,82,83} but subsequently shown to produce inhibition of other Ca²⁺ currents in conjunction with the P-type block.^{3,45}

ω-Aga IVA, a 48-amino acid peptide also found in the venom of *A. aperta* potently inhibits P-type Ca²⁺ channels.^{52,84,86} In Purkinje cells, complete inhibition is observed at concentrations below 200 nM, with half-maximal block produced at concentrations between 2 and 10 nM. Inhibition is rapid, occurring within two minutes of application, and while the inhibition is poorly reversible by wash-out, it can be removed by a series of strong depolarizations (i.e., to +70 mV). Block of P-type currents by ω -Aga IVA in other neurons is qualitatively similar to that in Purkinje cells although the kinetics vary slightly. For example, while inhibition of P-type current in spinal cord interneurons and neurons in the visual cortex occurs as rapidly as that in the Purkinje cells, the rate of block is several times slower in CA1 and CA3 hippocampal neurons.⁸⁶

A peptide toxin isolated from the cone snail *Conus magus* has also been shown to inhibit P-type channels.⁸⁸ This toxin, ω -CgTx MVIIC, blocks P-type channels with an IC₅₀ of 1-10 μ M. However, ω -CgTx MVIIC also inhibits N-type channels as well as the Q- and O-type conductances⁸⁸ (see chapter by Adams and Lewis for more detail).

P-type channels do not account for all of the DHP- and ω -CgTx-resistant current in neurons since a substantial fraction of current remains even after exposure to saturating concentrations of DHPs, ω -CgTx, and ω -Aga IVA. Cultured rat cerebellar granule cells express an HVA current that is unaffected by these inhibitors at concentrations which block L-, N- and P-type channels, respectively.^{45,89,90} However, the channels supporting this novel current (termed Q-type) are partially blocked by ω -Aga IVA at concentrations 10 to 100 times that required for P-type inhibition and are completely blocked by ω -CgTx MVIIC (IC₅₀= 30 to 300 nM). In addition to differing sensitivities to these toxins, Q-type channels partially recover from ω -Aga IVA-induced inhibition within minutes of toxin washout. Q-type channels also display electrophysiological properties distinct from those of P-type channels. While P-type currents in Purkinje cells and cerebellar granule cells show no inactivation over a 100 ms test depolarization, the Q-type current in granule cells decays to approximately 65% of the peak current over the same time period.

The existence of O-type channels has been inferred solely from pharmacological studies. O-type channels were identified as high affinity ω -CgTx MVIIC binding sites.⁹¹ These channels are significantly more sensitive to the toxin than are other ω -CgTx MVIIC-sensitive channels⁴⁵ It is possible that P-, Q-, and O-type channels are members of the same channel family which possess slightly different pharmacological and electrophysiological properties as a result of alternative splicing of the α_1 subunit gene and/or different complements of auxiliary subunits. While O-type channels have not been localized immunohistochemically, evidence from binding studies suggests that they are widely distributed in the mammalian CNS.⁴⁵ Estimates of O-type bindings sites in rat brain preparations suggest that O-type channels are more prevalent than N-type channels in the CNS, and it has been proposed that O-type channels are localized exclusively to synaptic termini, which would largely prevent their detection through electrophysiological means.

Many studies implicate P-, Q, and O-type channels in neurotransmitter release.⁴⁵ While N-type channels mediate release at some synapses in the mammalian CNS, the ω -Aga IVA-sensitive P- and Q-type channels appear to play a more prominent role.^{52,92} ω -Aga IVA potently blocks Ca²⁺ uptake into synaptosomes⁸⁴ and partially inhibits the release of dopamine and glutamate from synaptosomes^{93,94} and at CA1-CA3 synapses in the hippocampus.^{58,74,76} In the peripheral nervous system, ω -Aga IVA has little or no effect on the autonomic nervous system,⁹⁵ but P-type channels are probably responsible for neurotransmitter release at the mammalian NMJ.^{96,97} As ω -Aga IVA blocks both P- and Q-type channels, it is possible that both channel types are involved in neurotransmission. Wheeler and colleagues found that the pharmacological properties of the ω -Aga IVA-sensitive channels supporting neurotransmission in the hippocampus and for ω -Aga IVA-induced block of inhibitory postsynaptic potentials in the cerebellum were more similar to Q- than P-type channels.^{58,98} Finally, O-type channels may also mediate neurotransmission at certain synapses, as norepinephrine release in the hippocampus is inhibited by subnanomolar concentrations of ω -CgTx MVIIC.⁴⁵

R-Type Channels

A component of the HVA current in cerebellar granule cells remains even after the application of nimodipine, ω -CgTx, ω -Aga VIA, and ω -CgTx MVIIC. This current, categorized as R (residual or resistant)- type,⁸⁹ comprises approximately 15% of the HVA current in these cells. R-type current may not necessarily reflect a single channel type, but a family of molecularly distinct channels with similar pharmacological and electrophysiological characteristics.

R-type currents begin to activate around -40 mV and reach a peak amplitude at 0 mV. The current inactivates rapidly, and the increased rate of inactivation with Ca^{2+} as the charge carrier suggests that the channels supporting the R-type current inactivate in a Ca^{2+} -dependent manner. R-type channels are equally sensitive to block by Cd^{2+} and Ni^{2+} ions. The exact nature of the channels supporting this current is currently unknown. See the below section on Class E channels for further discussion.

Cloned Calcium Channels

HVA Ca²⁺ Channels Are Multi-Subunit Complexes

Biochemical studies have established that high threshold voltage-gated Ca²⁺ channels are multi-subunit complexes. Taking advantage of the high-affinity binding of organic antagonists, several groups purified the L-type channel from skeletal muscle. Four distinct polypeptides, designated α_1 (175-kDa), $\alpha_2\delta$ (170-kDa), β (52-kDa), and γ (32-kDa), co-migrate with the ligand-binding activity.⁹⁹⁻¹⁰² A minor 212-kDa band also co-purified and was shown to represent a larger, much less abundant form of the skeletal muscle α_1 subunit.¹⁰³ Similar approaches have been used to isolate the cardiac L-type¹⁰⁴ and brain N-type channels¹⁰⁵ These complexes also consist of an α_1 subunit associated with β and $\alpha_2\delta$ subunits. The β and α_2 - δ are highly similar, if not identical to, the subunits associated with the skeletal muscle α_1 .^{106,107} However, unlike the skeletal muscle L-type channel, no γ subunits appeared as part of either complex. A novel 95-kDa polypeptide was found to comigrate with the N-type channel although it is unclear whether this represents a bona fide channel subunit or a proteolytic fragment.¹⁰⁵

While subunit composition differs slightly depending on channel type, a general model has been proposed for HVA channels in which four to five proteins form a multisubunit complex (Fig. 1A). In this model, the α_1 subunit forms the channel proper, comprising both the voltage-sensing mechanism and the Ca²⁺ selective pore, and the remaining proteins interact with the α_1 subunit to modulate activity.

Primary Structure and Properties of Ca^{2+} Channel α_1 Subunits

The first cDNAs encoding Ca^{2+} channel α_1 subunits were isolated from rabbit skeletal muscle.^{5,108} The α_{1S} L-type subunit is an 1873-residue protein that bears a high degree of amino acid similarity to the voltage-gated Na⁺ and potassium (K⁺) channels (see Fig. 1). The α_1 subunit is predicted to consist of four homologous, mainly hydrophobic domains (designated domains I, II, III and IV). Each of the four domains is comprised of six putative membrane-spanning segments (S1-S6). The S4 segment in each domain contains positively-charged residues every third or fourth position and is believed to form part of the voltage-sensing mechanism of the channel. Between the S5 and S6 segments of each domain are two hydrophobic segments, SS1 and SS2, which are predicted to form the channel pore (Fig. 1B).

Based upon similarity to voltage-gated Na⁺ channels, Tanabe et al (1987)⁵ speculated that the α_1 subunit may form both the Ca²⁺-selective pore and the voltage sensor of the channel complex. This hypothesis was supported by studies demonstrating that expression of the α_{1S} in myotubes from dysgenic mice restored normal skeletal muscle-type E-C coupling and the slow Ca²⁺ current absent in these cells.⁷ In addition, α_{1S} expression in dysgenic myotubes restored the charge movement observed in normal myotubes upon membrane depolarization.¹⁰⁹ These results indicated that the skeletal muscle α_{1S} subunit acts both as a voltage-sensor, providing a physical connection between membrane depolarization and Ca²⁺-release from intracellular stores for the initiation of muscle contraction, and is also part of a functional VGCC.



Figure 1. Composition of a VGCC complex and structure of the α_1 subunit. A) Diagram of a high-voltage-activated VGCC complex, indicating the $\alpha_1, \alpha_2/\delta$, β , and γ subunits. The α_1 subunit forms the channel proper, comprising the voltage-sensing mechanism, the Ca selective pore, and target of identified pharmacological agents. B) Predicted structure and transmembrane topology of the α_1 subunit. Each domain possesses six putative membrane-spanning segments (1-6) and pore-forming P-loop (SS1-SS2). All high voltage-activated channel α_1 subunits possess a conserved region in the domain I-II linker that binds the Ca β subunit as well as a conserved EF hand motif in the carboxyl terminus. Other structural elements identified amongst the various types of high voltage-activated Ca²⁺ channels includes: a high affinity G-protein $\beta\gamma$ -subunit binding site in the I-II linker (Ca₄2.1 and Ca₄2.2); distinct regions in the domain II-III linker responsible for functional interaction with the synaptic release machinery (Ca₄2.1 and Ca₄2.2), cysteine string protein (Ca₄2.2) and the skeletal muscle excitation-contraction coupling machinery (Ca₄1.1); as well as carboxyl terminal regions shown to interact with calmodulin (Ca₄1.2, Ca₄2.1, Ca₄2.2, Ca₄2.3), binding to AKAP-79 (Ca₄1.2), Ca-binding protein-1 (Ca₄2.2).

Using the skeletal muscle clone as a probe, cDNAs encoding homologous L-type α_1 subunits have been subsequently cloned from cardiac¹¹⁰ and smooth muscle.^{111,112} Injection of the cardiac α_1 subunit into dysgenic myotubes resulted in the expression of a VGCC which differed markedly in terms of activation rate, Ba²⁺ permeability, and E-C coupling from the current conducted through channels formed by the skeletal muscle clone.¹¹³ Expression of



Figure 2. Similarity tree of mammalian VGCC α_1 subunits. The predicted amino acid sequences of representatives of each class of VGCC α_1 subunit were compared pairwise and the percent similarities plotted. *unc-2, egl-19* and *cca-1* represent the *Caenorhabditis elegans* ancestoral homologues of the mammalian subunits. GenBank Accession Numbers for VGCCs: rat α_{1A} , M64373; rat α_{1B} , M92905; rat α_{1C} , M67515; rat α_{1D} , AF370009; rat α_{1E} , L15453; human α_{1F} , AJ224874; rat α_{1G} , AF290212; rat α_{1H} , AF290213; rat α_{1I} , AF290214; rabbit α_{1S} , M23919.

cardiac and smooth muscle α_1 subunit clones in *Xenopus* oocytes^{110,111,114,115} resulted in large inward currents that were sensitive to the organic channel agonists and antagonists, thereby identifying them as L-type channels. Co-expression of skeletal muscle-derived α_2 - δ and β subunits, while affecting the amplitude and voltage dependence of the currents, was not required for channel activity or drug binding, suggesting that the α_1 subunit is capable of forming a functional channel in the absence of the other subunits. However, because some VGCC subunits may be endogenously expressed by *Xenopus* oocytes,^{116,117} it is possible that the α_1 protein forms a complex with these endogenous auxiliary subunits. This prompted several groups to examine the properties of the α_1 subunit in cells lacking these proteins. Murine L-cells^{118,119} and Chinese Hamster Ovary (CHO) cells¹¹⁴ stably transformed with α_1 subunits express voltage activated Ca²⁺ currents sensitive to L-type channel blockers. While Ca²⁺ currents in cells expressing the smooth muscle α_1 subunit displayed similar drug sensitivities and kinetics to the native currents, the currents supported by α_{15} activated considerably more slowly than currents recorded from skeletal muscle cells.

At least nine different α_1 subunit genes are now known to be expressed in the mammalian nervous system (see Fig. 2, Table 1). Initially, four distinct classes of α_1 subunits were isolated from a rat brain library on the basis of their homology to the rabbit skeletal muscle α_{1S} subunit.¹²⁰ Each cDNA hybridized to one of four distinct banding patterns on Northern blots of rat brain mRNA, allowing them to be grouped into four classes, designated α_{1A} , α_{1B} , α_{1C} and α_{1D} . Subsequently, a fifth α_1 subunit (α_{1E}) was isolated from rat brain.¹²¹ Southern blot analysis and DNA sequencing indicated that the five classes are separate members of a multigene family with the α_{1A} , α_{1B} , and α_{1E} channels being more similar to one another than they are to

Native Channel Type	α_1 Subunit	Activation	Pharmacological Range	Localization Characteristics
P/Q	α_{1A_r} (Ca _v 2.1)	HVA	ω-Aga IVA (P-type), ω-MVIIC (Q-type); insensitive to DHPs	CNS, heart, pituitary; some cell bodies, many dendrites
N	α_{1B} (Ca _v 2.2)	HVA	ω-CgTx GVIA, insensitive to DHPs	CNS; subset of cell bodies, dendrites and presynaptic terminals
L	$\begin{array}{l} \alpha_{1C} \left(Ca_v 1.2 \right) \\ \alpha_{1D} \left(Ca_v 1.3 \right) \\ \alpha_{1F} \left(Ca_v 1.4 \right) \\ \alpha_{1S} \left(Ca_v 1.1 \right) \end{array}$	HVA	ω-CgTx (reversible; α _{1D}), DHPs, benzothiazapines, phenylalkylamines	α_{1C} : CNS, smooth and cardiac muscle; α_{1D} : CNS, endocrine cells α_{1F} : retina, immune system α_{1S} : skeletal muscle; (α_{1C} , α_{1D}) cell bodies and proximal dendrites
R	α_{1E} (Ca _v 2.3)*	HVA	Ni ²⁺ ; insensitive to DHPs, ω-CgTx, and w-Aga- IVA	CNS; cell bodies, some distal dendrites and presynaptic terminals
Т		LVA	mibefradil, amiloride	CNS, heart, placenta, lung, kidney

Table 1. Voltage-gated calcium channel subunits

* While the α_{1E} subunit is often cited as encoding the R-type current first described in cerebellar granule cells, mice with a targeted gene deletion in the α_{1E} gene retain significant amounts of whole cell R-type currents.

the class C and D channels (Fig. 2). The class C clone is almost identical to the cardiac α_1 subunit, suggesting that the class C and D clones represent members of the DHP-sensitive L-type channels, while the A, B, and E clones are DHP resistant. Four other VGCC α_1 subunit genes have been identified in the mammalian genome. The $\alpha_{1F}^{122,123}$ shares the most sequence identity with the L-type channels. The α_{1G} , α_{1H} , and α_{1I} clones represent the LVA branch of the VGCC family.¹²⁴⁻¹²⁶

The individual α_1 subunit clones share the most homology in the transmembrane domains with the majority of sequence divergence occurring in the putative cytoplasmic regions of the channels. The loop between domains II and III, and the cytoplasmic tail vary in size as well as sequence. The DHP-sensitive channels (classes C, D, F, and S) have relatively short (≈130 amino acid) sequences linking domains II and III while the analogous region in the class A and B channels are significantly larger (≈ 430 amino acid). However, despite the size similarity between the linkers, the class A and B clones show little sequence homology in this region.¹²⁷ While the LVA channel clones (classes G, H, and I) share much less sequence identity with the other classes, the voltage-sensing S4 region and the loop that forms the channel pore are well conserved. Other motifs, such as the β -subunit binding site and the E-F hand, which are found in the HVA classes of VGCCs are absent in the LVA channels. Whole cell and single channel electrophysiological techniques have provided information about the functional and pharmacological properties of the cloned channels and allowed researchers to assign the individual clones to channel types (Table 1).

$\alpha_{IA}/Ca_v 2.1$

Class A α_l subunits have been cloned from both rabbit (BI-1, BI-2)^{128} and rat (rbA-I)^{129} brain and Drosophila melanogaster (Dmca1A).¹³⁰ Northern blot analysis identified a single RNA transcript of 9.4 kb in rabbit brain, while two transcripts of 8.3 and 8.8 kb were detected in rat brain. α_{1A} transcripts are widely distributed throughout the nervous system, as well as being present in the heart and pituitary, but not in skeletal muscle, stomach, or kidney. In brain, the highest levels of class A transcripts were found in the cerebellum, suggesting that this clone might encode a P-type channel and initial expression studies supported this hypothesis. Studies showed that α_{1A} clones expressed in *Xenopus* oocytes supported HVA currents which were insensitive to DHPs and ω -CgTx but inhibited by ω -Aga VIA.^{128,131,132} However, a number of discrepancies between currents elicited in oocytes expressing class A clones and native P-type currents have called this into question.^{131,132} The α_{1A} currents display prominent time- and voltage-dependent inactivation, yet P-type currents show little time-dependent inactivation and are relatively insensitive to holding potential. Furthermore, the pharmacological sensitivities of α_{1A} channels are quite different from those of P-type channels. While these currents are blocked by ω -Aga IVA, they are approximately 200-fold less sensitive to the toxin (IC₅₀ \approx 200 nM) than are P-type currents (IC₅₀ \approx 2-10 nM). In addition, α_{LA} channels are markedly more sensitive to block by the snail toxin ω -CgTx MVIIC than P-type channels (IC₅₀ \approx 150 nM vs. 1-10 μ M for P-type channels). Sather et al (1993)¹³¹ noted that the kinetic and electrophysiological features of the α_{1A} current were more similar to the Q-type current described in cerebellar granule cells by Randall et al (1993).¹³³ Based on these results, some researchers have suggested that the class A clones represent Q-type channels, and that P-type channels are the product of a different gene. However, Stea et al (1994)¹³² noted that the high correlation between the localization of α_{1A} transcripts and P-type channel immunoreactivity implied a possible structural similarity between P- and Q-type channels and the α_{1A} gene product. They further proposed that the functional differences between the two channel types may arise as a result of differential post-translational processing of the proteins (which could affect toxin binding), subunit composition of the channel complex, and/or alternative splicing of the α_{1A} gene.

The auxiliary subunits of the VGCC complex are known to modulate the properties of the α_1 subunit (see below). The inactivation kinetics of the α_{1A} subunit are dramatically affected by the type of β subunit with which it is associated.¹³² Expression of the α_{1A} subunit from rat brain in the absence of the β subunit results in a current that inactivates considerably (40% remained after a 400 ms test pulse). Co-expression of either the β_{1b} or β_3 subunit increased α_{1A} current inactivation to a rate similar to that of the Q-type current. In contrast, currents recorded from oocytes expressing the $\alpha_{1A} + \beta_{2a}$ combination show significantly slower inactivation kinetics, such that the waveform is more similar to that of native P-type currents. The β subunit also appears to affect voltage-dependent inactivation of the α_{1A} subunit. The β_{2a} subunit shifted the steady-state inactivation of the α_{1A} approximately 15 to 20 mV more depolarized, thus reducing the sensitivity of the channel to holding potential.

Multiple isoforms derived from the alternative splicing of α_{1A} transcripts have been detected by several groups.^{128,134-136} Bourinet et al (1999)¹³⁵ isolated an α_{1A} variant which possessed an number of sequence differences when compared to the rbA-1 clone and examined the functional implications of these splicing events. A valine insertion in the I-II linker both slowed time-dependent inactivation and altered steady-state inactivation. α_{1A} variants containing this valine have inactivation properties similar to P-type channels, while valine-less isoforms, such as rbA-1, appeared more Q-like. A second splice site consisted of the insertion of an asparagine-proline (N-P) pair in the IVS3-IVS4 linker. This affects the electrophysiological properties of the α_{1A} channel by producing a depolarizing shift in the current-voltage relationship. The N-P insertion also had the effect of decreasing the affinity of the channel for ω -Aga IVA by decreasing the on-rate of the toxin and increasing the off-rate. Thus, it is likely that the α_{1A} gene encodes both P- and Q-type channels, and the distinct channel properties reflect

differences both in subunit composition and alternative splicing. P-type channels may be comprised of splice variants that contain the valine insertion in the I-II linker, but not the N-P pair in the IVS3-IVS4 loop. Conversely, Q-type currents may be produced by channels lacking the valine, but containing the N-P insertion. In addition, the association of different β subunits may also be an important determinant of the P- versus Q-type phenotype.

$\alpha_{1B}/Ca_{v} 2.2$

Class B α_1 subunits have been cloned from rat (rbB-I)¹³⁷ or (α_{1B-I}),¹³⁸ human (α_{1B-1} , α_{1B-2}),¹³⁹ and rabbit brain (BIII),¹⁴⁰ as well as from the forebrain of the marine ray *Discopyge* ommata (doe-4).¹⁴¹ The various clones encode proteins of 2336 to 2339 amino acids with predicted molecular weights of ≈260 to 262 kDa.¹⁴² The α_{1B} amino acid sequence is more similar to that of the α_{1A} , with the majority of the sequence divergence occurring in the cytoplasmic loop between domains II and III and in the cytoplasmic carboxyl tail.

Initial indications that this class of α_1 subunit corresponds to N-type channels came from the work of Dubel et al (1992)¹³⁷ who showed that a polyclonal antibody (CNB-1) raised against the II-III loop region of the rbB-I clone immunoprecipitated almost 50% of the high-affinity ω -CgTx binding sites, but none of the DHP-binding sites from rat brain. Furthermore, Northern blot analysis of experimental cell lines showed that rbB-I expression was correlated with the presence of N-type channels in nerve tissues and cell lines that express N-type channels.^{137,139,140,143} Northern blotting and in situ immunohistochemistry experiments have localized the rbB-I transcripts to the cerebral cortex, hippocampus, forebrain, midbrain, cerebellum, and brainstem. At the subcellular level, rbB-I protein is found on dendrites, at presynaptic terminals and, to a lesser extent, neuronal cell bodies. The localization pattern of the α_{1B} compares well with that observed with a monoclonal antibody against ω -CgTx,⁵⁶ although the ω -CgTx antibody staining was more widely distributed.

Molecular cloning and biochemical studies have also provided evidence for the existence of multiple isoforms of the α_{1B} subunit.^{138-140,143-146} At least two of these isoforms represent channels with differentially spliced carboxyl tails, and the inability of CNB-1 to immunoprecipitate all of the ω -CgTx binding sites might suggest the existence of additional isoforms with distinct II-III loop sequences. In addition, α_{1B} clones with small insertions and deletions scattered throughout the channel have been identified, and expression studies indicate that these sequence variations have a profound influence on the properties of the channel¹³² (see below). These include a variant of the human N-type calcium channel that lacks the synaptic protein interaction site in the domain II-III linker¹⁴⁵ and can therefore not associate with synaptic proteins such as syntaxin 1A and SNAP-25.

Transient expression of both human α_{1B-1} in HEK cells¹⁴⁷ and rabbit brain BIII in dysgenic myotubes¹⁴⁰ produced HVA currents that first activated between -10 and -30 mV and reached a maximum between +10 and +30 mV. Currents partially inactivated over the time course of the depolarization and were sensitive to holding potential (showing 50% current inactivation at approximately -60 mV). At a holding potential of -40 mV, the bulk of the current (90%) was inhibited. In agreement with binding studies, the α_{1B} -induced currents were irreversibly blocked by 1 μ M ω -CgTx and were insensitive to DHPs.

The properties of currents generated in *Xenopus* oocytes by expression of the rbB-I clone agreed well with those seen with the α_{1B-1} and BIII clones in terms of pharmacological sensitivities and voltage-dependence of activation. However, there were some notable discrepancies in other properties. For example, the rbB-I channel was less sensitive to holding potential, and the rates of activation and inactivation of the rbB-I clone were markedly slower, resulting in significantly different current waveforms.¹⁴⁸ Co-expression of the β_{1b} subunit shifted the voltage-dependence of inactivation to more negative potentials similar to those observed with the human and rabbit clones. The β subunit also increased the rate of activation such that the current attained peak magnitude in approximately 120 ms (compared to 150-250 ms for the rbB-I subunit alone), and increased the rate of inactivation of the rate of activation of the rbB-I current. After 800 ms,

current through rbB-I alone had decreased by 15-20%, whereas co-expression of the β subunit resulted in a 65-70% reduction in peak current. Despite the rate increases produced by β subunit co-expression, these parameters remained dramatically different from those displayed by the other clones. The rate of activation of rbB-I (110 ms to peak) was still significantly slower than that of α_{1B-1} currents (10 ms). In addition, the α_{1B-1} clone showed biphasic inactivation; the first, rapid phase had a τ of 46-105 ms. The τ of the slow phase ranged between 291 and 453 ms. In contrast, decay of rbB-I currents was monophasic and much slower (τ = 700 ms).

Evidence obtained by Stea et al (1999)¹³⁸ from a second rat brain clone (rbB-II or α_{1B-II}) found that the differences in channel kinetics were the result of small amino acid alterations that are most likely the product of alternative splicing and/or cDNA cloning artifacts. While α_{1B-II} differs from α_{1B-I} in four regions, they found that the substitution of a glycine for a glutamate in transmembrane segment IS3 was sufficient to speed the activation and inactivation kinetics. It has been noted that, while N-type channels are typically described as having fast kinetics, this is not always the case (see N-type channels, above). It may be that isoforms containing a glutamate in IS3, such as the rbB-I (α_{1B-I}) clone may account for the slow and incomplete inactivation of N-type current that has been described in sympathetic neurons. As is the case with the α_{1A} gene, alternative splicing and differential subunit composition may combine to produce slight modifications in channel characteristics with tissue or developmental specificities. Just recently, a newly discovered tissue specific splice isoform variant of the N-type channel has been discovered in dorsal root ganglia (DRG).¹⁴⁹ This splice variant arising from the presence of exon 37a has the unique property of being expressed exclusively in nociceptive neurons of the DRG and ultimately may serve as a novel target for pain management.

α₁₀/ Ca_v 1.2

The first complete class C α_1 (α_{1C}) subunit to be cloned was isolated from cardiac muscle (CARD1).¹¹⁰ The cardiac and skeletal muscle L-type VGCCs arise from separate genes and are approximately 66% identical at the amino acid level. Subsequently, α_{1C} clones were isolated from rabbit lung (pSCaL)¹¹¹ and rat aorta (990: VSM α_1)¹¹² which shared 95% identity with the cardiac clone. Class C clones later isolated from rat (rbC-I, rbC-II)¹⁵⁰ and mouse (mbC)¹⁵¹ brain are also more closely related to the cardiac and smooth muscle α_1 subunits than to the skeletal muscle clone. The α_{1C} clones code for proteins of 2140 to 2171 amino acids with predicted molecular masses of 235 to 239 kDa. Antibodies directed against the II-III loop of the neuronal class C channel also identify a truncated form with an approximate mass of 195 kDa.⁶

The high degree of similarity amongst these proteins suggest that they are products of a single gene, and this is supported by genomic Southern blotting experiments. However, there are regions of considerable diversity in these clones which are the result of alternative splicing of the primary transcript.^{150,152,153} pSCaL, the smooth muscle channel isolated by Biel et al $(1990)^{111}$ differs from the cardiac form in the amino terminus, the IS6 and IVS3 transmembrane segments, and by a 25-amino acid insertion in the I-II linker. In contrast, the VSM α_1 clone, also isolated from smooth muscle, contains a cardiac channel-like IS6 segment and a 68 residue substitution in the carboxyl tail. This sequence is also found in the neuronal clones, rbC-I and -II.¹⁵⁰ Finally, rbC-I and rbC-II contain regions of identity with both the smooth muscle and cardiac clones, but also contain many substitutions, primarily in cytoplasmic regions of the protein and the IIIS2 transmembrane segment. Notably, many of these substitutions are localized to the cytoplasmic linker between domains II and III, and may reflect cell-specific functions of the channels. The truncated form of the neuronal protein may also be the result of alternative splicing, or may be due to post-translational processing as is the case with the skeletal muscle channel.⁶

As would be expected considering the diverse nature of the tissues from which class C cDNAs have been cloned, the α_{1C} gene has a widespread pattern of expression. Transcripts of 8.9 kb have been detected in heart.¹¹⁰ In smooth muscle and brain, hybridizing transcripts were slightly smaller (8.6 and 8 kb, respectively).^{112,150} Additional transcripts of 15.5 kb (cardiac) and 12 kb (smooth

muscle and brain) were also detected which were proposed to represent stable processing intermediates.¹¹² Northern blot analysis indicate that the class C gene is expressed in heart, smooth muscle (e.g., uterine, lung, stomach, and intestine), and throughout the CNS.^{112,150,151} Within the brain, high expression levels are detected in the olfactory bulb, cerebellum, striatum, thalamus, hypothalamus and cortex, and at much lower levels in the pons/medulla and spinal cord.^{6,150} Thus far, there is no evidence for exclusive expression of α_{1C} splice variants in specific tissues. cDNAs containing both variants of the IVS3 transmembrane segment have been isolated from heart, smooth muscle, and brain^{112,150,152} and the alternate carboxyl tail is expressed in both smooth muscle and neuronal tissues.^{112,150} However, a more detailed study of the expression pattern of class C variants in rat has revealed tissue-specific differences in expression of the rbC-I and rbC-II proteins.¹⁵⁰ Overall, rbC-II is the more abundant form, and generally more prevalent in any given tissue, although the relative amounts of the two transcripts vary between brain regions and tissue types.

The subcellular localization of class C α_1 subunits was studied using the polyclonal antibody, CNC1.⁶ Immunoprecipitation and Western blotting experiments indicated that class C α_1 subunits comprise approximately 75% of the DHP binding sites in rat cerebral cortex and hippocampus. CNC1 immunoreactivity was distributed at low levels on cell bodies and proximal dendrites, with staining diminishing along the length of the dendrite. In addition, clusters of high levels of immunoreactivity were observed on the surface of cells (as opposed to representing a cytoplasmic pool of channels).

Expression of α_{1C} clones in *Xenopus* oocytes resulted in currents with electrophysiological and pharmacological properties characteristic of L-type channels.^{110,111,115,154} In Ba²⁺, depolarizations to -10 to -30 mV elicited large inward currents that inactivated slowly, if at all, over the course of a several hundred millisecond the test pulse. The currents peaked between +10 and +30 mV and were inhibited by Cd²⁺ (100-200 μ M) and were sensitive to DHPs. Like native L-type currents, the cloned L-type channels showed little sensitivity to holding potential. At holding potentials as high as -20 mV, half of the channels remained available for opening.

The class C channels were shown to be modulated by the auxiliary subunits in much the same manner as the class A and B channels. Co-expression of α_{1C} with β_{1b} and α_{2} - δ significantly increased the magnitude of the whole cell currents. This increase appeared to be mediated primarily through interaction with the β subunit, while the addition of α_2 - δ had a slight synergistic effect. In addition, co-expression of rbC-II with the auxiliary subunits β_{1b} and/or α_2 - δ caused a small hyperpolarizing shift in the voltage dependence of activation of the channel and altered channel kinetics.¹⁵⁴ The rate of activation for rbC-II varied substantially among oocytes. Time constants of activation ranged between 4 and 50 ms with an average of approximately 10 ms. Coexpression with β_{1b} and α_2 - δ both increased the rate of activation and reduced the degree of variability. Furthermore, the β_{1b} and α_2 - δ subunits increased the rate of inactivation. Unlike the α_{1B} rbB-I channel (see above), neither auxiliary subunit had a significant effect on the voltage dependence of inactivation. With the exception of the voltage dependent parameters of the channel appear to be mediated primarily through interaction with the β subunit, while the addition of α_2 - δ had slight synergistic effects.

Whole cell recording using Ca^{2+} as the charge carrier resulted in current traces with markedly different waveforms. The magnitude of the whole cell current was significantly smaller in Ca^{2+} than Ba^{2+} , indicating that the channels are more permeable to Ba^{2+} than to Ca^{2+} . In addition, instead of eliciting currents that are essentially non-inactivating, depolarizing pulses produce currents that decay rapidly by more than 50%.^{154,155} The increase in inactivation seen with Ca^{2+} as the permeant ion retains all the hallmarks of Ca^{2+} -dependent inactivation (see above).

Calcium dependent inactivation (CDI) is predominantly linked to two regions of the Alpha1 subunit C-terminus. The EF hand,¹⁵⁶ located from aa 1526 to1554, is responsible for CDI and may also regulate voltage-dependent inactivation (VDI).¹⁵⁷ The second region, (found downstream of the EF hand), is comprised of three distinct binding motifs. Peptide A; (aa1588to1610) and Peptide C (1615to1636aa),¹⁵⁸ and IQ(1649to1669),¹⁵⁹ all work together to form a calcium bound Calmodulin binding site. In the absence of calcium, Ca²⁺ free calmodulin (ie Apo Cam) is pre-associated with the channel at a site localized between the EF motif and IQ region.^{23,160} Calcium entering through the channel binds to calmodulin, thus inducing a conformational change that relieves an inhibitory action of the calmodulin/ C-terminus complex on the voltage-dependent inactivation machinery.¹⁶¹

$\alpha_{1D}/Ca_v 1.3$

A class of VGCC cDNAs sharing about 70% amino acid identity with the cardiac clones has been cloned from a variety of species including rat (RBa1;¹⁶² rCACN4A, rCACN4B¹⁶³), human (α_{1D} ;⁵¹ neuroendocrine or β -cell α_1 or hCACN4:¹⁶⁴ HCa3a¹⁶⁵), and chicken.¹⁶⁶ A cDNA encoding an invertebrate ortholog of the class D α_1 subunit has been isolated from *Drosophila melanogaster* (Dmca 1 D).¹⁶⁷ These clones retained little similarity (-40% amino acid identity) with the non-DHP-sensitive class A clones, 51,164 but were almost identical to the partial rat brain clone designated class D.¹²⁰ In spite of the sequence divergence between cDNAs generated from class C and class D genes, the two channel types are remarkably similar in certain regions. As with all VGCC α_1 subunits discussed thus far, the transmembrane regions tend to be highly conserved, while the intracellular loop sequences are much more divergent. In addition to these regions, the α_{1D} clones are almost identical to the DHP-sensitive class C and S clones in the segments predicted to form the DHP and phenylalkylamine binding sites, suggesting that the class D α_1 subunit cDNAs also encode members of the DHP-sensitive L-type family of VGCCs. The exception to this lies in the DHP-binding region in the Drosophila Dmca 1D clone which contains a number of non-conserved changes. This finding, however, is consistent with the pharmacology of phenylalkylamine and DHP binding in Drosophila head membranes, ¹⁶⁷ and provides further support for the role of these regions in drug binding.

The cloned α_{1D} subunits range in size from the 1634-amino acid (187-kDa) rat brain isoform to the 2516-amino acid (276-kDa) *Drosophila* channel clone. The range in protein sizes is due primarily to the truncated carboxyl terminal ends of the RB α_1 , HCa3a, and rCACN4B clones.^{162,163,165} The rCACN4B clone is a full 535 residues smaller than its rCACN4A counterpart and is proposed to result from the use of an alternative splice acceptor site.¹⁶³ In addition to the truncation of the carboxyl tail, a number of other regions have been identified in which variants have been produced through alternative splicing.^{51,152,162,163} These regions include insertions in the cytoplasmic linker between domains I and II, the extracellular linker connecting IVS3 and IVS4, and the transmembrane segments IS6 and IVS3. In addition, Kollmar et al (1997)¹⁶⁶ have reported that the chicken brain and cochlear α_{1D} proteins differ in the IIIS2 segment and IVS2-IVS3 loops, as well as in the carboxyl tail. Presumably, these splice variants impart functional differences to the channel. While it is not yet clear what these functional differences may be, Ihara et al (1995)¹⁶³ note that RB α_1 , HCa3a and rCACN4B are all truncated at different sites. Furthermore, a number of potential PKA sites are eliminated by the truncations, which may result in the differential regulation of these isoforms by phosphorylation.

The class D channels, often termed "neuroendocrine" because of their presence in brain and pancreatic cells, have also been detected in the retina, ovaries, and cochlear hair cells, but not in heart, skeletal muscle, spleen, colon, or liver. Reports differ on whether α_{1D} transcripts are present in kidney.^{164,166} Within the CNS, class D expression is found in the hippocampus, habenula, basal ganglia, and thalamus.⁵¹ The subcellular localization of the class D α_1 subunit was characterized using the polyclonal antisera anti-CND1.⁶ Anti-CND1 was generated against a peptide homologous to the unique II-III loop of the rat brain α_{1D} clone.¹⁶² (Hui et al, 1991). Class D channels appear to be far less abundant in the rat CNS than class C channels. The sera labeled the cell bodies and proximal dendrites of both projection neurons and interneurons throughout the brain. In contrast to the punctate staining pattern seen with the class C antibody, anti-CND1 staining was evenly distributed over the cell body. The staining pattern of anti-CND1 was typical for neurons in all regions of the CNS with the notable exception of the cerebellar Purkinje cells. While the cell bodies of these neurons were labeled, there was a marked absence of staining on the Purkinje cell dendrites.

Transient expression of human α_{1D}^{51} in *Xenopus* oocytes and stable expression of the rat CACN4A and CACN4B clones (Ihara et al, 1995)¹⁶³ in CHO cells gives rise to DHP-sensitive currents, confirming the notion that class D channels are members of the L-type family. In both systems, functional expression of the α_{1D} subunit required co-expression of the β subunit. In *Xenopus* oocytes, transient expression of α_{1D} with the β and α_2 subunits yielded larger currents than those produced by expression of α_{1D} plus β alone.⁵¹ Ba²⁺ currents in oocytes expressing $\alpha_{1D+} \beta + \alpha_2$ first activated upon depolarizations positive to -30 mV and peak current attained with depolarizations to 0 mV, thus the current-voltage relationship of the α_{1D} is somewhat more negative than that of the α_{1C}^{154} (see above). α_{1D} channels activated rapidly and inactivated little over depolarizations lasting as long as 700 ms. α_{1D} channels inactivate to a considerably lesser degree over long test pulses than do α_{1C} channels.¹⁵⁴

As indicated, class D channels fall under the heading of DHP-sensitive L-type channels. Cd^{2*} produces substantial block, while Ni²⁺ has a minimal effect on the current. The DHP agonist Bay K8644 increases current magnitude and shifts the voltage-dependence of activation by approximately -10 mV. In addition, the current is inhibited by the DHP antagonist nifedipine.^{51,163} However, the affinity of DHPs for α_{1D} channels is generally lower than that observed with α_{1C} .^{168,169} Moreover, unlike other DHP-sensitive channels, the cloned α_{1D} is partially and reversibly blocked by high concentrations of ω -CgTx (10-15 μ M).⁵¹

The predominance of the α_{1D} subunit-containing VGCCs in the cochlear hair cells and in the β -cells of the pancreas suggest that these channels may be involved in tonic exocytotic release in these cells^{163,164,166,170,171} Kollmar et al (1997)¹⁶⁶ suggest that the electrophysiological properties of the α_{1D} subunit, such as its lack of inactivation during depolarizations may render it suitable for mediating tonic release. In addition, as suggested by the localization of α_{1D} channels on the cell body and at the base of dendrites of neurons in the CNS, these channels may be involved in integrating signals impinging upon the neuron from multiple sources.⁶

$\alpha_{IE}/Ca_v 2.3$

The class E gene encodes a VGCC α_1 subunit (α_{1E}) that does not fall neatly into either the HVA or LVA categories. α_{1E} cDNAs have been isolated from rabbit (BII-1, BII-2)¹⁷² and rat (rbE-II)¹²¹ brain, and from *Dyscopyge ommata*.¹⁴¹ These clones code for proteins between 2178 and 2259 amino acids with predicted molecular masses of approximately 250 kDa. Splice variants of the rabbit brain channel, BII-1 and BII-2, differ from one another in their carboxyl tails, resulting in the addition of a putative PKA site.

The class E clones appear to be more closely related to the DHP-insensitive non-L-type channels (54-60% amino acid identity) than to the L-type channels (less than 45% similarity). However, class E channels are less similar to either class A or B channels than these two classes are to one another, suggesting that the class E channels are members of a novel, more distantly related subgroup of DHP-insensitive channel (Fig. 2).^{121,141,172}

Northern blotting studies have identified transcripts ranging in size from 10.5 to 12 kb in the mammalian CNS.^{121,172} High levels of expression was identified in the cerebral cortex, hippocampus, and striatum, while lower levels were detected in the olfactory bulb, midbrain, and Purkinje and granule cell layers of the cerebellum. While α_{1E} appears abundant in brain, none was detected in skeletal muscle, heart, stomach or kidney. At the subcellular level, α_{1E} protein was localized nearly exclusively to the cell body of neurons throughout the CNS. Dendritic staining varies across brain regions. For example, in the cortex and hippocampal formation there is barely perceptible staining of the dendritic branches, while in Purkinje cells, α_{1E} antibodies labeled the distal dendritic branches, but not the main dendritic trunks.¹⁷³

The α_{1E} channel was initially reported to be a novel member of the LVA family of Ca²⁺ channels.¹²¹ Expression of rbE-II in *Xenopus* oocytes produced a channel that activated rapidly at low membrane potentials (threshold~ -50 mV) and inactivated significantly during

the depolarization. Other voltage-dependent parameters of this channel (current-voltage relationship, voltage-dependence of inactivation) were also considerably more negative than those of other cloned HVA channels. The rbE-II current magnitude increased steeply with increasing depolarizations, peaking at around 10 mV, and steady state inactivation analysis indicated that the channels were inactivated near the resting membrane potential of the cell. In addition, rbE-II channels were equally permeable to Ca24 and Ba2+, a property reported to be unique to the LVA channels. Another similarity with LVA channels was the high sensitivity of the current to block by Ni. Furthermore, the channel was found to be expressed in many of the cells that have been shown to possess T-type currents. However, Soong et al (1993)¹²¹ noted a number of discrepancies between rbE-II and native T-type currents. For example, although the voltage-dependent properties of rbE-II currents were more negative than those of the other cloned HVA Ca2+ channels, the activation and peak current potentials were not as hyperpolarized as for typical T-type channels.¹²¹ Analysis of the electrophysiological properties of other class E channels¹⁷⁴⁻¹⁷⁶ have produced some results that contradict those of Soong et al (1993).¹²¹ In these studies, the α_{1E} clones formed HVA channels, activating at approximately -10 mV and peaking at +30 mV. The single channel conductance of α_{1E} channels is also much larger than that of T-type channels (12-14 pS vs. -8 pS). ^{141,177} As α_{1E} channels share properties with LVA as well as HVA channels, the detection of pure α_{1E} currents in native cells may difficult.

It has been suggested that the class E channels may be one of a group of channels comprising the R-type current.^{89,178,179} The two currents share some electrophysiological and pharmacological characteristics, such as strong voltage-dependence of activation and insensitivity to DHPs, ω -CgTx, and ω -Aga IVA. However, the R-type current is smaller in Ca²⁺ than in Ba²⁺, whereas the α_{1E} channels support the two currents equally.^{89,177} Most relevant, mice lacking the α_{1E} gene entirely still exhibit significant R-type current.¹⁸⁰ Thus, while class E channels may comprise a component of R-type current in cerebellar granule cells, the R-type current may actually result from incomplete block of other Ca²⁺ channels by applied pharmacological agents, the expression of additional splice variants of already identified Ca²⁺ channel subtypes, or as yet to-be-identified α_1 subunits.

α_{1F}/ Ca, 1.4

The human class F gene (CACNA1F) was identified through genetic studies in which the X-linked visual disorder Congenital Stationary Night Blindness (CSNB) was mapped to a locus containing a putative VGCC gene.^{122,123} The predicted CACNA1F gene product (α_{1F}) is between 1912 and 1966 amino acids (alternatively spliced forms have been detected) with an estimated molecular mass of 219 kDa. Sequence analysis indicates that α_{1F} is 55-70% identical at the amino acid level to the L-type channel α_1 subunits, sharing the most similarity with α_{1D} , and 35% identical to the P- and N-type channels. In addition, the putative DHP-binding domains in IIIS6 and IVS6 appear relatively well conserved. These results suggest that the α_{1F} is an L-type channel that diverged from the α_{1D} subunit gene.¹²²

 α_{1F} expression was initially reported to be restricted to the retina in situ hybridization experiments indicate high levels of α_{1F} transcript in the two retinal layers containing the photoreceptors, and horizontal, bipolar, and amacrine cells, but not the ganglion-cell layers,^{122,123} however, recent reports indicate a more global distribution that includes the immune system and skeletal muscle.¹⁸¹ L-type Ca²⁺ channels have been implicated in synaptic release from photoreceptors¹⁸² and the correlation of the hereditary visual disorder CSNB with mutations in the α_{1F} gene^{122,123} suggests that the α_{1F} channel mediates neurotransmitter release at these synapses. Functional expression of α_{1F} calcium channels reveals that these channel encode a non-inactivating L-type calcium channel that is DHP sensitive,¹⁸³ and which is not regulated by ancillary subunits.¹⁸¹ Moreover the channel appears to lack CDI, and displays a large window current, thus making this channel ideally suited to support tonic glutamate release from photoreceptors.¹⁸¹

Low Voltage-Activated (T-Type) Channels

LVA (T-type) channels were first described in rat and chick sensory neurons,^{1,184} but also are present in other excitable tissues, including cardiac sinoatrial cells, smooth and developing skeletal muscle, neuroendocrine cells, and thalamic neurons, as well as non-excitable cells such as fibroblasts, osteoblasts, and astrocytes.^{2,4,185} Other cell types, such as sympathetic neurons, superior cervical ganglion cells, and adrenal chromaffin cells, appear not to express significant T-type currents.^{2,186} T-type Ca²⁺ channels typically first activate at potentials more positive to -70 mV and whole-cell currents are usually maximal by \sim -40 mV. T-type Ca²⁺ channels are fully inactivated at resting potentials greater than -40 mV, inactivate rapidly in a voltage-dependent manner, and deactivate, or close, relatively slowly. Because these channels are inactivated at positive holding potentials, very negative holding potentials (-80 mV or more negative) are required for full availability of the channels. The kinetics of activation and inactivation of T-type channels also display voltage dependency; rates are slow near threshold potentials and accelerate with increasing potentials.^{1,24}

While direct evidence linking \overline{T} -type channels to specific physiological roles is limited, their electrophysiological profiles and cellular and subcellular localizations suggest a number of likely functions. For example, their expression in many cell types that display spontaneous electrical activity (sinoatrial nodal cells of the heart, neuroendocrine cells, and thalamic neurons) together with their low threshold of activation and requirement for hyperpolarized membrane potentials to overcome inactivation, suggests that T-type channels play a role in pacemaker activity and bursting behavior. T-type channels may also exert an effect by generating a resting inward current which could in turn mediate the gating of Ca²⁺-dependent ion channels and regulate Ca²⁺-dependent enzymes and gene expression. Finally, T-type currents are highly expressed in developing muscle and nervous tissue, suggesting that these channels may play a developmental role.^{2,187-189}

The study of T-type Ca^{2+} channels has lagged behind that of other Ca^{2+} channel subtypes, in part due to the lack of cDNA clones representative of this type (see below), but primarily because of the lack of selective pharmacological agents. T-type channels are generally sensitive to the divalent cations nickel (Ni), cadmium (Cd²⁺), and zinc (Zn²⁺), with Ni²⁺ being the most potent. However, in some cell types, low concentrations of these cations fail to block LVA currents or also block other HVA Ca^{2+} currents.^{190,191} A number of organic compounds inhibit T-type channels, but often at concentrations that block other Ca^{2+} channels. For example, octanol and the sodium (Na) channel blocker amiloride have been utilized as T-type channel antagonists, although these compounds also inhibit some components of whole cell HVA currents.^{2,4,186,190,191} Ethosuximide, a drug used to treat absence epilepsy, has been shown to reduce current through T-type channels with little effect on HVA channels although the concentrations required for complete T-type block are quite high.^{186,190} The antihypertensive mibefridil may be the most potent T-type channel blocker identified to date (IC50 in the submicromolar range)¹⁹¹ although even mibefradil however has recently proven to be a relatively non-specific Ca²⁺ channel blocker.¹⁹²

α_{IG} , α_{IH} and α_{II}

Low stringency library screening strategies such as the ones used to isolate the HVA channels discussed above proved unsuccessful for cloning the T-type Ca^{2+} channels. The first members of the T-type Ca^{2+} channels were identified by screening data banks for sequences with similarity to previously cloned Ca^{2+} channels.^{124,193,200} Subsequently, other classes of T-type Ca^{2+} channels were identified by screening cDNA libraries.^{125,126,194}

Thus far, T-type clones have been isolated from rat $(\alpha_{1G})^{124} \alpha_{1G}$, α_{1H} , α_{1I} ,²⁰⁰ α_{1I}^{126} , mouse $(\alpha_{1G})^{193}$, human brain $(\alpha_{1G}, \alpha_{1I})^{194-196}$ and human heart $(\alpha_{1H})^{125}$ The α_{1G} and α_{1H} subunits are approximately 65% identical, whereas the α_{1I} subunit shares only 53% identity with the α_{1H} and 47% with the α_{1G} . As expected from the failure to identify T-type channels in the low stringency hybridization screens used to isolate many of the HVA channels, the T-type channels share limited sequence homology with HVA Ca²⁺ channels. The highest level of sequence similarity is found in the four membrane-spanning domains. Most of the amino acid changes in these regions are conservative, thereby maintaining structural elements common to voltage-gated ion channels. The charges located in the fourth transmembrane segment of each domain are conserved, as are the pore-forming loops between the fifth and sixth transmembrane segments. In HVA channels, a glutamate residue located in each of these four loops is believed to determine the ion selectivity of the channels.^{197,198} All T-type channels cloned thus far contain aspartate residues instead of glutamates in the domain III and IV P-regions.¹²⁴ This difference may account for the difference in the permeation properties seen between high and low voltage activated channels. The intra- and extracellular linkers joining the transmembrane domains share little homology with either HVA channels or with other T-type channels. Furthermore, the T-type channels do not seem to possess specific functional motifs that have been identified in HVA channels, including the binding site in the I-II linker or the putative EF-hand motif in the carboxyl tail.¹²⁴

The three classes of T-type channel have been localized using Northern blotting, in situ hybridization, and RT-PCR techniques.^{124-126,193,195,200,201} The α_{IG} subunit appears to be expressed abundantly throughout the brain and to a lesser degree in heart. Low levels have also been detected in placenta, lung, and kidney. High levels of transcript are observed in the cerebellum, hippocampus, thalamus, and olfactory bulb, with lesser amounts localized to the cerebral cortex and septal nuclei. Initially, the α_{1H} was detected only in cardiac tissue, kidney, and liver, with very little, if any, expression in the brain.¹²⁵ However, a subsequent study¹⁹⁹ suggests that the α_{1H} subunit may be responsible for a large proportion of the T-type current in sensory neurons, and another study indicates the expression of α_{1H} in all areas in the rat brain.²⁰¹ α_{11} transcripts have only been detected in brain, ^{126,195} with one study showing specific expression in the striatum of adult rats.²⁰⁰

Expression of these three subunits in Xenopus oocytes^{124,126} and HEK-293 cells^{125,193,195,196,200-203} demonstrates that they support currents with most of the characteristics expected of T-type channels. Currents activated upon weak depolarizations from negative holding potentials. In one study, the three T-type channel classes had differing permeability properties.²⁰⁰ As has been noted for classic T-type currents, α_{1G} channel was more permeable to Ca than to Ba. However, α_{1H} channels were more permeable to Ba²⁺ than Ca²⁺, while α_{1I} channels were equally permeable to the two ions. In most cases, currents were inhibited by mibefradil and Ni, although the IC50 of each T-type class varied significantly.^{193,200} The activation and inactivation kinetics of the T-type channels are strongly voltage-dependent. While rates of activation and inactivation are slow near threshold potentials, they accelerate as the strength of depolarization increases. Deactivation is also voltage-dependent, increasing at more hyperpolarized potentials. Steady-state inactivation analysis indicates that the majority of the channel population would be inactivated at the resting potential of most cells. However, because all the channels are not inactivated at the resting potential and the threshold of activation is so negative, a small proportion of channels are capable of opening at the resting potential, thus producing a "window" current. The window current refers to a small, but sustained influx of Ca^{2+} that occurs even when the cell is ostensibly at rest. This current can contribute to the overall excitability of the membrane and may contribute to the bursting and pacemaker activities attributed to the T-type channels. Finally, as anticipated for T-type channels, the three exogenously expressed channels have small single channel conductances of 5 (α_{1H}), 7.5 (α_{1G}), and 11(α₁₁) pS⁻¹²⁶

Similar to the different classes of channels within the HVA subfamily, the biophysical properties of the three T-type channels vary considerably.^{126,200} The α_{1G} and α_{1H} possess very similar activation and inactivation potentials, while those of the α_{1H} appear to be slightly more negative. Rates of activation and inactivation of α_{1G} and α_{1H} currents also are quite similar. In contrast, activation and inactivation rates for α_{1I} currents are significantly slower. In addition, the activation threshold of α_{1I} channels also differs from the values obtained for α_{1G} and α_{1H} channels. However, varying results have been reported concerning the direction of the observed voltage shift. The rat brain α_{1I} clone studied by J.-H. Lee et al $(1999)^{126}$ activated at more positive potentials than did the α_{1G} and α_{1H} channels, while McRory et al $(1999)^{200}$ reported α_{1I} current activation at considerably more negative potentials. That the properties of the α_{1I} channel differ from those of the α_{1G} and α_{1H} is not entirely unexpected when one takes into account the degrees of similarity seen amongst the three channels. Furthermore, multiple splice variants of the α_{1I} have been identified^{194,195} and may account for the contrasting results reported for α_{1I} currents. Finally, the properties of the three LVA channel clones do not account for all of the T-type characteristics in native cells and there may be additional classes of T-type channels and/or a set of as yet unknown auxiliary subunits specific to LVA channels which further modulate the properties of the LVA α_1 subunit. For example, robust alternate splicing for α_{1G} channels had been reported and shown to result in significantly altered biophysical characteristics.²⁰³

Auxiliary Ca²⁺ Channel Subunits

Biochemical studies have shown that in addition to the pore-forming α_1 subunit, HVA Ca^{2*} channel complexes include two or three other proteins: a β subunit, an α_2 - δ subunit, and in some cases, a γ subunit (Fig. 1).

β Subunits

The β subunit is the most extensively studied of the auxiliary subunits and appears to have the most profound effects on the functional properties of the α_1 subunit. In mammals, there are at least four different β subunits (β_1 , β_2 , β_3 , and β_4) which are encoded by distinct genes. The transcripts of at elast two of these genes, the β_1 and β_2 , are alternatively spliced to give rise to $\beta_{1a} \beta_{1b}$, and β_{1c} and β_{2a} and β_{2b} .

Biochemical and primary sequence analyses indicate that the β subunits are hydrophilic with no transmembrane segments or glycosylation sites.²⁰⁴⁻²¹⁰ The β subunits contain potential phosphorylation sites for both protein kinase C and cAMP- dependent protein kinase. The modulatory effects of these enzymes on VGCC function may, in part, be the result of their actions on this auxiliary subunit.²¹¹

Although the specific effects of channel modulation depend upon the β subunit isoform, all β subunits appear to have the same general impact on the properties of HVA α_1 subunits. Coexpression of the α_1 and β subunits in both L-cells and *Xenopus* oocytes increased whole-cell currents and DHP binding without affecting the level of α_1 message. This suggests that rather than enhancing expression of the α_1 subunit, the β subunit may promote insertion of the α_1 subunit into the membrane and/or stabilize a specific conformation of the protein²¹²⁻²¹⁵ have proposed that the β subunit potentiates coupling of the gating-charge movement caused by changes in membrane potential with the opening of the pore thereby increasing the probability of channel activation and, in turn, increasing the peak current.

In addition to increasing the magnitude of the current through the α_1 subunit, co-expression of the β subunit alters channel kinetics. For most β subunits, the rate of inactivation is increased and there is a shift in the voltage-dependence of activation to more negative potentials.^{148,154,207,209,216-219} The effect on kinetics of inactivation, however, varies depending upon the class of β subunit expressed. The β_1 and β_3 proteins increase the rate on inactivation, while the β_2 subunit significantly slows inactivation.

These modulatory effects are observed regardless of which α_1 and β subunits are co-expressed, suggesting that the mechanism through which the β subunit acts is common to all HVA VGCCs. The region required for β subunit modulation of the α_1 subunit has been localized to a stretch of 30 amino acids at the amino-terminal side of the second of two conserved domains.²²⁰ This region, known as the BID (β subunit interaction <u>d</u>omain) is also responsible for anchoring the β subunit to the α_1 . The β subunit has been shown to bind to a conserved motif of 18 amino acids in the intracellular loop between domains I and II of the α_1 subunit (the AID: α_1 subunit interaction <u>d</u>omain).²²¹ The observation that the β subunit from skeletal muscle dramatically increases the magnitude of the current through brain α_1 subunits when co-expressed in *Xenopus* oocytes¹²⁸ further supports the idea of a common mechanism of α_1 - β subunit interaction.

The β subunits exhibit homology with the Src homology 3-guanylate kinase domain of membrane associated guanylate kinases and this region appears to regulate inactivation of HVA VGCCs.²⁸⁹ A more detailed account of β subunit physiology is provided in the Chapter from the Charnet lab.

α_2 - δ Subunits

Purification studies indicate that the VGCC α_2 - δ subunit consists of two distinct subunits (α_2 and δ that are disulfide-bonded in the native state.^{8,222} The α_2 and δ subunits are derived from a single gene product that is proteolytically cleaved to form 143-kDa α_2 and 27-kDa δ subunits.²²³ There are currently four genes that code for the α_2 - δ family; α_2 - δ_1 , α_2 - δ_2 , α_2 - δ_3 , and α_2 - δ_4 .

Both proteins are heavily glycosylated,²²⁴ supporting the prediction that the α_2 - δ subunit is predominantly extracellular and a recent study has determined that no more than five residues comprise the cytoplasmic portion of the protein.²²⁵ The complex is anchored in the membrane by a single transmembrane segment formed by a portion of the δ subunit. The transmembrane domain is thought to interact with other subunit(s) in the VGCC complex while the extracellular domain is responsible for the modulatory effects.^{8,142,223-225}

There are several splice variants of the α_2 - δ_1 auxiliary subunit, due primarily to the alternative splicing of three specific regions. The total splicing combination of these three regions reveals 5 unique isoforms which are all expressed in a tissue specific manner.²²⁶ Skeletal muscle and brain express the isoforms α_2 - δ_{1A} and α_2 - δ_{1B} respectively. The heart expresses mainly α_2 - δ_{1C} and α_2 - δ_{1D} , and smooth muscle expresses α_2 - δ_{1D} and α_2 - δ_{1E} . Interestingly the cardiovascular system expresses all five isoforms.²²⁷

The α_2 - δ_2 subunit is expressed in many different tissues including heart, brain, pancreas, testis lung, liver, kidney.²²⁷ The α_2 - δ_2 subunit has two regions of alternative splicing. The first region is found on the α_2 subunit between residues 661/663 and involves the addition of eight amino acid residues. The second is located on the δ protein and is characterized by the addition of three different residues.²²⁸ The resulting three isoforms of the α_2 - δ_2 subunit are all expressed in hMTC (human medullary thyroid cells.) Alternately, in the human heart, only α_2 - δ_{2A} is expressed. cDNA cloning of the α_2 - δ_3 subunit did not uncover additional splice variants, and this particular α_2 - δ gene appears to be expressed exclusively in the brain.

In 2002, a new member of the α_2 - δ auxiliary subunit family was described. α_2 - δ_4 demonstrated a unique property in that it was shown to be expressed primarily in endocrine tissues. Immunohistochemical studies revealed that the α_2 - δ_4 subunit has limited distribution in special cell types of the pituitary, adrenal gland, colon, and fetal liver.²²⁹ Whether the a_2 - d_4 subunit plays a physiological role in certain endocrine tissues remains to be seen. Alternative splicing of the α_2 - δ_4 gene gives rise to four potential variants (called a-d.²²⁹

The functional effects of the α_2 - δ are thought to be more subtle that those of the β subunit and are highly dependent on the class of α_1 subunit and the cell type used for exogenous expression. For example, Singer et al (1991)²¹⁷ found that the Ca²⁺ current in *Xenopus* oocytes expressing the cardiac α_{1C} protein was greatly enhanced by co-expression of the α_2 - δ subunit from skeletal muscle. In addition, the rates of activation and inactivation were increased and the voltage dependence of inactivation was shifted to more negative potentials. In contrast, Varadi et al (1991)²¹⁸ did not observe these effects when they co-expressed the skeletal muscle α_1 subunit with the α_2 - δ subunit in L cells.²³⁰ Unlike *Xenopus* oocytes, L cells do not express endogenous calcium channel subunits.²¹⁹ Thus, it is possible that the α_2 - δ subunit acts synergistically with other auxiliary subunits to modulate the properties of the α_1 . Finally, there is some evidence that the α_2 - δ subunit is required for efficient expression and/or trafficking of the α_1 subunit to the cell membrane,¹¹⁰ an idea that is supported by recent studies in tsA-201 cells showing that α_2 - δ subunits are key modulators of current densities of α_{1C} , α_{1B} and α_{1E} channels.²³¹

y Subunits

γ_1 (Cacng1)

The VGCC γ_1 subunit protein was first identified in guinea pig skeletal muscle during the purification of 1,4-dihydrpyridine receptors. This VGCC heteromultimeric protein consisted of five different subunits. The γ_1 subunit, a 28-35 kDa on SDS-Page²³² proved to be one of them. Several years later Jay et al (1990)²³³ isolated rabbit skeletal muscle cDNA and uncovered the primary sequence the γ_1 subunit. The cDNA was a 666-nucleotide clone, with a reading frame that would yield a 222 amino acid glycoprotein containing four transmembrane domains. γ_1 has been shown to be expressed primarily in skeletal muscle,²³⁴ but recently has also been shown to be weakly expressed in the aorta.²³⁵ Mice lacking the γ_1 subunit display altered skeletal muscle calcium current. Functional effects of the γ_1 protein include a hyperpolarized shift in the steady state inactivation properties in skeletal muscleVGCC.^{236,237}

Stargazin or γ_2 (Cacng2)

For nearly a decade the presence of other γ -like subunits remained undetected. It was the discovery of the mouse stargazin gene Cacng2 by Letts et al (1998)²³⁸ that ultimately led to the description of seven new γ subunits. The stargazin gene and protein were named after the Stargazer mouse, a mouse strain that is prone to absence seizures including an upward neck tilt and prolonged gaze. These mice had acquired a transposon in a 1.5kb region on chromosome 15 and were heterozygous recessive.^{238,239} The stargazin gene, renamed γ_2 , had inherited a stop codon rendering the protein inactive and truncated. The etiological consequences of a mutated Cacng gene responsible for the absence epilepsy phenotype of the allelic stargazer (stg) and waggler (wag) mutant mice.^{238,240}

 γ_2 , has been classified as a γ subunit based on its structural similarity to γ_1 , despite having only weak protein sequence identity (25%).²³⁸ At the tissue expression level, unlike γ_1 , the γ_2 subunits are found to be expressed in the brain. Letts et al (1998)²³⁸ found mouse γ_2 mRNA to be expressed in adult mouse brain abundantly with highest expression in cerebellum, olfactory bulb, cerebral cortex, thalamus, and CA3 and dentate gyrus regions of the hippocampus.

γ_3/γ_4 (Cacng3/4)

Despite the low sequence homology of γ_2 with its original γ_1 counterpart, many of the newly discovered γ subunits demonstrate high similarity with the γ_2 subunit. γ_2 , γ_3 and γ_4 are of closest similarity and make up a subfamily of neuronal γ subunits. Klugbauer et al (2000)²⁴¹ used Northern blots to show that γ_3 and γ_4 expressions were exclusively restricted to the brain. However, Chu et al (2001)²³⁵ found γ_4 to be additionally present in the atrium, aorta, and lung.

γ_5 (Cacng5)

The γ_5 subunit is unique in that it is expressed not only in the brain and skeletal muscle, but also in different types of endocrine tissues, primarily the liver, kidney, heart, lung and testes. There is some disagreement on the categorization of this subunit as a bona fide γ subunit, and it is also referred to as the "pr protein". In exogenous expression experiments the mouse pr protein has been shown to the modulate properties of the α_{1G} T-type channel.²⁴¹

Y6. Y7, Y8

In 2001 Chu et al²³⁵ described three new human and rat γ -like subunits (human γ_6 , γ_7 , and γ_8). γ_6 was found in the atrium, ventricle, skeletal muscle and a short splice variant of its kind was found in atrium, ventricle, aorta, brain, and lung. γ_7 is expressed in all tissues except aorta, kidney, liver, and spleen. γ_8 was found only in brain and testis.

In summary, the eight γ subunits are technically considered to be part of the Claudin family of proteins, and are differentially expressed among a variety of different tissues. They all display four membrane-spanning regions with both their C and N termini located intracellularly, while

Gene	Channel Subunit	Disease State/Phenotype	Reference
CACNA1A	α _{1Α}	<u>Human</u> : episodic ataxia type 2, familial hemiplegic migraine, spinal cerebellar ataxia type 6 Mouse: tottering (tg), leaner (tg ^{ia})	240, 250-257
CACNA1S	α_{1S}	Human: hypokalemic periodic paralysis, malignant hypothermia susceptibility type 1 Mouse: muscular dysgenesis (mdg)	258-260
CACNA1H	α_{1H}	Human; childhood absence epilepsy; idiopathtic generalized epilepsy	261, 262, 288
CACNA1F	α_{1F}	Human: Incomplete X-linked congenital stationary night blindness	123, 181, 122
CACNA2D	$\alpha_2 - \delta_2$	Mouse: ducky (du), ataxia, paroxysmal dyskinesia	263-265
CACNB4	β4	Mouse: lethargic (lh), ataxia, focal seizures	266
CACNG2	γ2	<u>Mouse</u> : stargazer (stg), waggler stg ^{wag} , ataxia, spike wave seizures	240, 267

Table 2. Spontaneous mutations in calcium channel subunit genes

all extracellular regions display N-glycosylation sites. All the Cacng genes have four exons (with the exception of Canga5 and 7 which have five exons),²⁴² and exon1 is predominately the largest. The carboxyl terminus is of particular interest given that γ_2 , γ_3 , γ_4 and γ_8 have a PDZ binding motif in this region.^{243,244} The C-termini of the γ_7 and γ_5 are longer and lack this consensus motif, however it is interesting to note that they have inherited an SS/TSPC site, probably designated for protein interactions.²³⁵ Of particular note, stargazin and other member of the γ subunit family (γ_3 , γ_4 and γ_8) have recently been shown to define a novel family of transmembrane AMPA receptor regulatory proteins (TARPs).²⁹⁰ The TARPs appear to regulate two distinct roles in AMPA receptor signaling: trafficking of AMPA receptors to the plasma membrane and an agonist-mediated dynamic interaction that may contribute to synaptic plasticity.²⁹¹

Effects of y Subunits on Channel Biophysics

Over the years, many different combinations of all of the hetermultimer subunits with different accompanying γ subunits have been tested. Wei et al (1991)²¹⁹ co-expressed rabbit Cardiac α_{1C} with γ_1 , and observed increased peak currents. Letts et al, (1998)²³⁸ demonstrated the modulatory effects of neuronal γ_2 , by co-expressing the subunit with α_{1A} - β_1 - α_2 - δ . The effects of γ_2 included a hyperpolarizing shift of the steady state inactivation properties of the channel. Similar results were obtained by Klugbauer et al (2002)²⁴⁵ with α_{1G} and α_{1C} . The same hyperpolarizing effects on channel SSI properties were observed with γ_4 , but were not with γ_5 . It is interesting to note that γ_2 shifted the activation potential to a more depolarized level, when co-transfected with α_{1A} - β_1 - α_2 -d heteromultimers, while γ_3 , γ_4 , and γ_5 did not.

Rousset el al $(2001)^{246}$ studied the electrophysiological properties of α_{1A} - α_2 - δ channels expressed in Xenopus oocytes in the presence and absence of various γ subunits (i.e., $\gamma_{1,2,3}$, or 4), and found that γ_2 and γ_3 induced a small negative shift of the inactivation curve and an acceleration of inactivation kinetics. Green et al $(2001)^{247}$ studied the functional effects of γ_2 , γ_3 , and γ_4 on α_{11} T-type channels in HEK293 cells. Their results revealed a significant slowing of deactivation with γ_2 and a slight but insignificant increase in peak calcium current. γ_2 was further explored by Kang et al (2001).²⁴⁸ These authors reported that γ_2 decreased current amplitude of α_{1B} and α_{1A} calcium channels when co-expressed with β_3 - α_2 - δ subunits. These inhibitory effects were dependent upon the presence of the α_2 - δ subunit. Both γ_1 and γ_2 slowed the activation kinetics of α_{1B} .

Gene	Channel Subunit	Disease State/Phenotype	Reference
CACNA1A	α_{1A} (Ca. 2.1)	Mouse: targeted gene deletion	268
CACNA1B	α_{1B} (Ca _v 2.2)	Mouse: targeted gene deletion – viable, reduced ability to induce neuropathic & inflammatory pain	269-272
CACNA1E	α_{1E} (<i>Ca_v</i> 2.3)	<u>Mouse</u> : targeted gene deletion – viable, altered sensitivity to pain	273
CACNA1F	α_{1F} (<i>Ca_v</i> 1.4)	<u>Mouse</u> : targeted gene deletion – viable, blind	274
CACNA1D	α_{1D} (<i>Ca_v</i> 1.3)	<u>Mouse</u> : targeted gene deletion – viable, deaf, cardiac arrhythmias	170
CACNA1G	α_{1G} (<i>Ca_v</i> 3.1)	<u>Mouse</u> : targeted gene deletion – viable, reduced spike and wave discharges	275, 276
CACNA1H	α_{1H} (<i>Ca_v</i> 3.2)	<u>Mouse</u> : targeted gene deletion – viable, impaired relaxation of vasculature	277
CACNA1C	α_{1C} (<i>Ca_v</i> 1.2)	<u>Mouse</u> : targeted gene deletion – die at about day 12 pc, no heartbeat after day 14 pc	278
CACNA1S	α_{1S} (<i>Ca_v</i> 1.1)	Mouse: targeted gene deletion – non viable, die at birth due to inability to contract diaphragm	279
CACNB1	βι	<u>Mouse</u> : targeted gene deletion - perinatal lethality, no E-C coupling	280, 281
CACNB2	β ₂	Mouse: targeted gene deletion - embryonic lethal	282
CACNB3	β_3	<u>Mouse</u> : targeted gene deletion - no visible phenotype, viable	283, 284
CACNG1	γ 1	Mouse: targeted gene deletion - no visible phenotype, viable	236
unc-2	α_1	<u>C. elegans</u> : multiple alleles - mild to severe movement defects, egg laying constitutive, defecation defects, thin	285, 287
<i>egl</i> -19	α_1	<u>C. elegans</u> : multiple alleles - null allele is embryonic lethal; reduction of function mutants are egg-laying defective, slow, flaccid	286
unc-36	$\alpha_2\delta$	<u>C. elegans</u> : multiple alleles - very slow movement, almost paralyzed, thin	287

Table 3. Induced mutations in calcium channel subunit genes

Recently, Moss et al (2002 – EMBO J)²⁴⁹ showed that when α_7 was co-expressed transiently in either Xenopus oocytes or COS-7 cells, N-type current was completely abolished. This effect appears to be mediated by blocking expression rather than interfering with trafficking or the biophysical properties of the channel.

Summary

From the initial identification of native Ca²⁺ channel subtypes, tremendous progress has been made in our understanding of the molecular biology and physiology of voltage-gated

 Ca^{2+} channels, including the cloning and expression of representatives of all known Ca^{2+} channel types, the elucidation of their tissue distribution, and an in depth understanding of their structure and function. Moreover, we have come to understand the pathophysiology of Ca^{2+} channels through naturally occurring channelopathies in humans and mice (see Table 2), and through targeted gene deletions (see Table 3). The ensuing chapters in this book will provide additional details of our understanding of voltage-gated Ca^{2+} channels.

References

- 1. Nowycky MC, Fow AP, Tsien RW. Three types of neuronal calcium channels with different calcium agonist sensitivity. Nature 1985; 340:233-236.
- 2. Bean BP. Classes of calcium channels in vertebrate cells. Annu Rev. Physiol 1989; 51:367-384.
- 3. Scott RH, Pearson HA, Dolphin AC. Aspects on vertebrate neuronal voltage-activated calcium currents and their regulation. Progress in Neurobiology 1991; 36:485-520.
- Tsien RW, Ellinor PT, Horne WA. Molecular diversity of voltage-dependent Ca²⁺ channels. TIPS 1991; 12:349-354.
- 5. Tanabe T, Takeshima H, Flockerzi V et al. Primary structure of the receptor for calcium channel blockers from skeletal muscle. Nature 1987; 328:313-318.
- 6. Hell JW, Westenbroek RE, Warner C et al. Identification and differential subcellular localization of the neuronal class C and class D L-type calcium channel α_1 subunits. J Cell Biol 1993; 123(4): 949-962.
- 7. Tanabe TK, Beam G, Powell JA et al. Restoration of excitation-contraction coupling and slow calcium current in dysgenic muscle by dihydropyridine receptor complementary DNA. Nature 1988; 336:134-139.
- 8. Miller RJ. Voltage-sensitive Ca²⁺ channels. J Biol Chem 1992; 267(3):1403-1406.
- 9. Perney TM, Hirning LD, Leeman SE et al. Multiple calcium channels mediate neurotransmitter release from peripheral neurons. Proc Natl Acacd Sci USA 1986; 83(17):6656-6659.
- 10. Cazalis M, Dayanithi G, Nordmann JJ. Hormone release from isolated nerve endings of the rat neurohypophysis. J Physiol (London) 1987; 390:55-70.
- Rane SG, Holz 4th GG, Dunlap K. Dihydropyridine inhibition of neuronal calcium current and substance P release. Pflugers Arch 1987; 409(4-5):361-366.
- 12. Lemos JR, Nowycky MC. Two types of calcium channels co-exist in peptide releasing vertebrate nerve terminals. Neuron 1989; 2(5):1419-1426.
- Wang X, Wang G, Lemos R et al. Ethanol directly modulates gating of a dihydropyridine-sensitive Ca²⁺ channel in neurohypophysial terminals. J Neurosci 1994; 14(9):5453-5460.
- 14. Murphy TH, Worley PF, Baraban JM. L-type voltage-sensitive calcium channels mediate synaptic activation of immediate early genes. Neuron 1991; 7:625-635.
- Sutton KG, McRory JE, Guthrie H et al. P/Q-type channels mediate the activity-dependent feedback of syntaxin-1A. Nature 1999; 401:800-804.
- 16. Dolmetsch RE, Pajvani U, Fife K et al. Signaling to the nucleus by an L-type calcium channel-calmodulin complex through the MAP kinase pathway. Science 2001; 294:333-339.
- Mintz IM, Venema VJ, Adams ME et al. Inhibition of N- and L-type Ca²⁺ channels by the spider venom toxin ω-Aga-IIIA. Proc Natl Acad Sci USA 1991; 88:6628-6631.
- Cohen CJ, Ertel EA, Smith MM et al. High affinity block of myocardial L-type calcium channels by the spider toxin ω-Aga-toxin IIIA: Advantages over 1,4-dihydropyridines. Mol Pharmacol 1992; 42:947-951.
- 19. Tsien RW, Lipscombe D, Madison DV et al. Multiple types of neuronal calcium channels and their selective modulation. TINS 1988; 11(10):431-438.
- Imready JP, Yue DT. Mechanism of Ca²⁺-sensitive inactivation of L-type channels. Neuron 1994; 12:1301-1318.
- 21. Charnet P, Bourinet E, Dubel SJ et al. Calcium currents recorded from a neuronal α_{1C} L-type channel in Xenopus oocytes. FEBS Letts 1994; 344:87-90.
- 22. Neely A, Olcese R, Wei S et al. Ca²⁺-dependent inactivation of a cloned cardiac Ca²⁺ channel α_1 subunit (α_{1C}) expressed in Xenopus oocytes. Biophys J 1994; 66:1895-1903.
- Erickson MG, Alseikhan BA, Peterson BZ et al. Preassociation of calmodulin with voltage-gated Ca(2+) channels revealed by FRET in single living cells. Neuron 2001; 31(6):973-985.
- Fox AP, Nowycky MC, Tsien RW. Kinetics and pharmacological properties distinguishing three types of calcium currents in chick sensory neurons. J Physiol (Lond) 1987; 394:149-172.
- Fox AP, Nowycky MC, Tsien RW. Single-channel recordings of three types of calcium channels in chic sensory neurons. J Physiol (Lond) 1987; 394:173-200.

- 26. Gross RA, Macdonald RL. Dynorphin A selectively reduces a large transient (N-type) calcium current of mouse dorsal root ganglion neurons in cell culture. Proc Natl Acad Sci USA 1987; 84(15):5469-5473.
- 27. Green KA, Cottrell GA. Actions of baclofen on components of the Ca-current in rat and mouse DRG neurons in culture. Br. J Pharmacol 1988; 94(1):235-245.
- Petersen M, Wagner G, Pierau FK. Modulation of calcium currents by capsaicin in a subpopulation of sensory neurones of guinea pig. Nauyn Schmiedebergs Arch Pharmacol 1989; 339(1-2):184-191.
- 29. McCarthy RT, TanPiengco PE. Multiple types of high-threshold calcium channels in rabbit sensory neurons: high-affinity block of neuronal L-type by nimodipine. J Neurosci 1992; 12(6):2225-2234.
- 30. Wanke E, Ferroni A, Malgaroli A. Activation of a muscarinic receptor selectively inhibits a rapidly inactivated Ca²⁺ current in rat sympathetic neurons. Proc Natl Acad Sci USA 1987; 84(12):4313-4317.
- 31. Plummer MR, Logothetis DE, Hess P. Elementary properties and pharmacological sensitivities of calcium channels in mammalian peripheral neurons. Neuron 1989; 2(5):1453-1463.
- 32. Jones SW, Marks TN. Calcium currents in bullfrog sympathetic neurons. I. activation kinetics and pharmacology. J Gen Physiol 1989; 94(1):151-167.
- Carrier GO, Ikeda SR. TTX-sensitive Na⁺ channels and Ca²⁺ channels of the L- and N-type underlie the inward current in acutely dispersed coeliac-mesenteric ganglia neurons of adult rats. Pflugers Arch. 1992; 42(1):7-16.
- 34. Doerner D, Pitler TA, Alger BE. Protein kinase C activators block specific calcium and potassium current components in isolated hippocampal neurons. J Neurosci 1988; 8(11):4069-4078.
- 35. Williams PJ, MacVivar BA, Pittman QJ. Electrophysiological properties of neuroendocrine cells of the intact rat pars intermedia: multiple calcium currents. J Neurosci 1990; 10(3):748-756.
- 36. Mogul DJ, Fox AP. Evidence for multiple types of Ca²⁺ channels in acutely isolated hippocampal CA1 neurones of the guinea-pig. J Physiol (Lond) 1991; 433:259-281.
- Regan LJ, Sah DWY, Bean BP. Ca²⁺ channels in rat central and peripheral neurons: high-threshold current resistant to dihydropyridine blockers and ω-conotoxin. Neuron 1991; 6:269-280.
- 38. Baux G, Fossier P, Trudeau LE et al. Presynaptic receptors for FMRFamide, histamine and buccalin regulate acetylcholine release at a neuro-neuronal synapse of Aplysia by modulating N-type Ca²⁺ channels. J Physiol Paris 1992; 86(1-3):3-13.
- Umemiya M, Berger AJ. Single channel properties of four calcium channel types in rat motoneurons. J Neurosci 1995; 15(3):2218-2224.
- 40. Plummer MR, Hess P. Reversible uncoupling of inactivation in N-type calcium channels. Nature 1991; 351:657-659.
- Biagi BA, Enyeart JJ. Multiple calcium currents in a thyroid C-cell line: biophysical properties and pharmacology. Am J Physiol 1991; 260:C1253-1263.
- Jones SW, Elmslie KS. Separation and modulation of calcium currents in bullfrog sympathetic neurons. Can J Physiol Pharmacol 1992; 70(Suppl):S56-S63.
- Wang X, Treistman SN, Lemos JR. Single channel recordings of Nt- and L-type Ca²⁺ currents in rat neurohypophsial terminals. J Neurophysiol 1993; 70(4):1617-1628.
- 44. Olivera BM, Gray WR, Zeikus R et al. Peptide neurotoxins from fish-hunting cone snails. Science 1985; 230:1338-1343.
- 45. Olivera BM, Miljanich GP, Ramachandran J et al. Calcium channel diversity and neurotransmitter release: The ω-conotoxins and ω-agatoxins. Annu Rev Biochem 1994; 63:823-867.
- Olivera BM, McIntosh L JM, Cruz J et al. Purification and sequence of a presynaptic peptide toxin from Conus geographus venom. Biochemistry 1984; 23(22):5087-5090.
- Kasai H, Aosaki T, Fukuda J. Presynaptic Ca-antagonist omega-conotoxin irreversibly blocks N-type Ca-channels in chick sensory neurons. Neurosci Res 1987; 4(3):228-235.
- McCleskey EW, Fox AP, Feldman DH et al. Omega-conotoxin; direct and persistent blockade of specific types of calcium channels in neurons but not muscle. Proc Natl Acad Sci USA 1987; 84(12):4327-4331.
- 49. Aosaki T, Kasai H. Characterization of two kinds of high-voltage-activated Ca-channel currents in chick sensory neurons. Differential sensitivity to dihydropyridines and omega-conotoxin GVIA. Pflugers Arch 1989; 414(2):150-156.
- Wang X, Treistman SN, Lemos JR. Two types of high threshold calcium currents inhibited by omega-conotoxin in nerve terminals of rat neurohypophysis. J Physiol (Lond) 1992; 445:181-199.
- 51. Williams ME, Feldman DH, McCue AF et al. Structure and functional expression of a novel human neuronal calcium channel subtype. Neuron 1992; 8(1):71-84.

- Dunlap K, Luebke JI, Turner TJ. Exocytotic Ca²⁺ channels in mammalian central neurons. TINS 1995; 18(2):89-98.
- 53. Wagner JA, Snowman AM, Biswas A et al. Omega-conotoxin GVIA binding to a high-affinity receptor in brain: characterization, calcium sensitivity, and solubilization. J Neurosci 1988; 8(9):3354-3359.
- 54. Jones, OT, Kunze DL, Angelides KJ. Localization and mobility of ω-conotoxin-sensitive Ca²⁺ channels in hippocampal CA1 neurons. Science 1989; 244:1189-1193.
- 55. Takemura M, Kiyama H, Fukui H et al. Distribution of the omega-conotoxin receptor in rat brain. An autoradiographic mapping. Neuroscience 1989; 32(2):405-416.
- 56. Fortier LP, Trembley JP, Rafrafi J et al. A monoclonal antibody to conotoxin reveals the distribution of a subset of calcium channels in the rat cerebellar cortex. Brain Res Mol Brain Res. 1991; 9(3):209-215.
- 57. Catterall WA, De Jongh,K, Rotman E et al. Molecular properties of calcium channels in skeletal muscle and neurons. Annals NY Acad Sci 1993; 681:342-355.
- 58. Wheeler DB, Randall A, Tsien RW. Roles of N-type and Q-type calcium channels in supporting hippocampal synaptic transmission. Science 1994; 264:107-111.
- 59. Kerr LM, Yoshikami D. A venom peptide with a novel presynaptic blocking action. Nature 1984; 308:282-284.
- 60. Dooley DJ, Lupp A, Hertting G et al. Omega-conotoxin GVIA and pharmacological modulation of hippocampal noradrenaline release. Eur J Pharmacol 1988; 148(2):261-267.
- Lundy PM, Frew R. Evidence of omega conotoxin GVIA-sensitive Ca²⁺ channels in mammalian peripheral nerve terminals. Eur J Pharmacol 1988; 156(3):325-330.
- 62. Dutar P, Rascol O, Lamour Y. Omega-conotoxin GVIA blocks synaptic transmission on the CA1 field of the hippocampus. Eur J Pharmacol 1989; 174(2-3):261-266.
- 63. Herdon H, Nahorski SR. Investigations of the roles of dihydropyridine and omega-conotoxinsensitive calcium channels in mediating depolarization-evoked endogenous dopamine release from striatal slices. Naunyn Schmiedebergs Arch Pharmacol 1989; 340(1):36-40.
- 64. Takemura M, Kishino J, Yamatodani A et al. Inhibition of histamine release from rat hypothalamic slices by omega-conotoxin GVIA, but not by nilvadipine, a dihydropyridine derivative. Brain Res 1989; 496(1-2):351-356.
- 65. Wessler I, Dooley DJ, Werhand J et al. Differential effects of calcium channel antagonists (omega-conotoxin GVIA, nifedipine, verapamil) on the electrically-evoked release of [³H] acetylcholine from the myenteric plexus, phrenic nerve and neocortex. Naunyn Schmiedebergs Arch Pharmacol 1990; 341(4):288-294.
- 66. Horne AL, Kemp JA. The effect of omega-conotoxin GVIA on synaptic transmission within the nucleus accumbens and hippocampus of the rat in vitro. Br J Pharmacol 1991; 103(3):1733-1739.
- 67. Potier B, Dutar P, Lamour Y. Different effects of omega-conotoxin GVIA at excitatory and inhibitory synapses in rat CA1 hippocampal neurons. Brain Res 1993; 616(1-2):236-241.
- 68. Leveque C, Hoshino T, David P et al. The synaptic vesicle protein synaptotagmin associates with calcium channels and is a putative Lambert-Eaton myasthenic syndrome antigen. Proc Natl Acad Sci USA 1992; 89(8):3625-3629.
- 69. Leveque C, el Far O, Martin-Moutot N et al. Purification of the N-type calcium channel associated with syntaxin and synaptotagmin. J Biol Chem 1994; 269(9):6306-6312.
- Sheng Z-H, Rettig J, Takahashi M et al. Identification of a syntaxin -binding site on N-type calcium channels. Neuron 1994; 13:1303-1313.
- 71. Sano K, Enomoto K, Maeno T. Effects of synthetic omega-conotoxin, a new type of Ca²⁺ antagonist, on frog and mouse neuromuscular transmission. Eur J Pharmacol 1987; 141(2):235-241.
- 72. Protti DA, Szczupak L, Scornik FS et al. Effects of omega-conotoxin GVIA on neurotransmitter release at the mouse neuromuscular junction. Brain Res 1991; 557(1-2):336-339.
- Adams ME, Olivera BM. Neurotoxins: Overview of an emerging research technology. TINS 1994; 17(4):151-155.
- 74. Wu LG, Saggau P. Pharmacological identification of two types of presynaptic voltage-dependent calcium channels at CA3-CA1 synapse of the hippocampus. J Neurosci 1994; 14(9):5613-5622.
- 75. Turner TJ, Lampe RA, Dunlap K. Characterization of presynaptic calcium channels with omega-conotoxin MVIIC and omega-grammotoxin SIA: Role for a resistant calcium channel type in neurosecretion. Mol. Pharmacol 1995; 47(2):348-353.
- 76. Burke SP, Adams ME, Taylor CP. Inhibition of endogenous glutamate release from hippocampal tissue by Ca²⁺ channel toxins. Eur J Pharmacol 1993; 238(2-3):383-386.
- 77. Luebke JI, Dunlap K, Turner TJ. Multiple calcium channel types control glutaminergic synaptic transmission in the hippocampus. Neuron 1993; 11(5):895-902.

- Komuro H, Rakic P. Selective role of N-type calcium channels in neuronal migration. Science 1992; 257:809-806.
- Bean BP. Pharmacology of calcium channels in cardiac muscle, vascular muscle, and neurons. Am. J Hypertens 1991; 4:406S-411S.
- 80. Randall RD, Raabe W. A non-T-, N-, or L-type calcium channel mediates release of transmitter from cerebellar granule cells in tissue culture. Abstract presented at the 22nd meeting of the Society for Neuroscience 1992; 18:429.
- Regan LJ. Voltage-dependent calcium currents in Purkinje cells from rat cerebellar vermis. J Neurosci 1991; 11(7):2259-2269.
- 82. Llinas R, Sugimori M, Lin JW et al. Blocking and isolation of a calcium channel from neurons in mammals and cephalopods utilizing a toxin fraction (FTX) from funnel-web spider poison. Proc Natl Acad Sci USA 1989; 86(5):1689-1693.
- Lin J-W, Rudy B, Llinas R. Funnel-web spider venom and a toxin fraction block calcium current expressed from rat brain mRNA in Xenopus oocytes. Proc Natl Acad Sci USA 1990; 87:4538-4542.
- 84. Mintz IM, Venema VJ, Swiderek KM et al. P-type calcium channels blocked by the spider toxin ω-Aga-VIA. Nature 1992; 355:827-829.
- Bindokas VP, Brorson JR, Miller RJ. Characteristics of voltage sensitive calcium channels in dendrites of cultured rat cerebellar neurons. Neuropharmacology 1993; 32(11):1213-1220.
- 86. Mintz IM, Adams ME, Bean BP. P-type calcium channels in rat central and peripheral neurons. Neuron 1992; 9:85-95.
- Usowicz MM, Sugimori M, Cherskey B et al. P-type calcium channels in the somata and dendrites of adult cerebellar Purkinje cells. Neuron 1992; 9(6):1185-1199.
- 88. Hillyard DR, Monje VD, Mintz IM et al. A new Conus peptide ligand for mammalian presynaptic Ca²⁺ channels. Neuron 1992; 9:69-77.
- Zhang JF, Randall AD, Ellinor PT et al. Distinctive pharmacology and kinetics of cloned neuronal calcium channels and their possible counterparts in mammalian CNS neurons. Neuropharmacology 1993; 32(11):1075-1088.
- 90. Randall A, Tsien RW. Pharmacological dissection of multiple types of Ca²⁺ channel currents in rat cerebellar granule neurons. J.Neurosci 1995; 15(4):2995-3012.
- 91. Adams ME, Myers RA, Imperial JS et al. Toxityping rat brain calcium channels with ω-toxins from spider and cone snail venoms. Biochem 1993; 32:12566-12570.
- 92. Luebke JI, Dunlap K, Turner TJ. Multiple calcium channel types control glutamatergic synaptic transmission in the hippocampus. Neuron 1993: 11(5):895-902.
- 93. Turner TJ, Adams ME, Dunlap K. Calcium channels coupled to glutamate release identified by omega-Aga-IVA. Science 1992; 258:310-313.
- 94. Turner TJ, Adams ME, Dunlap K. Multiple Ca²⁺ channel types coexist to regulate synaptosomal neurotransmitter release. Proc Natl Acad Sci USA 1993; 90(20):9518-9522.
- 95. Lundy PM, Frew R. Effect f omega-agatoxin-IVA on autonomic neurotransmission. Eur J Pharmacol 1994; 261(1-2): 79-84.
- 96. Uchitel OD, Protti DA, Sanchez V et al. P-type voltage-dependent calcium channel mediates presynaptic calcium influx and transmitter release in mammalian synapses. Proc Natl Acad Sci USA 1992; 89:3330-3333.
- 97. Bowersox S, Ko C-P, Sugiura Y et al. Omega-conopeptide SNX-230 (MVIIC) blocks calcium channels in mouse neuromuscular junction nerve terminals. Abstract presented at the 23rd annual meeting of the Society for Neuroscience 1993; Vol. 19, p. 1478.
- Takahashi T, Momiyama A. Different types of calcium channels mediate central synaptic transmission. Nature 1993; 366:156-158.
- 99. Curtis BM, Catterall WA. Solubilization of the calcium antagonist receptor from rat brain. J. Biol. Chem. 1983; 256(12):7280-7283.
- 100. Flockerzi V, Oeken H-J, Hofmann F et al. Purified dihydropyridine-binding site from skeletal muscle t-tubules is a functional calcium channel. Nature 1986; 323: 66-68.
- 101. Takahashi M, Seagar MJ, Jones JF et al. Subunit structure of dihydropyridine-sensitive calcium channels from skeletal muscle. Proc Natl Acad Sci USA 1987; 84:5478-5482.
- 102. De Waard M, Gurnett CA, Campbell KP. Structural and functional diversity of voltage-gated calcium channels. In: T Narahashi, ed. Ion Channels. Vol. 4. New York: Plenum Press, 1996.
- 103. De Jongh KS, Merrick DK, Catterall WA. Subunits of purified calcium channels: a 212-kDa form of alpha 1 and partial amino acid sequence of a phosphorylation site of an independent beta subunit. Proc. Natl. Acad. Sci USA 1989; 86(21):8585-8589.
- 104. Norman RI, Leech RN. Subunit structure and phosphorylation of the cardiac L-type channel. Biochemical Society Transactions 1994; 22:492-496.

- 105. Witcher DR, De Waard M, Sakamoto J et al. Subunit identification and reconstitution of the N-type Ca²⁺ channel complex purified from brain. Science 1993; 261:486-489.
- 106. Ahlijanian MK, Striessnig J, Catterall WA. Phosphorylation of an alpha 1-like subunit of an omega-conotoxin-sensitive brain calcium channel by cAMP-dependent protein kinase and protein kinase. J Biol Chem 1991; 266(30):20192-20197.
- 107. Sakamoto J, Campbell KP. A monoclonal antibody to the beta subunit of the skeletal muscle dihydropyridine receptor immunoprecipitates the brain omega-conotoxin GIVA receptor. J Biol Chem 1991; 266(28):18914-18919.
- 108. Ellis SB, Williams ME, Ways NR et al. Sequence and expression of mRNAs encoding the α_1 and α_2 subunits of a DHP-sensitive calcium channel. Science 1988; 241:1661-1664.
- 109. Adams BA, Tanabe T, Mikami A et al. Intragenic charge movement restored in dysgenic skeletal muscle by injection of dihydropyridine receptor cDNAs. Science 1990; 346:569-572.
- 110. Mikami A, Imoto K, Tanabe T et al. Primary structure and functional expression of the cardiac dihydropyridine-sensitive calcium channel. Nature 1989; 340:230-233.
- 111. Biel M, Ruth P, Bosse E et al. Primary structure and functional expression of a high voltage activated calcium channel from rabbit lung. FEBS 1990; 269(2):409-412.
- 112. Koch WJ, Ellinor PT, Schwartz A., cDNA cloning of a dihydropyridine-sensitive calcium channel from rat aorta. J Biol Chem 1990; 265(29):17786-17791.
- 113. Tanabe T, Mikami A, Beam KG et al. Cardiac-type excitation-contraction coupling in dysgenic skeletal muscle injected with cardiac dihydropyridine receptor cDNA. Nature 1990; 344:451-453.
- 114. Bosse E, Bottlender R, Kleppisch T et al. Stable and functional expression of the calcium channel α1 subunit from smooth muscle in somatic cell lines. The EMBO J 1992; 11(6):2033-2038.
- 115. Itagaki K, Koch WJ, Bodi L et al. Native-type DHP-sensitive calcium channel currents are produced by clone rat aortic smooth muscle and cardiac α_1 subunits expressed in Xenopus laevis oocytes and are regulated by α_{2^-} and β -subunits. FEBS 1992; 297(3):221-225.
- 116. Singer-Lahat D, Lotan I, Itagaki K et al. Evidence for the existence of RNA of Ca^{2+} -channel $\alpha_2\delta$ subunit in Xenopus oocytes. Biochemica et Biophysica Acta 1992; 1137:39-44.
- 117. Tareilus E, Roux M, Qin N et al. A Xenopus oocyte β subunit: Evidence for a role in the assembly/expression of voltage-gated calcium channels that is separate from its role as a regulatory subunit. Proc Natl Acad Sci USA 1997; 94:1703-1708.
- 118. Perez-Reyes E, Kim HS, Lacerda AE et al. Induction of calcium currents by the expression of the α_1 subunit of the dihydropyridine receptor from skeletal muscle. Nature 1989; 340:233-236.
- 119. Kim HS, Wei X, Ruth P et al. Studies on the structural requirements for the activity of the skeletal muscle dihydropyridine receptor/ slow calcium channel. J Biol Chem 1990; 265(20):11858-11863.
- 120. Snutch TP, Leonard JP, Gilbert M et al. Rat brain expresses a heterogeneous family of calcium channels. Proc Natl Acad Sci USA 1990; 87:3391-3395.
- 121. Soong TW, Stea A, Hodson CD et al. Structure and functional expression of a member of the low voltage-activated calcium channel family. Science 1993; 260:1133-1136.
- 122. Bech-Hansen NT, Naylor MJ, Maybaum TA et al. Loss-of-function mutations in a calcium-channel α₁-subunit gene in Xp11.23 cause incomplete X-linked congenital stationary night blindness. Nature Genetics 1998; 19:264-267.
- 123. Strom TM, Nyakatura G, Apfelstedt-Sylla E et al. An L-type calcium-channel gene mutated in incomplete X-linked congenital stationary night blindness. Nature Genetics 1998; 19:260-263.
- 124. Perez-Reyes E, Cribbs LL, Daud A et al. Molecular characterization of a neuronal low-voltage activated T-type calcium channel. Nature 1998; 391:896-899.
- 125. Cribbs L, Lee J-H, Yang J et al. Cloning and characterization of α_{1H} from human heart, a member of the T-type Ca²⁺ channel gene family. Circ Res 1998; 83:103-109.
- 126. Lee J-H, Daud AN, Cribbs L et al. Cloning and expression of a novel member of the low voltage-activated T-type calcium channel family. J Neurosci 1999; 19(6):1912-1921.
- 127. Snutch TP, Reiner PB. Calcium channels: diversity of form and function. Current Opinion Neurobiol 1992; 2:247-253.
- 128. Mori Y, Friedrich T, Kim M-S et al. Primary structure and functional expression from complementary DNA of a brain calcium channel. Nature 1991; 350:398-402.
- 129. Starr TVB, Prystay W, Snutch TP. Primary structure of a calcium channel that is highly expressed in the rat cerebellum. Proc Natl Acad Sci USA 1991; 88:5621-5625.
- 130. Smith LA, Wang X, Piexoto AA et al. A Drosophila calcium channel alpha1 A subunit gene maps to a genetic locus associated with behavioral and visual defects. J Neurosci 1996; 16(24):7868-7879.
- 131. Sather WA, Tanabe T, Zhang J-F et al. Distinctive biophysical and pharmacological properties of class A (BI) calcium channel α₁ subunits. Neuron 1993; 11:291-303.

- 132. Stea A, Tomlinson J, Soong TW et al. Localization and functional properties of a rat brain α_{1A} calcium channel reflects similarities to neuronal Q- and P-type channels. Proc Natl Acad Sci USA 1994; 91:10576-10580.
- 133. Randall AD, Wendland B, Schweizer F et al. Five pharmacologically distinct high voltage-activated Ca²⁺ channels in cerebellar granule cells. Abstract presented at the 23rd meeting of the Society for Neuroscience. 1993; Vol. 19, p. 1478.
- 134. Zhuchenko O, Bailey J, Bonnen P et al. Autosomal dominant cerebellar ataxia (SCA6) associated with small polyglutamine expansions in the α_{1A} -voltage-dependent calcium channel. Nature Genetics 1997; 15:62-69.
- 135. Bourinet E, Soong TW, Sutton K et al. Splicing of α_{1A} subunit gene generates phenotypic variants of P- and Q-type calcium channels. Nature Neuroscience 1999; 2(5):407-415.
- 136. Soong TW, DeMaria CD, Alvania RS et al. Systematic identification of splice variants in human P/Q-type channel alpha1(2.1) subunits: implications for current density and Ca2+-dependent inactivation. J Neurosci 2002: 1;22(23):10142-52.
- 137. Dubel SJ, Starr TVB, Hell J et al. Molecular cloning of the α-1 subunit of an ω-conotoxin-sensitive calcium channel. Proc. Natl. Acad. Sci. USA 1992; 89:5058-5062.
- Stea A, Dubel SJ, Snutch TP. Alpha 1B N-type calcium channel isoforms with distinct biophysical properties. Ann NY Acad Sci 1999; 868:118-130.
- 139. Williams ME, Brust PF, Feldman DH et al. Structure and functional expression of an ω-conotoxin-sensitive human N-type calcium channel. Science 1992a; 257:389-395.
- 140. Fujita Y, Mynlieff M, Dirksen RT et al. Primary structure and functional expression of the ω-conotoxin-sensitive N-type calcium channel from rabbit brain. Neuron 1993; 10:585-598.
- 141. Horne WA, Ellinor PT, Inman I et al. Molecular diversity of Ca²⁺ channel α₁ subunits from the marine ray Discopyge ommata. Proc. Natl Acad Sci USA 1993; 90:3787-3791.
- 142. Stea A, Soong TW, Snutch TP. Voltage-gated calcium channels. In: RA North, ed. Handbook of Receptors and Channels: Ligand- and Voltage-gated Ion Channels. Boca Raton: CRC Press 1995:113-150.
- 143. Westenbroek RE, Hell JW, Warner C et al. Biochemical properties and subcellular distribution of an N-type calcium channel α_1 subunit. Neuron 1992; (9):1099-1115.
- 144. Pan JQ, Lipscombe D. Alternative splicing in the cytoplasmic II-III loop of the N-type Ca channel alpha 1B subunit: functional differences are beta subunit-specific. J Neurosci 2000; 1:20(13):4769-75.
- 145. Kaneko S, Cooper CB, Nishioka N et al. Identification and characterization of novel human Ca(v)2.2 (alpha 1B) calcium channel variants lacking the synaptic protein interaction site. J Neurosci 2002; 1;22(1):82-92.
- 146. Bell TJ, Thaler C, Castiglioni AJ et al. Cell-specific alternative splicing increases calcium channel current density in the pain pathway. Neuron 2004; 8;41(1):127-38.
- 147. Williams BD, Schrank B, Huynh C et al. A genetic mapping system in Caenorhabditis elegans based on polymorphic sequence-tagged sites. Genetics 1992; 131(3):609-624.
- 148. Stea A, Dubel SJ, Pragnell M et al. A β -subunit normalizes the electrophysiological properties of a cloned N-type Ca²⁺ channel α_1 subunit. Neuropharmacol 1993; 32(11):1103-1116.
- 149. Bell TJ, Thaler C, Castiglioni AJ et al. Cell-specific alternative splicing increases calcium channel current density in the pain pathway. Neuron 2004; 8:41(1):127-38.
- 150. Snutch TP, Tomlinson WJ, Leonard JP et al. Distinct calcium channels are generated by alternative splicing and are differentially expressed in the mammalian CNS. Neuron 1991; 7: 45-57.
- 151. Ma W-J, Holz RW, Uhler MD. Expression of a cDNA for a neuronal calcium channel α1 subunit enhances secretion from adrenal chromaffin cells. J Biol Chem 1992; 267(32):22728-22732.
- 152. Perez-Reyes E, Wei X, Castellano A et al. Molecular diversity of L-type calcium channels. J Biol Chem 1990; 265(33):20430-20436.
- 153. Diebold RJ, Koch WJ, Ellinor PT et al. Mutually exclusive exon splicing of the cardiac calcium channel α_1 subunit gene generates developmentally regulated isoforms in the rat heart. Proc. Natl. Acad. Sci USA 1992; 89:1497-1501.
- 154. Tomlinson J, Stea A, Bourinet E et al. Functional properties of a neuronal class C L-type calcium channel. Neuropharmacology 1993; 32(11):1117-1126.
- 155. Bourinet E, Charnet P, Tomlinson WJ et al. Voltage-dependent facilitation of a neuronal alpha 1C L-type calcium channel. EMBO J 1994; 13(21):5032-5039.
- 156. Babitch J. Channel hands. Nature 1990; 346:321-322.
- 157. Bernatchez G, Talwar D, Parent L. Mutations in the EF-hand motif impair the inactivation of barium currents of the cardiac alpha1C channel. Biophys J 1998; 75(4):1727-1739.
- 158. Pitt GS, Zuhlke RD, Hudmon A et al. Molecular basis of calmodulin ethering and Ca2+ dependent inactivation of L-type Ca2+ channels. J Biol Chem 2001; 276:30794-30802.

- 159. Zühlke RD, Pitt GS, Deisseroth K et al. Calmodulin supports both inactivation and facilitation of L-type calcium channels. Nature 1999; 399:159-162.
- 160. Mouton J, Ronjat M, Jona I et al. Skeletal and cardiac ryanodine receptors bind to the Ca(2+)-sensor region of dihydropyridine receptor alpha(1C) subunit. FEBS Lett 2001: 505(3):441-444.
- 161. Kim J, Ghosh S, Nunziato DA et al. Identification of the components controlling inactivation of voltage-gated Ca2+ channels. Neuron 2004; 41(5):745-754.
- 162. Hui A, Ellinor PT, Kiizanova O et al. Molecular cloning of multiple subtypes of a novel rat brain isoform of the α_1 subunit of the voltage-dependent calcium channel. Neuron 1991; 7:35-44.
- 163. Ihara Y,Yamada Y, Fujii Y et al. Molecular diversity and functional characterization of voltage-dependent calcium channels (CACN4) expressed in pancreatic β-cells. Mol. Endocrinol. 1995; 9(1):121-130.
- 164. Seino S, Chen L, Seino M et al. Proc Natl Acad Sci USA 1992; 89:584-588.
- 165. Yaney GC, Wheeler MB, Wei X et al. Cloning of a novel alpha 1-subunit of the voltage-dependent calcium channel from the beta-cell. Mol Endocrinol 1992; 6(12):2143-2152.
- 166. Kollmar R, Montgomery LG, Fak J et al. Predominance of the α_{1D} subunit in L-type voltage-gated Ca²⁺ channels of hair cells in the chicken's cochlea. Proc Natl Acad Sci USA 1997; 94:14883-14888.
- 167. Zheng WG, Feng D, Ren D et al. Cloning and characterization of a calcium channel α_1 subunit from Drosophila melanogaster with similarity to the rat brain type D isoform. J. Neurosci. 1995; 15(2):1132-1143.
- 168. Koschak A, Reimer D, Huber I et al. alpha 1D (Ca,1.3) subunits can form 1-type Ca2+ channels activating at negative voltages. J Biol Chem 2001; 276(25):22100-22106.
- 169. Xu W, Lipscombe D. Neuronal Ca(V)1.3alpha(1) L-type channels activate at relatively hyperpolarized membrane potentials and are incompletely inhibited by dihydropyridines. J Neurosci 2001; 21(16):5944-5951.
- 170. Platzer J, Engel J, Schrott-Fischer A et al. Congenital deafness and sinoatrial node dysfunction in mice lacking class D L-type Ca2+ channels. Cell 2000; 102(1):89-97.
- 171. Brandt A, Striessnig J, Moser T. Ca.1.3 channels are essential for development and presynaptic activity of cochlear inner hair cells. J Neurosci 2003; 23(34):10832-10840.
- 172. Niidome T, Kim M-S, Friedrich T et al. Molecular cloning and characterization of a novel calcium channel from rabbit brain. FEBS 1992; 308(1): 7-13
- 173. Yokoyama CT, Westenbroek RE, Hell JW et al. Biochemical properties and subcellular distribution of the neuronal class E calcium channel α_1 subunit. J Neurosci 1995; 15(10):6419-6432.
- 174. Ellinor PT, Zhang J-F, Randall AD et al. Functional expression of a rapidly inactivating neuronal calcium channel. Nature 1993; 363:455-458.
- 175. Wakamori M, Niidome T, Furutama D et al. Distinctive functional properties of the neuronal BII (class E) calcium channel. Recept. Channels 1994; 2:303-314.
- 176. Williams ME, Marubio LM, Deal R et al. Structure and functional characterization of neuronal α_{1E} calcium channel subtypes. J Biol Chem 1994; 269(35):22347-22357.
- 177. Bourinet E, Zamponi GW, Stea A et al. The α_{1E} calcium channel exhibits permeation properties similar to low-voltage-activated calcium channels. J Neurosci 1996; 16(6):4983-4993.
- 178. Smith SM, Piedras-Renteria ES, Namkung Y et al. Neuronal voltage-activated calcium channels: On the roles of the α_{1E} and β_3 subunits. Annals NY Acad Sci 1999; 868:175-198.
- 179. Tottene A, Volsen S, Pietrobon D. alpha(1E) subunits form the pore of three cerebellar R-type calcium channels with different pharmacological and permeation properties. J Neurosci 2000; 20(1):171-178.
- 180. Wilson SM, Toth PT, Oh SB et al. The status of voltage-dependent calcium channels in alpha 1E knock-out mice. J Neurosci 2000; 20(23):8566-8571.
- 181. McRory JE, Hamid J, Doering CJ et al. The CACNA1F gene encodes an L-type calcium channel with unique biophysical properties and tissue distribution. J Neurosci 2004; 24(7):1707-1718.
- 182. Tachibana M, Okada T, Arimura T et al. Dihydropyridine-sensitive calcium current mediates neurotransmitter release from bipolar cells of the goldfish retina. J Neurosci 1993; 13:2898-2090.
- 183. Koschak A, Reimer D, Walter D et al. Ca. 1.4alpha1 subunits can form slowly inactivating dihydropyridine-sensitive L-type Ca2+ channels lacking Ca2+-dependent inactivation. J Neurosci 2003: 23(14):6041-6049.
- 184. Carbone E, Lux HD. A low voltage-activated calcium conductance in embryonic chick sensory neurons. Biophys J 1984; 46(3):413-418.
- 185. Miller RJ. Multiple calcium channels and neuronal function. Science 1987; 235:46-52.
- 186. Bean BP, McDonough SI. Two for T Neuron 1998; 20:825-828.
- 187. Beam KG, Knudson CM. Calcium currents in embryonic and neonatal mammalian skeletal muscle. J Gen Physiol 1998; 91(6):781-798.

- 188. Beam KG, Knudson CM. Effect of postnatal development on calcium currents and slow charge movement in mammalian skeletal muscle. J Gen Physiol 1988; 91(6):799-815.
- Kostyuk PG. Diversity of calcium ion channels in cellular membranes. Neuroscience 1989; 28(2):253-261.
- 190. Huguenard JR. Low-threshold calcium currents in central nervous system neurons. Annu Rev Physiol 1996; 58:329-348.
- 191. Zamponi GW, Bourinet E, Snutch TP. Nickel block of a family of neuronal calcium channels: Subtype- and subunit-dependent action at multiple sites. J Membrane Biol 1996; 151:77-90.
- 192. Jimenez C, Bourinet E, Leuranguer V et al. Determinants of voltage-dependent inactivation affect Mibefradil block of calcium channels. Neuropharmacology 2000; 39(1):1-10.
- 193. Klugbauer N, Marais E, Lacinová L et al. A T-type channel from mouse brain. Eur. J. Physiol. 1999; 437:710-715.
- 194. Mittman SJ, Guo M, Emerick C et al. Structure and alternative splicing of the gene encoding α_{11} , a human brain T calcium channel α_1 subunit. Neurosci Letts 1999; 269:121-124.
- 195. Monteil A, Chemin J, Leuranguer V et al. Specific properties of T-type calcium channels generated by the human alpha 11 subunit. J Biol Chem 2000; 275(22):16530-16535.
- 196. Beedle AM, Hamid J, Zamponi GW. Inhibition of transiently expressed low- and high-voltage-activated calcium channels by trivalent metal cations. J Membr Biol 2002; 187(3):225-38.
- 197. Heinemann SH, Terlau H, Stühmer W et al. Calcium channel characteristics conferred of the sodium channel by single mutations. Nature 1992; 356:441-443.
- 198. Yang J, Ellinor PT, Sather WA et al. Molecular determinants of calcium selectivity and ion permeation in L-type calcium channels. Nature 1993; 366:158-161.
- 199. Lambert RC, McKenna F, Maulet Y et al. Low-voltage-activated Ca²⁺ currents are generated by members of Ca_vT subunit family (α1G/H) in primary sensory neurons. J Neurosci 1998; 18(21):8605-8613.
- 200. McRory JE, Santi CM, Hamming KSC et al. Molecular and functional characterization of family of rat brain T-type calcium channels 2001; J Biol Chem 276(6):3999-4011.
- 201. Talley EM, Cribbs LL, Lee J-H et al. Differential distribution of three members of a gene family encoding low voltage-activated (T-type) calcium channels. J Neurosci 1999; 19(6):1895-1911.
- 202. Monteil A, Chemin J, Bourinet E et al. Molecular and functional properties of the human alpha(1G) subunit that forms T-type calcium channels. J Biol Chem 2000; 275(9):6090-6100.
- 203. Chemin J, Monteil A, Bourinet E et al. Alternatively spliced alpha (1G) (Ca(V)3.1) intracellular loops promote specific T-type Ca(2+) channel gating properties. Biophys J 2001; 80(3):1238-1250.
- 204. Ruth P, Röhrkasten A, Biel M et al. Primary structure of the β subunit of the DHP-sensitive calcium channel from skeletal muscle. Science 1989; 245:1115-1118.
- 205. Pragnell M, Sakamoto J, Jay SD et al. Cloning and tissue-specific expression of the brain calcium channel β-subunit. FEBS 1991; 291(2):253-258.
- 206. Hullin R, Singer-Lahat D, Freichel M et al. Calcium channel β subunit heterogeneity: functional expression of cloned cDNA from heart, aorta, and brain. EMBO J 1992; 11(3):885-890.
- 207. Perez-Reyes E, Castellano A, Kim HS et al. Cloning and expression of a cardiac/brain β subunit of the L-type calcium channel. J Biol Chem 1992; 267(3):1792-1797.
- 208. Powers PA, Liu S, Hogan K et al. Skeletal muscle and brain isoforms of a β-subunit of human voltage-dependent calcium channels are encoded by a single gene. J Biol Chem 1992; 267(32):22967-22972.
- Castellano A, Wei X, Birnbaumer L et al. Cloning and expression of a third calcium channel β subunit. J Biol Chem 1993; 268(5):3450-3455.
- Castellano A, Wei X, Birnbaumer L et al. Cloning and expression of a neuronal calcium channel β subunit. J Biol Chem 1993; 268(17):12359-12366.
- Isom LL, De Jongh KS, Catterall WA. Auxiliary subunits of voltage-gated ion channels. Neuron 1994; 12:1183-1194.
- 212. Nishimura S, Takeshima H, Hofmann F et al. Requirement of the calcium channel β subunit for functional conformation. FEBS 1993; 324(3):283-286.
- 213. Lory P, Varadi G, Slish DF et al. Characterization of beta subunit modulation of a rabbit cardiac L-type Ca2+ channel alpha 1 subunit as expressed in mouse L cells. FEBS lett 1993; 315(2):167-172.
- 214. Chien AJ, Zhao X, Shirokov RE et al. Roles of membrane-localized β subunit in the formation and targeting of functional L-type Ca²⁺ channels. J Biol Chem 1995; 270(50):30036-30044.
- 215. Neely A, Wei X, Olcese R et al. Potentiation by the beta subunit of the ratio of the ionic current to the charge movement in the cardiac calcium channel. Science 1993; 262(5133):575-578.
- 216. Lacerda AE, Kim HS, Ruth P et al. Normalization of current kinetics by interaction between the α_1 and β subunits of the skeletal muscle dihydropyridine-sensitive Ca²⁺ channel. Nature 1991; 352:527-530.

- 217. Singer D, Biel M, Lotan I et al. The roles of the subunits in the function of the calcium channels. Science 1991; 253:1553-1557.
- 218. Varadi G, Lory P, Schultz D et al. Acceleration of activation and inactivation by the β subunit of the skeletal muscle calcium channel. Nature 1991; 352:159-162.
- 219. Wei, X, Perez-Reyes E, Lacerda AE et al. Heterologous regulation of the cardiac Ca^{2*} channel α_1 subunit by skeletal muscle β and γ subunits. J Biol Chem 1991; 266(32):21943-21947.
- 220. De Waard M, Pragnell M, Campbell KP. Ca²⁺ channel regulation by a conserved β subunit domain. Neuron 1994; 13:495-503.
- 221. Pragnell M, De Waard M, Mori Y et al. Calcium channel β -subunit binds to a conserved motif in the I-II cytoplasmic linker of the α 1 subunit. Nature 1994; 368:67-70.
- 222. Kim HL, Kim H, Lee P et al. Rat brain expresses an alternatively spliced form of the dihydropyridine-sensitive L-type calcium channel alpha 2 subunit. Proc Natl Acad Sci USA 1992; 89(8):3251-3255.
- 223. De Jongh K, Warner SC, Catterall WA. Subunits of purified calcium channels. J Biol Chem 1990; 265(25):14738-14741.
- 224. Gurnett CA, Campbell KP. Transmembrane auxiliary subunits of voltage-dependent ion channels. J Biol Chem 1996; 271(45):27975-27978.
- 225. Gurnett CA, De Waard M, Campbell KP. Dual function of the voltage-dependent Ca²⁺ channel $\alpha_2\delta$ subunit in current stimulation and subunit interaction. Neuron 1996; 16:431-440.
- 226. Angelotti T, Hofmann F. Tissue-specific expression of splice variants of the mouse voltage-gated calcium channel alpha2/delta subunit. FEBS Lett 1996; 397(2-3):331-337.
- 227. Klugbauer N, Marais E, Hofmann F. Calcium channel alpha2delta subunits: differential expression, function and drug binding. J Bioenerg Biomemr 2003; 35(6):639-647.
- 228. Hobom M, Dai S, Marais E et al. Neuronal distribution and functional characterization of the calcium channel alpha2delta-2 subunit. Eur J Neurosci 2000; 12(4):1217-1226.
- 229. Qin N, Yagel S, Momplaisir ML et al. Molecular cloning and characterization of the human voltage-gated calcium channel alpha(2)delta-4 subunit. Mol Pharmacol 2002; 62(3):485-496.
- 230. Catterall WA. Functional subunit structure of voltage-gated ion channels. Science 1991; 253:1499-1500.
- 231. Yasuda T, Lewis RJ, Adams DJ. Overexpressed Ca_v{beta}3 Inhibits N-type (Ca_v2.2) Calcium Channel Currents through a Hyperpolarizing Shift of "Ultra-slow" and "Closed-state" Inactivation. J Gen Physiol 2004; 123(4):401-416.
- 232. Glossmann H, Striessnig J, Hymel L et al. Purified L-type calcium channels: only one single polypeptide (alpha 1-subunit) carries the drug receptor domains and is regulated by protein kinases. Biomed Biochim Acta 1987; 46(8-9):S351-356.
- 233. Jay SD, Ellis SB, McCue AF et al. Primary structure of the γ subunit of the DHP-sensitive calcium channel from skeletal muscle. Science 1990; 248:490-492.
- 234. Powers PA, Liu S, Hogan K et al. Molecular characterization of the gene encoding the gamma subunit of the human skeletal muscle 1,4-dihydropyridine-sensitive Ca2+ channel (CACNLG), cDNA sequence, gene structure, and chromosomal location. J Biol Chem. 1993; 268(13):9275-9279.
- 235. Chu PH, Bardwell WM, Gu Y et al. FHL2 (SLIM3) is not essential for cardiac development and function. Mol Cell Biol 2000; 20(20):7460-7462.
- 236. Freise D, Held B, Wissenbach U et al. Absence of the gamma subunit of the skeletal muscle dihydropyridine receptor increases L-type Ca2+ currents and alters channel inactivation properties. J Biol Chem. 2000; 275(19):14476-14481.
- 237. Ahern CA, Powers PA, Biddlecome GH et al. Modulation of L-type Ca2+ current but not activation of Ca2+ release by the gammal subunit of the dihydropyridine receptor of skeletal muscle. BMC Physiol 2001; 1(1):8.
- 238. Letts VA, Felix R, Biddlecome GH et al. The mouse stargazer gene encodes a neuronal Ca²⁺-channel gamma subunit. Nat Genet 1998; 19(4):340-347.
- 239. Letts VA, Valenzuela A, Kirley JP et al. Genetic and physical maps of the stargazer locus on mouse chromosome 15. Genomics 1997; 43(1):62-68.
- 240. Chen L, Bao S, Qiao X et al. Impaired cerebellar synapse maturation in waggler, a mutant mouse with a disrupted neuronal calcium channel gamma subunit. Proc Natl Acad Sci USA 1999; 96(21):12132-7.
- 241. Klugbauer N, Dai S, Specht V et al. A family of gamma-like calcium channel subunits. FEBS Lett 2000; 24;470(2):189-97.
- 242. Moss FJ, Viard P, Davies A et al. The novel product of a five-exon stargazing-related gene abolishes Ca(V)2.2 calcium channel expression. EMBO J 2002; 21(7):1514-1523.
- 243. Kornau HC, Seeburg PH, Kennedy MB. Interaction of ion channels and receptors with PDZ domain proteins. Curr Opin Neurobiol 1997; 7(3):368-373.

- 244. Tomita S, Nicoll RA, Bredt DS. PDZ protein interactions regulating glutamate receptor function and plasticity. J Cell Biol 2001; 153(5):F19-24.
- 245. Klugbauer N, Welling A, Specht V et al. L-type Ca(2+) channels of the embryonic mouse heart. Eur J Pharmacol 2002; 447(2-3):279-284.
- 246. Rousset M, Cens T, Restituito S et al. Functional roles of gamma2, gamma3 and gamma4, three new Ca2+ channel subunits, in P/Q-type Ca2+ channel expressed in Xenopus oocytes. J Physiol 2001; 532(Pt 3):583-593.
- 247. Green PJ, Warre R, Hayes PD et al. Kinetic modification of the alpha(11) subunit-mediated T-type Ca(2+) channel by a human neuronal Ca(2+) channel gamma subunit. J Physiol 2001; 533(Pt 2):467-478.
- 248. Kang MG, Chen CC, Felix R et al. Biochemical and biophysical evidence for gamma 2 subunit association with neuronal voltage-activated Ca2+ channels. J Biol Chem 2001; 276(35):32917-32924.
- 249. Moss FJ, Viard P, Davies A et al. The novel product of a five-exon stargazing-related gene abolishes Ca(V)2.2 calcium channel expression. EMBO J 2002; 21(7):1514-1523.
- 250. Ophoff RA, Terwindt GM, Vergouwe MN et al. Familial hemiplegic migraine and episodic ataxia type-2 are caused by mutations in the Ca2+ channel gene CACNL1A4. Cell 1996; 87(3):543-52.
- 251. Matsuyama Z, Wakamori M, Mori Y et al. Direct alteration of the P/Q-type Ca2+ channel property by polyglutamine expansion in spinocerebellar ataxia 6. J Neurosci 1999; 19(12):RC14.
- 252. Fletcher CF, Lutz CM, O'Sullivan TN et al. Fletcher CF, et al; Absence epilepsy in tottering mutant mice is associated with calcium channel defects. Cell 1996; 87(4):607-617.
- 253. Mori Y, Wakamori M, Oda S et al. Reduced voltage sensitivity of activation of P/Q-type Ca2+ channels is associated with the ataxic mouse mutation rolling Nagoya (tg(rol)). J Neurosci 2000; 20(15):5654-5662.
- 254. Lorenzon NM, Lutz CM, Frankel WN et al. Altered calcium channel currents in Purkinje cells of the neurological mutant mouse leaner. J Neurosci 1998; 18(12):4482-4489.
- 255. Kraus RL, Sinnegger MJ, Koschak A et al. Three new familial hemiplegic migraine mutants affect P/Q-type Ca(2+) channel kinetics. J Biol Chem 2000; 275(13):9239-9243.
- 256. Kraus RL, Sinnegger MJ, Glossmann H et al. Familial hemiplegic migraine mutations change alpha1A Ca2+ channel kinetics. J Biol Chem 1998; 273(10):5586-5590.
- 257. Wappl E, Koschak A, Poteser M et al. Functional consequences of P/Q-type Ca2+ channel Ca, 2.1 missense mutations associated with episodic ataxia type 2 and progressive ataxia. J Biol Chem 2002; 277(9):6960-6966.
- 258. Ptacek LJ, Tawil R, Griggs RC et al. Dihydropyridine receptor mutations cause hypokalemic periodic paralysis. Cell 1994; 77(6):863-868.
- 259. Morrill JA, Brown RH Jr, Cannon SC. Gating of the L-type Ca channel in human skeletal myotubes: an activation defect caused by the hypokalemic periodic paralysis mutation R528H. J Neurosci 1998; 18(24):10320-10334.
- 260. Knudson CM, Chaudhari N, Sharp AH et al. Specific absence of the alpha 1 subunit of the dihydropyridine receptor in mice with muscular dysgenesis. J Biol Chem 1989; 264(3):1345-1348.
- 261. Chen Y, Lu J, Pan H et al. Association between genetic variation of CACNA1H and childhood absence epilepsy. Ann Neurol 2003; 54(2):239-243.
- 262. Khosravani H, Altier C, Simms B et al. Gating effects of mutations in the Ca, 3.2 T-type calcium channel associated with childhood absence epilepsy. J Biol Chem 2004; 279(11):9681-9684.
- 263. Brill J, Klocke R, Paul D et al. entla, a novel epileptic and ataxic Cacna2d2 mutant of the mouse. J Biol Chem 2004; 279(8):7322-7330.
- 264. Barclay J, Balaguero N, Mione M et al. Ducky mouse phenotype of epilepsy and ataxia is associated with mutations in the Cacna2d2 gene and decreased calcium channel current in cerebellar Purkinje cells. J Neurosci 2001; 21(16):6095-104.
- 265. Brodbeck J, Davies A, Courtney JM et al. The ducky mutation in Cacna2d2 results in altered Purkinje cell morphology and is associated with the expression of a truncated alpha 2 delta-2 protein with abnormal function. J Biol Chem 2002; 277(10):7684-7693.
- 266. Burgess DL, Jones JM, Meisler MH et al. Mutation of the Ca2+ channel beta subunit gene Cchb4 is associated with ataxia and seizures in the lethargic (lh) mouse. Cell 1997; 88(3):385-392.
- 267. Letts VA, Felix R, Biddlecome GH et al. The mouse stargazer gene encodes a neuronal Ca2+-channel gamma subunit. Nat Genet 1998; 19(4):340-347.
- 268. Jun K, Piedras-Renteria ES, Smith SM et al. Ablation of P/Q-type Ca(2+) channel currents, altered synaptic transmission, and progressive ataxia in mice lacking the alpha(1A)-subunit. Proc Natl Acad Sci USA 1999; 96(26):15245-15250.
- 269. Kim C, Jun K, Lee T et al. Altered nociceptive response in mice deficient in the alpha(1B) subunit of the voltage-dependent calcium channel. Mol Cell Neurosci 2001; (2):235-245.
- 270. Hatakeyama S, Wakamori M, Ino M et al. Differential nociceptive responses in mice lacking the alpha(1B) subunit of N-type Ca(2+) channels. Neuroreport 2001; 12(11):2423-2427.
- 271. Ino M, Yoshinaga T, Wakamori M et al. Functional disorders of the sympathetic nervous system in mice lacking the alpha 1B subunit (Ca_x 2.2) of N-type calcium channels. Proc Natl Acad Sci USA 2001; 98(9):5323-5328.
- 272. Saegusa H, Kurihara T, Zong S et al. Suppression of inflammatory and neuropathic pain symptoms in mice lacking the N-type Ca2+ channel. EMBO J 2001; 20(10):2349-2356.
- 273. Saegusa H, Kurihara T, Zong S et al. Altered pain responses in mice lacking alpha 1E subunit of the voltage-dependent Ca2+ channel. Proc Natl Acad Sci USA 2000; 97(11):6132-6137.
- 274. Vessey JP, Lalonde MR, Mansergh F et al. Mutation of the Ca channel gene Cacna1F disrupts calcium signaling and synaptic transmission in mouse retina. 33rd Annual Meeting Society for neuroscience meeting; Prog# 817.4.
- 275. Kim D, Park D, Choi S et al. Thalamic control of visceral nociception mediated by T-type Ca2+ channels. Science 2003; 302:117-119.
- 276. Kim D, Song I, Keum S, Lee T, Jeong MJ, Kim SS, McEnery MW, Shin HS. Lack of the burst firing of thalamocortical relay neurons and resistance to absence seizures in mice lacking alpha(1G) T-type Ca(2+) channels. Neuron 2001; 31(1):35-45.
- 277. Chen CC, Lamping KG, Nuno DW et al. Abnormal coronary function in mice deficient in alpha1H T-type Ca2+ channels. Science 2003; 302(5649):1416-1418.
- 278. Seisenberger C, Specht V, Welling A et al. Functional embryonic cardiomyocytes after disruption of the L-type alpha1C (Ca, 1.2) calcium channel gene in the mouse. J Biol Chem 2000; 275(50):39193-39199.
- 279. Strube C, Beurg M, Powers PA et al. Reduced Ca2+ current, charge movement, and absence of Ca2+ transients in skeletal muscle deficient in dihydropyridine receptor beta 1 subunit. Biophys J 1996; 71(5):2531-2543.
- Gregg RG, Messing A, Strube C et al. Absence of the beta subunit (cchb1) of the skeletal muscle dihydropyridine receptor alters expression of the alpha 1 subunit and eliminates excitation-contraction coupling. Proc Natl Acad Sci USA 1996; 93(24):13961-13966.
 Strube C, Beurg M, Powers PA et al. Reduced Ca2+ current, charge movement, and absence of
- Strube C, Beurg M, Powers PA et al. Reduced Ca2+ current, charge movement, and absence of Ca2+ transients in skeletal muscle deficient in dihydropyridine receptor beta 1 subunit. Biophys J 1996; 71(5):2531-2543.
- 282. Ball SL, Powers PA, Shin HS et al. Role of the beta(2) subunit of voltage-dependent calcium channels in the retinal outer plexiform layer. Invest Ophthalmol Vis Sci 2002; 43(5):1595-1603.
- 283. Namkung Y, Smith SM, Lee SB et al. Targeted disruption of the Ca2+ channel beta3 subunit reduces N- and L-type Ca2+ channel activity and alters the voltage-dependent activation of P/ Q-type Ca2+ channels in neurons. Proc Natl Acad Sci USA 1998; 20:12010-12015.
- 284. Cullinane AB, Coca-Prados M, Harvey BJ. Chloride dependent intracellular pH effects of external ATP in cultured human non-pigmented ciliary body epithelium. Curr Eye Res 2001; 23(6):443-447.
- 285. Mathews EA, Garcia E, Santi CM et al. Critical residues of the Caenorhabditis elegans unc-2 voltage-gated calcium channel that affect behavioral and physiological properties. J Neurosci 2003; 23(16):6537-6545.
- 286. Lee RY, Lobel L, Hengartner M et al. Mutations in the alpha1 subunit of an L-type voltage-activated Ca2+ channel cause myotonia in Caenorhabditis elegans. EMBO J 1997; 16(20):6066-6076.
- 287. Schafer WR, Sanchez BM, Kenyon CJ. Genes affecting sensitivity to serotonin in Caenorhabditis elegans. Genetics 1996; 143(3):1219-1230.
- 288. Heron Se, Phillips HA, Mulley JC et al. Genetic variation of CACNA1H in idiopathic generalized epilepsy. Annals Neurol 2004; 55(4):595-596.
- 289. McGee AW, Nunziato DA, Maltez JM et al. Calcium channel function regulated by the SH3-GK module in beta subunits. Neuron 2004; 42(1):89-99.
- 290. Tomita S, Chen L, Kawasaki Y et al. Functional studies and distribution define a family of transmembrane APMA receptor regulatory proteins. J Cell Biol 2003; 161(4):805-816.
- 291. Tomita S, Fukata M, Nicoll et al. Dynamic interaction of stargazing-like TARPs with cycling APMA receptors at synapses. Science 2004; 303:1508-1511.

Role of β Subunits in Voltage-Gated Calcium Channel Functions

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Abstract

 G^{2+} channel auxiliary subunits have been suspected to play fundamental roles in channel function from their early biochemical characterization (see Chapter 4). Their strong association with the main α_1 subunits and their role in the reconstitution of proper channel activity, were strong evidences for key functions. Later, the discovery of a whole family of β subunit genes, now counting four members, with regions of high similarity including channel binding sites as well as more ubiquitous protein-protein interaction domains, and expression studies challenging different combinations of calcium channel subunits, confirmed their modulatory functions in every aspect of channel activity, from expression and targeting to regulation by G-proteins. The discovery of neuropathologies linked to genetic defects in the β subunit gene constitutes one more argument for assigning to this auxiliary subunit a central role in channel function and regulation.

Isolation, Characterization and Cloning

A so-called β (Ca₄ β) subunit of molecular mass of 55 kDa was first isolated as one of the main subunits associated with the dihydropyridine receptor purified from rabbit skeletal muscle.¹⁻⁸ This subunit was later shown to be necessary for proper channel function, but also to be a substrate for various protein kinases. In 1989, Ruth et al,⁹ using peptide sequences derived from the purified proteins, were the first to report the complete cDNA and deduced amino-acid sequences of this skeletal muscle β subunit (now called β_{1a}). The 1835 nucleotides sequence encoded a protein of 524 amino-acids of predicted molecular mass of 57.8 kDa. This protein lacked a hydrophobic sequence signal as well as putative transmembrane domains, but displayed 4 major α helical regions, each containing a similar stretch of eight residues with negative charges (Fig. 1) and assumed to play a role in divalent cation binding.⁹ Thus the β_{1a} subunit was associated to the membrane only through its strong interaction with the $\alpha 1$ pore-forming subunit. PKA, PKC, PKG and casein kinase phosphorylation sites were also found, in accordance with in vitro phosphorylation studies. Tissue distribution and northern-blot analysis of the mRNA encoding this subunit however, soon suggested the existence of splice variants as well as other homologous, but not identical, β subunits.

Soon after, a novel β subunit cDNA (β_{1b}) was isolated from a rat brain cDNA library using a nucleotide probe derived from the skeletal muscle β subunit sequence.¹⁰ This 597 amino acid subunit showed a high homology with β_{1a} (82%), but with divergence in the central and C-terminal regions. Genomic analysis identified a third β_1 subunit and demonstrated that these three subunits derived from the same gene through alternative splicing.¹¹ While the β_{1a} subunit was exclusively expressed in skeletal muscle (with possible species differences¹²), the two other-splice variants were found in brain, heart and spleen.¹³ Four alternatively spliced

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Figure 1. A functional map of the β (Ca₂ β) subunit. Schematic representation of experimentally-identified or putative functional sites localized within the primary structure of the β subunit. The localization of the 13 exons of the β_3 subunit is shown on the top, and the sites identified in the four β subunits have all been placed on the homologous region of the β_3 subunit. C1, C2: regions of high homology between subunits V1, V2, V3: variable regions MAS, PEST, PDZ, SH3, BID, GuK, Helix, Ss1, Ss2 see text for details.

variants of a second β subunit gene (β_{2a} , β_{2b} , β_{2c} and β_{2d}) were then isolated from a rabbit heart library,¹⁴ which display ~70% homology with the β_{1a} subunit. These variants vary in size from 566 (β_{2c}) to 632 amino acids (β_{2b}), with splicing occurring in the central and amino-terminal regions of the protein.¹⁴ Putative phosphorylation sites for PKA, PKC and casein kinase were also found.¹⁵ This subunit is expressed in heart, aorta, brain, lung and trachea.¹⁶

Two new β subunit genes, predominantly expressed in brain, but also in other tissues, were then identified from a rat brain cDNA library: β_3^{15} and β_4 .¹⁷ Again, they showed a high percentage of homology (> 70%) with the two other β subunits in two conserved regions, the N and C-termini and a central domain being more variable (see ref. 18 for review). Three of the four α helical domains (with their stretch of negatively charged residues), and one PEST domain (a proline-rich region proposed to be implicated in protease sensitivity⁹), found in the β_{1a} subunit are conserved.¹⁷ These proteins, of 484 and 519 amino-acids respectively, possess several potential phosphorylation sites for PKC and casein kinase II, but as opposed to β_1 and β_2 , no consensus sequence for cAMP-dependent protein kinase A. An ATP/GTP binding site (motif A) is also found specifically on the β_4 subunit.¹⁷ Structure prediction studies have also identified a PDZ, an SH3 and a guanylate kinase-related potential domain¹⁹ in all four β subunits (see Fig. 1). A similar arrangement is also found in the members of the membrane-associated guanylate kinase (MAGUK) family, known to be implicated in ion channel and receptors clustering.²⁰ Although the roles of these domains are not yet known, they may participate to specific protein-protein interactions.

The chromosomal location places the β_1 , β_2 , β_3 and the β_4 subunit genes on human chromosomes 17q11-q22, 10p12, 12q13 and 2q22-q23 respectively.²¹⁻²³ Analysis of the genomic sequence of the β subunit gene reveals an organization highly conserved through species (rat, rabbit, mouse and human) and through β subunit genes.²⁴ The β_3 subunit gene spreads over 8kb and 13 exons of various sizes, from 20 base-pairs to 2.1 kb. The N- and C-termini and the central variable domain of the β subunit are contained in single exons: 1, 13 and 5, respectively, subject to alternative splicing (Fig. 1, refs. 24,25). The two conserved domains however, are split in several exons. Exons 5, 6^{24} and 7^{26} can be skipped, leading to a shift in the reading frame and a premature stop codon. It should be noted that short forms of the β_1 , β_2 , β_3 and β_4

subunits, without the Beta-Interaction Domain (BID, see below), have also been identified, without assignment of a specific functional role.^{26,27}

Association with Ca²⁺ Channels

The co-purification of the Ca²⁺ channel β subunit with the pore-forming α_1 subunit, as well as their functional effects on channel properties, strongly suggested a direct association between the α 1 and the β subunits. Indeed a short sequence of 30 amino acids (Beta Interaction Domain, or BID), located in the amino terminal end of the second conserved domain of all β subunits (V2, Fig. 1), was found to interact with the AID (Alpha Interaction Domain) an 18 amino acids segment present on the I-II loop of all high-threshold $\alpha 1$ subunits.²⁸ This interaction is necessary and sufficient to produce most of the functional effects of the β subunit (see below) and does not appear to be sensitive to pH, phosphorylation, ionic strength or Ca^{2+} concentration.²⁹ Despite a high percentage of homology between the BID of the four β subunits (> 85%), each β subunit displays a distinct apparent affinity for the AID of the α_{1A} subunit, with the following rank order $\beta_4 > \beta_2 > \beta_1 >> \beta_3$ (Kd from 3 to 55nM). This strong interaction has been shown to be potentially reversible, either in vitro, through the use of synthetic competitive peptides mimicking the AID sequence,³⁰ or in vivo, thereby regulating most of the processes which depend on this $\alpha 1/\beta$ association such as activation, inactivation, and regulation by G-proteins.³¹ These results are consistent with recent evidence suggesting a decrease in the affinity of the AID/Ca_x β interaction³² following insertion of the α_1 subunit in the polarized plasma membrane. It should be noted, that neither AID-like sequences, nor modifications in channel properties upon expression of β subunits, are observed in low threshold Ca²⁺ channels in heterologous systems or in neurons.^{33,34}

After initial unsuccessful attempts to characterize other sites of interaction between these $\alpha 1$ and βCa^{2+} channel subunits,³⁵ Walker and collaborators³⁶ identified two overlapping sequences in the C-terminal tail of the β_4 subunit that specifically interact, in a competitive manner, with the C- and N-terminal ends of some variants of the α_{1A} (Ca₂2.1) Ca²⁺ channel subunit (see also ref. 37). These sequences, called Ss1 and Ss2, could be the molecular support for some of the specific effects recorded with the $\beta 4$ subunit. These sites are of low affinity (Kd>90nM), and can take place only when the primary AID/Ca₂ β interaction is present. While the N-terminal interaction site (Ss1) has been precisely located on the β_4 subunit (aa 446-482), the Ss2 site appears to rely on multiple microdomains within the complex tertiary structure of the C-terminal tail of the β_4 subunit.³⁶ Similar interactions, albeit weaker, are also found between the C-tail of the β_{2a} subunit and the α_{1A} and α_{1E} (Ca₂2.3) subunits.³⁸ These secondary interactions are involved in the precise tuning of the voltage-dependent activation (for Ss2) and inactivation (for Ss1) of the α_{1A} subunit and may play a role in G-protein dependent regulation. There is still some controversy as to whether these interacting sequences form 3 spatially separate α_1/β binding sites or cooperate in a large interacting surface.

Post-translational modifications of the β subunits, other than phosphorylation, have only been described for specific variants of the β_2 subunit, where palmitoylation occurs on two cysteines at positions 3 and 4.³⁹ This palmitoylation site is required to anchor the β_{2a} subunit to the membrane without the necessity of the α_1 subunit (Fig. 4).⁴⁰⁻⁴³ Three positive charges, located just downstream of cysteines 3 and 4, participate to the translocation of the palmitoylation site to the membrane; possibly via an initial electrostatic interaction with the polar groups of the phospholipids, as already suggested for G-proteins.⁴⁴ Unaltered SH3 and BID domains (see Fig. 1) are also necessary for this membrane localization of the β_2 subunit.^{42,45} Such anchoring of the β_{2a} subunit has important consequences on Ca²⁺ channel inactivation and facilitation⁴³ (see Figs. 1, 4 and text below), possibly via interaction with the N-terminus of the α_1 subunit.⁴⁶ Another membrane anchoring site has also been found on the C-terminus of the β_{1b} subunit,⁴⁷ although in this case, anchoring occurs without palmitoylation.

However, despite this important amount of knowledge on the properties of the α_1/β subunit interaction, little is known about their physiological association and the actual pairs of α_1/β

Table 1.	Example of	preferential	association	between α ₁	β and β s	subunits in a	lifferent
	tissues						

Tissue	α_1/β combinations	•
Skeletal muscle	$\alpha_{1S} - \beta_{1a}$	
Cardiac muscle	$\alpha_{1C} - \beta_{2c}$	
Brain	$\alpha_{1B} - \beta_3$	
Cerebellum	α_{1A} - β_4 , α_{1A} - β_2	

subunits existing in vivo. In some cases only, where either the quantity of material, and/or the limited numbers of different subunits expressed are particularly favorable, these combinations have been resolved and they suggest that, even if one type of α_1 subunit can be purified with different types of β subunits,⁴⁸ preferential associations do exist (see Table 1) that could be regulated during development.⁴⁹

Altogether, the existence of conserved and specific sites of interaction between the α_1 and β subunits fits well with the report of generic and specific functional effects on Ca²⁺ channel properties.

Role in Channel Expression and Targeting

A role for the β subunit in channel trafficking was first suspected by Perez-Reyes et al¹⁴ on the basis of an increase in both, the number of DHP binding sites and the expressed current, upon co-expression of the α_{1C} (Ca, 1.2) and β_2 subunits. Despite an early controversy suggesting that β subunits were only increasing the effective coupling between gating-charge displacement and $\alpha_1 \operatorname{Ca}^{2+}$ channel opening,⁵⁰ this involvement of β subunits in α_1 subunit expression and/or trafficking to the membrane is now widely supported by experimental evidence and has been found for all four β subunits. A 2 to 100 fold increase in both Ca²⁺ current and amount of surface membrane toxin binding-sites was found upon co-expression of the B subunit with the α_{1A} , $\alpha_{1B}(Ca_v 2.2)$, α_{1C} , $\alpha_{1D}(Ca_v 1.3)$, $\alpha_{1S}(Ca_v 1.1)$, and α_{1E} subunits in L cells, CHO, COS, HEK293 cells and Xenopus oocytes^{14,51-58} illustrating the conservation of the stimulatory mechanim. This effect is potentiated by co-expression of the $\alpha 2-\delta$ and γ subunits^{52,56,59} (see Chapter 7) and clearly establishes a role for β subunits in channel surface expression. The increase in toxin binding sites, current gating-charge and current amplitude seems to be the result of a combination of an increase in channel gating, channel routing to the membrane, and protein stabilization, since immunocytochemistry, biochemistry, electrophysiology, and toxin binding all bring arguments in favor of one or several of these hypotheses.^{50,58,60} No changes in single channel conductance, or protein expression, however, were detected. 50,53,58,60 Interestingly, in the flatworm schistosomes, the same AID/ $(Ca_{\alpha}\beta)$ interaction induced a reduction in current amplitude, and conferred to the channel a new sensitivity to the antiparasitic drug Praziquantel.⁶¹ This differential action has been tantalizingly assigned to modifications of the schistosome β subunit BID.⁶¹

In fact, the increase in plasma membrane localization of α_{1C} recorded upon co-expression of the β_{2a} subunit arises through a direct inter-subunit association,⁴¹ probably in the endoplasmic reticulum,⁶²⁻⁶⁴ and a chaperone-like mechanism. This effect is also found, albeit with different efficacy, with the non-plasma membrane-associated, non-palmitoylated β_1 , β_3 and β_4 subunits,^{45,65} conferring upon palmitoylation of β_2 another role besides targeting the α_1 subunit to the membrane. Direct injection of β subunit proteins into α_{1C} expressing Xenopus oocytes, reproduced both the alteration of the properties of the Ca²⁺ channel and also the chaperoning of the α_1 subunit, the latter effect only, being sensitive to inhibitors of intracellular protein transport.⁶² These two regulatory roles thus represent two separate functions of the β subunit, involving different structures, protein-interactions and mechanisms,^{63,64} as suggested by the existence of secondary interaction sites. Recently, an interesting mechanism has been proposed for the role of the β subunit in channel expression. In this scheme, an ER retention signal is present in the I-II loop of the $\alpha 1$ subunit, close to the AID. This signal is suspected to severely limit plasma membrane insertion of the channel, in the absence of an expressed β subunit. Expression and rapid binding of the β subunit to the AID will favor masking of the ER retention sequence, thereby decreasing its efficacy,⁶⁶ and allowing channel trafficking. Regulation of the α_1/β interaction is thus of primary importance for channel expression, and not surprisingly, has been shown to be under the control of other intracellular partners. Kir/GEM, a member of the Ras-related small G-protein family, can bind Ca²⁺/calmodulin, GTP, phosphate and Ca²⁺ channel β subunit.⁶⁷ The association of Kir/GEM with Ca²⁺/calmodulin induces a re-localization of the complex from the nucleus to the cytoplasm, where the release of calmodulin will permit GTP-induced activation of Kir/GEM and association with the Ca²⁺ channel β subunit. The consequent destabilization of the α_1/β subunit association reverses the inhibition of the ER retention signal, and restricts cell surface expression of the α_1 subunit (see Fig. 2).⁶⁷ The long-term regulation of α_1 subunit trafficking by Kir/GEM small GTPases is observed with all four β subunits.

More specific and compartmentalized trafficking of the α_1 subunits, can also be induced by β subunits as discovered using polarized cell systems, where the α_{1A} subunit can be targeted to different plasma membrane areas depending on the β subunit expressed.^{47,68} This suggests the existence of other specialized interactions and partners that remain to be discovered. The concentration dependence of the effects of the β subunits on channel targeting and channel properties differs in one order of magnitude (17 nM, versus 120 nM, respectively).³² This difference in potency is suspected to arise from modifications in the affinity of the AID for the β subunit, a consequence of the polarization of the channel environment, when the α_1 subunit becomes inserted in the plasma membrane.³² Such a modification fits well with the recent finding of the existence of channels composed of α_1 subunits alone, even in conditions where β subunits are also expressed.³¹

Role in Channel Properties: Activation, Inactivation and Facilitation

Expression of the pore forming $\alpha 1$ subunit alone, in an expression system devoid of any noticeable amount of the other regulatory subunits ($\alpha 2-\delta$, β or γ) is sufficient to promote the apparition of voltage-gated Ca²⁺ current.^{54,69} However, the voltage-dependence and kinetics of both activation and inactivation, of the currents expressed do not fit with those of the native currents, such as can be recorded in skeletal muscle, cardiac myocytes or neurons.^{69,70} Normalization of these parameters can be obtained by co-expression of a regulatory β subunit. Co-expression of any β subunit with any α_1 subunit (except low-threshold T-type Ca²⁺ channel α_1 subunits) can promote acceleration of the activation kinetics and hyperpolarization of the current-voltage curve (10-15 mV),⁷¹⁻⁷³ suggesting that, in addition to regulating channel expression and trafficking, B subunits also play an important modulatory role in channel gating. This effect is found with β_1 , β_2 , β_3 and β_4 on L (Ca_v1.1, Ca_v1.2 and Ca_v1.3),^{15,52,72,74,75} as well as non-L type Ca^{2+} channel α_1 subunits (Ca.2.1, Ca.2.2 and Ca.2.3)^{51,70,73,76-78} and in different expression systems (L-cells, HEK293, Xenopus oocytes...). It is worth noting that for a same combination of subunits, or for combinations using the same β subunit, slight differences in the reported functional effects may exist between work performed in different laboratories. Although these differences may reflect truly different modes of regulation, they could also be the result of different experimental procedures (concentration and nature of the permeant ion used, temperature, channel protein processing by host cells, nature of the channel isoform used, contamination by endogenous conductances, or tonic G-protein regulation which is known to be influenced by the channel composition...see above).

A careful study of both ionic current and gating charge movement associated with pore opening demonstrated that the β subunit only slightly modified the voltage dependence, the effective valence or the kinetics of charge movement,⁷⁹ but increased the total gating charge movement.^{50,76,80} Therefore the modifications in voltage dependence and kinetics of Ca²⁺ current



Figure 2. Proposed mechanism for β subunit and Kir/Gem action on channel expression.

activation induced by β subunits must take place after the gating charges have moved, and probably reflect a decrease in the energy barrier of the last, weakly voltage-dependent, closed-to-open transition, i.e., a better coupling between the voltage-sensor and the opening of the channel, as illustrated by both, the increase in the ratio of current over total charge movement and the smaller shift between the gating- and current-voltage curves.^{50,76,79} A similar shift and acceleration of activation is observed with all four β subunits, and may depend on the sole AID/BID, or at the least, on the I-II loop/ β C2 domain interaction.^{73,81-83} However, variations of this modulation can be obtained by using different splice variants of the same β subunit, suggesting that additional N- and C-terminal sequences are also implicated in setting the voltage-dependent gating parameters.^{25,36,84}

A negative shift in the voltage dependence of inactivation is also recorded when the β_1 , β_3 or β_4 subunits are co-expressed with Ca_v1.2, ⁵² Ca_v2.1, ^{73,85,86} Ca_v2.2 ^{83,87} or Ca_v2.3 (Fig. 3). ^{76,88} In most cases, the β_2 subunit has been reported to modulate inactivation in the opposite direction (i.e., a positive shift). It should be noted that the magnitude of the shift can vary with the α_1 and β subunits expressed, ⁷³ but also, in a β -specific manner, with the nature and the concentration of the permeant ion (Ba, Sr, Ca at 1.8-40 mM). ^{85,89} Hence in different experimental conditions, a given β subunit can displace the inactivation curve in the opposite direction, thus explaining part of the contradictory results reported in the literature. The regulation of inactivation occurs independently of the regulation of channel activation by the β subunit,⁸¹ which suggests the existence of β subunit-specific modifications of the transmembrane electric- field in the vicinity of the voltage-sensor. The displacement of the inactivation curve is accompanied by drastic, and β -subunit specific, changes in current inactivation kinetics,^{73,76,81,82,90,91} with faster inactivation rates recorded with β_{1b} , β_3 or β_4 subunits versus slower inactivation observed with β_{2a} (see Fig. 3). These specific modifications are conserved not only between α_1 subunits but also between voltage- or Ca²⁺-dependent inactivation, ^{16,82,92} demonstrating the conservation of the molecular mechanisms by which β subunits regulate channel inactivation. An ultra-slow component of inactiva-



Figure 3. Effect of β subunits on channel activation and inactivation. Top) Scaled traces recorded from Xenopus oocytes expressing the α_{1A} subunit in combination with different β subunits. Currents were recorded in the presence of 10 mM Ba in response to the protocol shown on the top. Note the marked slowing of current decay induced by expression of the β_2 subunit. Bottom-left) Current-voltage relationship of Ca²⁺ channels composed of the α_{1A} subunit alone, or co-expressed with the β_1 , β_2 , β_3 or β_4 subunits. Recordings were performed in the presence of Ba²⁺ 10 mM. Bottom-right) Steady-state inactivation curves recorded with the same subunit combinations. Note the positive shift, and the decreased inactivation obtained upon expression of the β_2 subunit.

tion, present in Ca_v1.2 and Ca_v2.1 channels, has also been recently shown to be under the indirect control of the β subunit.⁹³ In fact, the ultra-slow mode of inactivation is more likely to occur from the open conformation of the channel, thus being promoted by β subunits that delay the fast inactivation (such as β_{2a}).⁹³ Fast and slow inactivation induced by β subunits are under the control of at least 3 different sequences:

- 1. the C2 domain, which is required for the attachment of the β subunit to the channel,
- 2. a palmitoylation site, only present at the very N-terminus of some variants of the β_2 subunit.^{39,42} This site, also called Membrane Anchoring Site (MAS, Fig. 1)⁴³ is responsible for the slow inactivation produced by the β_{2a} subunit^{81,94} through its interaction with the membrane, probably by immobilization of the I-II loop of the channel (Fig. 4)⁴³ and
- 3. an internal sequence in the V2 region of the β subunit (Fig. 1).⁹⁵ This site can also induce the slow inactivation mode, but only when encoded by a long alternatively spliced form and when MAS is deleted.⁹⁵ This region might therefore play a regulatory role only under physiological conditions where the MAS site is either proteolysed or depalmitoylated as recently suggested.⁹⁶ Such situation may directly influence neurotransmitter release and neuronal excitability.

Finally it should also be noted that the recovery from inactivation is under the influence of the β subunit too. In this case acceleration or slowing of recovery can be recorded depending only on the type of α_1 subunit, all four β subunits behaving qualitatively in a similar way.⁹⁷



Figure 4. A proposed mechanism for the β_2 subunit-induced Ca channel slow inactivation. Top) Traces showing the slow inactivation induced by expression of the β_2 subunit and its membrane localization when it is expressed alone in tsA-201 cells (right). Fast inactivation and cytoplasmic localization are obtained with the β_1 subunit expressed in the same conditions (current recorded in Xenopus oocytes with the α_{1A} subunit). Middle and Bottom) Mutations in the membrane anchoring site of the β_2 subunit (either the Cys 3 and 4, where palmitoylation occurs, or Arg9-11, that helps membrane insertion) attenuate both slowing of inactivation and membrane localization. Chimeric constructs that restore the membrane localization via addition of a transmembrane segment (CD8), restore also the slow inactivation (adapted from ref. 43, see text for details).

In addition to these classical effects on Ca^{2+} channel activation and inactivation, β subunits are also involved in more dynamic regulations of the Ca^{2+} influx occurring during sustained activity. A reversible enhancement of Ca^{2+} channel activity, also called Ca^{2+} channel facilitation, can be recorded following strong depolarizations, or short trains of activity.⁹⁸ Such facilitation has been recorded in different tissues including muscle (cardiac or skeletal), chromaffin cells and neurons,⁹⁹⁻¹⁰³ and has important consequences on cellular Ca^{2+} homeostasis, contraction, secretion, or neurotransmitter release. In these cases, are grouped under the term facilitation, different types of Ca^{2+} current enhancements that are characterized by specific

modulations by voltage, frequency of stimulation, phosphorylation, permeant ions and/or Ca²⁺ channel subunit composition.^{99,103-109} In the case of the cardiac/neuronal L-type Ca_v1.2 Ca²⁺ channel subunit, short conditioning depolarizations of moderate amplitude (50-100mV) produce a 100 to 300% increase in Ca^{2+} or Ba^{2+} current amplitude that most probably reflects a switch of the channel to a willing mode of high activity,¹⁰⁴ lasting several seconds to minutes and involving a phosphorylation step that has not been precisely characterized.^{107,110-112} Reproduction of such depolarizations in Xenopus oocytes, expressing the Ca_{1} 2 α_{1} subunit with various combinations of regulatory subunits has underlined the permissive role of the B subunit, ^{94,107} at least for some splice variants of the α_{1C} subunit. ^{110,111} The neuronal β_{2a} subunit, plays here again a particular role, since it inhibits the normal development of facilitation.¹¹³ This property has allowed, via the construction of mutations and chimera with permissive β subunits, the characterization of the permissive role of the C2 domain, conserved in all β subunits, and the inhibitory role of the two palmitoylated cysteines located at the N-terminus of the β_{2a} subunit.^{94,113,114} Indeed, the cardiac β_{2c} subunit, devoid of these two cysteines, is permissive for facilitation.^{16,94,111} The involvement of multiple domains of the α_1 subunit,¹¹⁵ and the capacity of the $\alpha 2-\delta$ subunit to occlude facilitation by driving the channel into a conformational state where openings occur easily even without prepulse, 111,116 suggest that the molecular mechanism underlying L-type Ca²⁺ channel facilitation is not restricted to the α_1/β interaction.

Role in Channel Regulation by Heterotrimeric G-Proteins

The use of heterologous expression systems, where specified Ca²⁺ channel subunits, seven-helix transmembrane receptors and G proteins can be expressed in the absence of other contaminating conductances, has been a key element in the analysis of the role of the β subunits in this type of regulation. Fast, membrane-delimited, G-protein inhibition appears to be mainly restricted to presynaptic Ca²⁺ channels (Ca₂2.1, Ca₂2.2 and Ca₂2.3) and involves the G-proteins sensitive to pertussis toxin, either Gi or Go.^{117,118} This inhibition of Ca²⁺ influx is mediated by a 1:1 interaction between the $\beta\gamma$ subunit of the G-protein and the channel α_1 subunit, favoring the transition of the channel from a "willing" to a "reluctant state", character-ized by slow activation and fewer channel openings.¹¹⁸⁻¹²² The opposite transition can be favored by strong membrane depolarizations, which are proposed to induce a rapid (time constant in the order of 2-5 ms) unbinding of the By dimer from the channel. Thus cellular activity may play an important modulatory role in this type of regulation. The direct binding of G $\beta\gamma$, and the subsequent functional effects, rely primarily on the I-II loop of the sensitive α_1 subunit, and comprise two sites that overlap with the AID, one of which contains a QXXR motif previously identified as a G $\beta\gamma$ binding-site on adenylyl cyclase.^{120,123-126} Such results suggest a regulatory role for the Ca²⁺ channel β subunit, an hypothesis that was previously suspected based on the enhancement of G-protein regulation following injection of ansisense oligonucleotides against β subunits in neurons. It was proposed at the time, and later confirmed using isolated neurons or expression systems, that Ca^{2+} channel β subunits and G protein $\beta\gamma$ subunits can compete for two overlapping sites and produce, via an allosteric mechanism, antago-nistic functional effects.^{119,120,127-129} Interestingly, expression of Ca^{2+} channel β subunits reduces both, the tonic and the receptor stimulated, G-protein dependent inhibition, 127, 128, 130 at least after expression in Xenopus oocytes, in a Ca²⁺ channel α_1 and β and G-protein $\beta\gamma$ subunit specific manner.¹³⁰⁻¹³² In addition, the Ca²⁺ channel B subunit, by allowing PKC-dependent regulation,¹³³ introduces an additional level of regulation via the negative coupling of G-protein regulation to PKC modulation (the so-called cross-talk).^{124,134} The PKC phosphorylation site, located close to the BID/GBY subunits binding site, operates as a molecular switch, triggering both PKC up-regulation and inhibition of the G-protein block. 135, 136

Several explanations have been put forward to explain the antagonistic properties of the Ca^{2+} channel β subunit, including an increased rate and hyperpolarization of the voltage-dependent reversal of G- $\beta\gamma$ inhibition, ^{132,137} and/or a β -subunit dependent facilitation

of the GTPase activity of the G-protein.¹³⁸ Moreover, other interaction sites between the α_1 and G $\beta\gamma$ subunits have been found in the N and C-termini of the channel, two regions already known to interact with some β subunits.^{46,130,136,139-142} G $\beta\gamma$ binding to the C-terminus of the α_1 sensitive subunits can be prevented by prior interaction with the C2 domain of the β_{2a} subunit, (that contains the BID),¹⁴¹ further supporting the notion of antagonism between G $\beta\gamma$ and Ca²⁺ channel β subunits. Whether these additional sites form a separate binding site or participate, with the I-II loop, to the formation of a unique, larger pocket, accommodating Ca²⁺ channel β or G-protein $\beta\gamma$ subunits is not yet known, but they surely influence G-protein inhibition of the channel.^{130,139,141}

The key question of the simultaneous presence of the G $\beta\gamma$ and the calcium channel β subunits on the channel, has been addressed by different group, but remains partly unanswered. Indeed, by recording changes in Fluorescence Resonance Energy Transfert between the α 1 and the β subunits during G-protein activation, evidences have been found for either a stronger association or a complete dissociation of the β subunit from the channel^{143,144} when G $\beta\gamma$ is bound.

Direct implication of the β subunit in the regulation of Ca^{2+} channels by PKA or PKC-induced phosphorylation has also been proposed, in the case of the α_{1C} , α_{1B} and α_{1E} subunits.^{133,145-148} The presence of the β subunit, either allows the functional effects of phosphorylation (Ca_v2.2, Ca_v2.3, Ca_v1.2, PKA or PKC), or carries itself in some cases, the phosphorylation sites (Ca_v1.2, β_{2a}).¹⁴⁵⁻¹⁵⁰ The role of the Ca²⁺ channel β subunit on the other regulatory pathway of the channels involving tyrosine kinase (src, PYK2 or the Mitogen-Activated-Protein Kinase)¹⁵¹⁻¹⁵⁵ has not yet been determined.

Recently two series of articles have brought new lights on the structural requirement necessary for the β subunit function. Using mutations in both the SH3 and the GK domains of the β subunit, it has been demonstrated that, similar to the proteins of the MAGUK family, these two domains form intramolecular interactions responsible (and necessary) for the stabilisation of the β subunit structure (interaction 2 in Fig. 5A).¹⁵⁶⁻¹⁵⁸ Mutation of either one of these two domains severely blunted the modulation of the current by the β subunit and the $\alpha 1$ - β interaction (interaction 1 in Fig. 5A). This core complex (C1+C2 without variable regions 1, 2 and 3) was perfectly able to function as a whole β subunit, and mutation or deletion of the first domain could be "trans-complemented" by intermolecular interaction with another subunits mutated or deleted in the second domain. Alternatively, Takahashi et al¹⁵⁷ have proposed that the SH3 domain could also participate to the transduction of a functional response by a direct interaction with the $\alpha 1$ subunit (interaction 3, Fig. 5B).¹⁵⁷

The core complex has now been crystallized alone and in association with the AID by 3 groups¹⁵⁹⁻¹⁶¹ (see Fig. 5B). They confirmed the interaction between the SH3 and GK domains. However, the BID was found to be buried in the Ca_v β core structure and unavailable for protein-protein interaction while being essential for the SH3-GK interaction. A hydrophobic pocket, located at one end of the β subunit, was largely responsible for the interaction with the AID. This interaction may be transduced deep in the channel structure via the S6 helice of the first domain and then affect channel gating by influencing the conformational changes of the channel protein that occurred during channel opening or inactivation. This arrangement refutes a direct role of the BID in the α 1- β association, but ignores the influence of the secondary interactions between the V3 domain and the N or C-terminus of the channel, present at least in β 2 and β 4 subunits. From a structural point of view, neither polyproline nor ATP binding in the SH3 and GK modules respectively seemed to be functional in β subunit.¹⁶⁰ The V2 domain however, connecting the SH3 and the GK modules, has been suggested to play the role of the HOOK domain in MAGUK proteins and be involved in protein-protein interaction.¹⁶¹

These new data thus extend the role of the β subunits beyond their regulatory action on Ca²⁺ influx and strongly suggest a major role for these protein-interacting modules in the construction of a complete signalling unit around the channel main pore subunit.



Figure 5. Structural analysis of the α 1- β subunits interactions. A) Schematic representation of the functional interactions underlying the b subunit-induced modulation of α 1. Interactions 1 and 2 between the GK (C2) domain and the α 1-AID or β -SH3 respectively, have been demonstrated in vitro.^{28,157,158} Interaction 3 has been proposed.¹⁵⁷ B) Three dimensional structure of the β subunit core complex (C1+C2) in association with the AID. The SH3 (C1) domain is represented in blue, the GK (C2) domain in pink and the AID in green. The BID sequence, represented with atoms in ball and stick, is buried in the GK domain and does not seem to participate directly to the interaction with the AID. The positions of the deleted V1, V2 and V3 sequences are shown as red doted lines (adapted from ref. 160, protein data bank accession code 1T3L).

Conclusions

The in vivo role of β subunits can been assessed by the analysis of a "naturally" occurring mutation which suppresses expression of a particular β subunit (see lethargic mice, in Chapter 16), or, more directly, by constructing β subunit KO mice or through the use of antisense oligonucleotides or adenoviral gene delivery.^{49,162-164} Most of these studies have confirmed the effects of the β subunit on channel activity, including the increase in total gating charge,¹⁶⁵ the increase in current amplitude, the shift of the voltage-dependence of activation and the regulation of inactivation. They also suggest a half life for the β subunit greater than 50 hours.¹⁶⁵⁻¹⁶⁷ The lack of β 1 subunit in β 1-/- mice muscles, where compensation by other β subunits does not occur, induces an important decrease in L-type of Ca²⁺ current that is accompanied by a loss of gating charge, membrane-expressed α_{1S} subunit, intracellular Ca²⁺ transient and hence spontaneous or evoked contraction.¹⁶⁸ All these effects are reversed after transfection of the β_{1-} - myotubes with a β_{1a} subunit, acting through its C-terminal region, possibly favoring colocalization of DHP and ryanodine receptors.¹⁶⁹ A role for the β subunit in calcium channel maturation during postnatal rat brain ontogeny has also been proposed,⁴⁹ underlying the important and specific regulatory roles played by β subunits not only in the precise tuning of the

calcium influx at the second or millisecond time-scale, but also in more integrated functions during development.

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References

- Sharp AH, ImagawaT, Leung AT et al. Identification and characterization of the dihydropyridinebinding subunit of the skeletal muscle dihydropyridine receptor. J Biol Chem 1987; 262:12309-12315.
- Leung AT, Imagawa T, Block B et al. Biochemical and ultrastructural characterization of the 1,4dihydropyridine receptor from rabbit skeletal muscle. Evidence for a 52,000 Da subunit. J Biol Chem 1988; 263:994-1001.
- 3. Takahashi M, Seagar MJ, Jones JF et al. Subunit structure of dihydropyridine-sensitive calcium channels from skeletal muscle. Proc Natl Acad Sci USA 1987; 84:5478-5482.
- 4. Vaghy PL, McKenna E, Itagaki K et al. Resolution of the identity of the Ca2(+)-antagonist receptor in skeletal muscle. Trends Pharmacol Sci 98i 9:398-402.
- 5. Campbell KP, Leung AT, Sharp AH. The biochemistry and molecular biology of the dihydropyridine-sensitive calcium channel. Trends Neurosci 1988; 11: 425-430.
- 6. Catterall WA. Structure and regulation of voltage-gated Ca²⁺ channels. Annu Rev Cell Dev Biol 2000; 16:521-555.
- 7. Catterall WA, Seagar MJ, Takahashi M. Molecular properties of dihydropyridine-sensitive calcium channels in skeletal muscle. J Biol Chem 1988; 263:3535-3538.
- 8. Hofmann F, Lacinova L, Klugbauer N. Voltage-dependent calcium channels: from structure to function. Rev. Physiol Biochem. Pharmacol 1999; 139:33-87.
- 9. Ruth P et al. Primary structure of the beta subunit of the DHP-sensitive calcium channel from skeletal muscle. Science 1989; 245:1115-1118.
- 10. Pragnell M, Sakamoto J, Jay SD et al. Cloning and tissue-specific expression of the brain calcium channel beta-subunit. FEBS Lett 1991; 291:253-258.
- 11. Powers PA, Liu S, Hogan K et al. Skeletal muscle and brain isoforms of a beta-subunit of human voltage- dependent calcium channels are encoded by a single gene. J Biol Chem 1992; 267:22967-22972.
- 12. Collin T, Wang JJ, Nargeot J et al. Molecular cloning of three isoforms of the L-type voltage-dependent calcium channel beta subunit from normal human heart. Circ Res 1993; 72:1337-1344.
- 13. Williams ME et al. Structure and functional expression of alpha 1, alpha 2, and beta subunits of a novel human neuronal calcium channel subtype. Neuron 1992; 8:71-84.
- 14. Perez-Reyes E et al. Cloning and expression of a cardiac/brain beta subunit of the L- type calcium channel. J Biol Chem 1992; 267:1792-1797.
- 15. Hullin R et al. Calcium channel beta subunit heterogeneity: functional expression of cloned cDNA from heart, aorta and brain. EMBO J 1992; 11:885-890.
- 16. Yamada Y et al. Cloning of a functional splice variant of L- type calcium channel beta2 subunit from rat heart. J Biol Chem 2001; 276: 47163-47170.
- 17. Castellano A, Wei X, Birnbaumer L et al. Cloning and expression of a neuronal calcium channel beta subunit. J Biol Chem 1993; 268:12359-12366.
- 18. Perez Reyes E, Schneider T. Molecular biology of calcium channels. Kidney Int. 1995; 48:1111-1124.
- Hanlon MR, Berrow NS, Dolphin AC et al. Modelling of a voltage-dependent Ca²⁺ channel beta subunit as a basis for understanding its functional properties. FEBS Lett 1999; 445:366-370.
- 20. Fanning AS, Anderson JM. Protein modules as organizers of membrane structure. Curr Opin Cell Biol 1999; 11:432-439.
- 21. Taviaux S, Williams ME, Harpold MM et al. Assignment of human genes for beta 2 and beta 4 subunits of voltage- dependent Ca²⁺ channels to chromosomes 10p12 and 2q22-q23. Hum Genet 1997; 100:151-154.
- 22. Feske S, Giltnane J, Dolmetsch R et al. Gene regulation mediated by calcium signals in T lymphocytes. Nat Immunol 2001; 2:316-324.

- 23. Collin T et al. Cloning, chromosomal location and functional expression of the human voltage-dependent calcium-channel beta 3 subunit. Eur J Biochem 1994; 220:257-262.
- Murakami M, Wissenbach U, Flockerzi V. Gene structure of the murine calcium channel beta3 subunit, cDNA and characterization of alternative splicing and transcription products. Eur J Biochem 1996; 236:138-143.
- Helton TD, Horne WA. Alternative Splicing of the beta 4 Subunit Has alpha 1 Subunit Subtype-Specific Effects on Ca²⁺ Channel Gating. J. Neurosci 2002; 22:1573-1582.
- 26. Yu AS et al. Molecular characterization of renal calcium channel beta-subunit transcripts. Am J Physiol 1995; 268:F525-31.
- 27. Castellano A, Perez Reyes E. Molecular diversity of Ca²⁺ channel beta subunits. Biochem Soc Trans 1994; 22:483-488.
- De Waard M, Pragnell M, Campbell KP. Ca²⁺ channel regulation by a conserved beta subunit domain. Neuron 1994; 13:495-503.
- 29. De Waard M, Witcher DR, Pragnell M et al. Properties of the alpha 1-beta anchoring site in voltage- dependent Ca²⁺ channels. J Biol Chem 1995; 270:12056-12064.
- 30. Bichet D, Lecomte C, Sabatier JM et al. Reversibility of the Ca(2+) channel alpha(1)-beta subunit interaction. Biochem Biophys Res Commun 2000; 277:729-735.
- 31. Restituito S, Cens T, Rousset M et al. Ca(2+) channel inactivation heterogeneity reveals physiological unbinding of auxiliary beta subunits. Biophys J 2001; 81:89-96.
- 32. Canti C et al. Evidence for Two Concentration-Dependent Processes for beta-Subunit Effects on alpha1B Calcium Channels. Biophys J 2001; 81:1439-1451.
- Leuranguer V, Bourinet E, Lory P et al. Antisense depletion of beta-subunits fails to affect T-type calcium channels properties in a neuroblastoma cell line. Neuropharmacology 1998; 37:701-708.
- 34. Lambert RC et al. T-type Ca²⁺ current properties are not modified by Ca²⁺ channel beta subunit depletion in nodosus ganglion neurons. J Neurosci 1997; 17:6621-6628.
- 35. Marquart A, Flockerzi V. alpha1-beta interaction in voltage-gated cardiac L-type calcium channels. FEBS Lett 1997; 407:137-140.
- 36. Walker D et al. A new beta subtype-specific interaction in alpha1A subunit controls P/Q- type Ca²⁺ channel activation. J Biol Chem 1999; 274:12383-12390.
- 37. Sandoz G et al. Distinct properties and differential beta subunit regulation of two C- terminal isoforms of the P/Q-type Ca(2+)-channel alpha(1A) subunit. Eur J Neurosci 2001; 14:987-997.
- 38. Tareilus E et al. A Xenopus oocyte beta subunit: evidence for a role in the assembly/expression of voltage-gated calcium channels that is separate from its role as a regulatory subunit. Proc Natl Acad Sci USA 1997; 94:1703-1708.
- 39. Chien AJ, Carr KM, Shirokov RE et al. Identification of palmitoylation sites within the L-type calcium channel beta2a subunit and effects on channel function. J Biol Chem 1996; 271: 26465-26468.
- 40. Zhou J et al. Molecular Cloning and Functional Expression of a Skeletal Muscle Dihydropyridine Receptor from Rana catesbeiana. J Biol Chem 1998; 273:25503-25509.
- 41. Chien AJ et al. Roles of a membrane-localized beta subunit in the formation and targeting of functional L-type Ca²⁺ channels. J Biol Chem 1995; 270:30036-30044.
- 42. Chien AJ, Gao T, Perez Reyes E et al. Membrane targeting of L-type calcium channels. Role of palmitoylation in the subcellular localization of the beta2a subunit. J Biol Chem 1998; 273:23590-23597.
- Restituito S et al. The β2a Subunit Is a Molecular Groom for the Ca²⁺ Channel Inactivation Gate J Neurosci 2000; 20:9046-9052.
- 44. Murray D et al. Electrostatics and the membrane association of Src: theory and experiment. Biochemistry 1998; 37:2145-2159.
- 45. Gao T, Chien AJ, Hosey MM. Complexes of the alpha1C and beta subunits generate the necessary signal for membrane targeting of class C L-type calcium channels. J Biol Chem 1999; 274:2137-2144.
- 46. Stephens GJ, Page KM, Bogdanov Y et al. The alpha1B Ca²⁺ channel amino terminus contributes determinants for beta subunit-mediated voltage-dependent inactivation properties. J Physiol (Lond) 2000; 525:377-390.
- 47. Bogdanov Y et al. Acidic motif responsible for plasma membrane association of the voltage- dependent calcium channel beta1b subunit. Eur. J. Neurosci 2000; 12:894-902.
- 48. Scott VE et al. Beta subunit heterogeneity in N-type Ca²⁺ channels. J Biol Chem 1996; 271:3207-3212.
- 49. Vance CL et al. Differential expression and association of calcium channel alpha1B and beta subunits during rat brain ontogeny. J Biol Chem 1998; 273:14495-14502.

- 50. Kamp TJ, Perez-Garcia MT, Marban E. Enhancement of ionic current and charge movement by coexpression of calcium channel beta 1A subunit with alpha 1C subunit in a human embryonic kidney cell line. J Physiol (Lond) 1996; 492: 89-96.
- 51. Mori Y et al. Primary structure and functional expression from complementary DNA of a brain calcium channel. Nature 1991; 350:398-402.
- 52. Singer D et al. The roles of the subunits in the function of the calcium channel. Science 1991; 253:1553-1557.
- 53. Wakamori M, Mikala G, Schwartz A et al. Single-channel analysis of a cloned human heart L-type Ca²⁺ channel alpha 1 subunit and the effects of a cardiac beta subunit. Biochem Biophys Res Commun 1993; 196:1170-1176.
- Mikami A et al. Primary structure and functional expression of the cardiac dihydropyridine-sensitive calcium channel. Nature 1989; 340:230-233.
- 55. Tarroni P et al. Anti-beta 2 subunit antisense oligonucleotides modulate the surface expression of the alpha 1 subunit of N-type omega-CTX sensitive Ca²⁺ channels in IMR 32 human neuroblastoma cells. Biochem Biophys Res Commun 1994; 201:180-185.
- 56. Brust PF et al. Human neuronal voltage-dependent calcium channels: studies on subunit structure and role in channel assembly. Neuropharmacology 1993; 32:1089-1102.
- 57. Varadi G, Lory P, Schultz D et al. Acceleration of activation and inactivation by the beta subunit of the skeletal muscle calcium channel. Nature 1991; 352:159-162.
- 58. Shistik E, Ivanina T, Puri T et al. Ca²⁺ current enhancement by alpha 2/delta and beta subunits in Xenopus oocytes: contribution of changes in channel gating and alpha 1 protein level. J Physiol (Lond) 1995; 489:55-62.
- 59. Wei XY et al. Heterologous regulation of the cardiac Ca²⁺ channel alpha 1 subunit by skeletal muscle beta and gamma subunits. Implications for the structure of cardiac L-type Ca²⁺ channels. J Biol Chem 1991; 266:21943-21947.
- 60. Nishimura S, Takeshima H, Hofmann F et al. Requirement of the calcium channel beta subunit for functional conformation. FEBS Lett 1993; 324:283-286.
- 61. Kohn AB, Anderson PA, Roberts-Misterly JM et al. Schistosome Calcium Channel beta Subunits. Unusual modulatory effects and potential role in the action of the antischistosomal drug Praziquantel. J Biol Chem 2001; 276:36873-36876.
- 62. Yamaguchi H et al. Multiple modulation pathways of calcium channel activity by a beta subunit. Direct evidence of beta subunit participation in membrane trafficking of the alpha1C subunit. J Biol Chem 1998; 273:19348-19356.
- 63. Neuhuber B, Gerster U, Mitterdorfer J et al. differential effects of Ca²⁺ channel beta1a and beta2a subunits on complex formation with alpha1S and on current expression in tsA201 cells. J Biol Chem 1998; 273:9110-9118.
- 64. Gerster U, Neuhuber B, Groschner K et al. Current modulation and membrane targeting of the calcium channel alpha1C subunit are independent functions of the beta subunit. J Physiol (Lond) 1999; 517:353-368.
- 65. Brice NL et al. Importance of the different beta subunits in the membrane expression of the alpha1A and alpha2 calcium channel subunits: studies using a depolarization-sensitive alpha1A antibody. Eur J Neurosci 1997; 9:749-759.
- 66. Bichet D et al. The I-II loop of the Ca²⁺ channel alpha1 subunit contains an endoplasmic reticulum retention signal antagonized by the beta subunit. Neuron 2000; 25:177-190.
- 67. Beguin P et al. Regulation of Ca²⁺ channel expression at the cell surface by the small G-protein kir/Gem. Nature 2001; 411:701-706.
- 68. Brice NL, Dolphin AC. Differential plasma membrane targeting of voltage-dependent calcium channel subunits expressed in a polarized epithelial cell line. J Physiol (Lond) 1999; 515:685-694.
- 69. Perez Reyes E et al. Induction of calcium currents by the expression of the alpha 1- subunit of the dihydropyridine receptor from skeletal muscle. Nature 1989; 340:233-236.
- 70. Stea A et al. A beta-subunit normalizes the electrophysiological properties of a cloned N-type Ca²⁺ channel alpha 1-subunit. Neuropharmacology 1993; 32:1103-1116.
- 71. McPhee JC, Ragsdale DS, Scheuer T et al. A mutation in segment IVS6 disrupts fast inactivation of sodium channels. Proc Natl Acad Sci USA 1994; 91:12346-12350.
- 72. Lacerda AE et al. Normalization of current kinetics by interaction between the alpha 1 and beta subunits of the skeletal muscle dihydropyridine-sensitive Ca²⁺ channel. Nature 1991; 352:527-530.
- De Waard M, Campbell KP. Subunit regulation of the neuronal alpha 1A Ca²⁺ channel expressed in Xenopus oocytes. J Physiol (Lond) 1995; 485:619-634.
- 74. Lory P, Varadi G, Slish DF et al. Characterization of beta subunit modulation of a rabbit cardiac L-type Ca²⁺ channel alpha 1 subunit as expressed in mouse L cells. FEBS Lett 1993; 315:167-172.

- 75. Tomlinson WJ et al. Functional properties of a neuronal class C L-type calcium channel. Neuropharmacology 1993; 32:1117-1126.
- 76. Jones LP, Wei SK, Yue DT. Mechanism of auxiliary subunit modulation of neuronal alpha1E calcium channels. J Gen Physiol 1998; 112:125-143.
- 77. Soong TW et al. Structure and functional expression of a member of the low voltage-activated calcium channel family. Science 1993; 260:1133-1136.
- Cahill AL, Hurley JH, Fox AP. Coexpression of cloned alpha(1B), beta(2a), and alpha(2)/delta subunits produces non-inactivating calcium currents similar to those found in bovine chromaffin cells. J Neurosci 2000; 20:1685-1693.
- 79. Neely A, Wei X, Olcese R et al. Potentiation by the beta subunit of the ratio of the ionic current to the charge movement in the cardiac calcium channel. Science 1993; 262:575-578.
- Josephson IR, Varadi G. The beta subunit increases Ca²⁺ currents and gating charge movements of human cardiac L-type Ca²⁺ channels. Biophys J 1996; 70:1285-1293.
- Olcese R et al. The amino terminus of a calcium channel beta subunit sets rates of channel inactivation independently of the subunit's effect on activation. Neuron 1994; 13:1433-1438.
- 82. Cens T, Restituito S, Galas S et al. Voltage and calcium use the same molecular determinants to inactivate calcium channels. J Biol Chem 1999; 274:5483-5490.
- Wakamori M, Mikala G, Mori Y. Auxiliary subunits operate as a molecular switch in determining gating behaviour of the unitary N-type Ca²⁺ channel current in Xenopus oocytes. J Physiol (Lond) 1999; 517:659-672.
- 84. Walker D, Bichet D, Campbell KP et al. A beta 4 isoform-specific interaction site in the carboxylterminal region of the voltage-dependent Ca²⁺ channel alpha 1A subunit. J Biol Chem 1998; 273:2361-2367.
- Mangoni ME, Cens T, Dalle C et al. Characterisation of alpha1A Ba²⁺, Sr²⁺ and Ca²⁺ currents recorded with ancillary beta1-4 subunits. Receptors. Channels. 1997; 5:1-14.
- Bourinet E et al. Splicing of alpha 1A subunit gene generates phenotypic variants of P- and Q-type calcium channels. Nat. Neurosci 1999; 2:407-415.
- Jones LP, DeMaria CD, Yue DT. N-type calcium channel inactivation probed by gating-current analysis. Biophys J 1999; 76:2530-2552.
- Bourinet E et al. (1996) The alpha1E Calcium Channel Exhibits Permeation Properties Similar to Low-Voltage-Activated Calcium Channels. J Neurosci 1996; 16:4983-4993.
- Cens T, Mangoni ME, Nargeot J et al. Modulation of the alpha 1A Ca²⁺ channel by beta subunits at physiological Ca²⁺ concentration. FEBS Lett 1996; 391:232-237.
- Castellano A, Wei X, Birnbaumer L et al. Cloning and expression of a third calcium channel beta subunit. J Biol Chem 1993; 268:3450-3455.
- 91. Sather WA et al. Distinctive biophysical and pharmacological properties of class A (BI) calcium channel alpha 1 subunits. Neuron 1993; 11:291-303.
- 92. Cens T, Restituito S, Charnet P. Regulation of Ca-sensitive inactivation of a 1-type Ca²⁺ channel by specific domains of beta subunits. FEBS Lett 1999; 450:17-22.
- Sokolov S, Weiss RG, Timin EN et al. Modulation of slow inactivation in class A Ca²⁺ channels by beta-subunits. J Physiol (Lond) 2000; 527:445-454.
- 94. Qin N et al. Unique regulatory properties of the type 2a Ca²⁺ channel beta subunit caused by palmitoylation. Proc Natl Acad Sci USA 1998; 95:4690-4695.
- 95. Qin N et al. Identification of a second region of the beta-subunit involved in regulation of calcium channel inactivation. Am J Physiol 1996; 271:C1539-45.
- Hurley JH, Cahill AL, Currie KP et al. The role of dynamic palmitoylation in Ca²⁺ channel inactivation. Proc Natl Acad Sci USA 2000; 97:9293-9298.
- 97. Jeziorski MC, Greenberg RM, Anderson PA. Calcium channel beta subunits differentially modulate recovery of the channel from inactivation. FEBS Lett 2000; 483:125-130.
- 98. Dolphin AC. Facilitation of Ca²⁺ current in excitable cells. Trends Neurosci 1996; 19:35-43.
- 99. Kammermeier PJ, Jones SW. Facilitation of L-type calcium current in thalamic neurons. J Neurophysiol 1998; 79:410-417.
- 100. Bates SE, Gurney AM. Use-dependent facilitation and depression of L-type Ca²⁺ current in guinea-pig ventricular myocytes: modulation by Ca²⁺ and isoprenaline. Cardiovasc Res 1999; 44:381-389.
- 101. Artalejo CR, Ariano MA, Perlman RL et al. Activation of facilitation calcium channels in chromaffin cells by D1 dopamine receptors through a cAMP/protein kinase A- dependent mechanism. Nature 1990; 348:239-242.
- 102. Artalejo CR, Rossie S, Perlman RL et al. Voltage-dependent phosphorylation may recruit Ca²⁺ current facilitation in chromaffin cells. Nature 1992; 358:63-66.

- 103. Sculptoreanu A, Scheuer T, Catterall WA. Voltage-dependent potentiation of L-type Ca²⁺ channels due to phosphorylation by cAMP-dependent protein kinase. Nature 1993; 364:240-243.
- 104. Pietrobon D, Hess P. Novel mechanism of voltage-dependent gating in L-type calcium channels. Nature 1990; 346:651-655.
- 105. Pollo A, Taglialatela M, Carbone E. Voltage-dependent inhibition and facilitation of Ca channel activation by GTP-gamma-S and Ca-agonists in adult rat sensory neurons. Neurosci Lett 1991; 123:203-207.
- 106. Sculptoreanu A, Figourov A, De Groat WC. Voltage-dependent potentiation of neuronal L-type calcium channels due to state-dependent phosphorylation. Am. J. Physiol. 1995; 269:C725-32.
- 107. Bourinet E et al. Voltage-dependent facilitation of a neuronal alpha 1C L-type calcium channel. EMBO J 1994; 13:5032-5039.
- 108. Artalejo CR, Mogul DJ, Perlman RL et al. Three types of bovine chromaffin cell Ca²⁺ channels: facilitation increases the opening probability of a 27 pS channel. J Physiol (Lond) 1991; 444:213-240.
- 109. Yazejian B et al. Direct measurements of presynaptic calcium and calcium-activated potassium currents regulating neurotransmitter release at cultured Xenopus nerve-muscle synapses. J Neurosci 1997; 17:2990-3001.
- 110. Kleppisch T et al. Double-pulse facilitation of smooth muscle alpha 1-subunit Ca²⁺ channels expressed in CHO cells. EMBO J 1994; 13:2502-2507.
- 111. Dai S, Klugbauer N, Zong X et al. The role of subunit composition on prepulse facilitation of the cardiac L-type calcium channel. FEBS Lett 1999; 442:70-74.
- 112. Sculptoreanu A, Rotman E, Takahashi M et al. Voltage-dependent potentiation of the activity of cardiac L-type calcium channel alpha 1 subunits due to phosphorylation by cAMP- dependent protein kinase. Proc Natl Acad Sci USA 1993; 90:10135-10139.
- 113. Cens T, Mangoni ME, Richard S, Nargeot J et al. Coexpression of the beta2 subunit does not induce voltage- dependent facilitation of the class C L-type Ca channel. Pflugers Arch 1996; 431:771-774.
- 114. Cens T, Restituito S, Vallentin A et al. Promotion and inhibition of L-type Ca²⁺ channel facilitation by distinct domains of the subunit. J Biol Chem 1998; 273:18308-18315.
- 115. Altier C, Spaetgens RL, Nargeot J et al. Multiple structural elements contribute to voltage-dependent facilitation of neuronal alpha(1C) (Ca(V)1.2) L-type calcium channels. Neuropharmacology 2001; 40:1050-1057.
- 116. Platano D et al. Expression of the alpha(2)delta Subunit Interferes with Prepulse Facilitation in Cardiac L-type Calcium Channels. Biophys J 2000; 78:2959-2972.
- 117. Kleuss C et al. Assignment of G-protein subtypes to specific receptors inducing inhibition of calcium currents. Nature 1991; 353:43-48.
- 118. Zamponi GW, Snutch TP. Modulation of voltage-dependent calcium channels by G proteins. Curr Opin Neurobiol 1998; 8:351-356.
- 119. Herlitze S et al. Modulation of Ca²⁺ channels by G-protein beta gamma subunits. Nature 1996; 380:258-262.
- 120. Ikeda SR. Voltage-dependent modulation of N-type calcium channels by G- protein beta gamma subunits. Nature 1996; 380:255-258.
- 121. Herlitze S, Zhong H, Scheuer T et al. Allosteric modulation of Ca²⁺ channels by G proteins, voltage-dependent facilitation, protein kinase C, and Cavbeta subunits. Proc Natl Acad Sci USA 2001; 98:4699-4704.
- 122. Clapham DE. Intracellular signalling: more jobs for G beta gamma. Curr Biol 1996; 6:814-816.
- 123. De Waard M et al. Direct binding of G-protein beta gamma complex to voltage-dependent calcium channels. Nature 1997; 385:446-450.
- 124. Zamponi GW, Bourinet E, Nelson D et al. Crosstalk between G proteins and protein kinase C mediated by the calcium channel α1 subunit. Nature 1997; 385:442-446.
- 125. Herlitze S, Hockerman GH, Scheuer T et al. Molecular determinants of inactivation and G protein modulation in the intracellular loop connecting domains I and II of the calcium channel alpha1A subunit. Proc Natl Acad Sci USA 1997; 94:1512-1516.
- 126. Page KM, Stephens GJ, Berrow NS et al. The intracellular loop between domains I and II of the B-type calcium channel confers aspects of G-protein sensitivity to the E-type calcium channel. J Neurosci 1997; 17:1330-1338.
- 127. Bourinet E, Soong TW, Stea, A et al. Determinants of the G protein-dependent opioid modulation of neuronal calcium channels. Proc Natl Acad Sci USA 1996; 93:1486-1491.
- 128. Roche JP, Anantharam V, Treistman SN. Abolition of G protein inhibition of alpha 1A and alpha 1B calcium channels by co-expression of the beta 3 subunit. FEBS Lett 1995; 371:43-46.

- 129. Campbell V, Berrow NS, Fitzgerald EM et al. (1995) Inhibition of the interaction of G protein G(o) with calcium channels by the calcium channel beta-subunit in rat neurones. J Physiol (Lond) 1995; 485:365-372.
- 130. Zhang JF, Ellinor PT, Aldrich RW et al. Multiple structural elements in voltage-dependent Ca²⁺ channels support their inhibition by G proteins. Neuron 1996; 17:991-1003.
- 131. Feng ZP, Arnot MI, Doering CJ et al. (2001) Calcium Channel beta Subunits Differentially Regulate the Inhibition of N-type Channels by Individual Gbeta Isoforms. J Biol Chem 2001; 276:45051-45058.
- 132. Canti C, Bogdanov Y, Dolphin AC. Interaction between G proteins and accessory subunits in the regulation of 1B calcium channels in Xenopus oocytes. J Physiol (Lond) 2000; 527:419-432.
- 133. Stea A, Soong TW, Snutch TP. Determinants of PKC-dependent modulation of a family of neuronal calcium channels. Neuron 1995; 15:929-940.
- 134. Swartz KJ. Modulation of Ca²⁺ channels by protein kinase C in rat central and peripheral neurons: disruption of G protein-mediated inhibition. Neuron 1993; 11:305-320.
- 135. Cooper CB et al. Cross-talk between G-protein and protein kinase C modulation of N-type calcium channels is dependent on the G-protein beta subunit isoform. J Biol Chem 2000; 275:40777-40781.
- 136. Hamid J et al. Identification of an integration center for cross-talk between protein kinase C and G protein modulation of N-type calcium channels. J Biol Chem 1999; 274:6195-6202.
- 137. Roche JP, Treistman SN. The Ca²⁺ channel beta3 subunit differentially modulates G-protein sensitivity of alpha1A and alpha1B Ca²⁺ channels. J Neurosci 1998; 18:878-886.
- 138. Campbell V et al. Voltage-dependent calcium channel beta-subunits in combination with alpha 1 subunits, have a GTPase activating effect to promote the hydrolysis of GTP by G alpha o in rat frontal cortex. FEBS Lett 1995; 370:135-140.
- 139. Canti C, Page KM, Stephens GJ et al. Identification of residues in the N terminus of alpha1B critical for inhibition of the voltage-dependent calcium channel by Gbeta gamma. J Neurosci 1999; 19:6855-6864.
- 140. Page KM, Canti C, Stephens GJ et al. Identification of the amino terminus of neuronal Ca²⁺ channel alpha1 subunits alpha1B and alpha1E as an essential determinant of G-protein modulation. J Neurosci 1998; 18:4815-4824.
- 141. Qin N, Platano D, Olcese R et al. Direct interaction of gbetagamma with a C-terminal Gbetagamma-binding domain of the Ca²⁺ channel alpha1 subunit is responsible for channel inhibition by G protein-coupled receptors. Proc Natl Acad Sci USA 1997; 94:8866-8871.
- 142. Dolphin AC, Page KM, Berrow NS et al. Dissection of the calcium channel domains responsible for modulation of neuronal voltage-dependent calcium channels by G proteins. Ann NY Acad Sci 1990; 868:160-174.
- 143. Hummer A, Delzeith O, Gomez SR et al. Competitive and synergistic interactions of G protein beta(2) and Ca(2+) channel beta(1b) subunits with Ca(v)2.1 channels, revealed by mammalian two-hybrid and fluorescence resonance energy transfer measurements. J Biol Chem 2003; 278:49386-49400.
- 144. Sandoz G, Lopez-Gonzalez I, Grunwald D et al. Cavbeta-subunit displacement is a key step to induce the reluctant state of P/Q calcium channels by direct G protein regulation. Proc Natl Acad Sci USA 2004; 101:6267-6272.
- 145. Haase H, Karczewski P, Beckert R et al. Phosphorylation of the L-type calcium channel beta subunit is involved in beta-adrenergic signal transduction in canine myocardium. FEBS Lett 1993; 335:217-222.
- 146. Klockner U, Itagaki K, Bodi I et al. Beta-subunit expression is required for cAMP-dependent increase of cloned cardiac and vascular calcium channel currents. Pflugers Arch 1992; 420:413-415.
- 147. Bouron A, Soldatov NM, Reuter H. The beta 1-subunit is essential for modulation by protein kinase C of an human and a non-human L-type Ca²⁺ channel. FEBS Lett 1995; 377:159-162.
- 148. Singer Lahat D et al. Modulation of cardiac Ca²⁺ channels in Xenopus oocytes by protein kinase C. FEBS Lett 1992; 306:113-118.
- 149. Gerhardstein BL, Puri TS, Chien AJ et al. Identification of the sites phosphorylated by cyclic AMP-dependent protein kinase on the beta 2 subunit of L-type voltage-dependent calcium channels. Biochemistry 1999; 38:10361-10370.
- 150. Bunemann M, Gerhardstein BL, Gao T et al. Functional regulation of L-type calcium channels via protein kinase A- mediated phosphorylation of the beta(2) subunit. J Biol Chem 1999; 274:33851-33854.
- 151. Schiff ML et al. Tyrosine-kinase-dependent recruitment of RGS12 to the N-type calcium channel. Nature 2000; 408:723-727.

- 152. Felsch JS, Cachero TG, Peralta EG. Activation of protein tyrosine kinase PYK2 by the m1 muscarinic acetylcholine receptor. Proc Natl Acad Sci USA 1998; 95:5051-5056.
- 153. Weiss JL, Burgoyne RD. Voltage-independent inhibition of P/Q-type Ca²⁺ channels in adrenal chromaffin cells via a neuronal Ca²⁺ sensor-1-dependent pathway involves Src family tyrosine kinase. J Biol Chem 2001; 276:44804-44811.
- 154. Fitzgerald EM. Regulation of voltage-dependent calcium channels in rat sensory neurones involves a Ras-mitogen-activated protein kinase pathway. J Physio (Lond) 2000; 527:433-444.
- 155. Cataldi M et al. Protein-tyrosine kinases activate while protein-tyrosine phosphatases inhibit L-type calcium channel activity in pituitary GH3 cells. J Biol Chem 1996; 271:9441-9446.
- 156. McGee AW, Nunziato DA, Maltez JM et al. Calcium Channel Function Regulated by the SH3-GK Module in beta Subunits. Neuron 2004; 42:89-99.
- 157. Takahashi SX, Miriyala J, Colecraft HM. Membrane-associated guanylate kinase-like properties of beta-subunits required for modulation of voltage-dependent Ca²⁺ channels. Proc Natl Acad Sci USA 2004; 101:7193-7198.
- 158. Opatowsky Y, Chomsky-Hecht O, Kang MG et al. The voltage-dependent calcium channel beta subunit contains two stable interacting domains. J Biol Chem 2003; 278:52323-52332.
- 159. Chen YH, Li MH, Zhang Y et al. Structural basis of the alpha(1)-beta subunit interaction of voltage-gated Ca(2+) channels. Nature 2004; 429(6992):675-80.
- 160. Opatowsky Y, Chen CC, Campbell KP et al. Structural analysis of the voltage-dependent calcium channel beta subunit functional core and its complex with the alpha1 interaction domain. Neuron 2004; 42:387-399.
- 161. Van Petegem F, Clark KA, Chatelain FC et al. Structure of a complex between a voltage-gated calcium channel beta-subunit and an alpha-subunit domain. Nature 2004; 429(6992):671-675.
- 162. Namkung Y et al. Targeted disruption of the Ca²⁺ channel beta3 subunit reduces N-and L-type Ca²⁺ channel activity and alters the voltage-dependant activation of P/Q type Ca²⁺ channels in neurons. Proc Natl Acad Sci USA 1998; 95:12010-12015.
- 163. Burgess DL et al. Beta subunit reshuffling modifies N and P/Q-type Ca²⁺channel subunit compositions in lethargic mouse brain. Mol Cell Neurosci 1999; 13293-311.
- 164. Burgess DL, Jones JM, Meisler MH et al. Mutation of the Ca^{2+} channel β subunit gene Cchb4 is associated with ataxia and seizures in the lethargic (lh) mouse. Cell 1997; 88:385-392.
- 165. Beurg M et al. Recovery of Ca²⁺ current, charge movements, and Ca²⁺ transients in myotubes deficient in dihydropyridine receptor beta 1 subunit transfected with beta 1 cDNA. Biophys J 1997; 73:807-818.
- 166. Wei SK et al. Ca(2+) channel modulation by recombinant auxiliary beta subunits expressed in young adult heart cells. Circ Res 2000; 86:175-184.
- 167. Berrow NS, Brice NL, Tedder I et al. Properties of cloned rat alpha1A calcium channels transiently expressed in the COS-7 cell line. Eur J Neurosci 1997; 9:739-748.
- 168. Strube C, Beurg M, Powers PA et al. Reduced Ca²⁺ current, charge movement, and absence of Ca²⁺ transients in skeletal muscle deficient in dihydropyridine receptor beta 1 subunit. Biophys J 1996; 71:2531-2543.
- 169. Beurg M et al. Involvement of the carboxy-terminus region of the dihydropyridine receptor betala subunit in excitation-contraction coupling of skeletal muscle. Biophys J 1999; 77:2953-2967.

CHAPTER 7

Distribution and Targeting Mechanisms of Voltage Activated Ca²⁺ Channels

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Voltage dependent Ca²⁺ channels control critical parameters of cell function. Their involvement in excitation contraction (EC)-coupling in muscle, their role in secretion in pancreas, their involvement in the acrosome reaction in sperm and their function in fast and slow signal transduction in brain predicts a variety of different Ca²⁺ channel complexes with defined biophysical properties. Since all these actions occur within specialized subcellular structures like the triad in muscle cells or the presynaptic terminal in neurons, Ca²⁺ channel complexes have to be targeted to their specific site of action. Thus mechanisms have to exist to control for subunit assembly and transport of the Ca²⁺ channel complex.

The human genome predicts more than 20 different Ca^{2+} channel subunits, which may assemble to a large variety of channel combinations. Functional Ca^{2+} channels consists of three to four subunits designated α_1 , β , α_2 - δ and γ . The α_1 subunit is the pore forming subunit consisting of four channel domains, which are connected via intracellular protein or peptide bridges. The ancillary subunits β , α_2 - δ and γ interact with the intracellular, extracellular and transmembrane regions of the α_1 subunit and modulate the channel function. Three large Ca^{2+} channel families can be distinguished according to their sequence homology of the α_1 subunit and their electrophysiological and pharmacological differences. These families are L-type channels, P/Q/N/R-type channels and T-type channels. Further characterization of the predicted Ca^{2+} channel types obtained from genome projects will likely extend each subgroup and may define new Ca^{2+} channel types. We will first describe the distribution of these different families in brain and periphery and will then discuss what we know about the transport mechanisms to the subcellular destiny of the Ca^{2+} channel subunit.

Distribution of Ca²⁺ Channel Types Specified by Their Pore Forming α_1 Subunit

Voltage dependent Ca²⁺ channels appear already in the most primitive animals like the single cell ciliate *Paramecium* where they trigger regenerative Ca²⁺ action potential necessary for environment sensing.^{1,2} In mammals Ca²⁺ channels are expressed in almost every cell throughout all tissues and organs such as brain, muscle, pancreas and testis.

Distribution of L-Type Channels

Ca_v1.1 and Ca_v1.4

L-type channels are encoded by the Ca_v1.1, Ca_v1.2, Ca_v1.3 and Ca_v1.4 α_1 subunits. L-type channels were first identified in large diameter muscle fibers of crab leg.³ Due to its high concentration in the T-tubular system of skeletal muscle it was the first Ca²⁺ channel complex purified.⁴ This complex consists of the Ca_v1.1 α_1 , β_{1a} , α_2 - δ_1 and γ_1 subunit.⁵ The Ca_v1.1 α_1 , subunit contains the DHP binding site and together with the other channel subunits are

Voltage-Gated Calcium Channels, edited by Gerald Zamponi. ©2005 Eurekah.com and Kluwer Academic/ Plenum Publishers located in the skeletal muscle transverse tubules, where it mediates the EC-coupling. Surprisingly, Ca_v1.1 mRNA and protein were also detected in cardiac myocytes.⁶⁻⁸

 $Ca_v 1.1$ as well as $Ca_v 1.4$ seem to have a very restricted distribution in comparison to the other members of the L-type channel family. The $Ca_v 1.4 \alpha_1$ subunit was identified, because loss of function mutations in this α_1 subunit caused congenital stationary night blindness.^{9,10} $Ca_v 1.4$ has been first postulated to be retina specific and is localized in punctate clusters in the outer and inner plexiform layer. The clusters in the outer plexiform layer are most likely in the rod active zones, suggesting that these channels are involved in the glutamate release from rod photoreceptors.¹¹ Recently, $Ca_v 1.4 \alpha_1$ subunit mRNA has also been detected in dorsal root ganglion neurons.¹²

Ca_v1.2 and Ca_v1.3

 $Ca_v 1.2$ and $Ca_v 1.3 \alpha_1$ subunits encode for most of the L-type currents in brain, heart, smooth muscle, pancreas, adrenal gland, kidney, ovary, testis and cochlea.¹³⁻¹⁸ The relative contribution of either $Ca_v 1.2$ or $Ca_v 1.3$ to L-type current is difficult to address since both channel types have similar pharmacological and biophysical properties and different splice variants.¹⁶ However, $Ca_v 1.3$ seems to activate at more negative potentials and is less sensitive to dihydropyridines.^{19,20} Thus, the correlation between the mRNA transcript and/or protein expression levels in certain tissues and cells with the reconstruction of the currents in heterologous expression systems will eventually lead to a clear distinction between these two channel types and their splice variants.

L-type Ca²⁺ currents in heart have two major functions: They determine the long plateau phase of the heart action potential and mediate EC-coupling.²¹ EC-coupling occurs at interaction sites (junctions) between the invaginations of the plasma membrane (T-tubules) and the internal Ca²⁺ stores (sarcoplasmic reticulum (SR)) (Fig.1).²² In cardiac muscle L-type Ca²⁺ channels are clustered in these junctional domains, where they trigger Ca2+ induced Ca2+ release from SR necessary for muscle contraction. Ca, 1.2 and Ca, 1.3 mRNAs are present in atria, but only Cav1.2 is expressed in ventricles. Atria expresses a long form (splice variant in extracellular loop in repeat IV) of the Ca_v1.3 α_1 subunits.²³ Three splice variants of Ca_v1.2 have been detected, which reveal a tissue specific distribution.^{15,24} The alternative splicing in the domain IS6 region of Ca₁1.2 α_1 subunits, which creates L-type channel isoforms with different DHP sensitivity determine the tissue specific distribution of the cardiac and vascular smooth muscle L-type channel. While the $Ca_v 1.2a$ form is expressed in heart and ventricular myocytes, the Ca₄1.2b α_1 subunit is expressed in aorta and smooth muscle myocytes. Embryonic cardiac cells express both splice variants (2a and 2b).⁸ In neonatal Ca, 1.2 (-/-) myocytes, Ca, 1.1 and two splice variants of Cav1.3 were detected by RT-PCR, however their functions remain yet to be determined. Alternative splicing of Cav1.3 has been described in cochlea, pancreas and other tissues.²⁵⁻²⁸

L-type channels, which are involved in the pacemaker activity, are found in the sinoatrial node. The main mRNA found in sinoatrial node is Ca_v1.2, while Ca_v1.3 mRNA is expressed at lower levels.^{23,29} According to their voltage dependence of activation it seems reasonable that Ca_v1.3 containing channels, which activate at more negative potentials, contribute to the upstroke of the action potential, while Ca_v1.2 channels are responsible for the long diastolic depolarization of the heart action potential.^{30,31}

According to the finding that L-type channel blockers cause male infertility, numerous isoforms of $Ca_v 1.2 \alpha_1$ subunits in human and rat testis and spermatozoa have been detected.³² Interestingly, the splicing of the testis L-type $Ca_v 1.2 \alpha_1$ subunit occurs in regions which are responsible for the gating kinetics and dihydropyridine sensitivity, suggesting that these channel types will express L-type currents different from the ones detected in heart or brain. In addition, $Ca_v 1.3 \alpha_1$ subunit transcripts were detected via RT-PCR in testis. Clustered pattern of localization was observed for the $Ca_v 1.2 \alpha_1$ subunit in mouse sperm. The L-type channels are clustered at the acrosome and at the principal piece of the flagellum. In addition, they are diffusely distributed in spermatogenic cells.^{33,34}

L-type channels have been described to be involved in triggering hormone secretion in (neuro)endocrine cells, like pancreatic β cells.^{35,36} Secretion of neurotransmitter and hormones occurs at a much slower time scale than fast excitatory transmission in the CNS and PNS. It involves the release from low density secretory granules. This release is sensitive to L-type channel blockers suggesting that Ca_v1 family members are responsible for the slow Ca²⁺ dependent hormone and transmitter release. Ca_v1.2 and Ca_v1.3 transcripts^{17,25,26,37} and β_{1b} , β_2 and $\beta_3^{26,38,39}$ have been identified in insulin secreting pancreatic β cells. In the insulin secreting cell line RINm5F Ca_v1.2 α_1 subunits (existing in two lengths) assembled with β_{1b} and β_3 subunits are the major constituents of DHP-labeled Ca²⁺ channels in these cells.⁴⁰ L-type channels and secretory granules colocalize in β cells.⁴¹ While both L-type channel transcripts were detected in mouse pancreas, the Ca²⁺ current underlying insulin secretion in mouse β cells is most likely mediated by Ca_v1.2 α_1 subunits rather than Ca_v1.3 α_1 subunits. In Ca_v1.3 (-/-) β cells the L-type channel amplitude is unaltered and in wild type β cells Ca_v1.3 protein is only weakly expressed.⁴²

L-type channel currents, transcripts and proteins were described in various brain regions, including hippocampus, cerebral cortex, cerebellum and retina to contribute to signal integration in dendrites and soma.^{13-18,28,43-46} L-type channels are also involved in excitation transcription coupling, linking signaling cascades from the plasma membrane to the nucleus. For example in cortical neurons, L-type channels are responsible for the CREB phosphorylation, 47 which drives the expression of various genes involved in neuronal plasticity and survival.⁴⁸ Early immunocytochemical studies revealed the presence of DHP sensitive Ca^{2+} channels in the cell bodies and dendrites (or the corresponding inner segments of retinal photoreceptors) of various brain regions including dentate granule cells and many different classes of interneurons. 49,50 In particular in hippocampal pyramidal cells, L-type channels are clustered at the base of the major dendrites.⁵¹ Further analysis of the distribution of Ca_v1.2 and Ca_v1.3 α_1 subunits indicated that both subunits reveal a similar distribution across the CNS with a high density of expression in cell bodies in particular at the origin of dendrites. In addition, weak immunoreactivity was detected in the distal dendrites.⁵² Cav1.2 channels appear to be more clustered than the Ca_x1.3 channels, which have smoother distribution along the cell surface. The differential distribution was not observed in GABAergic mouse cortical neurons. Here both Cav1.2 and $Ca_v 1.3 \alpha_1$ subunits were localized at the proximal dendrites and the cell bodies.⁵³

Both Ca_v1.2 and Ca_v1.3 transcripts are expressed in cochlea.¹⁸ In hair cells of the chick basilar papilla the Ca_v1.3 α_1 subunits are predominantly expressed²⁷ suggesting a role in afferent synaptic transmission in these cells. In fact, Ca_v1.3 knock out mice are deaf due to a loss of L-type Ca²⁺ current in the cochlear inner hair cells.³⁰ Thus, L-type currents couple sound-evoked depolarization to neurotransmitter release.

L-type channels also play a role in immature neurotransmitter release. In embryonic chick ciliary ganglion neurons acetylcholine (ACh) release is sensitive to L-type and N-type channel blockers, while after hatching ACh release becomes DHP insensitive. In newly developed regenerated neuromuscular junctions but not in the adult synapse, L-type channel blockers increase the evoked but not the spontaneous release, suggesting a role of L-type channels in immature transmitter release.⁵⁴ For example in NCAM (-/-) mice, L-type channels are expressed at the adult mouse NMJ and are most likely responsible for the immature transmitter release.⁵⁵ In addition, L-type channels were localized on developing axons and growth cones, where they probably also trigger the immature release.^{56,57}

Recently, L-type channels ($Ca_v 1.2$ and $Ca_v 1.3$) have been localized on axons of the adult rat optic nerve using anti- α_1 -antibodies.⁵⁸ The channels are not clustered at the nodes of the axons, since a diffuse rather than a punctate staining was detected along the axon. In addition, L-type Ca^{2+} channels were also detected in GFAP-positive glial cells with high expression of $Ca_v 1.2$ in the cell bodies and processes. While Ca^{2+} influx through L-type Ca^{2+} channels contribute to anoxic injury,⁵⁸⁻⁶⁰ the precise physiological role of the axonal Ca^{2+} channel is unknown. Ca^{2+} might sense axonal activity and could play a role in the regulation of axonal



Figure 1. See legend next page.

transport. In addition to L-type channels, N-type channels have been also suggested to play a role in anoxic injury and might therefore also be found in the axon.^{59,60} However, the localization of N-type channels is controversial.⁵⁸

Distribution of P/Q-, N- and R-Type Channels

The second group of voltage gated Ca²⁺ channels contains the P/Q-type channels encoded by the Ca_v2.1 α_1 subunit, the N-type channels encoded by Ca_v2.2 α_1 subunit, and R-type channels encoded by the Ca_v2.3 α_1 subunit.

Cav2.1 (P/Q-Type Channels)

P-type channels were first identified in and named after the cerebellar Purkinje cells.^{61,62} They were distinguished from Q-type currents in cerebellar granule neurons, ^{63,64} which differ in their inactivation properties and their sensitivity to the spider toxin ω -Aga-IVA. Later studies revealed that P- and Q-type channels most likely are encoded by Ca_v2.1 splice variants.⁶⁵

Northern blot analysis and antibody labeling revealed that $Ca_v 2.1 \alpha_1$ subunits are expressed throughout the brain including hippocampus, dorsal cortex, olfactory bulb and at highest levels in the cerebellum.^{44,45,66-69} Within the cerebellum both Purkinje and granule cells are stained. Punctate staining suggesting presynaptic localization of $Ca_v 2.1 \alpha_1$ subunits was observed along dendrites of many types of neurons in the CNS and in particular along dendrites and cell bodies of cerebellar Purkinje cells, hippocampal neurons (in particular mossy fibers of

Figure 1. Protein domains involved in tissue specific distribution and membrane targeting of Ca²⁺ channels. Schematic representation of protein domains within the α_1 and β subunit involved in membrane and subcellular targeting of voltage dependent Ca²⁺ channels (1-12, black) and tissue specific distribution (a-d, grey). Ca^{2+} channel α_1 subunits consist of 4 domains, which are connected by intracellular peptide loops. These protein domains are targets for intracellular protein-protein interactions. The β subunit can be divided into 5 domains. β subunits are highly conserved in the middle of the protein (thick grey bars, high homology domains), while the N- and C-termini are not conserved among the subunit members (thin lines, low homology domains). 1) The $\beta_{2\alpha}$ subunit is the only β subunit that is palmitoylated. Palmitoylation occurs at Cys 3 and 4 within the β_2 N-terminus. Exchange of both Cys against Ser results in loss of palmitoylation and decrease in L-type current. Palmitoylation involves also the SH3 domain and the α_1 interaction domain.¹⁹⁴ 2) An 11 amino acid long acidic motif (WEEEEDYEEE) within the C-terminal region of β_{1b} is responsible for membrane localization in COS-7 cells.¹⁹¹ 3) Point mutations in the β subunit, which disrupts the α_1/β subunit interaction results in perinuclear staining of α_1 subunits. The conserved core region of the β subunit excluding N- and C-terminus is sufficient to localize α_1 in punctate channel clusters at the plasma membrane.¹⁹⁵ 4) The C-terminus of β_{1a} is important for sufficient transport and localization of Ca, $1.1\alpha_1/\beta_{12}$ channel in muscle cells.²²⁷ 5) Synaptic targeting and clustering of β_4 subunits involves the nonconserved N- and C-terminus.²³⁸ 6) Point mutations within the intracellular I-II linker of the Ca_v1.2 α_1 subunit, which disrupt the α_1/β interaction,^{196,197} interferes with membrane localization of α_1 .¹⁹⁰7) The I-II linker contains an ER retention signal, which is shielded by the β subunit for ER-Golgi-plasma membrane transport.²¹³ 8) L-type channel expression can be upregulated by A-kinase anchoring proteins (AKAP). It involves a functional, but not physical interaction of AKAP79 with the intracellular II-III linker domain of the Ca_x1.2 α_1 subunit. Within the C-terminal half of the II-III linker, a poly proline sequence is conserved among the L-type channel subunits and has been suggested to act as a suppressor retention of surface expression of L-type channels.²²⁰ 9) Ca₂2.1 splice variants differ in their interaction with SNARE proteins and their subcellular distribution. The isoform which binds only to SNAP-25 (Cav2.1a, rbA) is localized predominantly in cell bodies and presynaptic terminals, while the isoforms that bind to syntaxin and SNAP-25 ($\alpha_1 2.1a$, B-I, $\alpha_1 2.1b$, B-II) are located along the surface of dendrites as well as in cell bodies and nerve terminals.^{53, 70} 10) Deletion mutants Ca_v1.2- Δ 1623 and Ca_v1.2- Δ 1623-1673 within the 664 amino acid long C-terminus of Ca, 1.2 abolish membrane targeting.¹⁹⁸ 11) A 27 amino acid long sequence which contains a consensus PDZ binding motif within the C-terminus of Ca₄1.1 is responsible for α_1 subunit targeting.^{224, 225} 12) The interaction between Ca²⁺ channel α_1 subunit with the modular adaptor proteins Mint-1, CASK and Veli involves the sequence motif (E/D-X-W-C/S-COOH) which is located at the C-terminal end of the long splice variant of Ca₂2.1 and Ca₂2.2 but not from α_1 subunits from the Ror L-type channel. CASK interaction involves a proline rich region in the middle of the α_1 subunit C-terminus. The binding motif within the C-terminus of the N-type α_1 subunit is also necessary for sufficient targeting and clustering of the N-type channels, when exogenously expressed with β_3 subunits in hippocampal cells. Deletion of the C-terminus results in somatodendritic localization of the channel complex.²⁵⁸ a) The alternative splicing in IS6 of $Ca_v 1.2 \alpha_1$ subunits determines the tissue specific distribution of the cardiac and vascular smooth muscle L-type channel. The Cav1.2a form is expressed in heart and ventricular myocytes and the $\alpha_1 1.2 b$ subunit is expressed in a rta and smooth muscle myocytes. Embryonic cardiac cells express both splice variants (2a and 2b).8 b) A three amino acid insertion in the II-III linker and a 28 amino acid substitution in domain IV S3 region creates two alternatively spliced forms of Cav1.2c. Both splice forms are detected in the tissues analyzed. The Ca_v1.2c-II variant is the predominant transcript in brain. In pituitary Cav1.2c-I is expressed higher.¹⁵ c) The Cav2.1 splice variants underlying P- and Q-type current characteristics differ in three sites. The Cav2.1b variant contains a valine (Val421) insertion in the I-II linker region, an asparagine-proline (NP) insertion in the domain IV S3-S4 linker and a stretch of 10 substituted amino acids in the C-terminus within the EF hand region (EF hand). Val421 containing Ca₂2.1 transcripts are widely expressed in brain and are also detected in kidney. According to the distribution of the EF-hand sequence, Ca, 2.1a shows high levels of expression in cerebellar cortex and lower levels in cortex, hippocampus and olfactory tubercule. Cav2.1b reveals strong expression in CA1-CA2 pyramidal and dentate granule cells in the hippocampus. NP carrying $C_{a_1}2.1 \alpha_1$ subunits are expressed in hippocampus, while only low levels of NP carrying $Ca_{1}2.1 \alpha_{1}$ subunits mRNA are detected in cerebellum.⁶⁵ d) N-type channel isoforms containing a SFMG tetrapeptide sequence in the IIIS3-S4 region are primarily expressed in rat brain, while the other isoform, which lacks the SFMG sequence but contains an ET dipeptide sequence in IVS3-S4 is highly expressed in peripheral neurons like dorsal root ganglia and superior cervical ganglia.^{89,90}e) AN-type channel splice variant within the II-III linker region (additional 63 bases or its absence) are predominantly expressed in sympathetic ganglia and significant amount of both splice variants are detected in more caudal regions of the CNS (spinal cord and brain stem).⁹¹



Figure 2. Targeting and distribution of L-type Ca²⁺ channels in HEK-tsA201 cells.¹⁹⁵ Confocal images of tsA cells expressing (A) α_2 - δ (detection with antibody against α_2 - δ), (B) Ca₄1.2, α_2 - δ (detection with antibody against Ca₄1.2), (C) Ca₄1.2, β_{2a} , α_2 - δ (detection with antibody against Ca₄1.2), (D) Ca₄1.2, β_{2a} , α_2 - δ (detection with antibody against Ca₄1.2), (D) Ca₄1.2, β_{2a} , α_2 - δ (detection with antibody against Ca₄1.2), (D) Ca₄1.2, β_{2a} , α_2 - δ (detection with antibody against α_2 - δ). Expression pattern of the subunits within these cells were detected with subunit specific antibodies as indicated. The antibody staining reveals that α_2 - δ alone targets to the plasma membrane (A), but is not able to transport the Ca₄1.2, α_1 subunit sufficiently to the membrane (B). However, coexpression of all three subunits results in localization of all three subunits to the plasma membrane (C-E).

the dentate granule cell synapses onto the proximal dendrites of CA3 pyramidal cells) and cortical pyramidal neurons. In addition to the presynaptic staining, Ca_v2.1 protein was detected along the primary dendrites and their arborizations.⁶⁸

The Ca_v2.1 splice variants underlying P- and Q-type current characteristics differ in three sites. The Ca, 2.1b variant contains a valine (Val421) insertion in loopI-II, an asparagine-proline (NP) insertion in domain IV S3-S4 linker and a stretch of 10 substituted amino acids in the C-terminus within the EF hand region (EF hand). Analysis of the distribution of the splice variants according to the existence of Val421 insertion and C-termini substitution revealed that Val421 containing Cav2.1 transcripts are widely expressed in brain and were also detected in kidney. In situ hybridization with the different EF hand sequences revealed that Cav2.1a and Ca₂2.1b are differentially expressed. Ca₂2.1a showed high levels of expression in cerebellar cortex and lower levels in cortex, hippocampus and olfactory tubercule. Both Cav2.1a and $Ca_v 2.1b$ were expressed in cerebellar granule cells with predominant expression of $Ca_v 2.1a$ in Purkinje cells. Cav2.1b revealed strong expression in CA1-CA2 pyramidal and dentate granule cells in the hippocampus. NP carrying Ca_v2.1 subunits were expressed in hippocampus and only low levels of NP carrying Cav2.1 subunits mRNA were detected in cerebellum. The differential expression of certain combinations of splice variants and subsequent assembly of the cell type specific $Ca_v 2.1$ splice variants with different β subunits may account for the expression of P-, Q- or intermediate P/Q-type currents in various neurons. In addition to the Ca,2.1a

and b splice variants, other isoforms are described for the Ca_v2.1 α_1 subunit with different localization in hippocampal pyramidal cells⁷⁰ and different interactions with presynaptic membrane proteins. These isoforms differ in their loop II-III region and in particular in their C-termini. The isoform which binds only to SNAP-25 (Ca_v2.1a, rbA) is localized predominantly in cell bodies and presynaptic terminals, while the isoforms that bind to syntaxin and SNAP-25 (Ca_v2.1a, B-I, Ca_v2.1b, B-II) are located along the surface of dendrites as well as in cell bodies and nerve terminals. The same distribution pattern of the Ca_v2.1 isoforms was observed in GABAergic mouse cortical neurons.⁵³

Most studies performed at the adult mammalian neuromuscular junction suggest that ACh release is mediated by P/Q-type channels.⁷¹⁻⁷⁸ Immunolocalization studies of the human and rat neurosmuscular junction revealed that $Ca_v 2.1$ subunits (P/Q) are localized in discrete puncta at the presynaptic terminals of motorneurons.^{79,80} Surprisingly, low levels of N-type channels were detected in terminals form motorneurons of tibialis anterior, gastrocnemius, and soleus muscles but not at the NMJ.⁸⁰

Ca_v2.2 (N-Type Channels)

N-type channels were first discovered in sensory neurons as channels which are neither L- nor T-type channels according to their biophysical and pharmacological properties.^{81,82} They are blocked specifically by the snail venom toxin ω -conotoxin GVIA (ω -CTx GVIA),⁸³ and are involved in neurotransmitter and hormone release. Hence, they are found in neurons and secretory cells. Indeed, Northern blot analyses and in situ hybridization assays using specific antibodies against the $Ca_v 2.2$ subunit revealed that N-type channels are widely expressed in the brain, as well as the spinal cord.^{44,46,84-87} N-type channels are highly expressed within the cerebral cortex (layers 2 and 4), cerebellum, olfactory bulb, hippocampus (pyramidal cell layers CA1, CA2 and CA3), dentate gyrus, in the subiculum and habenula, hypothalamus and thalamus.⁸⁸ Interestingly, several N-type channel splice variants have been identified, which differ in their tissue distribution and their biophysical properties. One of these isoforms containing a SFMG tetrapeptide sequence in IIIS3-S4 is primarily expressed in rat brain, while the other isoform, which lacks the SFMG sequence but contains an ET dipeptide sequence in IVS3-S4, is highly expressed in peripheral neurons like dorsal root ganglia and superior cervical ganglia.^{89,90} Another splice variant within the II-III linker also revealed cell type specific expression. mRNAs containing the additional 63 bases were predominantly expressed in sympathetic ganglia and significant amount of both splice variants were detected in more caudal region of the CNS (spinal cord and brainstem).⁹¹ Other studies concerning the expression pattern of the II-III linker splice variants suggest high levels of expression of N-type channels in monaminergic neurons.⁹²

Dendritic Ca²⁺ channels have been suggested to be involved in the generation of Ca²⁺ dependent action potentials and in the integration and amplification of synaptic inputs within the dendritic arbor.⁹³ Ca₂2.2 channels are localized along the entire length of the dendrites. The distribution of the channels appears to be patchy rather than even suggesting clustering of these channels at specific sites.⁸⁷ It seems that L- and N-type channels reveal a complementary distribution. In Purkinje cells N-type channel levels are increased in the branch point of dendrites.^{84,87} In addition, N-type channels are localized in a subset of neuronal cell bodies, such as pyramidal neurons in the dorsal cortex and Purkinje cells in the cerebellum.

N-type channels have been suggested to play a prominent role in synaptic transmission and have been therefore detected in various presynaptic terminals, like the presynaptic active zones of the frog but not the mammalian neuromuscular junction,^{71,94-98} in cultured hippocampal neurons^{99,100} or in calyx type synapses.^{101,102} Punctate staining of N-type channels, suggesting nerve terminal localization, was observed along cell bodies and dendrites of many neurons in particular of cortical and hippocampal pyramidal neurons.⁸⁷ In mouse GABAergic cortical neurons, N-type channels seem to be exclusively localized in presynaptic nerve terminals.⁵³ Interestingly, these nerve terminals expressed either N-type channels alone or in combination with the P/Q-type channels.



Figure 3. Distribution and function of Ca^{2+} channel β_4 subunits in cultured hippocampal neurons.²³⁸ A) distribution of GFP-tagged Ca^{2+} channel β_4 subunits. Hippocampal neurons were infected with Semliki forest virus carrying GFP tagged β_4 subunits (left), stained with an anti-synaptobrevin II antibody (visualized with an Alexa546 coupled secondary antibody) (middle). Overlay in the indicated area demonstrates that GFP- β_4 is partly colocalized with the synaptic vesicle marker synaptobrevin II (Scale bar in left and middle 10 µm and right 2 µm). B) (left) Representative autaptic EPSC traces from hippocampal neurons (control) and neurons infected with synaptically targeted GFP- β_4 or somatodendritically targeted GFP- β_4 (Δ 50-407), respectively. 30 EPSCs were elicited at 20 Hz stimulation are significant different between noninfected neurons (control; white bar) or GFP- β_4 (Δ 50-407)- (striped bar) and GFP- β_4 - (grey bar) infected neurons (p<0.01, two tailed t test). EPSC ratios were calculated by dividing the amplitude of the 1st EPSC by the 4th EPSC within each set of experiments.

N-type channels have also been identified in growth cones indicating a role of N-type channels in neurite outgrowth and migration of immature neurons.¹⁰³⁻¹⁰⁶ Activity and developmental dependent alterations in the expression of T-, L- and N-type channels have been described, which may be correlated with the occurrence of certain Ca²⁺ channel types in the neurites of the developing neuron.^{105,107,108} Interestingly, N-type channels (Ca_v2.2 α_1 and β_3 subunits) were diffusely distributed within immature hippocampal neurons in soma, neurites and growth cones and became clustered and colocalized with synaptotagmin after neuron-neuron contact formation.¹⁰⁶

Cav2.3 R-Type Channels

 Ca^{2*} currents resistant to the common L- and N/P/Q-type blockers were detected in cerebellar granule cells^{64,109,110} and designated R-type currents. Since the Ca_v2.3 α_1 subunit when coexpressed with the auxiliary subunits β and α_2 - δ resembles some of the properties of these currents, it has been suggested that Ca_v2.3 α_1 subunits encode for R-type currents.^{63,64,110} Indeed, the majority of R-type currents were absent in central amygdala neurons in Ca_v2.3 knock out mice.¹¹¹ However, a significant R-type current component was still observed in cerebellar granule neurons,¹¹² suggesting that R-type currents may be encoded by additional α_1 subunits. Several different Ca_v2.3 isoforms have been described in brain, pancreas and kidney.¹¹³ R-type channels are described to be involved in neurotransmitter release and secretion^{102,114,115} and might be a major source of Ca²⁺ influx at dendritic spines in response to presynaptic action potentials.¹¹⁶⁻¹¹⁹

Cav2.3 protein is distributed all over the brain including both projection neurons and interneurons. The highest staining was observed in the deep ventral structures (caudate putamen, globus pallidus, thalamus, hypothalamus and amygdala.^{46,113,120-126} Ca,2.3 channels in Purkinje cells are expressed in cell bodies and dendritic trees, and to a lower extent in axons. Lower expression was also observed in the molecular layer.¹¹³ Using a Ca₂2.3 driven lacZ reporter, Cav2.3 expressing cells were visualized in particular in regions involved in the control of pain transmission (e.g., dorsal root ganglia and dorsal horn of the spinal cord).¹²⁷ The highest expression was observed in the cell soma but staining was detected also in dendrites.^{80,127} In cortical neurons, Ca_v2.3 staining extends only into the proximal dendrites, while in the olfactory bulb extensive dendritic labeling is observed in the external plexiform layer. In the plexiform layer, dendrodendritic synapses between granule and mitral cells are formed. The globus pallidus and thalamus neurons revealed dendritic and somatic R-type channel staining. In addition, the surrounding neuropil is also stained suggesting the participation of Ca_v2.3 at the presynaptic terminal. In fact at Calyx type neurons, R-type channels were described to be involved in synaptic transmission and immunostaining revealed the existence of these channel types at the presynaptic terminal.^{102,114} Punctate distribution in the neuropil and along dendritic branches was also observed for neurons in the amygdala.

Ca_v2 in Testis and Sperm

All Ca_v2 transcripts were detected in testis with RT-PCR with high expression of Ca_v2.3 in spermatogenic cells.¹²⁸ Ca_v2.1 and Ca_v2.3 α 1 subunits are clustered in mouse sperm.³⁴ While Ca_v2.1 α 1 subunits are found in the flagellum and apical tip and equatorial segment of the sperm head, Ca_v2.3 α 1 subunits are clustered in the acrosomal segment and the principal piece of the flagellum. The role of these Ca²⁺ channels in sperm is still unclear. However, due to their clustered localization in the acrosome and flagellum, these Ca²⁺ channels are probably involved in the flagellar beat, acrosome reaction and gamete fusion. Indeed, involvement of N- and R-type channels have been reported in the depolarization-evoked Ca²⁺ entry into mouse sperm.¹²⁹

Ca_v2 in Pancreas

Besides L-type channels, N- and P/Q-type channels have also been identified in pancreatic β cells.¹³⁰⁻¹³⁴ In fact, P/Q-type channel variants were identified, which mediated the DHP and ω -CTx resistant component of insulin secretion suggesting a corelease mechanism between L-, N- and P/Q-type channels.¹³¹ In addition, Ca₄2.3 protein is also expressed in endocrine cells of the pancreas and in the gut suggesting also a role of R-type currents in hormone secretion.¹¹³

Distribution of T-Type Channels

Three α_1 subunits encoding T-type channels have been identified so far, designated Ca_v3.1 through Ca_v3.3. Extensive in situ hybridization studies and northern blot analysis have been performed to describe the localization of mRNA transcripts in several tissues including brain, heart and kidney.^{135,136}

All three subunits are expressed abundantly in brain.¹³⁶⁻¹⁴⁰ High concentrations of all three subtypes are found in the olfactory bulb, granule cells and hippocampal pyramidal cells. Ca, 3.1 is the most abundant T-type channel subunit in the brain. It is highly expressed in the claustrum and bed nucleus of the stria terminalis of the basal forebrain, in the amygdala, layers IV and VI of the cerebral and piriform cortex, in hypothalamus, spinal cord, principal relay nuclei, intralaminar nuclei and lateral habenula of the thalamus, in the tegmental nuclei of the midbrain, in Purkinje cells of the cerebellum and in the inferior olive. Ca₂3.2 α_1 subunits are highly expressed in the island of Calleja in the olfactory system, pineal gland, pituitary and sensory ganglia. The brain specific Ca₂3.3 α_1 subunits are highly expressed in the olfactory bulb and the islands of Calleja in the olfactory system, the subthalamic nucleus in the basal forebrain and the reticular and lateral habenula of the thalamus.¹⁴⁰ However, using RT-PCR to detect Ca. 3.3 mRNA it was found that Ca. 3.3 transcipts are ubiquitously expressed in juvenile rat brain, but are selectively expressed in striatum in the adult rat.¹³⁶ According to their function in neurons, e.g., Ca²⁺ dependent burst firing, neuronal oscillation, and lowering threshold for spike generation, T-type channels are expected to be localized within the somatodendritic membrane. Indeed, T-type currents were recorded in the soma of relay cells and from the dendrites of thalamic reticular, hippocampal CA1 and Purkinje cells. To date, T-type channels have not been detected in presynaptic terminals and thus may not play a role in synaptic transmission.¹⁴¹

In heart T-type currents are involved in pacemaker activity during the heart action potential¹³⁵ and are therefore found in the sinoatrial node. Here, Ca_v3.1 is the most prominently expressed LVA channel, while Ca_v3.2 is only moderately expressed.²⁹ T-type currents have been identified in several cell types from heart, such as atrial myocytes, sino-atrial nodal cells, latent atrial pacemaker cells and Purkinje cells. In adult heart Ca_v3.1 and Ca_v3.2 are the predominant T-type channel subunits, while only Ca_v3.1 transcripts and protein were identified in fetal mouse ventricular myocytes. Ca_v3.1 protein and transcripts were detected in the ventrical as well as vasculature and trial walls, indicating that T-type Ca²⁺ currents are encoded by Ca_v3.1 and contribute to contraction in the developing myocardium.¹⁴²

T-type channels have also been suggested to play a role in the acrosome reaction in spermatozoa and are therefore important for fertilization. mRNA transcripts of Ca₄3.1 and Ca₄3.2 are expressed in human, rat and mouse testis, Sertoli cells and in particular germ cells.¹⁴³⁻¹⁴⁶ Several splice variant of Ca₄3.1 and two splice variants of Ca₄3.2 were also detected.¹⁴⁶

Distributions of the Ancillary Subunits β , α_2 - δ and γ

The Ca²⁺channel ancillary β , α_2 - δ and γ subunits assemble with the α_1 subunit to form functional Ca²⁺channel complexes.

β Subunits

Four β subunits and several splice variants have been identified in mammals. β subunits modify, in a subunit specific manner, the gating properties of Ca²⁺channels probably through their direct interaction with the pore forming α_1 subunit.¹⁴⁷ Thus assembly of α_1 and β subunits will characterize in particular the biophysical properties of the channel complex. β subunits assemble with all α_1 subunits of the L and P/Q/N/R-type family but not with T-type channels.

In skeletal muscle, β_{1a} is associated with Ca_v1.1 α_1 subunits as part of the DHP-sensitive L-type channel.¹⁴⁸ This β_{1a} subunit splice variant is tissue specific. Skeletal muscle from β_1 (-/-) mice lack EC-coupling and therefore die after birth.¹⁴⁹

The most dominant subunit in heart is the β_2 subunit, ^{38,45,150,151} which assembles with the Ca_v1.2 α_1 subunit to form functional L-type channels in the T-tubule system (Fig.1). In addition to β_2 subunits, β_4 subunits are temporally expressed in the developing heart.¹⁵² Exogenous expression of GFP-tagged β subunits in heart cells revealed that only β_{2a} -tagged subunits

localize at the surface sarcolemma, thus having the proper structural information to target to the physiological site of action.¹⁵³ In addition, only β_2 subunits were found to form L-type channels in heart muscle.¹⁵⁴ In smooth muscle, β_2 and β_3 subunits seem to be the major constituent of L-type channels. β_2 and β_3 are expressed in uterus and trachea, while only β_3 is expressed in aorta.¹⁵¹

In kidney hormone regulated Ca²⁺ channels are involved in controlling renal Ca²⁺ secretion, which probably involves P/Q-type channels. Several splice variants of β_2 , β_3 and β_4 were identified by PCR. Northern blot analysis revealed that β_4 is preferentially expressed in the kidney cortex, while all three β subunits are expressed in the nephron segments. Only β_4 was found in distal convoluted tubule and connecting tubule, where it colocalizes with the Ca_v2.1 α_1 subunit.¹⁵⁵ β_1 transcripts were detected in spleen,¹⁵⁶ and all four β subunits were found in testis (germ cells).³³ β subunits reveal a diffuse distribution in spermatogenic cells and appear clustered in sperm.

The expression of all four β subunits has been extensively investigated in the brain. Two β_1 splice variants, β_{1b} and β_{1c} , are expressed in brain. β_{1b} is highly expressed in the cerebral hemispheres and hippocampus.¹⁵⁷ Moderate to high mRNA and protein levels were found in olfactory bulb, cortex, hippocampus, caudate putamen, amygdala, habenula, nucleus intermeduncularis, superior colliculus, inferior colliculus and cerebellum. β_2 subunits reveal the weakest expression of all β subunits in brain. β_3 is highly expressed in olfactory bulb and habenula, which overlaps with a high expression of Ca_v2.3 α_1 subunits, suggesting that R-type channels in this brain region might be assembled with β_3 subunits. β_4 subunits show the highest expression in the cerebellum (granule cells and Purkinje neurons) overlapping with a high expression of Ca_v2.1 (P/Q-type) and Ca_v2.3 (R-type) α_1 subunits.^{45,154} According to the high expression of β_4 in cerebellum and the association with P/Q-type channels, β_4 seems to play a prominent role at the presynaptic terminal.^{154,158} Interestingly in the hippocampus, β_1 , β_2 , and β_3 subunits have similar patterns of distribution, while β_4 reveals a different expression pattern. β_1 and β_2 subunits are found in all regions of the hippocampus. β_4 is absent from CA1 in human brain but is present in rat. In human β_4 is highly expressed in the subiculum. The subcellular distribution of β subunits in hippocampal neurons revealed that in general all β subunits were found in the soma, dendrites and neuropil suggesting that β subunits are not excluded from certain subcellular compartments. β_4 subunits were intensively expressed in dendrites, while the remaining β subunits revealed a higher relative expression in the soma.^{159,160}

A particular role for the β_2 subunit has been suggested in the assembly of the retinal specific L-type channel.¹⁶¹ CNS β_2 (-/-) mice revealed an altered retinal morphology with an altered pattern of Ca_v1.4 protein expression in the thinner outer plexiform layer.

Subunit specific correlation of brain expression pattern between α_1 and β subunits suggest that P/Q-type channels coexpress with β_4 subunits, $Ca_v 1.2 \alpha_1$ subunit containing L-type channels coexpress with β_3 subunits and L-type channels containing $Ca_v 1.3 \alpha_1$ subunits coexpress with β_1 subunits.⁴⁴ All β subunits can assemble with $Ca_v 1$ and $Ca_v 2$ family members. The purification of the N-, P/Q and L-type channel complexes from rabbit, guinea and/or rat brain membranes indicates the association of all channel types with all four β subunits.^{154,158,162,163} In general, β_3 and β_4 subunits were found in a higher fraction than β_{1b} and β_{2a} subunits. However, fractional contribution of the β subunits for channel assembly was brain region dependent. In addition, the relative fraction of β subunits assembled with at least N-type channels is developmentally regulated. While N-type channels assemble with $\beta_1 > \beta_3 > \beta_4$ subunits at postnatal day 2, at day 14 N-type channels contain $\beta_3 > \beta_1 = \beta_4$.¹⁶³ In particular β_1 and β_4 subunit expression is unregulated during development, while β_2 and β_3 subunit expression remain constant from birth to the adult stage.¹⁶⁴ The developmental regulation of the assembly and expression of Ca^{2+} channel subunits is probably also responsible for the discrepancy in distribution observed for example between rat and human brain regions.

α_2 - δ Subunits

The α_2 - δ subunit transcript is posttranslationally cleaved into a disulfide-linked α_2 and δ portion.^{165,166} The highly glycosylated extracellular α_2 domain is less conserved than the δ domain, which contains the transmembrane anchor.¹⁶⁷⁻¹⁶⁹ The α_2 domain increases the membrane expression of functional channels and facilitates the assembly of α_1 at the cell surface. In contrast the δ protein is necessary for assembly with the α_1 subunit.^{167,170}

Four different α_2 - δ genes (α_2 - δ_1 -4) have been identified in mammals.^{171,172} α_2 - δ_1 is highly expressed in brain, heart, lung, spleen, kidney, liver, testis and skeletal muscle, while α_2 - δ_2 and α_2 - δ_3 are highly expressed in brain with lower levels of expression in kidney and testis.¹⁷³ Northern blots analysis of human tissue indicated a high expression of α_2 - δ_2 in lung and testis and lower expression in heart and brain.¹⁷⁴ Functional splice variants of α_2 - δ_2 have been described, which differ in the α_2 and δ protein in several amino acid positions and appear to be differentially expressed in cardiac tissue and human medullary thyroid carcinoma cells.^{175,176} Differences in the tissue distribution between humans and mice were observed for α_2 - δ_2 and α_2 - δ_3 . In humans, all α_2 - δ_1 in lung (note that highest expression in heart, pancreas and skeletal muscle and lower levels in kidney, liver, placenta and brain were reported by Klugbauer et al).¹⁷² Mouse α_2 - δ_3 was only detected in brain and α_2 - δ_2 was not expressed in lung.¹⁷⁷ The differences in α_2 - δ_3 was only detected in brain and α_2 - δ_2 was not expressed in lung.¹⁷⁷ The differences in α_2 - δ_3 was only detected in brain and α_2 - δ_2 was not expressed in lung.¹⁷⁷ The differences in α_2 - δ_3 used, age and/or species dependent expression of the various subunits.

 α_2 - δ_2 and α_2 - δ_3 revealed similar expression patterns in brain. α_2 - δ_2 mRNA had high levels in cerebellum, moderate levels in medulla, pons and striatum. α_2 - δ_2 is also expressed in cortex, hippocampus, habenula and nucleus reticularis thalami.¹⁷³ Within the cerebellum, α_2 - δ_2 revealed high levels in Purkinje cells and lower levels in granule cells. Correlated with the high expression of α_2 - δ_2 in Purkinje cells is the reduction of Ca²⁺ currents in these cells observed in the α_2 - δ_2 mouse mutant ducky, which suffers from ataxia, wide-based gait and paroxysmal dyskinesia.¹⁷³ α_2 - δ_1 has high levels of expression in the granule cell layers and α_2 - δ_3 in the molecular layer. Thus, the α_2 - δ subunits have distinct pattern of expression in cerebellum.^{173,176}

A complementary pattern of distribution was described for $\alpha_2 - \delta_1 / \alpha_2 - \delta_2$ and $\alpha_2 - \delta_3$ in DRG neurons. While high amounts of $\alpha_2 - \delta_1$ and $\alpha_2 - \delta_2$ mRNAs were found in small c-type sensory neurons, $\alpha_2 - \delta_3$ was highly expressed in large-diameter cells.¹² Since the $\alpha_2 - \delta$ proteins are highly glycosylated, glycosylation levels may play a role for tissue specific and functional expression of this subunit. Indeed, differences in the glycosylation levels between two forms of the $\alpha_2 - \delta_2$ subunit have been observed in DRG neurons.¹⁷⁸

y Subunits

 γ subunits are integral membrane proteins with four transmembrane regions and cytoplasmatically located N- and C-termini. 8 different γ (γ_{1-8}) subunits have been identified in mammals, which are divided into two different subgroups: subfamily one includes γ_1 and γ_6 and subfamily 2 consists of γ_{2-5} and γ_7 .¹⁷⁹⁻¹⁸³⁻¹⁸⁵

The γ_1 subunit is highly expressed in skeletal muscle. Since this subunit is part of the skeletal muscle DHP sensitive Ca²⁺ channel complex, the γ_1 subunit is localized in the triads. In addition, γ_1 subunit transcripts were detected in aorta using RT-PCR. The related γ_6 subunit is expressed in various tissues including cardiac and skeletal muscle, aorta, brain and lung. RT-PCR detected two isoforms of γ_6 (long and short, which differentially distribute among the tissues.¹⁸⁶

The other subfamily members were all detected in brain by RT-PCR.¹⁸⁶ Western blot analysis of mouse brain using γ -specific antibodies as well as northern blot and dot-blot hybridization revealed that $\gamma_{2.4}$ protein and $\gamma_{3.4}$ mRNA were exclusively detected in brain^{183,187} (note: RT-PCR products for γ_2 and γ_4 were also detected outside of the brain in testis (γ_2) and cardiac muscle, aorta and lung (γ_4)).¹⁸⁶ High mRNA levels for γ_2 were found in cerebellum, moderate levels in hippocampus, cerebral cortex and olfactory bulb. γ_3 mRNA was detected in hippocampus, cortex, olfactory bulb and caudate putamen. γ_4 was highly expressed in caudate putamen, olfactory bulb, habenula and at lower levels in the thalamus and cerebellum.¹⁸³ High levels of γ_2 protein were found in cerebellum and cortex, moderate levels are detected in midbrain, thalamus, hippocampus and striatum and low levels in pons and brain stem. γ_2 subunit was enriched in mouse synaptic plasma membranes indicating its role in synaptic function.¹⁸¹ Electron microscopy of hippocampal mossy fiber synapses detected γ_2 -immunoreactivity in dendrites.¹⁸⁷ γ_2 subunits interact here at least with AMPA receptors and PSD95. The interaction has been shown to be required for transport of AMPA receptors to the synapses.^{1,2} Thus, γ_2 subunits are localized at the postsynaptic side rather than the presynaptic terminal.

 γ_3 revealed high levels of expression in cortex, moderate in midbrain and striatum and low levels in thalamus and hippocampus. γ_4 was high in cortex and midbrain, hippocampus and striatum and low in thalamus, pons, brainstem and cerebellum.¹⁸⁷

 γ_5 has high mRNA levels in liver, moderate levels in kidney, heart and lung and low levels in testis¹⁸³, while RT-PCR products for γ_5 were only found in brain.¹⁸⁶

 γ_7 RT-PCR products were detected in cardiac muscle (atria and ventricle), brain, skeletal muscle, lung and testis,¹⁸⁶ and northern blots only detected two γ_7 subunit isoforms in brain. Here, a high concentration of γ_7 was found in the amygdala, hippocampus, thalamus, cerebellum and specifically in cerebral cortex.¹⁸⁸ γ 8 was detected in brain and testis.¹⁸⁶

Mechanisms of Ca²⁺ Channel Targeting: Transport from the ER to the Plasma Membrane and Specified Subcellular Structures

Transmembrane proteins like Ca^{2+} channels are synthesized at endoplasmic reticulum (ER) ribosomes and transported through the ER and Golgi. Eventually, they are packed into transport vesicles and moved to the plasma membrane. Depending on the cell type and the specific function of the Ca^{2+} channel complex within the cell, a decision has to be made to which subcellular structure the channel complex will be transported. In neurons for example, P/Q-and N-type channels may be transported to the synaptic terminals, while L-type channels may remain at the soma. In epithelial cells, certain ancillary subunits might be excluded from the apical or basolateral membrane, when assembled with a specific α_1 subunit. In any case, once the channel arrives at the plasma membrane, the protein complex has to be anchored at the subcellular structure through interaction with intracellular proteins or assembly within a certain signaling complex. The combination of electrophysiological measurements to detect ion channel currents with imaging of fluorescently tagged ion channel subunits creates the possibility to monitor the life time targeting events of a channel complex and its subsequent physiological effects.

Ca²⁺ Channel Complex Formation in Heterologous Expression Systems

 Ca^{2+} channel complex formation was in particular studied in heterologous expression systems. Expression systems like *Xenopus* oocytes, HEK293 or COS-7 cells contain low levels of endogenous Ca^{2+} channels and are therefore suitable to exogenously express various Ca^{2+} channel subunit combinations and analyze their distribution and function. Early studies of recombinant Ca^{2+} channel complexes expressed in these expression systems already revealed that the whole cell current amplitude as well as the number of drug binding sites measured was drastically increased, when pore forming Ca^{2+} channel α_1 subunits were coexpressed with ancillary Ca^{2+} channel β and/or α_2 - δ subunits. These early results suggested, that α_1 , β and/or α_2 - δ subunits are critical for efficient transport of the Ca^{2+} channel complex.

The transport and localization of L-type and P/Q-type channels in heterologous expression systems revealed an important role of the Ca²⁺ channel β subunits for transporting the α_1 subunit to the plasma membrane. When expressed alone in HEK293 cells, Ca_v1.2 α_1 subunits revealed a predominantly intracellular and perinuclear staining.¹⁸⁹ 80% of α_1 subunits expressed alone in these cells were localized in the ER, while 15 % were transported to the plasma membrane.¹⁹⁰ A similar expression pattern was observed when P/Q-type channel Ca_v2.1 α_1 subunits were expressed alone in COS-7 cells. Coexpression of β subunits in both cell types

caused dramatic increase in plasma membrane staining and punctate channel clustering of Ca_v1.2 containing L-type and Ca_v2.1 containing P/Q-type channels.¹⁸⁹⁻¹⁹¹ Interestingly, β_{1a} and β_3 subunit were only detected in the ER in the presence of α_1 subunits.¹⁹⁰ The time course of β subunit action on functional Ca²⁺ channel expression was also analyzed. In pulse chase studies, the half life of the channel complex was estimated to be 3 h. β subunit mediated Ca²⁺ channel expression measured as whole cell currents increased up to 50 h and then slowly declined. In Ca_v1.2 expressing *Xenopus* oocytes, whole cell currents could be measured 1-4 hours after injection of purified his-tagged β_3 subunits. The increase in whole cell current was mediated by an increase in the amount of α_1 subunits at the plasma membrane involving the intracellular glycoprotein transport.¹⁹² β subunits might also be involved in the maturation of the α_1 subunit containing channel complexes. This was suggested by the finding that coexpression of β_{2a} subunits with α_1 subunits increased DHP binding of the L-type channels.¹⁸⁹

In contrast to α_1 , β_3 and β_4 subunits, β_1 and β_{2a} subunits alone are able to localize to the plasma membrane, which probably involves different mechanisms. The β_{2a} subunit is the only β subunit which is palmitoylated. Palmitoylation occurs at Cys 3 and 4 within the β_2 N-terminus. Exchange of both Cys against Ser results in loss of palmitoylation. All non palmitoylated β subunits (i.e., β_{1b} , β_3 and β_2 -palmitoylation deficient splice variants and mutants) showed a diffuse intracellular staining pattern in comparison to the plasma membrane staining of palmitoylated β_{2a} . The non palmitoylated β subunits still fractionated with the membrane but not with the cytosolic fraction, indicating that β subunits are associated with intracellular membranes. Mutated β_{2a} subunits decreased the whole cell currents when coexpressed with $Ca_v 1.2 \alpha_1$ subunit. Surprisingly, the size of the charge movement was not altered, suggesting that the same amount of Ca, 1.2 α_1 subunits are located at the plasma membrane. Interestingly, exchange of the N-terminus of β_{1b} and β_3 against the β_{2a} palmitoylated N-terminus did not result in plasma membrane localization of the particular β subunit, indicating that other parts of β_{2a} are involved in plasma membrane localization.^{193,194} While no membrane staining of β_{1b} subunits was observed in HEK293 (tsA201) cells, expression of this subunits in COS-7 cells revealed plasma membrane targeting of β_{1b} . Chimeras between the membrane localized β_{1b} subunit and the diffused distributed β_3 subunit identified an 11 amino acid long acidic motif (WEEEEDYEEE) within the C-terminal region of β_{1b} responsible for membrane targeting. This sequence motif might be important for cell type specific localization and clustering of β_{1b} assembled channels.¹⁹¹

The targeting of α_1 subunits to the plasma membrane is mediated by all four β subunits and involves the direct interaction between these two proteins. The interaction between α_1 and β subunits occurs at subunit specific protein domains. Point mutations in the β subunit, which disrupt the α_1/β subunit interaction, results in perinuclear staining of α_1 subunits. In addition, mutations within the SH3-motif of β , which also interfere with binding of α_1 to β , disrupt plasma membrane targeting of α_1 . Interestingly, the conserved core region of the β subunit excluding N- and C-terminus still localizes α_1 in punctate channel clusters at the plasma membrane.¹⁹⁵ Point mutations within the intracellular I-II linker of the Ca_v1.2 α_1 subunit, which disrupt the α_1/β interaction,^{196,197} interfere with membrane localization of α_1 , leaving 90% of the subunit within the ER.¹⁹⁰

The importance of the α_1 subunit C-terminus for channel targeting was identified by using deletion mutants of the $Ca_v 1.2$ L-type channel.¹⁹⁸ The C-terminus of the $Ca_v 1.2 \alpha_1$ subunit contains 664 amino acids (i.e., it starts at amino acid position 1507 and ends at 2171). Truncation of the C-terminus reduced membrane staining as detected with immunocytochemical methods. Two mutations were of particular interest, since they completely abolished membrane staining and functional expression of the channel (i.e., $Ca_v 1.2$ - $\Delta 1623$ -1673). This region overlaps with the calmodulin binding site suggesting a role for calmodulin in channel targeting. However, mutations, which reduce or abolish calmodulin binding, do not abolish L-type channel expression.¹⁹⁹⁻²⁰² Interestingly, at the more C-terminal end of the Ca_v1.2 α_1 subunits, sites were identified which increased the intracellular accumulation

of the protein. These channels seemed to be functional, since no differences in the PN200 binding were detected. The protein domain might be involved in the regulation of the constitutive recycling of the channel complex between the plasma membrane and the intracellular compartments.

Several studies also suggested a role of α_2 - δ in membrane targeting of the Ca²⁺ channel in heterologous expression systems. However, the precise function of these subunits on channel targeting are not as clear and as characterized as for the β subunits. Coexpression of α_2 - δ with different α_1 and or α_1/β combinations in *Xenopus* oocytes, HEK 293 and COS-7 cells increased N-, P/Q-, L-type current and even T-type currents.^{66,167,172-174,176,203-205} The increase in current could be correlated with an increase in gating current²⁰⁵⁻²⁰⁷ or PN2001 binding (L-type channel specific).²⁰⁸ While the extracellular part of α_2 - δ in its glycosylated form interacted with the extracellular region of the L-type α_1 subunits (Ca_v1.2 and Ca_v1.1), it was necessary but not sufficient for increase in current density and drug binding affinity (PN2001). It has to be mentioned, that other studies could not detect increase in current levels and drug binding for coexpression of α_1 and α_2 - δ subunits.^{121,209}

Visualization of α_2 - δ targeting events using fluorescent antibodies or tags also yielded controversial results. α_2 - δ subunits expressed alone showed plasma membrane staining in HEK-tsA201 cells¹⁹⁵ but not in COS-7 cells.²¹⁰ No increase in membrane fluorescence was observed for coexpression of α_2 - δ with Ca_v1.2 or Ca_v2.1 in some studies, while other investigators reported that coexpression of α_2 - δ and Ca_v1.2 increased membrane fluorescence of Ca_v1.2 α_1 subunits and L-type currents. Increase in fluorescence intensity was maximal, when all three subunits α_1 , β and α_2 - δ were coexpressed.²¹¹ The results suggest, that the environment within the cell may play an important role for the targeting process. The α_2 part is highly glycosylated and interacts with the extracellular domains of α_1 subunit. Thus, glycosylation may play an important role in Ca²⁺ channel targeting.²¹² Since purified Ca²⁺ channel complexes are assembled of at least α_1 , β and α_2 - δ subunits, it seems likely that α_2 - δ and β subunits may cooperatively affect channel assembly and targeting to the plasma membrane.

Up and Down Regulation of Ca²⁺ Channel Expression: β Subunits, γ Subunits, AKAP and kir/Gem

By using the I-II linker of the Ca_v2.1 α_1 subunit (the interaction site with the β subunit) and analyzing its way through the cell membrane system a mechanisms was suggested as to how Ca²⁺ channel complex targeting to the plasma membrane may occur.²¹³ Fusion of this intracellular loop to an unrelated ion channel, the *Shaker* potassium channel, drastically decreased whole cell potassium currents of *Shaker* when expressed in *Xenopus* oocytes. This current was rescued by coexpression of the Ca²⁺ channel β subunit, suggesting that β subunits antagonized the suppressor effect of the I-II linker on *Shaker* channel expression. In addition, fusion of the transmembrane protein CD8 with I-II linker revealed restricted distribution of the fusion construct to the ER. Coexpression of β_3 subunits targeted the CD8-I-II linker to the plasma membrane. Pulse chase experiments indicated that the association between β and the I-II linker occurs very early during the biosynthetic pathway of the Ca²⁺ channel complex mostlikely at the ER level. ER retention and ER retention signal shielding seem to be a common mechanisms for ion channel complex assembly and membrane targeting as described for several other ion channels like K_{ATP} channels and NMDA receptors.²¹⁴

Recently, it has been shown that Ca^{2+} channel β subunits also interact with the small G protein kir (kir/Gem), a member of the Ras-related small G-protein family.²¹⁵ Kir/Gem exists as an active GTP and inactive GDP bound form and binds Ca^{2+}/CaM . It has been suggested, that Ca^{2+}/CaM bind to the GDP form where it localizes kir/Gem close to β subunits within the cell. Once activated, GTP bound kir/Gem binds to the β subunit and prevents trafficking of the α_1 subunit through the ER to the plasma membrane. Indeed, coexpression of $Ca_v 1.2$ or $Ca_v 1.3$ plus β subunits and kir/gem in *Xenopus* oocytes or BHK cells suppresses Ca^{2+} currents. In addition, exogenous expression of kir/gem in secretory PC12 and MIN6 cells decreased

endogenous L-type currents and hormone secretion. Since kir/Gem is expressed in secretory cells like the pituitary, adrenal cells and pancreatic islets the small G protein might be involved in the regulation of L-type channel surface expression necessary for secretion of hormones.

In addition to kir/Gem, the stargazin-like γ subunits ($\gamma_{1,2 \text{ and }7}$) also reduced N-type, P/Q and L-type channel expression in *Xenopus* oocytes and COS cells. ^{188,216} Interestingly, γ_7 almost completely abolished N-type current expression in COS-7 cells (coexpression of Ca_v2.2/ β_{1b} / γ_7) via lowering α_1 but not β protein levels. However, exogenous expression of γ_7 did not affect endogenous N-type channel currents in sympathetic neurons. This suggests, that γ_7 does not directly act on the channel but rather alters the degradation, folding, synthesis or targeting of the Ca²⁺ channel complex.

One of the mechanisms for L-type channel upregulation involves the A-kinase anchoring proteins. L-type channels are phosphorylated by PKA, which increases the channel activity in brain, skeletal and heart muscle.²¹⁷⁻²¹⁹ The postsynaptic scaffolding protein AKAP79 increases L-type but not non L-type currents in heterologous expression systems. These effects are independent of PKA and involve a functional, but not physical interaction of AKAP79 with the intracellular linker domain (loop II-III) of the Ca_v1.2 subunit. Within the C-terminal half of the loop II-III a poly proline sequence is conserved among the L-type channel Ca_v1.1, 1.2 and 1.3 α_1 subunits and has been suggested to act as a suppressor retention of surface expression of L-type channels.²²⁰

Targeting of Ca²⁺ Channels in Skeletal and Cardiac Muscle

L-type channels in striated muscle mediate EC-coupling via activating of RyR. These L-type channels consists of Ca₄1.1 α_1 subunits and β_{1a} subunits in skeletal muscle and Ca₄1.2 α_1 and β_{2a} subunits in heart and are located in the plasma membrane invaginations, i.e., the surface membrane of the T-tubuli.²² Cell lines derived from the dysgenic muscle (GLT cells) do not contain functional Ca_v1.1 α_1 subunits and lack EC-coupling. Therefore, these cell lines were extensively used to study the targeting and function of Ca_v1.1 α_1 subunits. Exogenous expression of GFP tagged Ca₂1.1 and Ca₂1.2 or untagged Ca₂1.1 α_1 subunits revealed that the pore forming Ca^{2+} channel α_1 subunits cluster in GLT cells, suggesting incorporation of the subunit into the T-tubule SR junction. Electrically evoked contraction was restored only in cells, which overexpressed L-type α_1 subunits but not P/Q or N-type α_1 subunits.²²¹ In contrast to heterologous expression systems, the Ca_v1.1 α_1 subunit was responsible for targeting the β subunits to its precise localization. GFP tagged β_{1a} subunits redistributed to the T-tubule/SR junction only in the presence of Ca_v1.1 α_1 subunits.²²² The targeting involves also the direct interaction between α_1 and β subunits, since mutations within the α_1 subunit, which disrupted the α_1/β interaction, abolished the redistribution of β_{1a} .²²³ The role of β subunits for the localization of the muscle specific Ca_v1.1 α_1 subunit was also investigated in heterologous expression systems.¹⁹⁷ Coexpression of Ca_v1.1 and GFP-tagged β_{1a} subunits attracted the β_{1a} subunit to the intracellular cytoplasmic membrane system. The targeting was again dependent on the interaction between α_1 and β subunits as demonstrated with Ca_v1.1 α_1 subunits deficient in Ca²⁺ channel β binding. In contrast to β_{1a} subunits, β_{2a} subunits, which physiologically do not interact with Ca_v1.1, targeted Ca_v1.1 α_1 subunits to the plasma membrane but could not modulate Ca, 1.1 channel function.

Targeting and precise localization of L-type channels into the triads involves the C-terminus of Cav1.1 α_1 subunits. C-terminal deletion mutants of Cav1.1 α_1 subunits identified a 27 amino acid long sequence which contains a consensus PDZ binding motif. Point mutations within these motif disrupted the interaction with muscle specific proteins as shown in a yeast two hybrid assay and reduced the EC-coupling in dysgenic myotubes after nuclear injection of the mutated constructs.²²⁴ The reduction in EC-coupling was due to non localization or targeting of the mutated subunit, since these subunits were localized close to the injected nucleus and did not distribute like the full length Cav1.1 α_1 subunit along the length of the myotube. Chimeras between the targeted Cav1.1 α_1 subunit and the nontargeted Cav2.1 α_1 subunit, which is retained in the ER/SR system, revealed that transfer of the C-terminus but not exchange of the other intracellular protein loops transferred triad targeting from L-type channels to P/Q-type channels. Triad targeting of P/Q-type channels also restored the EC coupling in the dysgenic myotubes.²²⁵

Since dysgenic myotubes still contain functional β_{1a} subunits, the role of β subunits for skeletal muscle distribution and function was studied in β_1 subunit knockout mice, which die at birth from asphyxia.¹⁴⁹ $\beta_1(-/-)$ mice reveal a drastic decrease in L-type current, charge movement and lack EC-coupling. The effects are mostlikely due to a drastic reduction in Ca_v1.1 α_1 subunits. The loss of punctate distribution of L-type Ca²⁺ channels suggests, that β subunits are important for function and localization of α_1 in the triads.^{149,226} Coexpression of either β_{1a} or β_{2a} subunits in these $\beta_1(-/-)$ muscles restored L-type currents. However, β_{1a} transfected cells revealed higher density of charge movement and a larger amplitude of Ca²⁺ transients, suggesting that EC coupling is more efficient for β_{1a} assembled channels. Transfer of the C-terminus of β_{1a} to β_{2a} subunits reversed the effects.²²⁷ Due to the C-terminus of β_{1a} , Ca_v1.1 α_1/β_{1a} channels may thus couple more effectively to RyR or are more sufficiently transported and localized at the triads than Ca_v1.1 α_1/β_{2a} assembled channels.

Sorting of Ca²⁺ Channels in Polarized Cells: A Correlation between Polarized Sorting in Epithelial Cells and Neurons

N-, P/Q- R-, L- and T-type channels are differently distributed within neurons. While N-, P/Q- and R-type channels are found in presynaptic terminals, L- and T-type channels are localized primarily on cell bodies and proximal dendrites. In addition, β and α_2 - δ subunits have been observed in neuronal cell bodies, dendrites and neuropil. Thus, mechanisms have to exist to account for the different sorting of various channel complex combinations in neurons. The Madin-Darby canine kidney (MDCK) epithelial cell line has been widely used to study the polarized transport of neuronal proteins. This appears to be due to a correlation between apical versus basolateral transport in epithelial cells and somatodendritic versus axonal sorting within neurons.^{228,229} Thus, it was interesting to analyze whether L-type channels distribute differently from N- and P/Q-type channels as would be predicted from their neuronal distribution. In MDCK cells, coexpression of Ca²⁺ channel subunits α_1 , β and α_2 - δ was necessary to study the channel complex targeting.²³⁰ Interestingly, L-type channels targeted to the basolateral side (comparable to somatodendritic targeting) and N-type channels to the apical side (comparable to the presynaptic targeting). However, P/Q-type channels distributed to the apical side when assembled with β_1 and β_4 subunits, while β_2 assembled channels were transported to the basolateral side. β_3 subunit assembled channels were distributed equally to both poles of the cell.²³⁰ The results indicate that the channel type as well as the subunit combination determines channel targeting within polarized cells, pointing to a complex pattern of protein interactions necessary to decide if a channel is transported to dendrites, the soma or axons within neuronal cells.

Neurons transport newly synthesized membrane proteins along axons by microtubule- mediated fast axonal transport.⁷⁰ Using GFP tagged proteins various vesicle types were identified, which are involved in the transport process. For example Nakata et al²³¹ identified punctate structures as tubulovesicular organelles with various incorporated GFP fusion proteins like GAP-43, SNAP-25, synaptophysin, trkA and TGN-3, which moved along the axon. Other studies in sympathetic nerve fibers revealed that synaptobrevin, a highly enriched presynaptic vesicle protein involved in transmitter release,²³² was present in large dense-core vesicles and in lighter vesicles, whereas SNAP-25, syntaxin and two types of Ca²⁺ channels (N- and L-type) were only found in lighter vesicles.²³³ In hippocampal neurons GFP-tagged synaptobrevin was found in so called cytoplasmic transport packets consisting of dense-core vesicles, pleiomorphic small vesicles and tubulovesicular structures. Colocalization revealed the existence of P/Q-type Ca²⁺ channels, synaptic vesicle proteins SV2 and synapsin I and a component of the endocytosis machinery normally localized at presynaptic terminals (amphiphysin I).²³⁴ In addition, N-type channels could be localized to membranes of secretory granules in neurosecretory cells.²³⁵⁻²³⁷
Colocalization of the GFP- β_4 construct with endogenous synaptobrevin II and the presynaptic P/Q-type Ca²⁺-channel Ca_v2.1 α_1 subunit in hippocampal neurons suggests that GFP- β_4 is also targeted and clustered at presynaptic terminals. Costaining between the dendritic marker MAP2 and GFP- β_4 revealed that β_4 is found in the axon as well as in the dendrites. The localization and targeting involves the nonconserved N- and C-terminus of β_4 subunits. Deletion of β_4 N- and C-termini localized β_4 to the soma with drastically reduced punctate clustering.²³⁸ So far several synaptic targeting signals have been described.²³⁹⁻²⁴¹ Synaptobrevin contains a 92 amino acid long N-terminal region,²⁴² mGluR7 a 60 amino acid domain,²⁴³ the neuronal glycine transporter contains a di-leucine motif²⁴⁴ and the transferrin receptor a tyrosine based motif,²⁴² but so far no truly conserved motif has been described. However, a di-leucine motif is conserved in all β subunits, while a tyrosine based motif (EEDY) is found in β_1 , β_3 and β_4 but not β_2 .

Mutations in the ancillary subunits cause severe malfunctions. A mutation in β_4 , which results in a loss of β_4 subunit in the mouse, leads to an epileptic phenotype (lethargic; lh/lh).²⁴⁵ Excitatory synaptic transmission in lethargic mouse is reduced, suggesting a presynaptic function for β_4 subunits in transmitter release.²⁴⁶ Indeed, overexpression of GFP-tagged β_4 subunits in hippocampal cells but not the non targeted β_4 deletion mutant altered short term synaptic plasticity, i.e.,paired pulse facilitation.²³⁸ Paired pulse facilitation involves an increase in the presynaptic Ca²⁺ levels at low release probability synapses.^{247,248} Thus, changes in paired pulse facilitation reflects a presynaptic function of β_4 subunits. The change in paired pulse facilitation might be explained by a change in the biophysical properties of the presynaptic Ca²⁺ channel (i.e.,inactivation from the open state), assuming that the overall population of presynaptic Ca²⁺ channels have assembled with β_4 rather than with β_1 or β_3 subunits.

Fast synaptic transmission at specific synapses in the CNS depends on the concerted action of the Ca²⁺ channel Ca_v2 family, including N-, P/Q- and R-type channels.²⁴⁹⁻²⁵⁴ It has been suggested, that different types of channels are required for kinetically distinct phases of release, depending on their precise location relative to the fusion machinery and the electrophysiological characteristics of the channel type involved.^{102,251,255} Distant Ca²⁺ channels located far from release sites may contribute little to the Ca²⁺ concentration necessary to trigger transmitter release but may increase the residual Ca2+ following an action potential influencing short term plasticity like paired pulse facilitation.²⁵⁶ For example, P/Q-type Ca²⁺ channels at granule to Purkinje cell synapses or calyx type terminals in the rat medial nucleus couple more efficiently to release sites than N-or R-type channels, as suggested by the steeper Ca^{2+} dependence of transmitter release.^{102,251} Therefore, the precise localization of Ca^{2+} channel complexes within the synaptic terminal will determine the synaptic output. Recently, it has been shown that Nand P/Q-type channels interact with modular adaptor proteins. The modular adaptor proteins Mint-1, CASK and Veli form a tripartite complex within the presynaptic terminal, which may underlie the precise localization of the presynaptic terminals. The interaction with the Ca²⁺ channel α_1 subunit involves the sequence motif (E/D-X-W-C/S-COOH), which is located at the C-terminal end of the long splice variants of Ca₂.1 and Ca₂.2 but not in the α_1 subunit C-termini of the R- or L-type channels. This sequence interacts with the PDZ domain of Mint-1 and the SH3 domain of CASK. The CASK interaction also involves a proline rich region in the middle of the α_1 subunit.²⁵⁷ The binding motif within the C-terminus of the N-type a1 subunit is also necessary for sufficient targeting and clustering of the N-type channels, when exogenously expressed with β_3 and α_2 - δ_1 subunits in hippocampal cells. Deletion of the C-terminus and/or disruption of the PDZ and SH3 binding motif within the C-terminus results in disruption of channel clustering.²⁵⁸

The understanding of Ca²⁺ channel assembly and targeting in particular in brain is at its infancy. The development of new fluorescent tags and dyes for life time imaging with combined new microscopic techniques and physiological recordings will shine more light into our brain and other mysterious organs like testis and pancreas.

References

- Kung C, Saimi WJ, Haynes KY et al. Recent advances in the molecular genetics of Paramecium. J Eukaryot Microbiol 2000l 47:11-14.
- 2. Hille B. (2001). Ion channels of excitable membranes, 3 Edition, I. Sinauer Associates, ed.
- 3. Fatt P, Katz B. The electrical properties of crustacean muscle fibres. J Physiol 1953; 120:171-204.
- Curtis BM, Catterall WA. Purification of the calcium antagonist receptor of the voltage-sensitive calcium channel from skeletal muscle transverse tubules. Biochemistry 1984; 23:2113-8.
- 5. Takahashi M, Seagar MJ, Jones JF et al. Subunit structure of dihydropyridine-sensitive calcium channels from skeletal muscle. Proc Natl Acad Sci USA 1987; 84:5478-82.
- 6. Haase H, Wallukat G, Flockerzi V et al. Detection of skeletal muscle calcium channel subunits in cultured neonatal rat cardiac myocytes. Receptors Channels 1994; 2:41-52.
- Mejia-Alvarez R, Tomaselli GF, Marban E. Simultaneous expression of cardiac and skeletal muscle isoforms of the L-type Ca²⁺ channel in a rat heart muscle cell line. J Physiol 1994; 478:315-29.
- Klugbauer N, Welling A, Specht V et al. L-type Ca(2+) channels of the embryonic mouse heart. Eur J Pharmacol 2002; 447::279-84.
- 9. Bech-Hansen NT, Naylor MJ, Maybaum TA et al. Loss-of-function mutations in a calcium-channel alpha1-subunit gene in Xp11.23 cause incomplete X-linked congenital stationary night blindness. Nat Genet 1998; 19:264-7.
- Strom TM, Nyakatura G, Apfelstedt-Sylla E et al. An L-type calcium-channel gene mutated in incomplete X-linked congenital stationary night blindness. Nat Genet 1998; 19:260-3.
- 11. Morgans CW. Localization of the alpha(1F) calcium channel subunit in the rat retina. Invest Ophthalmol Vis Sci 2001; 42:2414-8.
- 12. Yusaf SP, Goodman J, Pinnock RD et al. Expression of voltage-gated calcium channel subunits in rat dorsal root ganglion neurons. Neurosci Lett 2001; 311:137-41.
- 13. Biel M, Ruth P, Bosse E et al. Primary structure and functional expression of a high voltage activated calcium channel from rabbit lung. FEBS Lett 1990; 269:409-12.
- Mikami A, Imoto K, Tanabe T et al. Primary structure and functional expression of the cardiac dihydropyridine-sensitive calcium channel. Nature 1989; 340:230-3.
- 15. Snutch TP, Tomlinson WJ, Leonard JP Distinct calcium channels are generated by alternative splicing and are differentially expressed in the mammalian CNS. Neuron 1991; 7:45-57.
- 16. Williams ME, Feldman DH, McCue AF et al. Structure and functional expression of alpha 1, alpha 2, and beta subunits of a novel human neuronal calcium channel subtype. Neuron 1992; 8:71-84.
- Iwashima Y, Pugh W, Depaoli AM et al. Expression of calcium channel mRNAs in rat pancreatic islets and downregulation after glucose infusion. Diabetes 1993; 42:948-55.
- Green GE, Khan KM, Beisel DW et al. Calcium channel subunits in the mouse cochlea. J Neurochem 1996; 67:37-45.
- Koschak A, Reimer D, Huber IG, Grabner M et al. alpha 1D (Ca_v1.3) subunits can form l-type Ca²⁺ channels activating at negative voltages. J Biol Chem 2001; 276:22100-6.
- Xu W, Lipscombe D. Neuronal Ca(V)1.3alpha(1) L-type channels activate at relatively hyperpolarized membrane potentials and are incompletely inhibited by dihydropyridines. J Neurosci 2001; 21:5944-51.
- 21. Roden DM, Balser JR, George A et al. Cardiac ion channels. Annu Rev Physiol 2002; 431-75:Review.
- 22. Flucher BE, Franzini-Armstrong C. Formation of junctions involved in excitation-contraction coupling in skeletal and cardiac muscle. Proc Natl Acad Sci USA 1996; 93:8101-6.
- 23. Takimoto K, Li D, Nerbonne JM et al. Distribution, splicing and glucocorticoid-induced expression of cardiac alpha 1C and alpha 1D voltage-gated Ca²⁺ channel mRNAs. J Mol Cell Cardiol 1997; 29:3035-42.
- 24. Welling A, Ludwig A, Zimmer S et al. Alternatively spliced IS6 segments of the alpha 1C gene determine the tissue-specific dihydropyridine sensitivity of cardiac and vascular smooth muscle L-type Ca²⁺ channels. Circ Res 1997; 81:526-32.
- 25. Seino S, Chen L, Seino M et al. Cloning of the alpha 1 subunit of a voltage-dependent calcium channel expressed in pancreatic beta cells. Proc Natl Acad Sci USA 1992; 89:584-8.
- Ihara Y, Yamada Y, Fujii Y et al. Molecular diversity and functional characterization of voltage-dependent calcium channels (CACN4) expressed in pancreatic beta-cells. Mol Endocrinol 1995; 9:121-30.
- 27. Kollmar R, Fak J, Montgomery LG et al. Hair cell-specific splicing of mRNA for the alpha1D subunit of voltage-gated Ca²⁺ channels in the chicken's cochlea. Proc Natl Acad Sci USA 1997; 94:14889-93.

- Safa P, Boulter J, Hales TG. Functional properties of Cav1.3 (alpha1D) L-type Ca²⁺ channel splice variants expressed by rat brain and neuroendocrine GH3 cells. J Biol Chem 2001; 276:38727-37.
- 29. Bohn G, Moosmang S, Conrad H et al. Expression of T- and L-type calcium channel mRNA in murine sinoatrial node. FEBS Lett 2000; 481:73-6.
- Platzer J, Engel J, Schrott-Fischer A et al. Congenital deafness and sinoatrial node dysfunction in mice lacking class D L-type Ca²⁺ channels. Cell 2000; 102:89-97.
- 31. Zhang Z, Xu Y, Song H et al. Functional Roles of Ca(v)1.3 (alpha(1D)) calcium channel in sinoatrial nodes: insight gained using gene-targeted null mutant mice. Circ Res 2002; 90:981-7.
- 32. Benoff S. Voltage dependent calcium channels in mammalian spermatozoa. Front Biosci 1998; 3:D1220-40.
- 33. Serrano CJ, Trevino CL, Felix R et al. Voltage-dependent Ca(2+) channel subunit expression and immunolocalization in mouse spermatogenic cells and sperm. FEBS Lett. 1999; 462:171-6.
- 34. Westenbroek RE, Babcock DF. Discrete regional distributions suggest diverse functional roles of calcium channel alpha1 subunits in sperm. Dev Biol 1999; 207:457-69.
- 35. Holz GGt, Dunlap K, Kream RM. Characterization of the electrically evoked release of substance P from dorsal root ganglion neurons: methods and dihydropyridine sensitivity. J Neurosci 1988; 8:463-71.
- 36. Ashcroft FM, Rorsman P. Electrophysiology of the pancreatic beta-cell. Prog Biophys Mol Biol 1989; 54:87-143.
- 37. Yaney GC, Wheeler MB, Wei X et al. Cloning of a novel alpha 1-subunit of the voltage-dependent calcium channel from the beta-cell. Mol Endocrinol 1992; 6:2143-52.
- 38. Perez-Reyes E, Castellano A, Kim HS et al. Cloning and expression of a cardiac/brain beta subunit of the L-type calcium channel. J Biol Chem 1992; 267:1792-7.
- 39. Castellano A, Wei X, Birnbaumer L et al. Cloning and expression of a neuronal calcium channel beta subunit. J Biol Chem 1993; 268:12359-66.
- 40. Safayhi H, Haase H, Kramer U et al. L-type calcium channels in insulin-secreting cells: biochemical characterization and phosphorylation in RINm5F cells. Mol Endocrinol 1997; 11:619-29.
- Bokvist K, Eliasson L, Ammala C et al. Co-localization of L-type Ca²⁺ channels and insulin-containing secretory granules and its significance for the initiation of exocytosis in mouse pancreatic B-cells. EMBO J 1995; 14:50-7.
- Barg S, Ma X, Eliasson L et al. Fast exocytosis with few Ca(2+) channels in insulin-secreting mouse pancreatic B cells. Biophys J 2001; 81:3308-23.
- Chin H, Smith MA, Kim HL et al. Expression of dihydropyridine-sensitive brain calcium channels in the rat central nervous system. FEBS Lett 1992; 299:69-74.
- 44. Tanaka O, Sakagami H, Kondo H. Localization of mRNAs of voltage-dependent Ca(2+)-channels: four subtypes of alpha 1- and beta-subunits in developing and mature rat brain. Brain Res Mol Brain Res 1995; 30:1-16.
- 45. Ludwig A, Flockerzi V, Hofmann F. Regional expression and cellular localization of the alpha1 and beta subunit of high voltage-activated calcium channels in rat brain. J Neurosci 1997; 17:1339-49.
- 46. Volsen SG, Day NC, McCormack AL et al. The expression of neuronal voltage-dependent calcium channels in human cerebellum. Brain Res Mol Brain Res 1995; 34:271-82.
- 47. Dolmetsch RE, Pajvani U, Fife K et al. Signaling to the nucleus by an L-type calcium channel-calmodulin complex through the MAP kinase pathway. Science 2001; 294:333-9.
- 48. Shaywitz AJ, Greenberg ME. CREB: a stimulus-induced transcription factor activated by a diverse array of extracellular signals. Annu Rev Biochem 1999; 68:821-61.
- 49. Schmid A, Barhanin J, Mourre C et al. Antibodies reveal the cytolocalization and subunit structure of the 1,4-dihydropyridine component of the neuronal Ca²⁺ channel. Biochem Biophys Res Commun 1986; 139:996-1002.
- 50. Ahlijanian MK, Westenbroek RE, Catterall WA. Subunit structure and localization of dihydropyridine-sensitive calcium channels in mammalian brain, spinal cord, and retina. Neuron 1990; 4:819-32.
- Westenbroek RE, Ahlijanian MK, Catterall WA. Clustering of L-type Ca²⁺ channels at the base of major dendrites in hippocampal pyramidal neurons. Nature 1990; 347:281-4.
- 52. Hell JW, Westenbroek RE, Warner C et al. Identification and differential subcellular localization of the neuronal class C and class D L-type calcium channel alpha 1 subunits. J Cell Biol 1993; 123:949-62.
- 53. Timmermann DB, Westenbroek RE, Schousboe A et al. Distribution of high-voltage-activated calcium channels in cultured gamma-aminobutyric acidergic neurons from mouse cerebral cortex. J Neurosci Res 2002; 67:48-61.

- 54. Sugiura Y, Ko CP. Novel modulatory effect of L-type calcium channels at newly formed neuromuscular junctions. J Neurosci 1997; 17:1101-11.
- 55. Polo-Parada L, Bose CM, Landmesser LT. Alterations in transmission, vesicle dynamics, and transmitter release machinery at NCAM-deficient neuromuscular junctions. Neuron 2001; 32:815-28.
- Sun YA, Poo MM. Evoked release of acetylcholine from the growing embryonic neuron. Proc Natl Acad Sci USA 1987; 84:2540-4.
- 57. Zakharenko S, Chang S, O'Donoghue M et al. Neurotransmitter secretion along growing nerve processes: comparison with synaptic vesicle exocytosis. J Cell Biol 1999; 144:507-18.
- Brown AM, Westenbroek RE, Catterall WA et al. Axonal L-type Ca²⁺ channels and anoxic injury in rat CNS white matter. J Neurophysiol 2001; 85:900-11.
- 59. Fern R, Ransom BR, Waxman SG. Voltage-gated calcium channels in CNS white matter: role in anoxic injury. J Neurophysiol 1995; 74:369-77.
- 60. Imaizumi T, Kocsis JD, Waxman SG. The role of voltage-gated Ca²⁺ channels in anoxic injury of spinal cord white matter. Brain Res 1999; 817:84-92.
- 61. Llinas R, Sugimori M, Lin JW et al. Blocking and isolation of a calcium channel from neurons in mammals and cephalopods utilizing a toxin fraction (FTX) from funnel-web spider poison. Proc Natl Acad Sci USA 1989; 86:1689-93.
- 62. Mintz IM, Adams ME, Bean BP. P-type calcium channels in rat central and peripheral neurons. Neuron 1992; 9:85-95.
- 63. Zhang JF, Randall AD, Ellinor PT et al. Distinctive pharmacology and kinetics of cloned neuronal Ca²⁺ channels and their possible counterparts in mammalian CNS neurons. Neuropharmacology 1993; 32:1075-88.
- 64. Randall AD, Tsien RW. Pharmacological dissection of multiple types of Ca²⁺ channel currents in rat cerebellar granule neurons. J Neurosci 1995; 15:2995-3012.
- 65. Bourinet E, Soong TW, Sutton K et al. Splicing of alpha 1A subunit gene generates phenotypic variants of P- and Q-type calcium channels. Nat Neurosci 1999; 2:407-15.
- 66. Mori Y, Friedrich T, Kim MS et al. Primary structure and functional expression from complementary DNA of a brain calcium channel. Nature 1991; 350:398-402.
- 67. Starr TV, Prystay W, Snutch TP. Primary structure of a calcium channel that is highly expressed in the rat cerebellum. Proc Natl Acad Sci USA 1991; 88:5621-5.
- 68. Westenbroek RE, Sakurai T, Elliott EM et al. Immunochemical identification and subcellular distribution of the alpha 1A subunits of brain calcium channels. J Neurosci 1995; 15:6403-18.
- 69. Craig PJ, McAinsh AD, McCormack AL et al. Distribution of the voltage-dependent calcium channel alpha(1A) subunit throughout the mature rat brain and its relationship to neurotransmitter pathways. J Comp Neurol 1998; 397:251-67.
- 70. Sakurai T, Westenbroek RE, Rettig J et al. Biochemical properties and subcellular distribution of the BI and rbA isoforms of alpha1A subunits of brain calcium channels. J Cell Biol 1996; 134:511-28.
- Sano K, Enomoto K, Maeno T. Effects of synthetic omega-conotoxin, a new type Ca²⁺ antagonist, on frog and mouse neuromuscular transmission. Eur J Pharmacol 1987; 141:235-41.
- De Luca A, Rand MJ, Reid JJ et al. Differential sensitivities of avian and mammalian neuromuscular junctions to inhibition of cholinergic transmission by omega-conotoxin GVIA. Toxicon 1991; 29:311-20.
- 73. Uchitel OD, Protti DA, Sanchez V et al. P-type voltage-dependent calcium channel mediates presynaptic calcium influx and transmitter release in mammalian synapses. Proc Natl Acad Sci USA 1992; 89:3330-3.
- Protti DA, Uchitel OD. Transmitter release and presynaptic Ca²⁺ currents blocked by the spider toxin omega-Aga-IVA. Neuroreport 1993; 5:333-6.
- Bowersox SS, Miljanich GP, Sugiura Y et al. Differential blockade of voltage-sensitive calcium channels at the mouse neuromuscular junction by novel omega-conopeptides and omega-agatoxin-IVA. J Pharmacol Exp Ther 1995; 273:248-56.
- Hong SJ, Chang CC. Calcium channel subtypes for the sympathetic and parasympathetic nerves of guinea-pig atria. Br J Pharmacol 1995; 116:1577-82.
- 77. Ousley AH, Froehner SC. An anti-peptide antibody specific for the class A calcium channel alpha 1 subunit labels mammalian neuromuscular junction. Proc Natl Acad Sci USA 1994; 91:12263-7.
- Sugiura Y, Woppmann A, Miljanich GP et al. A novel omega-conopeptide for the presynaptic localization of calcium channels at the mammalian neuromuscular junction. J Neurocytol 1995; 24:15-27.
- 79. Day NC, Wood SJ, Ince PG et al. Differential localization of voltage-dependent calcium channel alpha1 subunits at the human and rat neuromuscular junction. J Neurosci 1997; 17:6226-35.

- Westenbroek RE, Hoskins L, Catterall WA. Localization of Ca²⁺ channel subtypes on rat spinal motor neurons, interneurons, and nerve terminals. J Neurosci 1998; 18:6319-30.
- Nowycky MC, Fox AP, Tsien RW. Three types of neuronal calcium channel with different calcium agonist sensitivity. Nature 1985; 316:440-3.
- 82. Fox AP, Nowycky MC, Tsien RW. Kinetic and pharmacological properties distinguishing three types of calcium currents in chick sensory neurones. J Physiol 1987; 394:149-72.
- Sher E, Pandiella A, Clementi F. Omega-conotoxin binding and effects on calcium channel function in human neuroblastoma and rat pheochromocytoma cell lines. FEBS Lett 1988; 235:178-82.
- 84. Fortier LP, Tremblay JP, Rafrafi J et al. A monoclonal antibody to conotoxin reveals the distribution of a subset of calcium channels in the rat cerebellar cortex. Brain Res Mol Brain Res 1991; 9:209-15.
- Dubel SJ, Starr TV, Hell JW et al. Molecular cloning of the alpha-1 subunit of an omega-conotoxin-sensitive calcium channel. Proc Natl Acad Sci USA 1992; 89:5058-62.
- Fujita Y, Mynlieff M, Dirksen RT et al. Primary structure and functional expression of the omega-conotoxin-sensitive N-type calcium channel from rabbit brain. Neuron 1993; 10:585-98.
- 87. Westenbroek RE, Hell JW, Warner C et al. Biochemical properties and subcellular distribution of an N-type calcium channel alpha 1 subunit. Neuron 1992; 9:1099-115.
- Coppola T, Waldmann R, Borsotto M et al. Molecular cloning of a murine N-type calcium channel alpha 1 subunit. Evidence for isoforms, brain distribution, and chromosomal localization. FEBS Lett 1994; 338:1-5.
- 89. Lin Z, Haus S, Edgerton J et al. Identification of functionally distinct isoforms of the N-type Ca²⁺ channel in rat sympathetic ganglia and brain. Neuron 1997; 18:153-66.
- Lin Z, Lin Y, Schorge S et al. Alternative splicing of a short cassette exon in alpha1B generates functionally distinct N-type calcium channels in central and peripheral neurons. J Neurosci 1999; 19:5322-31.
- 91. Pan JQ, Lipscombe D. Alternative splicing in the cytoplasmic II-III loop of the N-type Ca channel alpha 1B subunit: functional differences are beta subunit-specific. J Neurosci 2000; 20:4769-75.
- 92. Ghasemzadeh MB, Pierce RC, Kalivas PW. The monoamine neurons of the rat brain preferentially express a splice variant of alpha1B subunit of the N-type calcium channel. J Neurochem 1999; 73:1718-23.
- 93. Llinas R, Sugimori M. Calcium conductances in Purkinje cell dendrites: their role in development and integration. Prog Brain Res 1979; 51:323-34.
- 94. Kerr LM, Yoshikami D. A venom peptide with a novel presynaptic blocking action. Nature 1984; 308:282-4.
- Koyano K, Abe T, Nishiuchi Y et al. Effects of synthetic omega-conotoxin on synaptic transmission. Eur J Pharmacol 1987; 135:337-43.
- Robitaille R, Adler EM, Charlton MP. Strategic location of calcium channels at transmitter release sites of frog neuromuscular synapses. Neuron 1990; 5:773-9.
- Cohen MW, Jones OT, Angelides KJ. Distribution of Ca²⁺ channels on frog motor nerve terminals revealed by fluorescent omega-conotoxin. J Neurosci 1991; 11:1032-9.
- 98. Torri Tarelli F, Passafaro M, Clementi F et al. Presynaptic localization of omega-conotoxin-sensitive calcium channels at the frog neuromuscular junction. Brain Res 1991; 547:331-4.
- 99. Jones OT, Kunze DL, Angelides KJ. Localization and mobility of omega-conotoxin-sensitive Ca²⁺ channels in hippocampal CA1 neurons. Science 1989; 244:1189-93.
- 100. Reid CA, Bekkers JM, Clements JD. N- and P/Q-type Ca²⁺ channels mediate transmitter release with a similar cooperativity at rat hippocampal autapses. J Neurosci 1998; 18:2849-55.
- 101. Stanley EF, Atrakchi AH. Calcium currents recorded from a vertebrate presynaptic nerve terminal are resistant to the dihydropyridine nifedipine. Proc Natl Acad Sci USA 1990; 87:9683-7.
- 102. Wu LG, Westenbroek RE, Borst JGG et al. Calcium channel types with distinct presynaptic localization couple differentially to transmitter release in single calyx-type synapses. J Neurosci 1999; 19:726-36.
- 103. Usowicz MM, Porzig H, Becker C et al. Differential expression by nerve growth factor of two types of Ca²⁺ channels in rat phaeochromocytoma cell lines. J Physiol 1990; 426:95-116.
- 104. Reber BF, Reuter H. Dependence of cytosolic calcium in differentiating rat pheochromocytoma cells on calcium channels and intracellular stores. J Physiol 1991; 435:145-62.
- 105. Komuro H, Rakic P. Orchestration of neuronal migration by activity of ion channels, neurotransmitter receptors, and intracellular Ca²⁺ fluctuations. J Neurobiol 1998; 37:110-30.
- 106. Bahls FH, Lartius R, Trudeau LE et al. Contact-dependent regulation of N-type calcium channel subunits during synaptogenesis. J Neurobiol 1998; 35:198-208.
- 107. Fields RD. Effects of ion channel activity on development of dorsal root ganglion neurons. J Neurobiol 1998; 37:158-70.

- 108. Pravettoni E, Bacci A, Coco S et al. Different localizations and functions of L-type and N-type calcium channels during development of hippocampal neurons. Dev Biol 2000; 227:581-94.
- 109. Forti L, Tottene A, Moretti A et al. Three novel types of voltage-dependent calcium channels in rat cerebellar neurons. J Neurosci 1994; 14:5243-56.
- Randall AD, Tsien RW. Contrasting biophysical and pharmacological properties of T-type and R-type calcium channels. Neuropharmacology 1997; 36:879-93.
- 111. Lee SC, Choi S, Lee T et al. Molecular basis of R-type calcium channels in central amygdala neurons of the mouse. Proc Natl Acad Sci USA 2002; 99:3276-81.
- 112. Wilson SM, Toth PT, Oh SB et al. The status of voltage-dependent calcium channels in alpha 1E knock-out mice. J Neurosci 2000; 20:8566-71.
- 113. Grabsch H, Pereverzev A, Weiergraber M et al. Immunohistochemical detection of alpha1E voltage-gated Ca(2+) channel isoforms in cerebellum, INS-1 cells, and neuroendocrine cells of the digestive system. J Histochem Cytochem 1999; 47:981-94.
- 114. Wu LG, Borst JG, Sakmann B. R-type Ca²⁺ currents evoke transmitter release at a rat central synapse. Proc Natl Acad Sci USA 1998; 95:4720-5.
- 115. Albillos A, Neher E, Moser T. R-Type Ca²⁺ channels are coupled to the rapid component of secretion in mouse adrenal slice chromaffin cells. J Neurosci 2000; 20:8323-30.
- 116. Magee JC, Johnston D. Characterization of single voltage-gated Na^{*} and Ca²⁺ channels in apical dendrites of rat CA1 pyramidal neurons. J Physiol 1995; 487:67-90.
- 117. Kavalali ET, Zhuo M, Bito H et al. Dendritic Ca²⁺ channels characterized by recordings from isolated hippocampal dendritic segments. Neuron 1997; 18:651-63.
- 118. Sabatini BL, Svoboda K. Analysis of calcium channels in single spines using optical fluctuation analysis. Nature 2000; 408:589-93.
- Sabatini BL, Maravall M, Svoboda K. Ca(2+) signaling in dendritic spines. Curr Opin Neurobiol 2001; 11:349-56.
- 120. Soong TW, Stea A, Hodson CD et al. Structure and functional expression of a member of the low voltage-activated calcium channel family. Science 1993; 260:1133-6.
- 121. Wakamori M, Niidome T, Furutama D et al. Distinctive functional properties of the neuronal BII (class E) calcium channel. Receptors Channels 1994; 2:303-14.
- 122. Yokoyama CT, Westenbroek RE, Hell JW et al. Biochemical properties and subcellular distribution of the neuronal class E calcium channel alpha 1 subunit. J Neurosci 1995; 15:6419-32.
- Pereverzev A, Klockner U, Henry M et al. Structural diversity of the voltage-dependent Ca²⁺ channel alpha1E-subunit. Eur J Neurosci 1998; 10:916-25.
- 124. Vajna R, Schramm M, Pereverzev A et al. New isoform of the neuronal Ca²⁺ channel alpha1E subunit in islets of Langerhans and kidney—distribution of voltage-gated Ca²⁺ channel alpha1 subunits in cell lines and tissues. Eur J Biochem 1998; 257:274-85.
- 125. Williams ME, Marubio LM, Deal CR et al. Structure and functional characterization of neuronal alpha 1E calcium channel subtypes. J Biol Chem 1994; 269:22347-57.
- 126. Marubio LM, Roenfeld M, Dasgupta S et al. Isoform expression of the voltage-dependent calcium channel alpha 1E. Receptors Channels 1996; 4:243-51.
- 127. Saegusa H, Kurihara T, Zong S et al. Altered pain responses in mice lacking alpha 1E subunit of the voltage-dependent Ca²⁺ channel. Proc Natl Acad Sci USA 2000; 97:6132-7.
- 128. Lievano A, Santi CM, Serrano CJ et al. T-type Ca²⁺ channels and alpha1E expression in spermatogenic cells, and their possible relevance to the sperm acrosome reaction. FEBS Lett 1996; 388:150-4.
- 129. Wennemuth G, Westenbroek RE, Xu T et al. Ca_v2.2 and Ca_v2.3 (N- and R-type) Ca²⁺ channels in depolarization-evoked entry of Ca²⁺ into mouse sperm. J Biol Chem 2000; 275:21210-7.
- 130. Horvath A, Szabadkai G, Varnai P et al. Voltage dependent calcium channels in adrenal glomerulosa cells and in insulin producing cells. Cell Calcium 1998; 23:33-42.
- 131. Ligon B, Boyd AEr, Dunlap K. Class A calcium channel variants in pancreatic islets and their role in insulin secretion. J Biol Chem 1998; 273:13905-11.
- 132. Keahey HH, Rajan AS, Boyd AE et al. Characterization of voltage-dependent Ca²⁺ channels in beta-cell line. Diabetes 1989; 38:188-93.
- 133. Ohta M, Nelson D, Wilson JM et al. Relationships between energy level and insulin secretion in isolated rat islets of Langerhans. Manipulation of [ATP]/[ADP][Pi] by 2-deoxy-D-glucose. Biochem Pharmacol 1992; 43:1859-64.
- 134. Davalli AM, Biancardi E, Pollo A et al. Dihydropyridine-sensitive and -insensitive voltage-operated calcium channels participate in the control of glucose-induced insulin release from human pancreatic beta cells. J Endocrinol 1996; 150:195-203.
- Perez-Reyes E. Three for T: molecular analysis of the low voltage-activated calcium channel family. Cell Mol Life Sci 1999; 56:660-9.

- 136. McRory JE, Santi CM, Hamming KS et al. Molecular and functional characterization of a family of rat brain T-type calcium channels. J Biol Chem 2001; 276:3999-4011.
- 137. Perez-Reyes E, Cribbs LL, Daud A et al. Molecular characterization of a neuronal low-voltage-activated T-type calcium channel. Nature 1998; 391:896-900.
- 138. Lee JH, Daud AN, Cribbs LL et al. Cloning and expression of a novel member of the low voltage-activated T-type calcium channel family. J Neurosci 1999; 19:1912-21.
- 139. Cribbs LL, Lee JH, Yang J et al. Cloning and characterization of alpha1H from human heart, a member of the T-type Ca²⁺ channel gene family. Circ Res 1998; 83:103-9.
- 140. Talley EM, Cribbs LL, Lee JH et al. Differential distribution of three members of a gene family encoding low voltage-activated (T-type) calcium channels. J Neurosci 1999; 19:1895-911.
- 141. Huguenard JR. Low-threshold calcium currents in central nervous system neurons. Annu Rev Physiol 1996:329-48.
- 142. Cribbs LL, Martin BL, Schroder EA et al. Identification of the t-type calcium channel (Ca(v)3.1d) in developing mouse heart. Circ Res 2001; 88:403-7.
- 143. Espinosa F, Lopez-Gonzalez I, Serrano CJ et al. Anion channel blockers differentially affect T-type Ca(2+) currents of mouse spermatogenic cells, alpha1E currents expressed in Xenopus oocytes and the sperm acrosome reaction. Dev Genet. 1999; 25:103-14.
- 144. Jacob A, Benoff S. J Androl 2000; 56(March/April Suppl.):48.
- 145. Son WY, Lee JH, Lee JH et al. Acrosome reaction of human spermatozoa is mainly mediated by alpha1H T-type calcium channels. Mol Hum Reprod 2000; 6:893-7.
- 146. Jagannathan S, Punt EL, Gu Y et al. Identification and localization of T-type voltage-operated calcium channel subunits in human male germ cells. Expression of multiple isoforms. J Biol Chem 2002; 277:8449-56.
- 147. Birnbaumer L, Qin N, Olcese R et al. Structures and functions of calcium channel beta subunits. Bioenerg. Biomembr. 1998; 30:357-75.
- 148. Ruth P, Rohrkasten A, Biel M et al. Primary structure of the beta subunit of the DHP-sensitive calcium channel from skeletal muscle. Science 1989; 245:1115-8.
- 149. Gregg RG, Messing A, Strube C et al. Absence of the beta subunit (cchb1) of the skeletal muscle dihydropyridine receptor alters expression of the alpha 1 subunit and eliminates excitation-contraction coupling. Proc. Natl. Acad. Sci. USA 1996; 93:13961-6.
- 150. Hullin R, Singer-Lahat D, Freichel M et al. Calcium channel beta subunit heterogeneity: functional expression of cloned cDNA from heart, aorta and brain. EMBO J 1992:885-90.
- 151. Reimer D, Huber IG, Garcia ML et al. beta subunit heterogeneity of L-type Ca(2+) channels in smooth muscle tissues. FEBS Lett 2000; 467:65-9.
- 152. Haase H, Pfitzmaier B, McEnery MW et al. Expression of Ca(2+) channel subunits during cardiac ontogeny in mice and rats: identification of fetal alpha(1C) and beta subunit isoforms. J Cell Biochem 2000; 76:695-703.
- 153. Colecraft HM, Alseikhan B, Takahashi SX et al. Novel functional properties of Ca(2+) channel beta subunits revealed by their expression in adult rat heart cells. J Physiol 2002; 541:435-52.
- 154. Pichler M, Cassidy TN, Reimer D et al. Beta subunit heterogeneity in neuronal L-type Ca²⁺ channels. J Biol Chem 1997; 272:13877-82.
- 155. Yu AS, Boim M, Hebert SC et al. Molecular characterization of renal calcium channel beta-subunit transcripts. Am J Physiol 1995; 268:F525-31.
- 156. Powers PA, Liu S, Hogan K et al. Skeletal muscle and brain isoforms of a beta-subunit of human voltage-dependent calcium channels are encoded by a single gene. J Biol Chem 1992; 267:22967-72.
- 157. Pragnell M, Sakamoto J, Jay SD et al. Cloning and tissue-specific expression of the brain calcium channel beta-subunit. FEBS Lett 1991; 291:253-8.
- 158. Liu H, De Waard M, Scott VES et al. Identification of three subunits of the high affinity omega-conotoxin MVIIC-sensitive Ca²⁺ channel. J Biol Chem 1996; 271:13804-10.
- 159. Day NC, Volsen SG, McCormack AL et al. The expression of voltage-dependent calcium channel beta subunits in human hippocampus. Brain Res. Mol Brain Res 1998; 60:259-69.
- 160. Lie AA, Blumcke I, Volsen SG et al. Distribution of voltage-dependent calcium channel beta subunits in the hippocampus of patients with temporal lobe epilepsy. Neuroscience 1999; 93:449-56.
- 161. Ball SL, Powers PA, Shin HS et al.Role of the beta(2) subunit of voltage-dependent calcium channels in the retinal outer plexiform layer. Invest Ophthalmol Vis Sci 2002; 43:1595-603.
- 162. Scott VE, De Waard M, Liu H et al. Beta subunit heterogeneity in N-type Ca²⁺ channels. J Biol Chem 1996; 271:3207-12.
- 163. Vance CL, Begg CM, Lee WL et al. Differential expression and association of calcium channel alpha1B and beta subunits during rat brain ontogeny. J Biol Chem 1998; 273:14495-502.
- 164. McEnery MW, Vance CL, Begg CM et al. Differential expression and association of calcium channel subunits in development and disease. J Bioenerg Biomembr 1998; 30:409-18.

- 165. De Jongh KS, Warner C, Catterall WA. Subunits of purified calcium channels. Alpha 2 and delta are encoded by the same gene. J Biol Chem 1990; 265:14738-41.
- 166. Jay SD, Sharp AH, Kahl SD et al. Structural characterization of the dihydropyridine-sensitive calcium channel alpha 2-subunit and the associated delta peptides. J Biol Chem 1991; 266:3287-93.
- 167. Gurnett CA, De Waard M, Campbell KP. Dual function of the voltage-dependent Ca²⁺ channel alpha 2 delta subunit in current stimulation and subunit interaction. Neuron 1996; 16:431-40.
- 168. Brickley K, Campbell V, Berrow N et al. Use of site-directed antibodies to probe the topography of the alpha 2 subunit of voltage-gated Ca²⁺ channels. FEBS Lett 1995; 364:129-33.
- 169. Wiser O, Trus M, Tobi D et al. The alpha 2/delta subunit of voltage sensitive Ca²⁺ channels is a single transmembrane extracellular protein which is involved in regulated secretion. FEBS Lett 1996; 379:15-20.
- 170. Felix R, Gurnett CA, De Waard M et al. Dissection of functional domains of the voltage-dependent Ca²⁺ channel alpha2delta subunit. J Neurosci 1997; 17:6884-91.
- 171. Ellis SB, Williams ME, Ways NR et al. Sequence and expression of mRNAs encoding the alpha 1 and alpha 2 subunits of a DHP-sensitive calcium channel. Science 1988; 241:1661-4.
- 172. Klugbauer N, Lacinova L, Marais E et al. Molecular diversity of the calcium channel alpha2delta subunit. J Neurosci 1999; 19:684-91.
- 173. Barclay J, Balaguero N, Mione M et al. Ducky mouse phenotype of epilepsy and ataxia is associated with mutations in the Cacna2d2 gene and decreased calcium channel current in cerebellar Purkinje cells. J Neurosci 2001; 21:6095-104.
- 174. Gao B, Sekido Y, Maximov A et al. Functional properties of a new voltage-dependent calcium channel alpha(2)delta auxiliary subunit gene (CACNA2D2). J Biol Chem 2000; 275:12237-42.
- 175. Angelotti T, Hofmann F. Tissue-specific expression of splice variants of the mouse voltage-gated calcium channel alpha2/delta subunit. FEBS Lett 1996; 397:331-7.
- 176. Hobom M, Dai S, Marais E et al. Neuronal distribution and functional characterization of the calcium channel alpha2delta-2 subunit. Eur J Neurosci 2000; 12:1217-26.
- 177. Gong HC, Hang J, Kohler W et al. Tissue-specific expression and gabapentin-binding properties of calcium channel alpha2delta subunit subtypes. J Membr Biol 2001; 184:35-43.
- 178. Luo ZD. Rat dorsal root ganglia express distinctive forms of the alpha2 calcium channel subunit. Neuroreport 2000; 11:3449-52.
- 179. Bosse E, Regulla S, Biel M et al. The cDNA and deduced amino acid sequence of the gamma subunit of the L-type calcium channel from rabbit skeletal muscle. FEBS Lett 1990; 267:153-6.
- 180. Jay S, Ellis S, McCue A et al. Primary structure of the gamma subunit of the DHP-sensitive calcium channel from skeletal muscle. Science 1990; 248:490-2.
- 181. Letts VA, Felix R, Biddlecome GH et al. The mouse stargazer gene encodes a neuronal Ca²⁺-channel gamma subunit. Nat Genet 1998; 19:340-7.
- Black JLr, Lennon VA. Identification and cloning of putative human neuronal voltage-gated calcium channel gamma-2 and gamma-3 subunits: neurologic implications. Mayo Clin Proc 1999; 74:357-61.
- Klugbauer N, Dai S, Specht V et al. A family of gamma-like calcium channel subunits. FEBS Lett 2000; 470:189-97.
- 184. Powers PA, Liu S, Hogan K et al. Molecular characterization of the gene encoding the gamma subunit of the human skeletal muscle 1,4-dihydropyridine-sensitive Ca²⁺ channel (CACNLG), cDNA sequence, gene structure, and chromosomal location. J Biol Chem 1993; 268:9275-9.
- 185. Burgess DL, Gefrides LA, Foreman PJ et al. A cluster of three novel Ca²⁺ channel gamma subunit genes on chromosome 19q13.4: evolution and expression profile of the gamma subunit gene family. Genomics 2001; 71:339-50.
- 186. Chu PJ, Robertson HM, Best PM. Calcium channel gamma subunits provide insights into the evolution of this gene family. Gene 2001; 280:37-48.
- 187. Sharp AH, Black JLr, Dubel SJ et al. Biochemical and anatomical evidence for specialized voltage-dependent calcium channel gamma isoform expression in the epileptic and ataxic mouse, stargazer. Neuroscience 2001; 105:599-617.
- 188. Moss FJ, Viard P, Davies A et al. The novel product of a five-exon stargazin-related gene abolishes Ca(V)2.2 calcium channel expression. EMBO J 2002; 21:1514-23.
- 189. Chien AJ, Zhao X, Shirokov RE et al. Roles of a membrane-localized beta subunit in the formation and targeting of functional L-type Ca²⁺ channels. J Biol Chem 1995; 270:30036-44.
- 190. Gerster U, Neuhuber B, Groschner K et al. Current modulation and membrane targeting of the calcium channel alpha1C subunit are independent functions of the beta subunit. J Physiol (Lond) 1999; 517:353-68.
- 191. Bogdanov Y, Brice NL, Canti C et al. Acidic motif responsible for plasma membrane association of the voltage-dependent calcium channel beta1b subunit. Eur J Neurosci 2000; 12:894-902.

- 192. Yamaguchi H, Hara M, Strobeck M et al. Multiple modulation pathways of calcium channel activity by a beta subunit. Direct evidence of beta subunit participation in membrane trafficking of the alpha1C subunit. J. Biol. Chem. 1998; 273:19348-56.
- 193. Chien AJ, Cart KM, Shirokov RE et al. Identification of palmitoylation sites within the L-type calcium channel beta2a subunit and effects on channel function. J Biol Chem 1996; 271:26465-8.
- 194. Chien AJ, Gao T, Perez-Reyes E et al. Membrane targeting of L-type calcium channels. Role of palmitoylation in the subcellular localization of the beta2a subunit. J Biol Chem 1998; 273:23590-7.
- 195. Gao T, Chien A, Hosey MM. Complexes of the alpha1C and beta subunits generate the necessary signal for membrane targeting of class C L-type calcium channels. J Biol Chem 1999; 274:2137-44.
- 196. Pragnell M, De Waard M, Mori Y et al. Calcium channel beta-subunit binds to a conserved motif in the I-II cytoplasmic linker of the alpha 1-subunit. Nature 1994; 368:67-70.
- 197. Neuhuber B, Gerster U, Mitterdorfer J et al. Differential effects of Ca²⁺ channel beta1a and beta2a subunits on complex formation with alpha1S and on current expression in tsA201 cells. J Biol Chem 1998; 273:9110-8.
- 198. Gao T, Bunemann M, Gerhardstein BL et al. Role of the C terminus of the alpha 1C (CaV1.2) subunit in membrane targeting of cardiac L-type calcium channels. J Biol Chem 2000; 275:25436-44.
- 199. Zuhlke RD, Reuter H. Ca²⁺-sensitive inactivation of L-type Ca²⁺ channels depends on multiple cytoplasmic amino acid sequences of the alpha1C subunit. Proc Natl Acad Sci USA 1998; 95:3287-94.
- 200. Zuhlke RD, Pitt GS, Deisseroth K et al. Calmodulin supports both inactivation and facilitation of L-type calcium channels. Nature 1999; 399:159-62.
- 201. Peterson BZ, DeMaria CD, Adelman JP et al. Calmodulin is the Ca²⁺ sensor for Ca²⁺ -dependent inactivation of L-type calcium channels. Neuron 1999; 22:549-58.
- 202. Qin N, Olcese R, Bransby M et al. Ca²⁺-induced inhibition of the cardiac Ca²⁺ channel depends on calmodulin. Proc Natl Acad Sci USA 1999; 96:2435-8.
- 203. Singer D, Biel M, Lotan I et al. The roles of the subunits in the function of the calcium channel. Science 1991; 253:1553-7.
- 204. Shistik E, Ivanina T, Puri T et al. Ca²⁺ current enhancement by alpha 2/delta and beta subunits in Xenopus oocytes: contribution of changes in channel gating and alpha 1 protein level. J Physiol 1995; 489:55-62.
- 205. Brodbeck J, Davies A, Courtney JM et al. The ducky mutation in Cacna2d2 results in altered Purkinje cell morphology and is associated with the expression of a truncated alpha 2 delta-2 protein with abnormal function. J Biol Chem 2002; 277:7684-93.
- 206. Bangalore R, Mehrke G, Gingrich K et al. Influence of L-type Ca channel alpha 2/delta-subunit on ionic and gating current in transiently transfected HEK 293 cells. Am J Physiol 1996; 270:H1521-8.
- 207. Jones LP, Wei SK, Yue DT. Mechanism of auxiliary subunit modulation of neuronal alpha1E calcium channels. J Gen Physiol 1998; 112:125-43.
- 208. Gurnett CA, Felix R, Campbell KP. Extracellular interaction of the voltage-dependent Ca²⁺ channel alpha2delta and alpha1 subunits. J Biol Chem 1997; 272:18508-12.
- 209. Stephens GJ, Page KM, Burley JR et al. Functional expression of rat brain cloned alpha1E calcium channels in COS-7 cells. Pflugers Arch 1997; 433:523-32.
- 210. Brice NL, Berrow NS, Campbell V et al. Importance of the different beta subunits in the membrane expression of the alpha1A and alpha2 calcium channel subunits: studies using a depolarization-sensitive alpha1A antibody. Eur J Neurosci 1997; 9:749-59.
- 211. Yamaguchi H, Okuda M, Mikala G et al. Cloning of the beta(2a) subunit of the voltage-dependent calcium channel from human heart: cooperative effect of alpha(2)/delta and beta(2a) on the membrane expression of the alpha(1C) subunit. Biochem Biophys Res Commun 2000; 267:156-63.
- Puri TS, Gerhardstein BL, Zhao XL et al. Differential effects of subunit interactions on protein kinase A- and C-mediated phosphorylation of L-type calcium channels. Biochemistry 1997; 36:9605-15.
- 213. Bichet D, Cornet V, Geib S et al. The I-II loop of the Ca²⁺ channel alpha1 subunit contains an endoplasmic reticulum retention signal antagonized by the beta subunit. Neuron 2000; 25:177-90.
- 214. Ma D, Jan LY. ER transport signals and trafficking of potassium channels and receptors. Curr Opin Neurobiol 2002; 12:287-92.
- 215. Beguin P, Nagashima K, Gonoi T et al. Regulation of Ca²⁺ channel expression at the cell surface by the small G-protein kir/Gem. Nature 2001; 411:701-6.
- 216. Kang MG, Chen CC, Felix R et al. Biochemical and biophysical evidence for gamma 2 subunit association with neuronal voltage-activated Ca²⁺ channels. J Biol Chem 2001; 276:32917-24.
- 217. Bean BP, Nowycky MC, Tsien RW. Beta-adrenergic modulation of calcium channels in frog ventricular heart cells. Nature 1984; 307:371-5.

- 218. Gray R, Johnston D. Noradrenaline and beta-adrenoceptor agonists increase activity of voltage-dependent calcium channels in hippocampal neurons. Nature 1987; 327:620-2.
- 219. Sculptoreanu A, Scheuer T, Catterall WA. Voltage-dependent potentiation of L-type Ca²⁺ channels due to phosphorylation by cAMP-dependent protein kinase. Nature 1993; 364:240-3.
- 220. Altier C, Dubel SJ, Barrere C et al. Trafficking of L-type calcium channels mediated by the postsynaptic scaffolding protein AKAP79. J Biol Chem 2002; epub ahead of print.
- 221. Grabner M, Dirksen RT, Beam KG. Tagging with green fluorescent protein reveals a distinct subcellular distribution of L-type and non-L-type Ca²⁺ channels expressed in dysgenic myotubes. Proc Natl Acad Sci USA 1998; 95:1903-8.
- 222. Neuhuber B, Gerster U, Doring F et al. Association of calcium channel alpha1S and beta1a subunits is required for the targeting of beta1a but not of alpha1S into skeletal muscle triads. Proc Natl Acad Sci USA 1998; 95:5015-20.
- 223. Flucher BE, Kasielke N, Gerster U et al. Insertion of the full-length calcium channel alpha(1S) subunit into triads of skeletal muscle in vitro. FEBS Lett 2000; 474:93-8.
- 224. Proenza C, Wilkens C, Lorenzon NM et al. A carboxyl-terminal region important for the expression and targeting of the skeletal muscle dihydropyridine receptor. J Biol Chem 2000; 275:23169-74.
- 225. Flucher BE, Kasielke N, Grabner M. The triad targeting signal of the skeletal muscle calcium channel is localized in the COOH terminus of the alpha(1S) subunit. J Cell Biol 2000; 151:467-78.
- 226. Strube C, Beurg M, Sukhareva M et al. Molecular origin of the L-type Ca²⁺ current of skeletal muscle myotubes selectively deficient in dihydropyridine receptor beta1a subunit. Biophys J 1998; 75:207-17.
- 227. Beurg M, Sukhareva M, Ahern CA et al. Differential regulation of skeletal muscle L-type Ca²⁺ current and excitation-contraction coupling by the dihydropyridine receptor beta subunit. Biophys J 1999; 76:1744-56.
- 228. Dotti CG, Simons K. Polarized sorting of viral glycoproteins to the axon and dendrites of hippocampal neurons in culture. Cell 1990; 62:63-72.
- 229. Jareb M, Banker G. The polarized sorting of membrane proteins expressed in cultured hippocampal neurons using viral vectors. Neuron 1998; 20:855-67.
- 230. Brice NL, Dolphin AC. Differential plasma membrane targeting of voltage-dependent calcium channel subunits expressed in a polarized epithelial cell line. J Physiol (Lond) 1999; 515:685-94.
- 231. Nakata T, Terada S, Hirokawa N. Visualization of the dynamics of synaptic vesicle and plasma membrane proteins in living axons. J Cell Biol 1998; 140:659-74.
- 232. Elferink LA, Trimble WS, Scheller RH. Two vesicle-associated membrane protein genes are differentially expressed in the rat central nervous system. J Biol Chem 1989; 264:11061-4.
- 233. Leitner B, Lovisetti-Scamihorn P, Heilmann J et al. Subcellular localization of chromogranins, calcium channels, amine carriers, and proteins of the exocytotic machinery in bovine splenic nerve. J Neurochem 1999; 72:1110-6.
- 234. Ahmari SE, Buchanan J, Smith SJ. Assembly of presynaptic active zones from cytoplasmic transport packets. Nat Neurosci 2000; 3:445-51.
- 235. Passafaro M, Rosa P, Sala C et al. N-type Ca²⁺ channels are present in secretory granules and are transiently translocated to the plasma membrane during regulated exocytosis. J Biol Chem 1996; 271:30096-104.
- 236. Sher E. Voltage-operated calcium channels in secretory vesicles? Cell Biol Int 1997; 21:779-81.
- 237. Sher E, Rosa P, Francolini M et al. Metabolism and trafficking of N-type voltage-operated calcium channels in neurosecretory cells. J Bioenerg Biomembr 1998; 30:399-407.
- 238. Wittemann S, Mark MD, Rettig J et al. Synaptic localization and presynaptic function of calcium channel beta 4-subunits in cultured hippocampal neurons. J Biol Chem 2000; 275:37807-14.
- 239. Keller P, Simons K. Post-Golgi biosynthetic trafficking. J Cell Sci 1997; 110:3001-9.
- 240. Bradke F, Dotti CG. Membrane traffic in polarized neurons. Biochim. Biophys. Acta 1998; 1404:245-58.
- 241. Winckler B, Mellman I. Neuronal polarity: controlling the sorting and diffusion of membrane components. Neuron 1999; 23:637-40.
- 242. West AE, Neve RL, Buckley KM. Targeting of the synaptic vesicle protein synaptobrevin in the axon of cultured hippocampal neurons: evidence for two distinct sorting steps. J Cell Biol 1997; 139:917-27.
- 243. Stowell JN, Craig AM. Axon/dendrite targeting of metabotropic glutamate receptors by their cytoplasmic carboxy-terminal domains. Neuron 1999; 22:525-36.
- 244. Poyatos I, Ruberti F, Martinez-Maza R et al. Polarized distribution of glycine transporter isoforms in epithelial and neuronal cells. Mol Cell Neurosci 2000; 15:99-111.
- 245. Burgess DL, Jones JM, Meisler MH et al. Mutation of the Ca²⁺ channel beta subunit gene Cchb4 is associated with ataxia and seizures in the lethargic (lh) mouse. Cell 1997; 88:385-92.

- 246. Caddick SJ, Wang C, Fletcher CF et al. Excitatory but not inhibitory synaptic transmission is reduced in lethargic (Cacnb4(lh)) and tottering (Cacna1atg) mouse thalami. J. Neurophysiol. 1999; 81:2066-74.
- 247. Fisher SA, Fischer TM, Carew TJ. Multiple overlapping processes underlying short-term synaptic enhancement. Trends Neurosci. 1997; 20:170-7.
- 248. Zucker RS. Calcium- and activity-dependent synaptic plasticity. Curr Opin Neurobiol 1999; 9:305-13.
- 249. Castillo PE, Weisskopf MG, Nicoll RA. The role of Ca²⁺ channels in hippocampal mossy fiber synaptic transmission and long-term potentiation. Neuron 1994; 12:261-9.
- 250. Luebke JI, Dunlap K, Turner TJ. Multiple calcium channel types control glutamatergic synaptic transmission in the hippocampus. Neuron 1993; 11:895-902.
- 251. Mintz IM, Sabatini BL, Regehr WG. Calcium control of transmitter release at a cerebellar synapse. Neuron 1995; 15:675-88.
- 252. Regehr WG, Mintz IM. Participation of multiple calcium channel types in transmission at single climbing fiber to Purkinje cell synapses. Neuron 1994; 12:605-13.
- 253. Takahashi T, Momiyama A. Different types of calcium channels mediate central synaptic transmission. Nature 1993; 366:156-8.
- 254. Wheeler DB, Randall A, Tsien RW. Roles of N-type and Q-type Ca²⁺ channels in supporting hippocampal synaptic transmission. Science 1994; 264:107-11.
- 255. Meir A, Ginsburg S, Butkevich A et al. Ion channels in presynaptic nerve terminals and control of transmitter release. Physiol Rev 1999; 79:1019-88.
- 256. Zucker RS. Exocytosis: a molecular and physiological perspective. Neuron 1996; 17:1049-55.
- 257. Maximov A, Sudhof TC, I. B. Association of neuronal calcium channels with modular adaptor proteins. J Biol Chem 1999; 274:24453-6.
- Maximov A, Bezprozvanny I. Synaptic targeting of N-type calcium channels in hippocampal neurons. J Neurosci 2002; 22:6939-52.

CHAPTER 8

The Calcium Channel and the Transmitter Release Site

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Summary

The Ca^{2+} channel exhibits multiple interactions at the presynaptic terminal. Not only is the channel critical for the action potential-gated influx of Ca^{2+} ions that leads to the activation of the transmitter release mechanism, a feed-forward pathway, but it is in itself modulated by a complex web of molecular interactions that involve both transmitter release site and non-release site proteins. Clearly, we do not yet nearly understand the full complexity of these molecular interactions since entirely new facets are being discovered apace. However, the picture is emerging of a highly structured and yet subtly designed molecular machine that is involved in complex forward and backward regulatory mechanisms in the control of transmitter release and, hence, of synaptic strength.

Background

Involvement of Ca²⁺ Ions in Transmitter Release

The importance of Ca²⁺ in the transmission of the neural impulse was recognized initially by Locke in a classic publication in 1894.¹ This paper which occupied 2 sides of Pflugers Archiv demonstrated that the indirect (via the motor nerve) activation of muscle occurred in the presence of external Ca²⁺ ions but was not supported by an alternative divalent cation, barium. Further elucidation of the role of Ca²⁺ occurred in tandem with the development of the chemical basis of neurotransmission and its key features, including the release of transmitter from secretory vesicles and the demonstration and acceptance of the ion channel hypothesis. Key discoveries were made by Katz and colleagues. They first recorded the miniature potential and demonstrated that it must be composed of more than one transmitter molecule and proposed the hypothesis that each quantum of transmitter corresponded to the release of the contents of the secretory vesicle.² In 1967 Katz and Miledi³ carried out the critical experiment of applying external Ca²⁺ and depolarizing pulses separately, demonstrating that evoked transmitter release only occurred when external Ca²⁺ was combined with nerve terminal depolarization. This strongly supported the hypothesis that Ca2+ ion entry into the nerve terminal during the action potential triggers transmitter release. This hypothesis was established on demonstrations in the squid giant synapse that transmitter release could be triggered by the direct injection of Ca²⁺ ions into the nerve terminal, in the absence of membrane depolarization,⁴ and that Ca²⁺ ions actually enter the terminal during action potentials, as demonstrated by the Ca²⁺ sensitive luminescent dye Aequorin.⁵ The basic features of presynaptic Ca²⁺ channel behaviour were established by Llinas in the first voltage clamp analysis of Ca^{2+} currents in the presynaptic nerve terminal⁶ which was followed by an analysis of the input/output kinetics of Ca²⁺ entry and transmitter release.^{7,8}

Ca²⁺ Channel Diversity

Until the mid 1970s it was generally assumed that there was only one Ca²⁺ channel species which was blocked by drugs such as verapamil and nifedipine. Indeed, the idea that there were might be more than one Ca^{2+} channel type was strongly resisted. The eventual dissection of the distinct types was achieved based on two main criteria: the biophysical characteristics of the current,⁹ and, more importantly, with toxins and drugs that exhibit differential Ca²⁺ current block. It was established that verapamil or nifedipine-like drugs blocked the L-type (now $Ca_v 1.2/$.3/.4) channel. The T-type (Ca₂3.1/.2/.3) Ca²⁺ current component was relatively easily distinguished by its low voltage thresholds and inactivation range and also its barely resolvable single channel current events.¹⁰ Tsien and colleagues proposed the existence of N-type (Ca, 2.2) Ca²⁺ channel¹¹⁻¹³ on the basis of whole cell and single channel properties. The discovery of the N-type Ca^{2+} channel blockers from cone shell venom, ω -conotoxin GIVA (ω -CTX), provided a highly specific tool to dissect these channels from their close relatives.¹⁴ The P type Ca²⁺ channel (Ca_v2.1), was discovered in cerebellar Purkinje cells¹⁵ and was found to be blocked by a spider toxin, Agatoxin GIVA.¹⁶ The demonstration that there were two classes of Ca²⁺ currents with respect to their Agatoxin GIVA sensitivity led to the notion that there were two distinct channel types, dubbed the P and Q types. However, once it was agreed that these subtypes derive from the same fundamental Ca²⁺ channel species the channel became known as the 'P/Q type'. The Ca₂2.3 (R-type) channel was named to account for the Ca²⁺ current that could not be blocked with the L, N- or P/Q type specific toxins. Further characterization and nomenclature of Ca^{2+} channels is dealt with in detail elsewhere in this volume (Chapters 3 and 4).

Presynaptic Ca²⁺ Channel Types

As discussed above, during the early 70s it was generally accepted that there was only one type of Ca²⁺ channel and also that transmitter release required Ca²⁺ influx through Ca²⁺ channels. However, verapamil, which blocked smooth muscle (L-type) Ca²⁺ current did not affect transmitter release.^{17,18} Thus, the pharmacology of transmitter release indicated that there was more than one type of Ca²⁺ channel several years prior to the recognition that there was more than one Ca2+ channel species.9 Indeed, in most nerve terminals transmitter release is not regulated by L-type Ca2+ channels, 19-21 the type blocked by verapamil, and it was demonstrated both at the vertebrate chick ciliary ganglion calyx synapse²² and at the invertebrate squid giant synapses²³ that the presynaptic Ca²⁺ current was insensitive to this drug. However, the L-type channel is often predominant at synapses that mediate tonic secretion, non-neuronal presynaptic structures, such as at hair cells²⁴ and retinal receptors^{25,26} but also at tonically secreting retinal ganglion neurons.²⁵⁻²⁸ In contrast, N-type channels are commonly associated with transmitter release. This was recognized very soon after the discovery of W-CTX.^{14,19,29-31} It appears, however, that evolution appears to have gradually favored P/Q-type Ca²⁺ channel as the predominant Ca²⁺ channel at presynaptic terminals. This channel type was first associated with presynaptic terminals and transmitter release by Llinas and colleagues^{15,32} and has been localized to a great number of mammalian presynaptic terminal types, as determined by the sensitivity of these terminals to specific blockers,^{33,34} most notably Agatoxin GIVA.^{34,35} Many synapses exhibit a predominance of the N and P/Q types but in others a combined treatment of these blockers for L, N and P/Q still does not eliminate transmitter release with residual attributed to the R type Ca²⁺ channel.³⁶⁻³⁸ Which channel type predominates at any specific synapse appears to be highly regulated with complex combinations at different synapses in any one species. It should be noted that much of this analysis has relied on toxin block: the actual Ca²⁺ current combination has only been examined with direct voltage clamp techniques at a handful of synapse types. These range from pure L-type²⁷ to virtually pure N-type³⁹ and to terminals where the Ca²⁺ channel complement is complex^{40,41} and changing with time.⁴¹ It is also of interest that the T-type Ca²⁺ channels are very uncommon at presynaptic terminals, with compelling evidence only at the non-neuronal rod photoreceptor.⁴² The general absence

of this channel type from neuronal nerve terminals raises the question whether the T-type channel group lacks a molecular feature required for targeting to nerve terminals.

Ca²⁺ Channel Localization at the Presynaptic Nerve Terminal

Synaptic Delay Places the Ca²⁺ Channels at the Release Sites

Since nerve terminals are generally exceedingly small structures the location of the Ca^{2+} channels that gate transmitter release was never considered an issue. Definitive evidence for a localization of the Ca^{2+} channels at the release site was concluded from measurements of synaptic delay. In a classic experiment at the voltage clamped presynaptic terminal of the squid giant synapse Llinas triggered transmitter release using a pure Ca^{2+} tail current.⁷ The membrane potential was rapidly depolarized to beyond the Ca^{2+} current reversal potential so that the Ca^{2+} channels opened but, due to the lack of a net driving force, no Ca^{2+} influx occurred. When the membrane potential was repolarized an instantaneous rapid influx of Ca^{2+} ions occurred through the open channels as the channels started to close. The latency from the onset of Ca^{2+} influx to the first detected transmitter release in the postsynaptic axon was 0.2 ms. Since it can be presumed that in order to trigger release the Ca^{2+} ions bind directly to the release site (and not some remote trigger) and, hence, must diffuse from the open channel to their binding sites, the available time limits the distance from one to the other to less than 100 nm. The subsequent demonstration that a single release site could be activated by a single Ca^{2+} channel⁴³ argued for an even tighter co-localization, estimated to be <25 nm (see below).

Morphological Evidence

The first glimpse of nerve terminal structure at the molecular level was obtained by the application of the freeze-fracture experimental technique to the frog neuromuscular junction. This technique takes advantage of the fact that when biological tissue is frozen the water-filled spaces are harder than the lipid-filled ones and when the tissue is literally 'fractured' the rupture plane occurs primarily along the bimolecular lipid membranes. The fractured tissue is shadowed with platinum vapor, the tissue is digested off and the resulting surface replica examined in an electron microscope. The membranes are generally seen as smooth flat surfaces. However, proteins that extend through the membrane remain associated with one or other membrane leaflet and can be observed as particles with a characteristic size in the freeze fracture replica. At the frog neuromuscular junction the transmitter release site is observed as two parallel arrays of large particles separated by a smooth hump.⁴⁴ Within these linear arrays the particles are distributed with a periodicity of ~16 nm.⁴⁵ Secretory vesicle exocytosis was observed immediately external to these particle arrays and it was hypothesized that the large particles correspond to the Ca²⁺ channels themselves.⁴⁶ An approximate correlation was noted at the squid giant synapse between the number of functional channels, as assessed by Ca²⁺ current recording, and the number of large particles at the release sites.⁴⁷ However, it remains possible that these particle arrays may include other large proteins known to be located close to the release sites, including the calcium-activated potassium channel (BK).⁴⁸ Haydon et al⁴⁹ used atomic force microscopy to examine the distribution of Ca²⁺ channels at the release face of the chick ciliary ganglion calyx synapse. The channels were identified with biotinylated ω -conotoxin GVIA and then tagged with avidin-coated colloidal gold particles. At this synapse the channels do not form the orderly array observed at the frog neuromuscular junction but instead form clusters at the release site. However, linear arrangements were observed within the cluster and a nearest-neighbor analysis revealed an inter-channel distance of -16 nm, in close correspondence with the inter-particle distance in freeze-fracture.⁴⁵ Recently Harlow et al ⁴⁵ have applied computer-assisted tomography to electron micrographs of the frog neuromuscular junction to explore the structure of the protein 'scaffold' underlying the releases sites. This scaffold included longitudinal proteins, beams, within the inter-particle hump region and transverse proteins, ribs

that could be superimposed on the freeze fracture array of particles and that appear to terminate on the secretory vesicles. In addition, small processes projected from the ribs to the surface membrane in a pattern that was similar to the particle array in freeze fracture images, suggesting that these 'pegs' represent the anchors for the Ca²⁺ Channels.

The Calcium Channel and the Triggering of Transmitter Release

Action Potential Gated Ca²⁺ Influx

 Ca^{2+} ions, as with any other ions, move across the cell membrane subject to two forces: a concentration gradient, in this case a high Ca²⁺ ion concentration on the outside drives the ions inward, and, since the ion is charged, a membrane potential gradient. Thus at resting membrane potentials (--65 mV in a nerve terminal) there is a strong double force attracting the ions into the cell. However, admission in depends on a diffusion pathway and for a cell membrane this is usually (but not exclusively) via the opening of voltage sensitive Ca²⁺ channels. The voltage sensitivity of Ca²⁺ channel opening is quite steep ensuring that at the normal negative resting membrane potentials these channels are very unlikely to open. Thus, there is a very low probability that spontaneous Ca2+ channel flickering will trigger transmitter release. However, this steep dependence ensures that during a depolarization, even a very rapid one, a significant fraction of the channels will open. What fraction that is depends on multiple factors: the amplitude and shape of the depolarization; the biophysical properties of the channel (rate constants, cooperativity) and whether the channels are modulated by other factors. The typical nerve terminal action potential has a waveform that triggers what is essentially a Ca²⁺ channel tail current. Thus, the abrupt depolarization at the beginning of the spike to a very positive membrane potential, -+60 mV opens the channels but also removes the driving force for Ca²⁺ entry. The action potential ends as abruptly as it begins triggering a rapid influx of Ca²⁺ ions as the membrane potential moves away from the reversal potential-but also the closure of the channels—resulting in a pulse of Ca^{2+} ion influx that gates the secretory mechanism. Note that action potential triggered tail current Ca2+ entry has the very distinct advantage of being very rapid and very abrupt and the total duration of the inward Ca²⁺ current is typically less than 0.5 ms.⁵⁰ Note that the amplitude of the action potential-triggered Ca²⁺ pulse can be affected by several different factors: the Ca²⁺ concentration gradient (such as by external Ca^{2+} depletion); the duration of the action potential (such as by the excitability of K channels); the number of available Ca2+ channels (such as by voltage-insensitive block); the voltage dependence of the Ca²⁺ channels opening (such as by G protein inhibition, Chapter 10) and by the voltage dependence of Ca²⁺ channel closing.

Latency of Secretion

As discussed above, for most nerve terminals we can approximate Ca^{2+} ion entry as a very brief duration inward pulse. The latency between this pulse and the onset and peak of transmitter release is an important value with respect to the understanding of the transmitter release mechanism since it sets a time limit to the reaction sequence between binding of the Ca^{2+} ion to its receptor and fusion of the vesicle with the membrane. As discussed above, the first accurate estimate of this latency was by Llinas and colleagues giving a minimum latency of 0.2 ms. Since this time interval includes both vesicle fusion, diffusion of the transmitter across the cleft and binding and activation of the postsynaptic receptor it can be seen that the latency between Ca^{2+} binding to the release mechanism and the onset of fusion must be very fast indeed. This time interval could be termed the 'killer amendment' since it sets such a rigorous limit to any model designed to explain how the release mechanism works.

Ca²⁺ Dependency of Transmitter Release—Multiple Ion Gating of Release

One of the extraordinary features of transmitter secretion at a presynaptic nerve terminal is the element of control. The nerve terminal goes from a spontaneous vesicular fusion frequency

of ~1/sec (as with miniature endplate potentials at the neuromuscular junction) to rates that are several orders of magnitude higher and then abruptly falls to very low levels again. This acceleration depends on two main factors: first the very brief Ca²⁺ influx pulse discussed above, and second, the finding that it appears to take the binding of multiple Ca2+ ions to the transmitter release site to actually gate the fusion mechanism. This conclusion is based on the early work of Robinson⁵¹ and Dodge and Rahamimoff.⁵² These authors noted that when the external Ca²⁺ ion concentration is varied the transmitter release triggered by an action potential does not go up as a linear function but far more steeply. Dodge and Rahamimoff described this dependence by a power relation such that transmitter release was the fourth power of the external Ca^{2+} ion concentration. If it could be assumed (and as has been shown for Ca²⁺ channels in general and at the presynaptic nerve terminal of the squid giant synapse) that within the low external Ca²⁺ ion concentration range Ca^{2+} ion entry is essentially a linear function of external Ca^{2+} ion levels the fourth power dependency would seem to reflect the binding of the Ca²⁺ ions to the release site itself. Thus, at least four Ca²⁺ ions must bind to the release site to trigger the fusion of the secretory vesicle. Since this discovery the steep dependence of release on cytoplasmic Ca²⁺ concentration has been described as Ca²⁺ cooperativity. However, this term has caused some confusion since the term cooperativity can be used both for a process triggered by the action of several independent ligands, as here, and for a change in the binding characteristics of the target protein for a second ligand upon binding of the first, as is the case for O2 binding to hemoglobin. It is not known whether the gating of the release site involves one or both of these so called 'cooperative' actions.

Ca²⁺ Dependency of Transmitter Release—Domain Size

The above consideration of cooperativity refers solely to the titration of Ca²⁺ ion concentration against the activation of the transmitter release site, it does not consider the complications introduced by the distribution of Ca²⁺ channels and the fact that at nm resolution Ca²⁺ does not enter the terminal evenly across the surface membrane but does so only at the open mouth of the ion channel. Thus, when the channel is open there is a sharp drop-off in Ca2+ ion concentration radially away from the pore in all directions, both inwardly into the cell and along the inner surface membrane.⁵³ It is believed that this concentration gradient is established and dissipates virtually instantaneously after channel opening and closing. This area of elevated Ca²⁺ ion concentration was originally called a 'domain' but is usually referred to as a 'microdomain'. Unfortunately, some confusion has arisen by the use of this term for both the Ca^{2+} plume generated by a single channel or the plume resulting when a cluster of nearby Ca^{2+} channels open. This double use is unfortunate since the two are functionally different in that when a single channel opens the domain can be thought of as essentially an instantaneously all-or-nothing, or a quantal, event whereas with multiple channels the amplitude and radial dimensions of the domain are graded. For this reason I will use the term 'nanodomain' here for the Ca²⁺ influx through a single channel and 'microdomain' for that through multiple simultaneously opening, and colocalized channels.

One can increase the amount of Ca^{2+} entering the cell in two fundamentally different ways that have very different implications as to how the secretion sites in the cell are organized: first, as above, by a graded external Ca^{2+} concentration or, second, by maintaining external Ca^{2+} constant and recruiting an increasing number of Ca^{2+} channels (such as with depolarizing pulses of different amplitude). The contrast between these methods is that in the former there is a true and continuous titration of Ca^{2+} influx into the cell, even at the highest spatial resolution. However, when the number of channels activated is increased, locally Ca^{2+} influx goes up **quantally** since current through an open channel is an all-or-nothing event. If we compare these methods at the level of the nanodomain the fundamental difference is that with graded external Ca^{2+} the number of nanodomains remains constant while the amplitude through each is varied whereas with graded Ca^{2+} channel recruitment the amplitude of the Ca^{2+} nanodomain is constant but the number of such domains varies. Evidence suggests that in most secretory cells the ion channels appear to be sufficiently remote from the transmitter release sites that secretion can be modeled as if the individual channels are essentially irrelevant: the Ca^{2+} ions from each channel pool so that in effect in both cases there is a global increase in concentration. In such cells it would make no difference if the Ca^{2+} dependence of transmitter release were titrated by graded or quantal Ca^{2+} influx.

Where Is the Magic Button? Ca²⁺ Binding Sites on the Release Mechanism

The initial demonstration that transmitter release required both the depolarization of the nerve terminal and the presence of external Ca2+ ions3 was one of the critical pieces of evidence indicating that an influx of Ca2+ ions is required to gate the release mechanism. This immediately begged the question of what comprises the Ca²⁺ binding site? Katz and Miledi speculated that the divalent Ca²⁺ ion simply cross links the two membranes to trigger fusion, an attractive, if simplistic hypothesis. However, this idea could not account for the tight linkage between Ca2+ influx and transmitter release nor the consistent 4th power cooperativity. These key features are more compatible with a specific protein-based gating mechanism. Other ideas that have been proposed include transmitter release triggered by a calcium-gated ion channel that either releases the transmitter directly from the cytoplasm⁵⁴ or the secretory vesicle⁵⁵ or that leads to the intracellular rupture of the secretory vesicle.⁵⁶ Such ideas have been generally dropped in favor of hypotheses based on the role of a 'SNARE' complex fusion mechanism and Ca²⁺ binding sites on synaptotagmin, a secretory vesicle integral membrane protein (but see ref. 57). The fact that release is blocked upon cleavage of any of the SNAREs with botulinum toxins⁵⁸ is compelling evidence that these proteins are critical to the fusion mechanism. However, whether this complex comprises the fusion mechanism itself or simply forms a frame to enable fusion by some other mechanism has not as yet been resolved. The C2B domain of synaptotagmin, an integral protein of the secretory vesicle, is an attractive putative Ca^{2+} binding site:^{59,60} the protein is known to interact with both the Ca^{2+} channel itself (see below) and with the SNARE complex while synaptotagmin knockouts exhibit a greatly reduced Ca²⁺-dependent transmitter release,⁶¹ as does molecular modification of the putative Ca²⁺ binding site.⁵⁹ Other studies have suggested more complex Ca2+ binding sites resulting from the tertiary structure of the intertwined SNARE protein complex. It should be noted that all of the putative four cooperating binding sites may not have the same Ca^{2+} binding characteristics^{62,63} and may not even be located on the same protein.

Calcium Channel Interaction with the Proteins of the Transmitter Release Site

Early concepts of the presynaptic nerve terminal organization did not recognize that the location of the Ca²⁺ channel within the nerve terminal is critical for rapid transmitter release. The demonstration that transmitter release occurred at a sub-millisecond interval after Ca²⁺ entry⁷ was critical to change this concept. Since the Ca²⁺ ions can only diffuse a fraction of a μ m within this time interval the Ca²⁺ channel had to be located within a small distance of the transmitter release site. The subsequent finding that the transmitter release site could be gated by the opening of a single Ca²⁺ channel⁴³ provided an even greater restriction to the channel-release site distance and provided functional evidence that Ca²⁺ channels must be an integral component of the release site complex.

In the early 90s a number of studies demonstrated that proteins which were then or subsequently identified as associated with the release site complex could be co-immunoprecipitated with N-type⁶⁴⁻⁶⁶ and P-type⁶⁷ Ca²⁺ channels. It was recognized early on that this protein link, in particular via the protein syntaxin, might represent a mechanism whereby the channels were actually attached to the release site.^{66,68} Sheng et al⁶⁹ demonstrated that syntaxin, and subsequently several of the proteins involved in exocytosis, bound to a defined 'synprint' region of the N-type Ca²⁺ channel on its II-III linker region (the cytoplasmic loop between the 2nd and 3rd of the four transmembrane domains). SNAP-25, a surface membrane-associated protein, has also been reported to link to the Ca^{2+} channel as has the vesicle protein synaptotagmin^{65,68,70,71} and RIM,⁷² a potential release site scaffolding protein that interacts with Rab3. While the synprint region plays an important role in Ca^{2+} channel-release site protein interactions it is not obligatory for nerve terminal function since since invertebrate ion channels that lack this region still exhibit normal rapid transmitter release.⁷³

Ion channels are finely tuned devices and are sensitive to changes in their immediate environment. The demonstration of a specific protein binding site raised the possibility that this interaction might have functional consequences on the activity of the Ca²⁺ channel. Cysteine string protein (CSP) was the first transmitter release site-associated protein suggested to modulate the Ca²⁺ channel. This protein was discovered independently both as a *Drosophila* mutant⁷⁴ and as a potential Ca²⁺ channel subunit on the grounds that coexpression of CSP with Ca²⁺ channels greatly enhanced the net Ca²⁺ current.⁷⁵ However, the protein was subsequently localized to the secretory vesicle.^{76,77} This observation led to a novel hypothesis linking these two findings: that when the secretory vesicle docks at the transmitter release site CSP increases the excitability of nearby Ca²⁺ channels.⁷⁶ Thus, when an action potential subsequently invades the nerve terminal the CSP-bound, and hence, secretory vesicle associated, Ca²⁺ channels will be preferentially recruited. While CSP appears to have multiple functions in transmitter release,^{78,79} the Ca²⁺ channel modulation hypothesis is supported by the observation that CSP greatly enhances the Ca²⁺ current at intact presynaptic nerve terminals.⁸⁰

Recent studies have identified what may be a different interaction between CSP and Ca²⁺ channels. In these studies the effect of CSP on N-type Ca²⁺ channels was examined by co-expression of the proteins in a cell line. The Ca²⁺ channels were inhibited by a mechanism that likely involves G proteins since the effect was relieved by a strong depolarizing prepulse (see below for an introduction to G protein inhibition of Ca²⁺ channels).⁸¹ Biochemical studies indicated that CSP can bind to both the G protein α and $\beta\gamma$ subunits. While this interaction is interesting there is no clear evidence as yet that CSP generates a tonic G protein-dependent inhibition at the presynaptic nerve terminal.

A different effect has been noted when Ca²⁺ channels are co-expressed with the release site-associated protein, syntaxin I. The evoked Ca²⁺ current exhibited a negative shift in its 'steady state inactivation characteristics (refs. 82-90, but see ref. 91, an effect that is seen with both syntaxin 1A and syntaxin1B.92 In practical terms, this means that at a given resting membrane potential and in the presence of syntaxin I the Ca²⁺ channel is likely to be less recruited during a transient depolarization. This effect has attracted a considerable degree of attention (see reviews, ref. 87) since it has been demonstrated that the negative shift in the inactivation curve can be reversed by the simultaneous expression of other presynaptic proteins including the integral vesicle protein, synaptotagmin. This latter observation led to the following hypothesis.⁸² At the intact release site the Ca²⁺ channel is generally inhibited by its interaction with syntaxin I but when the secretory vesicle docks one of its associated proteins relieves the syntaxin I effect making the local Ca²⁺ channel preferentially excitable. Thus, when an action potential invades the nerve terminal the Ca²⁺ channel next to a 'cocked' secretory vesicle will be more likely to open. This hypothesis is essentially the same as that suggested for CSP and could be complementary since syntaxin could be the 'off' switch while CSP is the 'on'. However, two findings are not entirely consistent with this conclusion. First, the finding that SNAP-25, a non-vesicular, surface membrane release site protein and a functional partner with syntaxin I,93 could also relieve the inhibition has made this hypothesis less attractive. Second, the observations that Ca²⁺ currents in intact presynaptic nerve terminals, where the Ca²⁺ channel should be syntaxin I associated, are very resistant to steady-state inactivation and the finding that cleavage of syntaxin I with botulinum toxin C1 at intact nerve terminals fail to cause large shifts in the Ca²⁺ current inactivation curve raise questions about the biological relevance of this effect at the release site.^{94,95} In contrast, a study using Ca²⁺ sensitive dyes detected an enhanced influx of depolarization-triggered Ca2+ influx into synaptosomes after botulinum treatment.96

Modulation of Presynaptic Ca²⁺ Channels

The recognition that \dot{Ca}^{2+} channel activity can be up or down regulated via second messenger pathways has led naturally to the question as to whether these pathways play a role in the regulation of transmitter release at synapses. Since the numbers of presynaptic terminals is in vast excess over that of the postsynaptic neurons the potential additional processing complexity afforded by regulating transmitter release is enormous.

Interestingly, only a few second messenger pathways have been proposed to regulate presynaptic Ca²⁺ channels. The most important, ubiquitous and generally accepted of these is the membrane delimited G protein linked pathways. This mechanism is of particular interest since it affords a potentially highly rapid and effective means of controlling transmitter release. A second pathway that has been implicated in the modulation of transmitter release is via protein kinase C (PKC) which has been reported to enhance N type Ca²⁺ current.

G Protein Mediated Inhibition

The inhibition of Ca^{2+} channels via neurotransmitter-induced,⁹⁷ G-protein mediated pathways has long been recognized as a potentially critical mechanism for the modulation of transmitter release at synapses.^{97,98} This mechanism of inhibition is described to be 'membrane delimited' and 'voltage sensitive'. The membrane delimited term results from the observation that Ca^{2+} channels recorded in a cell-attached patch are not inhibited when the GPCR agonist is applied to the extra-patch regions of the cell. This isolation is attributed to the fact that the active component of the trimeric G protein, the $\beta\gamma$ subunit, is membrane anchored and, hence, can not traverse the pipette/membrane seal region. The 'voltage sensitivity' term recognizes that the G protein-dependent inhibition of the Ca^{2+} channel is rapidly relieved by a preceding depolarization. In excitatory synapses the most common GPCR mediating this type of inhibition is the Adenosine type1 receptor though several other GPCR types inhibit presynaptic Ca^{2+} channels. As for most N-type Ca^{2+} channels^{99,100} the G proteins involved in this modulation at the presynaptic terminals are usually, if not exclusively, of the $G\alpha_{O/I}$ family,¹⁰¹ despite the fact that other G α protein types can mediate this pathway in experimental models.^{100,102}

There has been some debate as to whether the inhibition of presynaptic Ca^{2+} channels via the G protein pathway actually plays a physiological role in the release of neurotransmitter and whether, since the inhibition is voltage sensitive, it can be relieved by trains of impulses. The answer to these questions are complex and may depend on the cell type or cellular structure examined. Thus, when DRG neurons were used as an experimental model, G protein activation clearly reduced the evoked Ca^{2+} current when tested with short duration action potentials.¹⁰³ Many studies have reported that activation of presynaptic GPCRs will inhibit transmitter efflux but few have tested if this inhibition can be attributed to an effect on Ca^{2+} channels. In a study at the parallel fiber to Purkinje cell synapse activation of GABA(B) or adenosine(A1) receptors reduced both transmitter release and Ca^{2+} influx.¹⁰⁴

If G protein activation can indeed inhibit transmitter release by reducing Ca^{2+} influx then this raises the question as to whether this inhibition be relieved by a train of impulses. This question is complicated by two issues: intrinsic changes in the biophysical properties of the Ca^{2+} channel, such as by inactivation, and, where transmitter release is used as a monitor of channel behaviour, superimposed train-dependent facilitation or depression of the release mechanism. Studies in the DRG cell model, as above, indicated G protein-dependent Ca^{2+} channel inhibition could indeed be relieved during an action potential train.¹⁰² However, in the parallel fiber/Purkinje cell presynaptic model treated with GPCR agonists very little increase (15%) was noted in the amplitude of the action potential-induced Ca^{2+} influx during a train, suggesting that action potential trains were unlikely to result in much inhibitory relief.¹⁰⁴ These two studies can be reconciled by the fact that the action potentials used in the DRG neurons were probably of significantly longer duration than those normally occurring in nerve terminals. Hence, unless a specific synapse type utilizes action potentials of unusually long duration, inhibitory relief due to action potential trains may play a minor factor in neural coding.

The G protein-mediated inhibition pathway is known to be highly rapid. This speed results in part from the involvement of a minimum number of second messenger elements and to the membrane delimited nature of the pathway. The speed from GPCR activation to Ca^{2+} current inhibition has been reported to be as fast as ~1 sec in rat superior cervical ganglion neurons.¹⁰⁵ We do not as yet know how fast this inhibitory pathway is in nerve terminals. The finding that cleavage of syntaxin, a protein associated with the transmitter release site, interferes with the G protein-dependent inhibition of presynaptic Ca^{2+} channels suggests that at the nerve terminal this inhibitory mechanism may be an integral element of the release site itself. Thus, it is possible that the speed of inhibition may be much faster than that determined in somata experimental models.

The finding that cleavage of syntaxin using botulinum toxin C1 interferes with the G protein-dependent inhibition of presynaptic Ca²⁺ channels suggested a structural and functional coupling between G-protein action and the transmitter release site.⁹⁴ It was subsequently found that expression of syntaxin 1A in tsA-201 cells induced a tonic G-protein inhibition that could be greatly attenuated with botulinum toxin C treatment.¹⁰⁶ Recent evidence has suggested that in vitro syntaxin is capable of linking the G β subunit to the Ca²⁺ channel resulting in tonic inhibition. Of particular interest is the finding that this action appears to occur independently of G γ suggesting that syntaxin may act as a G γ substitute.⁹¹

Protein Kinase C

Initial findings that PKC stimulation could increase cellular Ca^{2+} currents suggested that this may represent a unique direct mechanism for the enhancement of transmitter release. However, a detailed study on rat superior cervical ganglion neurons concluded that this increase in transmitter release mediated by PKC could be attributed entirely to the relief of inhibition via the G protein pathway.¹⁰⁷ Few studies have contradicted this conclusion but a recent report suggests that the PKC activator enhances the N-type Ca^{2+} current via changes in channel kinetics, even in the presence of the tonic G protein inhibitor GDP β S and hence, independently of the G protein pathway.¹⁰⁸ The interaction of these pathways is of particular interest and recently protein kinase C has been reported to antagonize syntaxin binding to the channel II-III linker¹⁰⁹ while phorphorylation of the I-II linker upregulates channel activity and antagonizes G protein inhibition.¹¹⁰

Commentary

Since we still have a relatively limited knowledge of how the transmitter release site functions with respect to vesicle exocytosis it is highly likely that we are also barely scraping the surface with respect to the complexities of presynaptic Ca2+ channel function. This field has been hampered by the general inaccessibility of presynaptic nerve terminals to direct experimentation. The emergence of immunoprecipitation as a means of detecting biochemically interacting proteins in neural extracts and cellular expression systems as a means to analyze Ca²⁺ channel functional interactions with potential molecular neighbors has resulted in a surge of findings with respect to the modulation of Ca²⁺ channels. However, enthusiasm with these approaches must be tempered with the simple fact that these approaches alone demonstrate only what can happen. In order to determine if these phenomena actually do occur it is essential to return to the intact presynaptic terminal, despite its complexities. At this stage it is not extreme to hypothesize that the Ca²⁺ channel responds to a host of competing influences: synapse development, incorporation into the release site, docking and exocytosis of secretory vesicles and extraneous modulatory influences, to name but a few. Resolving which particular molecular interactions mediate these processes and how they are suppressed or override each other will be the primary challenge for work in this field.

References

- Locke FS. Notiz über den Einfluss physiologischer Kochsalzlösung auf die elektrische Erregbarkeit von Muskel und Nerv. Pflugers Arch 1894; 8:166-167.
- 2. Katz B. The Release of Neural Transmitter Substances. 1969. Liverpool, Liverpool University Press. Ref Type: Serial (Book,Monograph)
- 3. Katz B, Miledi R. The timing of calcium action during neuromuscular transmission. J Physiol (Lond) 1967; 189:535-544.
- 4. Miledi R. Transmitter release induced by injection of calcium ions into nerve terminals. Proc R Soc Lond (B) 1969; 183:421-425.
- Llinas R, Blinks JR, Nicholson C. Calcium transient in presynaptic terminal of squid giant synapse: detection with acquorin. Science 1972; 176(39):1127-1129.
- 6. Llinas RR, Steinberg IZ, Walton K. Presynaptic calcium currents and their relation to synaptic transmission: Voltage clamp study in squid giant synapse and theoretical model for the calcium gate. Proc Natl Acad Sci USA1976; 73:2918-2922.
- 7. Llinas RR, Steinberg IZ, Walton K. Relationship between presynaptic calcium current and postsynaptic potential in squid giant synapse. Biophys J 1981; 33:323-351.
- Augustine GJ, Charlton MP, Smith SJ. Calcium action in synaptic transmitter release. Annu Rev Neurosci 1987; 10:633-693.
- 9. Hagiwara S, Ozawa S, Sand O. Voltage clamp analysis of two inward current mechanisms in the egg cell membrane of a starfish. J Gen Physiol 1975; 65(5):617-644.
- Carbone E, Lux HD. A low voltage-activated, fully inactivating Ca²⁺ channel in vertebrate sensory neurones. Nature(Lond) 1984; 310(5977):501-502.
- 11. Nowycky MC, Fox AP, Tsien RW. Three types of neuronal calcium channel with different agonist sensitivity. Nature(Lond) 1985; 316:440-443.
- 12. Fox AP, Nowycky MC, Tsien RW. Kinetic and pharmacological properties distinguishing three types of calcium currents in chick sensory neurons. J Physiol (Lond) 1987; 394:149-172.
- Fox AP, Nowycky MC, Tsien RW. Single-channel recordings of three types of calcium channels in chick sensory neurons. J Physiol (Lond) 1987; 394:173-200.
- Hirning LD, Fox AP, McCleskey EW et al. Dominant role of N-type Ca²⁺ channels in evoked release of norepinephrine from sympathetic neurons. Science 1988; 239:57-60.
- Llinás R, Sugimori M, Hillman DE et al. Distribution and functional significance of the P-type, voltage-dependent Ca²⁺ channels in the mammalian central nervous system. Trends Neurosci 1992; 15:351-355.
- Mintz IM, Venema VJ, Swiderek KM et al. P-type calcium channels blocked by the spider toxin omega- Aga-IVA. Nature(Lond) 1992; 355:827-829.
- Hauesler G. Differential effect of verapamil on excitation-secretion coupling in smooth muscle and on excitation-secretion coupling in adrenergic nerve terminals. J Pharmacol Exp Ther 1972; 180:672-682.
- 18. Nachshen DA, Blaustein MP. The effects of some organic calcium antagonists on calcium influx in presynaptic nerve terminals. Mol Pharmacol 1979; 16:576-586.
- 19. Miller RJ. Multiple calcium channels and neuronal function. Science 1987; 235:46-52.
- 20. Miller RJ. Voltage-sensitive Ca2+ channels. J Biol Chem 1992; 267:1403-1406.
- Suszkiw JB, Murawsky MM, Shi M. Further characterization of phasic calcium influx in rat cerebrocortical synaptosomes: inferences regarding calcium channel type(s) in nerve endings. J Neurochem 1989; 52:1260-1269.
- 22. Stanley EF, Atrakchi AH. Calcium currents recorded from a vertebrate presynaptic nerve terminal are resistant to the dihydropyridine nifedipine. Proc Natl Acad Sci USA1990; 87(24):9683-9687.
- 23. Charlton MP, Augustine GJ. Classification of presynaptic calcium channels at the squid giant synapse: neither T-, L- nor N-type. Brain Res 1990; 525:133-139.
- 24. Roberts WM, Jacobs RA, Hudspeth AJ. The hair cell as a presynaptic terminal. Ann NY Acad Sci 1991; 635:221-233.
- Nachman-Clewner M, St Jules R, Townes-Anderson E. L-type calcium channels in the photoreceptor ribbon synapse: localization and role in plasticity. J Comp Neurol 1999; 415(1):1-16.
- 26. Pan ZH. Voltage-activated Ca²⁺ channels and ionotropic GABA receptors localized at axon terminals of mammalian retinal bipolar cells. Vis Neurosci 2001; 18(2):279-288.
- 27. Heidelberger R, Matthews G. Calcium influx and calcium current in single synaptic terminals of goldfish retinal bipolar neurons. J Physiol (Lond) 1992; 447:235-256.
- Tachibana M, Okada T, Arimura T et al. Dihydropyridine-sensitive calcium current mediates neurotransmitter release from retinal bipolar cells. Ann NY Acad Sci 1993; 707:359-361.

- 29. Kerr LM, Yoshikami D. A venom peptide with a novel presynaptic blocking action. Nature(Lond) 1984; 308:282-284.
- 30. Perney TM, Hirning LD, Leeman SE et al. Multiple calcium channels mediate neurotransmitter release from peripheral neurons. Proc Natl Acad Sci USA1986; 83:6656-6659.
- Yoshikami D, Bagaboldo Z, Olivera BM. The inhibitory effects of omega-conotoxins on Ca²⁺ channel and synapses. Ann N Y Acad Sci 1989; 560:230-248.
- Uchitel OD, Protti DA, Sanchez V et al. P-type voltage-dependent calcium channel mediates presynaptic calcium influx and transmitter release in mammalian synapses. Proc Natl Acad Sci USA 1992; 89:3330-3333.
- 33. Fariñas I, Solsona C, Marsal J. Omega-conotoxin differentially blocks acetylcholine and adenosine triphosphate releases from Torpedo synaptosomes. Neuroscience 1992; 47:641-648.
- 34. Hillyard DR, Monje VD, Mintz IM et al. A new conus peptide ligand for mammalian presynaptic Ca²⁺ channels. Neuron 1992; 9:69-77.
- Turner TJ, Adams ME, Dunlap K. Calcium channels coupled to glutamate release identified by omega-Aga-IVA. Science 1992; 258:310-313.
- Wu LG, Borst JG, Sakmann B. R-type Ca²⁺ currents evoke transmitter release at a rat central synapse. Proc Natl Acad Sci USA1998; 95(8):4720-4725.
- 37. Rhee JS, Ishibashi H, Akaike N. Calcium channels in the GABAergic presynaptic nerve terminals projecting to meynert neurons of the rat. J Neurochem 1999; 72(2):800-807.
- Dunlap K, Luebke JI, Turner TJ. Identification of calcium channels that control neurosecretion. Science 1994; 266:828-830.
- Yawo H, Momiyama A. Re-evaluation of calcium currents in pre- and postsynaptic neurones of the chick ciliary ganglion. J Physiol (Lond) 1993; 460:153-172.
- 40. Sivaramakrishnan S, Laurent G. Pharmacological characterization of presynaptic calcium currents underlying glutamatergic transmission in the avian auditory brainstem. J Neurosci 1995; 15(10):6576-6585.
- Iwasaki S, Takahashi T. Developmental changes in calcium channel types mediating synaptic transmission in rat auditory brainstem. J Physiol (Lond) 1998; 509(Pt 2):419-423.
- 42. Pan ZH, Hu HJ, Perring P et al. T-type Ca(2+) channels mediate neurotransmitter release in retinal bipolar cells. Neuron 2001; 32(1):89-98.
- Stanley EF. Single calcium channels and acetylcholine release at a presynaptic nerve terminal. Neuron 1993; 11:1007-1011.
- Dreyer F, Peper K, Akert K et al. Ultrastructure of the "active zone" in the frog neuromuscular junction. Brain Res 1973; 62(2):373-380.
- 45. Harlow M, Ress D, Koster A et al. Dissection of active zones at the neuromuscular junction by EM tomography. J Physiol Paris 1998; 92(2):75-78.
- 46. Heuser JE, Reese TS, Landis DMD. Functional changes in frog neuromuscular junctions studied with freeze fracture. J Neurocytol 1974; 3:109-131.
- Pumplin DW, Reese TS, Llinas RR. Are the presynaptic membrane particles the calcium channels? Proc Natl Acad Sci USA1981; 78:7210-7213.
- Yazejian B, Sun XP, Grinnell AD. Tracking presynaptic Ca²⁺ dynamics during neurotransmitter release with Ca²⁺-activated K+ channels. Nat Neurosci 2000; 3(6):566-571.
- 49. Haydon PG, Henderson E, Stanley EF. Localization of individual calcium channels at the release face of a presynaptic nerve terminal. Neuron 1994; 13:1275-1280.
- Llinas RR, Sugimori M, Simon SM. Transmission by presynaptic spike-like depolarization in the squid giant synapse. Proc Natl Acad Sci USA1982; 79:2415-2419.
- 51. Jenkinson DH. The nature of the antagonism between calcium and magnesium ions at the neuromuscular junction. J Physiol (Lond) 1957; 138:434-444.
- 52. Dodge FA, Jr., Rahamimoff R. Co-operative action of calcium ions in transmitter release at the neuromuscular junction. J Physiol (Lond) 1967; 193:419-432.
- Chad JE, Eckert R. Calcium domains associated with individual channels can account for anomalous voltage relations of Ca²⁺-dependent responses. Biophys J 1984; 45:993-999.
- 54. Brochier G, Gulik-Krzywicki T, Lesbats B et al. Calcium-induced acetylcholine release and intramembrane particle occurrence in proteoliposomes equipped with mediatophore. Biol Cell 1992; 74:225-230.
- Breckenridge LJ, Almers W. Currents through the fusion pore that forms during exocytosis of a secretory vesicle. Neuron 1987; 328:814-817.
- Heuser JE, Reese TS. Structural changes after transmitter release at the frog neuromuscular junction. J Cell Biol 1981; 88(3):564-580.

- 57. Coorssen JR, Blank PS, Tahara M et al. Biochemical and functional studies of cortical vesicle fusion: the SNARE complex and Ca²⁺ sensitivity J Cell Biol 1998; 143(7):1845-1857.
- Jahn R, Hanson PI, Otto H et al. Botulinum and tetanus neurotoxins: Emerging tools for the study of membrane fusion. Cold Spring Harbor Symp Quant Biol 1995; 60:329-335.
- 59. Mackler JM, Drummond JA, Loewen CA et al. The C(2)B Ca(2+)-binding motif of synaptotagmin is required for synaptic transmission in vivo. Nature (Lond) 2002; (6895):340-344.
- Robinson IM, Ranjan R, Schwarz TL. Synaptotagmins I and IV promote transmitter release independently of Ca(2+) binding in the C(2)A domain Nature(Lond) 2002; 418(6895):336-340.
- 61. Geppert M, Goda Y, Hammer RE et al. Synaptotagmin I: a major Ca²⁺ sensor for transmitter release at a central synapse.
- 62. Stanley EF. Decline in calcium cooperativity as the basis of facilitation at the squid giant synapse. J Neurosci 1986; 6:782-789.
- 63. Liu Y, Stanley EF. Calcium binding sites of the transmitter release mechanism: Clues from short-term facilitation. J Physiol (Paris) 1995; 89:161-164.
- 64. Saisu H, Ibaraki K, Yamaguchi T et al. Monoclonal antibodies immunoprecipitating omegaconotoxin-sensitive calcium channel molecules recognize two novel proteins localized in the nervous system. Biochem Biophys Res Commun 1991; 181:59-66.
- 65. Yoshida A, Oho C, Omori A et al. HPC-1 is associated with synaptotagmin and omega-conotoxin receptor. J Biol Chem 1992; 267:24925-24928.
- Bennett MK, Calakos N, Scheller RH. Syntaxin: A synaptic protein implicated in docking of synaptic vesicles at presynaptic active zones. Science 1992; 257:255-259.
- Martin-Moutot N, Charvin N, Leveque C et al. Interaction of SNARE complexes with P/Q-type calcium channels in rat cerebellar synaptosomes. J Biol Chem 1996; 271(12):6567-6570.
- 68. O'Connor VM, Shamotienko O, Grishin E et al. On the structure of the 'synaptosecretosome': Evidence for a neurexin/synaptotagmin/syntaxin/Ca²⁺ channel complex. FEBS Lett 1993; 326:255-260.
- 69. Sheng Z-H, Rettig J, Takahashi M, Catterall WA. Identification of a syntaxin-binding site on N-type calcium channels. Neuron 1994; 13:1303-1313.
- 70. Leveque C, Hoshino T, David P et al. The synaptic vesicle protein synaptotagmin associates with calcium channels and is a putative Lambert-Eaton myasthenic syndrome antigen. Proc Natl Acad Sci USA1992; 89:3625-3629.
- 71. Abe T, Saisu H, Horikawa HPM. Synaptocanalins (N-type Ca²⁺ channel-associated proteins) form a complex with SNAP-25 and synaptotagmin. Ann NY Acad Sci 1993; 707:373-375.
- 72. Coppola T, Magnin-Luthi S, Perret-Menoud V et al. Direct interaction of the Rab3 effector RIM with Ca²⁺ channels, SNAP- 25, and synaptotagmin.
- 73. Spafford JD, Munno DW, Van Nierop P et al. Calcium channel structural determinants of synaptic transmission between identified invertebrate neurons. J Biol Chem 2002.
- 74. Zinsmaier KE, Hofbauer A, Heimbeck G et al. A cysteine-string protein is expressed in retina and brain of Drosophila. J Neurogenet 1990; 7(1):15-29.
- 75. Gundersen CB, Umbach JA. Suppression cloning of the cDNA for a candidate subunit of a presynaptic calcium channel. Neuron 1992; 9:527-537.
- 76. Mastrogiacomo A, Parsons SM, Zampighi GA et al. Cysteine string proteins: A potential link between synaptic vesicles and presynaptic Ca²⁺ channels. Science 1994; 263:981-982.
- Braun JE, Scheller RH. Cysteine string protein, a DnaJ family member, is present on diverse secretory vesicles. Neuropharmacology 1995; 34(11):1361-1369.
- 78. Buchner E, Gundersen CB. The DnaJ-like cysteine string protein and exocytoric neurotransmitter release. Trends Neurosci 1997; 20(5):223-227.
- Chamberlain LH, Burgoyne RD. Cysteine string protein functions directly in regulated exocytosis. Mol Biol Cell 1998; 9(8):2259-2267.
- Chen S, Zheng X, Schulze KL et al. Enhancement of presynaptic calcium current by cysteine string protein. J Physiol 2002; 538(Pt 2):383-389.
- Magga JM, Jarvis SE, Arnot MI et al. Cysteine string protein regulates G-protein modulation of N-type channels. Neuron 2000; 28(1):195-204.
- Bezprozvanny I, Scheller RH, Tsien RW. Functional impact of syntaxin on gating of N-type and Q-type calcium channels. Nature(Lond) 1995; 378(6557):623-626.
- Miralles F, Marsal J, Peres J et al. Niflumic acid-induced increase in potassium currents in frog motor nerve terminals: Effects on transmitter release. Bain Res 1996; 714(1-2):192-200.
- 84. Wiser O, Tobi D, Trus M et al. Synaptotagmin restores kinetic properties of a syntaxin- associated N- type voltage sensitive calcium channel. FEBS Lett 1997; 404(2-3):203-207.

- Bezprozvanny I, Zhong P, Scheller RH et al. Molecular determinants of the functional interaction between syntaxin and N-type Ca²⁺ channel gating. Proc Natl Acad Sci USA 2000; 97(25):13943-13948.
- Degtiar VE, Scheller RH, Tsien RW. Syntaxin modulation of slow inactivation of N-type calcium channels. J Neurosci 2000; 20(12):4355-4367.
- Atlas D. Functional and physical coupling of voltage-sensitive calcium channels with exocytotic proteins: ramifications for the secretion mechanism. J Neurochem 2001; 77(4):972-985.
- Jarvis SE, Zamponi GW. Distinct molecular determinants govern syntaxin 1A-mediated inactivation and G-protein inhibition of N-type calcium channels. J Neurosci 2001; 21(9):2939-2948.
- Lu Q, AtKisson MS, Jarvis SE et al. Syntaxin 1A supports voltage-dependent inhibition of alpha1B Ca²⁺ channels by Gbetagamma in chick sensory neurons. J Neurosci 2001; 21(9):2949-2957.
- 90. Tobi D, Wiser O, Trus M et al. N-type voltage-sensitive calcium channel interacts with syntaxin, synaptotagmin and SNAP-25 in a multiprotein complex. Receptors Channels 1998; 6(2):89-98.
- 91. Mochida S, Saisu H, Kobayashi H et al. Impairment of syntaxin by botulinum neurotoxin C_1 or antibodies inhibits acetylcholine release but not Ca^{2+} channel activity. Neuroscience 1995; 65:905-915.
- Jarvis SE, Barr W, Feng ZP et al. Molecular Determinants of Syntaxin 1 Modulation of N-type Calcium Channels. J Biol Chem 2002; 277(46):44399-44407.
- 93. McMahon HT, Südhof TC. Synaptic core complex of synaptobrevin, syntaxin, and SNAP25 forms high affinity a-SNAP binding site. J Biol Chem 1995; 270:2213-2217.
- 94. Marsal J, Ruiz-Montasell B, Blasi J et al. Block of transmitter release by botulinum C1 action on syntaxin at the squid giant synapse. Proc Natl Acad Sci USA1997; 94(26):14871-14876.
- Stanley EF, Mirotznik RR. Cleavage of syntaxin prevents G-protein regulation of presynaptic calcium channels. Nature(Lond) 1997; 385(6614):340-343.
- 96. Bergsman JB, Tsien RW. Syntaxin modulation of calcium channels in cortical synaptosomes as revealed by botulinum toxin C1. J Neurosci 2000; 20(12):4368-4378.
- 97. Dunlap K, Fischbach GD. Neurotransmitters decrease the calcium conductance activated by depolarization of embryonic chick sensory neurones. J Physiol 1981; 317:519-535.
- 98. Scott RH, Dolphin AC. Regulation of calcium currents by a GTP analogue: potentiation of (-)-baclofen-mediated inhibition. Neurosci Lett 1986; 69:59-64.
- 99. Hille B. Modulation of ion channels by G-protein coupled receptors. TINS 1994; 17:531-535.
- Ikeda SR, Dunlap K. Voltage-dependent modulation of N-type calcium channels: role of G protein subunits. Adv Second Messenger Phosphoprotein Res 1999 1999;131-151.
- 101. Mirotznik RR, Zheng X, Stanley EF. G-Protein types involved in calcium channel inhibition at a presynaptic nerve terminal. J Neurosci 2000; 20(20):7614-7621.
- 102. Hille B, Beech DJ, Bernheim L et al. Multiple G-protein-coupled pathways inhibit N-type Ca²⁺ channels of neurons. Life Sci 1995; 56:989-992.
- 103. Park D, Dunlap K. Dynamic regulation of calcium influx by G-proteins, action potential waveform, and neuronal firing frequency. J Neurosci 1998; 6757-6766.
- 104. Kreitzer AC, Regehr WG. Retrograde signaling by endocannabinoids. Curr Opin Neurobiol 2002; 12(3):324-330.
- 105. Stotz SC, Zamponi GW. Structural determinants of fast inactivation of high voltage-activated Ca(2+) channels. Trends Neurosci 2001; 24(3):176-181.
- 106. Jarvis SE, Magga JM, Beedle AM et al. G protein modulation of N-type calcium channels is facilitated by physical interactions between syntaxin 1A and Gbetagamma. J Biol Chem 2000; 275(9):6388-6394.
- 107. Barrett CF, Rittenhouse AR. Modulation of N-type calcium channel activity by G-proteins and protein kinase C. J Gen Physiol 2000; 115(3):277-286.
- 108. Garcia-Ferreiro RE, Hernandez-Ochoa EO, Garcia DE. Modulation of N-type Ca²⁺ channel current kinetics by PMA in rat sympathetic neurons.
- 109. Yokoyama CT, Sheng ZH, Catterall WA. Phosphorylation of the synaptic protein interaction site on N- type calcium channels inhibits interactions with SNARE proteins. J Neurosci 1997; 17(18):6929-6938.
- 110. Zamponi GW, Bourinet E, Nelson D et al. Crosstalk between G proteins and protein kinase C mediated by the calcium channel a1 subunit. Nature(Lond) 1997; 385:442-446.

Determinants of G Protein Inhibition of Presynaptic Calcium Channels

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Summary

The modulation of presynaptic calcium channels following the activation of G-protein coupled receptors is a key regulatory mechanism of synaptic transmission. The past two decades have yielded a tremendous advance in our understanding of this phenomenon at the molecular level. It is now widely accepted that the closed conformation of the channel is stabilized upon binding of G protein $\beta\gamma$ dimers directly to the cytoplasmic region linking domains I and II, and perhaps also to the C-terminus region, of the calcium channel α_1 subunit. The channels consequently become reluctant to open, resulting in inhibition of current activity. The molecular mechanisms that control G protein regulation of calcium channels are immensely complex, as the extent of modulation depends on the membrane potential, G β subunit subtype, the presence of ancillary calcium channel subunits, PKC-dependent phosphorylation of the channel, RGS proteins, and on interactions with the presynaptic vesicle release protein complex. These intricate interactions between second messenger pathways, synaptic release proteins, calcium channels and G proteins allow for the potential of fine tuning the entry of calcium into the presynapse, and consequently, neurotransmitter release.

Introduction

The influx of calcium ions through voltage gated calcium channels triggers a wide array of cytoplasmic processes, including excitation contraction coupling in heart muscle, the activation of calcium dependent enzymes, calcium dependent gene transcription, and the release of neurotransmitter from presynaptic nerve terminals.¹⁻⁶ Most neurons express multiple types of calcium channels (i.e., L-, N-, T-, P-, Q-, and R-types), of which the N-type and P/Q-type are targeted predominantly to presynaptic nerve terminals.⁷⁻¹⁰ Calcium entry through these channels is triggered by incoming action potentials, which have propagated along the axon, and culminates in the release of neurotransmitter. Hence, any inhibition of these channels by either pharmacological agents, or cytoplasmic messengers, results in decreased neurotransmission. One of the key cellular mechanisms regulating presynaptic calcium influx is the activation of G protein coupled receptors (GPCRs) linked to either $G\alpha_0$ (the main neuronal $G\alpha$ isoform) or $G\alpha_i$ proteins (see ref. 11). Agonist binding to these receptors activates a cytoplasmic messenger response that ultimately depresses calcium channel activity. The significance of this inhibitory pathway is illustrated by the opioid receptor control of pain transmission in dorsal root ganglion cells. Activation of opioid or opioid like receptors downregulates N-type calcium channel activity, and hence, the transmission of pain signals in the spinal cord (for review, see ref. 12). Here, we shall provide an overview of our current state of understanding of the molecular mechanisms that underlie GPCR control of presynaptic calcium channels.

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Functional Consequences of Direct G Protein Action on Calcium Channels

The phenomenon of G-protein inhibition of calcium currents was first discovered over two decades ago.¹³ Using chick DRG neurons, Dunlap and Fischbach¹³ elegantly showed that the application of serotonin or adrenergic receptor agonists resulted in a pronounced inhibition of calcium currents. In the ensuing years, a number of additional GPCRs have been shown to inhibit voltage gated calcium channels, including muscarinic, opioid and somatostatin receptors.^{2,14-26} It was also noted that the receptor mediated inhibition could typically be abolished following treatment with pertussis toxin (an inhibitor of G α_0 and G α_1 proteins), and could be blocked with GDP β S. These results indicated that a G protein pathway was involved in calcium channel inhibition.¹⁵ However, curiously, the inhibitory effects appeared to occur independently of a soluble second messenger, giving rise to the term "direct membrane delimited inhibition"¹⁴ (for review, see ref. 11).

In whole cell patch clamp recordings, membrane delimited G protein inhibition of N-type and P/Q-type calcium channels is observed as a reduction in peak current amplitude, accompanied by an often dramatic slowing of the apparent rate of activation, and inactivation (see Fig. 1A, inset). Moreover, the degree of inhibition is strongly dependent on the membrane potential such that inhibition is more effective at hyperpolarizing voltages.^{17,18,27} This effect arises predominantly from a rightward shift in the activation curve of the channel, which indicates that in the presence of G proteins, channels have a reduced probability of opening at any given potential. This pronounced voltage dependence results in a destabilization of the G protein inhibited channel conformation at depolarized voltages, such that G protein inhibition can be effectively relieved by application of strongly depolarizing voltage steps (or prepulses before the test depolarization, see Fig. 1B)^{11,27-30} or following a rapid train of action potentials.^{31,32} This has given rise to the term "prepulse facilitation," although the term "prepulse relief of G protein inhibition" is probably a more accurate reflection. It is noteworthy that the relief from inhibition following the rapid successive membrane depolarizations may contribute to the magnitude of paired pulse facilitation at the synapse, such that in the presence of G protein receptor agonists, the degree of paired pulse facilitation is augmented.^{33,34} Thus, the de-inhibition of G protein modulated presynaptic calcium channels could significantly contribute to short term plasticity.

Single channel patch clamp recordings reveal that the first latency to opening is increased following GPCR activation, without any detectable effect on single channel conductance.³⁵ It is interesting to note that this can account for all of the functional consequences at the whole cell level. The increase in first latency to opening results in a slowing of the macroscopic time course of activation, and a reduced open probability at intermediate test potentials. At greater membrane depolarizations, the decrease in first latency becomes diminished, thus resulting in less inhibition. Moreover, due to the occurrence of late openings, the apparent macroscopic time constant for inactivation appears increased, thus accounting for the slower inactivation kinetics. The G protein induced change in the probability of opening gave rise to the terminology of "willing" (i.e., non inhibited) and "reluctant" (inhibited) gating modes of the channels.^{17,25,27,36,37} Thus, in order for a channel to open, the channel needs to become disinhibited by the G protein, hence accounting for the increase in first latency to opening. However, this may not be universally true, as there is increasing evidence from modeling data that N-type channels (but apparently not P/Q-type channels) are able to undergo reluctant openings, albeit with a relatively low probability.^{38,39} As will be discussed in the ensuing section, the disinhibition of channels appears to be linked to a physical dissociation of the G proteins from the channel complex. It may ultimately be interesting to attempt to correlate G protein dissociation with channel kinetics by combining single channel recordings with FRET analysis.



Figure 1. A) Schematic representation of GPCR signaling to N-type calcium channels. Activation of a GPCR results in the dissociation of the heterotriomeric G protein complex. The G protein $\beta\gamma$ subunit physically interacts with binding sites in the calcium channel domain I-II linker, and in the C-terminus region. Inset: Whole cell patch clamp recording from a tsA-201 cell expressing Ca_v2.2 (+ $\beta_{1b}+\alpha_2-\delta$) channels. Application of 100 nM somatostatin (agonist) activates endogenous somatostatin receptors and results in a peak current inhibition, as well as kinetic slowing. B) Prepulse relief of tonic G protein inhibition mediated by overexpression of G $\beta_1\gamma_2$ in tsA-201 cells expressing N-type channels. Top. Pulse paradigm to study prepulse relief. A 50 ms prepulse to +150 mV 5 ms prior to a typical test depolarization results in unbinding of the G proteins from the channels, thus revealing disinhibited N-type currents (see recordings +PP). In the absence of the prepulse, a smaller current with slower kinetics is observed.

Stoichiometry between G Proteins and the Calcium Channel

Nearly a decade ago, there was a debate about the G protein/channel stoichiometry, and as to whether G proteins physically dissociate during prepulse relief.^{11,17,20,25,36,37} Boland and Bean³⁶ suggested that G protein inhibition of N-type calcium channels involved a simultaneous interaction of the channel with 4 G-proteins (see review by ref. 11). Moreover, the authors suggested that prepulse relief required the dissociation of the G protein subunits.³⁶ Golard and Siegelbaum²⁵ proposed an analogous model based on two G protein molecules. Other groups suggested different models in which strong membrane depolarizations were proposed to result in a temporary conformational change in the channel protein, which decays over time.¹⁷ This question is best addressed with a stoichiometric experiment examining the dependence of recover from prepulse relief on G protein concentration. One possible means to address this issue is to examine the G protein concentration dependence underlying the inhibition. In case of a conformational change, one would expect the recovery kinetics to be G protein concentration independent. This was examined by Zamponi and Snutch²⁸ by adding various concentrations of purified G protein subunits to the intracellular recording solution, showing that the time constant for re-inhibition of the channel following the application of the prepulse was inversely proportional to the G protein concentration in the pipette. Moreover, the concentration dependence was best described by a model based on a 1:1 stoichiometry between the G proteins and the channel.²⁸ Subsequently, this was supported further by elegant modeling data of Bertram and Behan.³⁴

G Protein Modulation Depends on the Nature of the Calcium Channel Subunits

Among native calcium channels, membrane delimited inhibition is typically not observed with L-type, T-type, or R-type calcium channels. In contrast both N-type and P/Q-type calcium channels can be inhibited by G proteins, albeit to different extents,⁴⁰ with the N-type channels typically showing a greater degree of inhibition. As with many other functional properties of voltage gated calcium channels, a detailed investigation into the molecular details of G protein inhibition is more effectively conducted using recombinant expression systems. For transiently expressed calcium channels, the selective modulation of presynaptic calcium channels, and more specifically, the differential inhibition of N-type and P/Q-type channels was first examined by Bourinet et al⁴¹ in Xenopus oocytes. Using co-expressed µ-opioid receptors to activate G proteins, neither Ca, 1.2 nor Ca, 2.3 channels seemed to be susceptible to inhibition. In contrast, Ca. 2.2 (N-type) showed a robust (~55%) inhibition that was two-to three fold greater than that of Ca_v2.1 (P/Q-type) channels. However, the modulation of the Ca_v2.1 channels was dramatically enhanced when the calcium channel B subunit was omitted, consistent with data of Campbell et al⁴² This important result was subsequently confirmed by a number of other groups. 43^{245} Curiously, in the absence of the β subunit, Ca₂2.3 channels became sensitive to G protein inhibition,^{46,47} indicating that the structural homology among the Cav2 calcium channel family allows for a fundamentally conserved ability of Ca.2 channels to be regulated by G proteins. The fact that the presence of the calcium channel β subunit could regulate the extent of G protein inhibition of Ca. 2 channels raised that possibility that the type of calcium channel β subunit that is co-expressed could affect G protein regulation. Indeed, as shown recently by both the Dolphin laboratory (see refs. 48, 49) and our group,⁵⁰ this is indeed the case. Both for receptor mediated inhibition, and in the presence of co-expressed G proteins, the nature of the calcium channel beta subunit appears to regulate the extent of G protein inhibition of N-type calcium channels. In particular, in the presence of the rat β_{2a} subunit, the extent modulation and particularly the degree of kinetic slowing became dramatically enhanced (Dolphin lab, also see refs. 50-52). The rat β_{24} subunit is unique as it contains two cysteine residues at its N-terminal and which can be palmitoylated.⁵³ Replacement of these cysteines with serines significantly attenuates the effect of β_{2a} on kinetic slowing;⁵⁰ suggesting the possibility that palmitoylation of calcium channel subunits could be a regulatory mechanism of G protein inhibition. To date, it is unclear if the remaining calcium channel subunits (α_2 - δ , γ) are determinants of G protein inhibition of calcium channels.

Gβ Subunits Mediate Calcium Channel Inhibition

The activation of GPCRs results in the dissociation of the G α subunit from the G $\beta\gamma$ complex. Historically, the G α subunit was considered to be the active G protein species, but it is now clear that the G $\beta\gamma$ dimer also acts as an essential signaling molecule (Fig. 1). An involvement of the G $\beta\gamma$ complex in N-type calcium channel inhibition was first suggested by Bourinet et al⁴¹ but first demonstrated by Ikeda⁵⁴ and Herlitze et al⁵⁵ The authors showed that overexpression of G $\beta\gamma$, but not G α could mimic the effects of GPCR activation on calcium channel function (see also Fig. 1B). Along these lines, addition of purified G $\beta\gamma$ subunits to the intracellular solution in patch clamp experiments is sufficient to induce G protein regulation.⁵⁶ The degree of G protein inhibition appears to depend on the type of G β subunit dependence of the inhibition. Garcia et al⁵⁷ reported that in bullfrog sympathetic neurons, G β_1 and G β_2 both effectively inhibited N-type channel activity, with a smaller effect caused by G β_3 , while no inhibition was observed with either G β_4 or G β_5 . Using the same experimental setting, Ruiz-Velasco and Ikeda⁵⁸ determined that all of the G β isoforms with the exception of G β_5 inhibited N-type channels. However, both groups utilized native N-type channels, which due

to alternate splicing⁶⁰ and β subunit heterogeneity may not form a homogeneous population of channels. Using tsa-201 cells as an expression system to co-express individual types of calcium channels with cloned G β subunits, allows one to investigate the interaction between a homogeneous population of calcium channels with a single identified G protein species. Using this approach, Arnot et al³⁰ reported that rat Ca_v2.2 channels were effectively inhibited by G β_1 and G β_3 , with less inhibition by G β_4 and G β_2 , and no effect by G β_5 . This contrasts with data obtained with human Ca_v2.2 channels⁶¹ where a small degree of inhibition is also seen with G β_5 . Rat Ca_v2.2 channels were most potently inhibited by G β_4 ,³⁰ but overall seemed to be less susceptible to inhibition, consistent with the earlier work of Bourinet et al.⁴¹ More recently, Feng et al⁵⁰ showed that the relative rank order of the inhibitory effects of different G β subunits on N-type calcium channel activity is affected by the type of calcium channel β subunit, thus adding further complexity to the regulation of presynaptic calcium channels by G $\beta\gamma$. Despite several attempts, ^{62,63} it remains to be determined whether individual types of GPCRs can couple to N-type calcium channels via specific subsets of G β subunits.

The G γ subunit cannot by itself support G protein inhibition of voltage gated calcium channels; however, it is not clear if its presence is required for inhibition. While Herlitze et al⁵⁵ showed that in transient expression systems, the G γ subunit is not needed, Ikeda's work⁵⁴ in intact neurons suggest a need for G γ to be present. Transiently expressed G β might perhaps be able to combine with endogenous G γ . Even if there is a need to co-express a G γ subunit, the particular type of G protein γ subunit seems to be a relatively minor determinant of calcium channel inhibition.⁵⁸

Taken together, the differential modulation of individual presynaptic calcium channel complexes, by different combinations of Gβγsubunits adds to the capability of neurons to fine tune presynaptic calcium channel activity via GPCR activation.

Channel and G Protein Structural Basis of G Protein Modulation

The first attempt to delineate the calcium channel structural determinants of Gβγ modulation was based on a chimeric approach using Cav2.2 and Cav2.1 channels as a template.⁶⁴ This work suggested that domain I, and the carboxy terminal region of the channel, were important for G protein inhibition. By combining electrophysiological, molecular biological and biochemical techniques, Zamponi et al⁵⁶ and DeWaard et al⁶⁵ identified two separate sites in the domain I-II linker of Ca_v2.1 and Ca_v2.2 channels that could physically bind to G $\beta\gamma$ subunits (Fig. 1A). It is interesting to note that one of the two G $\beta\gamma$ binding sites in the I-II linker overlaps with the calcium channel β subunit interaction site, consistent with the observation that calcium channel β subunit subtype regulates G protein action.^{41,42,48,50} Despite some contradictory results by Qin et al⁴⁷ who suggested that the I-II linker region was inconsequential for G protein action, a number of other groups have now shown that the domain I-II linker is of critical importance of G protein action. 66,44 However, additional evidence implicating the C-terminus region of the Ca_v2.3 calcium channel as a G protein target has been presented,⁴⁷ suggesting that there may be as many as three distinct G protein binding sites on the N-type calcium channel (Fig. 1A). To make matters even more complicated, work from the Mori laboratory⁶⁷⁻⁶⁹ revealed that the C-terminus region of P/Q-type calcium channels could also associate with G α subunits in vitro but the exact functional significance of this finding remains unclear. In addition, other regions of the N-type calcium channel have also been implicated in G protein inhibition, including the N-terminus. 45,51,70-72 However, as no direct binding interactions between $G\beta\gamma$ and this region of the channel have been shown, it seems likely that this region is involved in G protein inhibition of the channel in general, rather than in G protein binding per se. For example, it is possible that the N-terminus could be involved in translating G protein binding into a change in the activation properties of the channel.

Unlike with the channel structural determinants that control G protein inhibition, only limited information is available about the G β subunit structural determinants. A study by Ford et al⁷³ identified several important residues on G β that seem to regulate the ability of G β_5 to modulate N-type channels, but interestingly, these residues are entirely conserved in all type of G β subunits, and hence cannot account for the G β subtype dependent effects observed by us and other groups.^{30,57,58} Thus, there must be other residues in G β that contribute to G protein inhibition of presynaptic calcium channels. Our group has recently elucidated G protein β subunit structural determinants that underlie the inhibition of N-type calcium channels. We showed that regulation of N-type channel activity is mediated by at least three distinct G β regions. Moreover, we identified a pair of asparagine residues in positions 35 and 26 of the G β_1 subunit that are unique to G β_1 , and which allow this subunit to detect PKC-dependent phosphorylation of the N-type calcium channel I-II linker.^{73a}

Interactions between G Protein and Protein Kinase C (PKC) Pathways

The activation of PKC results in an intrinsic upregulation of N-type calcium channel activitv. 56,74,75 In addition, however, PKC activation antagonizes inhibition of N-type calcium channels by a range of different GPCRs in both native neurons^{76,77} and in transient expression systems.^{56,59,75} Interestingly, the magnitude of this effect varies with GPCR subtype, indicating some specificity for the G protein cascades activated by these individual receptors. The putative GBy binding region of the N-type channel I-II linker contains two PKC consensus sites, T422 and S425.^{56,75} Using site directed mutagenesis of these residues, Hamid et al^{/>} were able to show that showed that phosphorylation of either one of these two PKC sites resulted in an all or none upregulation of current activity. By contrast, PKC phosphorylation of the T422, but not the S425 residue, could antagonize G protein inhibition triggered by somatostatin receptor activation (see Fig. 2, ref. 75). The effect of phosphorylation of this residue differentially affected somatostatin and opioid receptor mediated inhibition of the channel.⁵⁹ Cooper et al⁵⁹ showed that only responses mediated by $G\beta_1$ were affected by phosphorylation of T422, while other types of GB subunits were not affected. Thus, depending on which GB subunit a particular GPCR can couple to, one may expect more or less G protein-PKC crosstalk, thereby perhaps proving a molecular explanation for the varying degrees of crosstalk seen in native cell.⁷⁷ and the differential sensitivity of opioid and somatostatin mediated inhibition to PKC activation.

In some types of native neurons, the effects of PKC dependent phosphorylation on N-type channel activity appear to be linked predominantly to a removal of tonic G protein inhibition rather than an intrinsic upregulation of N-type channel activity.⁷⁸ The differences with the work on expressed channels could perhaps be due to alternative splicing events, such as in the domain I-II linker region (see ref. 60), constitutive activation of other second messengers in these neurons, or perhaps even the type of calcium channel β subunit that is expressed.

RGS Proteins and G Protein Modulation of Calcium Channels

A key regulatory mechanism of G protein signaling are regulator of G protein signaling (RGS) proteins. This family of proteins modulates G protein function by three pathways: First, they accelerate GTP hydrolysis of the G α subunit,⁷⁹ thus favoring the reassociation of the G $\alpha\beta\gamma$ complex and termination of receptor mediated G protein action.⁸⁰ Second, some members of the RGS family can interfere with the interactions between G α subunits and their effectors.⁸¹ Finally, several types of RGS proteins (RGS6, RGS7, RGS9, and RGS11) can associate with G β molecules (in particular, G β_5) through G protein gamma subunit like (GGL) domains, and interfere with G β action on effector systems.⁸²

Effects of RGS proteins on G protein inhibition of calcium channels have only recently been described.⁸³⁻⁸⁷ Muscarinic and adrenergic inhibition of N-type channels is attenuated by various RGS proteins (RGS3, RGS4, RGS4) via a reduction of free G $\beta\gamma$ levels.^{84,86} Consistent



Figure 2. Top: Schematic illustration of G protein PKC crosstalk at the level of the N-type calcium channel. G protein modulation of mediated by somatostatin receptor activation is antagonized by activation of a receptor pathway coupled to PKC (i.e., mGluR1). Phosphorylation of residue T422 in the N-type channel domain I-II linker antagonizes G protein interactions with the channel. Bottom: In tsA-201 cells expressing the N-type calcium channel and G $\beta_1\gamma_2$, direct activation of PKC via phorbol esters reduces the degree of prepulse relief, thus indicating that G protein inhibition of the channels was antagonized by PKC activation (see ref. 59). The records were scaled to facilitate comparison. Note that the effect is specific for G β_1 mediated responses.

with such a mechanism, dialysis of neurons with an RGS4 antibody enhances norepinephrine inhibition of N-type channels in chick DRGs.⁸⁵ Finally, Zhou et al⁶¹ showed that RGS proteins could regulate G β_5 mediated inhibition of heterologously expressed human N-type calcium channels. Taken together, these observations support an important role of RGS proteins in N-type calcium channel modulation.

Interactions between G Proteins and Synaptic Release Proteins

Besides binding G $\beta\gamma$, presynaptic calcium channels also physically couple to proteins involved in neurotransmission, such as syntaxin 1 and SNAP-25. These proteins interact with the domain II-III linker regions of both Ca_v2.1 and Ca_v2.2 calcium channels.⁸⁸⁻⁹⁰ This raised the possibility that there might be functional effects of synaptic proteins on G protein inhibition of voltage gated calcium channels. Indeed, experiments by Stanley and Mirotznik⁹¹ showed that cleavage of syntaxin 1 via botulinum toxin C1 abolishes the ability of N-type calcium channels by G proteins (triggered by GTP γ S application), suggesting that syntaxin 1A may be required in order for G protein inhibition of N-type channels to occur. And yet, in transient expression system that lack syntaxin (such as *Xenopus* oocytes or tsa-201 cells), G protein inhibition can be readily observed, raising the possibility that syntaxin 1A may perhaps only have a modulatory function. In accordance with such a mechanism, Jarvis et al⁹² showed that the coexpression of syntaxin 1A with N-type calcium channels resulted in a tonic G protein inhibition of the channels in the absence of any exogenous activation of the G protein pathway (see



Figure 3. The presence of syntaxin 1A induces tonic G protein regulation of N-type channels expressed in tsA-201 cells. A) In the absence of syntaxin, endogenous G $\beta\gamma$ subunits are unlikely to associate with N-type channels, thus no prepulse relief can be observed (see whole cell tracings). B) Syntaxin colocalizes endogenous G β with the N-type channels, leading to tonic G protein inhibition which can be relived by application of a prepulse. C) Cleavage of syntaxin 1A with botulinum toxin C1 removes the tonic inhibition induced by syntaxin.

Fig. 3). Overexpression of a peptide corresponding to the syntaxin binding site on the channel, or cleavage of syntaxin 1 via botulinum toxin C abolished this effect (Fig. 3). 92,93 The authors also showed that syntaxin 1A could concomitantly bind to $G\beta$ and to the N-type calcium channels, thus acting like a chaperone to colocalize free endogenous GB and the calcium channel. Interestingly, more recent work⁹⁴ showed that this binding interaction occurred in the absence of the Gy subunit, raising the possibility that syntaxin 1A might perhaps act as a GGL protein. The syntaxin 1 induced modulation was maintained in the presence of other synaptic protein such as SNAP25 and n-Sec1,93 and was also observed in intact chick DRG neurons.95 Surprisingly, despite 85% sequence identity to syntaxin 1A, the syntaxin 1B isoform could not induce tonic modulation of N-type channels despite binding both to the channel and to GB.94 Hence, depending on which syntaxin 1 isoform is expressed in a given neuron, tonic, receptor independent G protein regulation may or may not occur. Moreover, the notion that the expression of certain P/O-type calcium channel isoforms can trigger the expression of syntaxin 1A through calcium dependent gene transcription⁹⁶ suggests the possibility that P/Q-type calcium channels can indirectly regulate N-type calcium channel activity. It is noteworthy that the syntaxin G protein interactions are not confined to calcium channels, but seem to play a major role in modulation of voltage gated potassium channels.97

Besides syntaxin 1A, cysteine string protein (CSP) also appears to chaperone G proteins towards to N-type calcium channel to induce tonic modulation.⁹⁸

Moreover, both the J-domain and cysteine string domain of CSP appear to be able to stimulate G protein modulation of the channel, albeit through separate pathways, with the cysteine string region serving to anchor G proteins close to the channel, whereas the effects of the J-domain do not depend on the interaction with the calcium channel per se, and may instead occur indirectly.⁹⁹ It remains unclear as to whether the binding of G β to CSP involves the G γ subunit. The fact that synaptic proteins can interact with G protein subunits suggests the possibility that G proteins might be able to directly regulate synaptic activity, independently of their action on presynaptic calcium channels. Indeed, in lamprey neurons, the binding of G $\beta\gamma$ to syntaxin 1 and SNAP25 appears to regulate neurotransmitter release without involving voltage gated calcium channels,¹⁰⁰ thus adding to the complement of modulatory mechanisms in the presynapse.

Conclusion

Over the past five years, tremendous advances in our understanding of G protein regulation of presynaptic calcium channels have occurred, including the identification of G $\beta\gamma$ as the active G protein species, novel insights into channel and G protein structure an function, and novel concepts of interactions between the synaptic release machinery and G proteins. This intricate web of complex interactions within the presynaptic nerve terminal provides for a plethora of avenues for precise control of calcium homeostasis, and exocytosis.

Notes Added in Proof

Recently, we revealed that N-type calcium channels and opioid receptor like (ORL1) receptors form a signalling complex.¹⁰¹ A low levels of constitutive receptor activity mediates tonic G protein inhibition of complexed channels in the absence of receptor agonist. As a result, N-type channel activity can be regulate by variations in ORL1 receptor density.

Two recent studies based on fluorescence resonance energy transfer measurements aimed to determine whether the calcium channel β subunit remains associated with P/Q-type calcium channels when G protein β subunits are activated. While the Herlitze laboratory¹⁰² reached the conclusion that the calcium channel β subunit remains attached to the calcium channel in the presence of G $\beta\gamma$, the deWaard laboratory¹⁰³ reported that the calcium channel β subunit dissociated from the channel following G protein activation. Our own electrophysiological measurements⁵⁰ support, in principle, the conclusions reached by the Herlitze group. Indeed, upon coexpression of different types of calcium channel β subunits with Ca₂2.2 calcium channels, the current kinetics seen in the presence of G $\beta\gamma$ vastly differ, which implies that the calcium channel β subunit can still regulate channel activity following G protein activation. This clearly argues against a dissociation of the calcium channel β subunit from the calcium channel complex.

Finally, work from the Barrett lab showed that Ca_3.2 T-type calcium channels can be inhibited by G protein $\beta 2$ subunits. 104

References

- 1. Tsien RW, Lipscombe D, Madison DV et al. Multiple types of neuronal calcium channels and their selective modulation. Trends Neurosci 1988; 11(10):431-438.
- 2. Bean BP. Classes of calcium channels in vertebrate cells. Annu Rev Physiol 1989a; 51:367-384.
- 3. Wheeler DB, Randall A, Tsien RW. Roles of N-type and Q-type channels in supporting hippocampal synaptic transmission. Science 1994; 264(5155):107-111.
- Dunlap K, Luebke JL, Turner TJ. Exocytotic Ca⁺⁺ channels in the mammalian central nervous system. Trends Neurosci 1995; 18(2):89-98.
- 5. Sutton KG, McRory JE, Guthrie H et al. P/Q-type calcium channels mediate the activity-dependent feedback of syntaxin-1A. Nature 1999; 401(6755):800-804.
- 6. Dolmetsch RE, Pajvani U, Fife K et al. Signaling to the nucleus by an L-type calcium channel-calmodulin complex through the MAP kinase pathway. Science 2001; 294(5541):333-339.
- 7. Westenbroek RE, Hell JW, Warberm C et al. Biochemical properties and subcellular distribution of an N-type calcium channel alpha 1 subunit. Neuron 1992; 9(6);1099-1115.

- Westenbroek RE, Sakurai T, Elliott EM et al. Immunochemical identification and subcellular distribution of the alpha 1A subunits of brain calcium channels. J Neurosci 1995; 15(10):6403-6418.
- 9. Hell JW, Westenbroek RE, Warner C et al. Identification and subcellular localization of the neuronal class C and D L-type calcium channel alpha 1 subunits. J Cell Biol 1993; 123(4):949-962.
- Maximov A, Bezprozvanny I. Synaptic targeting of N-type calcium channels in hippocampal neurons. J Neurosci 2002; 22(16):6939-52.
- Hille B. Modulation of ion-channel function by G-protein-coupled receptors. Trends Neurosci 1994; 17(12):531-536.
- Beedle AM, Zamponi GW. Molecular determinants of opioid analgesia: Modulation of presynaptic calcium channels. Drug Dev Res 2001; 54: 118-128.
- 13. Dunlap K, Fischbach GD. Neurotransmitters decrease the calcium conductance activated by depolarization of embryonic chick sensory neurones. J Physiol 1981; 317:519-535.
- Forscher P, Oxford G, Schulz D. Noradrenaline modulates calcium channels in avian dorsal root ganglion cells through tight receptor-channel coupling. J Physiol 1986; 379:131-144.
- Holz GG, Rane SG, Dunlap K. GTP-binding proteins mediate transmitter inhibition of voltage-dependent calcium channels. Nature 1986; 319(6055):670-672.
- Ikeda SR, Schofield G. Somatostatin blocks a calcium current in rat sympathetic ganglion neurones. J Physiol 1989; 409:221-240.
- 17. Kasai H, Aosaki T. Modulation of Ca-channel current by an adenosine analog mediated by a GTP-binding protein in chick sensory neurons. Pfluegers Arch 1989; 414(2):145-149.
- Lipscombe D, Kongsamut S, Tsien RW. α-adrenergic inhibition of sympathetic neurotransmitter release mediated by modulation of N-type calcium-channel gating. Nature 1989; 340(6235):639-642.
- 19. Ikeda SR. Prostaglandin modulation of Ca²⁺ channels in rat sympathetic neurones is mediated by guanine nucleotide binding proteins. J Physiol 1992; 459():339-359.
- 20. Beech DJ, Bernheim L, Hille B. Pertussis toxin and voltage dependence distinguish multiple pathways modulating calcium channels of rat sympathetic neurons. Neuron 1992; 8(1):97-106.
- Bernheim L, Mathie A, Hille B. Characterization of muscarinic receptor subtype inhibiting Ca²⁺ current and M current in rat sympathetic neurons. Proc Natl Acad Sci USA 1992; 89(20):9544-9548.
- Zhu Y, Ikeda SR. Adenosine modulates voltage-gated Ca²⁺ channels in adult rat sympathetic neurons. J Neurophysiol 1993; 70(2):610-620.
- Mintz IM, Bean BP. GABA_B receptor inhibition of P-type Ca²⁺ channels in central neurons. Neuron 1993; 10(5):889-898.
- 24. Shapiro MS, Hille B. Substance P and somatostatin inhibit calcium channels in rat sympathetic neurons via different G protein pathways. Neuron 1993; 10(1):11-20.
- Golard A, Siegelbaum SA. Kinetic basis for the voltage-dependent inhibition of N-type calcium current by somatostatin and norepinephrine in chick sympathetic neurons. J Neurosci 1993; 13(9):3884-3894.
- 26. Caulfield MP, Jones S, Vallis Y et al. Muscarinic M-current inhibition via $G\alpha_{q/11}$ and α -adrenoreceptor inhibition of Ca²⁺ current via $G\alpha_{o}$ in rat sympathetic neurons. J Physiol 1994; 477(Pt 3):415-422.
- Bean BP. Neurotransmitter inhibition of neuronal calcium channels by changes in channel voltage dependence. Nature 1989b; 340(6229):153-156.
- 28. Zamponi GW, Snutch TP. Decay of prepulse facilitation of N-type calcium channels during G protein inhibition is consistent with binding of a single G $\beta\gamma$ subunit. Proc Natl Acad Sci USA 1998a; 95(7):4035-4039.
- Zamponi GW, Snutch TP. Modulation of voltage-dependent calcium channels by G proteins. Curr Opin Neurobiol 1998b; 8(3):351-356.
- 30. Arnot MI, Stotz SC, Jarvis SE et al. Differential modulation of N-type (α_{1B}) and P/Q-type (α_{1A}) by different G protein β subunit isoforms. J Physiol 2000; 527(Pt 2): 203-212.
- Brody DL, Patil PG, Mulle JG et al. Bursts of action potential waveforms relieve G-protein inhibition of recombinant P/Q-type Ca2+ channels in HEK 293 cells. J Physiol 1997; 499(Pt 3):637-644.
- 32. Williams S, Serafin M, Mühlethaler M et al. Facilitation of N-type calcium current is dependent on the frequency of action potential-like depolarizations in dissociated cholinergic basal forebrain neurons of the Guinea Pig. J Neurosci 1997; 17(19):1625-1632.

- Brody DL, Yue DT. Release-independent short-term synaptic depression in cultured hippocampal neurons. J Neurosci 2000; 20(3):2480-2494.
- Bertram R, Behan M. Implications of G-protein-mediated Ca²⁺ channel inhibition for neurotransmitter release and facilitation. J Computational Neurosci 1999; 7(3):197-211.
- 35. Patil PG, deLeon M, Reed RR et al. Elementary events underlying voltage-dependent G protein inhibition of N-type calcium channels. Biophys J 1996; 71(5):2509- 2521.
- 36. Boland LM, Bean BP. Modulation of N-type calcium channels in bullfrog sympathetic neurons by luteinizing hormone-releasing hormone: Kinetics and voltage dependence. J Neurosci 1993; 13(2):516-533.
- Elmslie KS, Kammermeir PJ, Jones SW. Reevaluation of Ca²⁺ channel types and their modulation in bullfrog sympathetic neurons. J Physiol 1992; 456:107-123.
- Colecraft HM, Patil PG, Yue DT. Differential occurrence of reluctant openings in G-protein-inhibited N- and P/Q-type calcium channels. J Gen Physiol 2000; 115(2):175-192.
- Lee HK, Elmslie KS. Reluctant gating of single N-type calcium channels during transmitter-induced inhibition in bullfrog sympathetic neurons. J Neurosci 2000; 20(9):3115-3128.
- Currie KP, Fox AP. Comparison of N- and P/Q-type voltage-gated calcium channel current inhibition. J Neurosci 1997; 17(12):4570-4579.
- 41. Bourinet E, Soong TW, Stea A et al. Determinants of the G-protein dependent opioid modulation of neuronal calcium channels. Proc Natl Acad Sci USA 1996; 93(4):1486-1491.
- 42. Campbell V, Berrow NS, Fitzgerald EM et al. Inhibition of the interaction of G protein G_o with calcium channels by the calcium channel β-subunit in rat neurones. J Physiol 1995; 485(Pt 2):365-372.
- Toth PT, Shekter LR, Ma GH et al. Selective G-protein regulation of neuronal calcium channels. J Neurosci 1996; 16(15):4617-4624.
- 44. Page KM, Stephens GJ, Berrow NS et al. The intracellular loop between domains I and II of the B-type calcium channel confers aspects of G protein sensitivity to the E-type calcium channel. J Neurosci 1997; 17(4):1330-1338.
- 45. Stephens GJ, Canti C, Page KM et al. Role of domain I in neuronal Ca2+ channel alpha 1 subunits in G protein modulation. J Physiol 1998; 509(Pt 1):163-169.
- Mehrke G, Pereverzev A, Grabsch H et al. Receptor-mediated modulation of recombinant neuronal class E calcium channels. FEBS Lett. 1997; 408(3):261-270.
- 47. Qin N, Platano D, Olcese R et al. Direct interaction of gbetagamma with a C-terminal gbetagamma-binding domain of Ca2+ channel alpha1 subunit is responsible for channel inhibition by G protein-coupled receptors. Proc Natl Acad Sci USA 1997; 94(16):8866-8871.
- 48. Meir A, Dolphin AC. Kinetics and Gbetagamma modulation of Ca(v)2.2 channels with different auxiliary beta subunits. Pflugers Arch 2002; 444(1):263-75.
- 49. Canti C, Bogdanoy Y, Dolphin AC. Interaction between G proteins and accessory subunits in the regulation of 1B calcium channels in Xenopus oocytes. J Physiol 2000; 527 (Pt 3):419-32.
- Feng ZP, Arnot MI, Doering CJ et al. Calcium channel beta subunits differentially regulate the inhibition of N-type channels by individual Gbeta isoforms. J Biol Chem 2001; 276(48):45051-8.
- 51. Canti C, Page KM, Stephens GJ et al. Identification of residues in the N terminus of alpha 1B critical for inhibition of the voltage-dependent calcium channel by G beta gamma. J Neurosci 1999; 19(16):6855-6864.
- 52. Canti C, Bogdanov Y, Dolphin AC. Interaction between G proteins and accessory subunits in the regulation of 1B calcium channels in Xenopus oocytes. J Physiol 2000; 527(Pt 3):419-32.
- 53. Chien AJ, Gao T, Perez-Reyes E et al. Membrane targeting of L-type calcium channels. Role of palmitoylation in the subcellular localization of the beta2a subunit. J Biol Chem 1998; 273(36):23590-7.
- 54. Ikeda SR. Voltage-dependent modulation of N-type calcium channels by G-protein βγ subunits. Nature 1996; 380(6751):255-258.
- 55. Herlitze S, Garcia DE, Mackie K et al. Modulation of Ca²⁺ channels by G-protein βγ subunits. Nature 1996; 280(6571):258-262.
- 56. Zamponi GW, Bourinet E, Nelson D et al. Crosstalk between G proteins and protein kinase C mediated by the calcium channel α₁ subunit. Nature 1997; 385(6615):442-446.

- 57. Garcia DE, Li B, Garcia-Ferreiro RE et al. G-protein β-subunit specificity in the fast membrane-delimited inhibition of Ca²⁺ channels. J Neurosci 1998; 18(22):9163-9170.
- Ruiz-Velasco V, Ikeda SR. Multiple G-protein βγ combinations produce voltage-dependent inhibition of N-type calcium channel in rat superior cervical ganglion neurons. J Neurosci 2000; 20(6):2183-2191.
- 59. Cooper CB, Arnot MI, Feng ZP et al. Cross-talk between G-protein and protein kinase C modulation of N-type calcium channels is dependent on the G-protein beta subunit isoform. J Biol Chem 2000; 275(52):40777-81.
- 60. Lu Q, Dunlap K. Cloning and functional expression of novel N-type Ca(2+) channel variants. J Biol Chem 1999; 274(49):34566-34575.
- 61. Zhou JY, Siderovski DP, Miller RJ. Selective regulation of N-type Ca channels by different combinations of G-protein beta/gamma subunits and RGS proteins. J Neurosci 2000; 20(19):7143-8.
- 62. Jeong SW, Ikeda SR. Sequestration of G-protein beta gamma subunits by different G-protein alpha subunits blocks voltage-dependent modulation of Ca2+ channels in rat sympathetic neurons. J Neurosci 1999; 19(12):4755-4761.
- 63. Jeong SW, Ikeda SR. Effect of G protein heterotrimer composition on coupling of neurotransmitter receptors to N-type Ca(2+) channel modulation in sympathetic neurons. Proc Natl Acad Sci USA 2000a; 97(2):907-912.
- 64. Zhang JF, Ellinor PT, Aldrich RW et al. Multiple structural elements in voltage-dependent Ca²⁺ channels support their inhibition by G proteins. Neuron 1996; 17(5):991-1003.
- 65. De Waard M, Liu H, Walker D et al. Direct binding of G protein βγ complex to voltage-dependent calcium channels. Nature 1997; 385(6615):446-450.
- 66. Herlitze S, Hockermann GH, Scheuer T et al. Molecular determinants of inactivation and G protein modulation in the intracellular loop connecting domains I and II of the calcium channel α_{1A} subunit. Proc Natl Acad Sci USA 1997; 94(4):1512-1516.
- 67. Furukawa T, Nukada T, Mori Y et al. Differential interactions of the C terminus and the cytoplasmic I-II loop of neuronal Ca2+ channels with G-protein alpha and beta gamma subunits. I. Molecular determination. J Biol Chem 1998; 273(28):17585-94.
- 68. Furukawa T, Miura R, Mori Y et al. Differential interactions of the C terminus and the cytoplasmic I-II loop of neuronal Ca2+ channels with G-protein alpha and beta gamma subunits. II. Evidence for direct binding. J Biol Chem 1998; 273(28):17595-603.
- 69. Kinoshita M, Nukada T, Asano T et al. Binding of G alpha(o) N terminus is responsible for the voltage-resistant inhibition of alpha(1A) (P/Q-type, Ca(v)2.1) Ca(2+) channels. J Biol Chem 2001; 276(31):28731-8
- 70. Page KM, Canti C, Stephens GJ et al. (1998) Identification of the amino terminus of neuronal Ca2+ channel alpha 1 subunits alpha 1B and alpha 1E as an essential determinant of G-protein modulation. J Neurosci 1998; 18:4815-4824.
- Simen AA, Miller RJ. Structural features determining receptor regulation of neuronal Ca channels. J Neurosci 1998; 18(10):3689-3698.
- 72. Simen AA, Miller RJ. Involvement of regions in domain I in the opioid receptor sensitivity of alpha 1B (Ca2+) channels. Mol Pharmacol 2000; 57(5):1064-1074.
- 73. Ford CE, Skiba NP, Bae H et al. Molecular basis for interactions of G protein betagamma subunits with effectors. Science 1998; 280(5367):1271-1274.
- 73a. Doering CJ, Kisilevsky AE, Feng ZP et al. A single Gbeta subunit locus controls crosstalk between PKC and G protein regulation of N-type calcium channels. J Biol Chem 2004; 279:29709-29717.
- 74. Stea A, Soong TW, Snutch TP. Voltage-Gated Calcium Channels. In: North RA, ed. Handbook of Receptors and Channels; Ligand- and voltage-gated ion channels. Boca Raton: CRC Press Inc, 1995:113-152.
- 75. Hamid J, Nelson D, Spaetgens R et al. Identification of an integration center for crosstalk between PKC and G protein modulation of N-type calcium channels. J Biol Chem 1999; 274(10):6195-6202.
- 76. Swartz KJ, Merrit A, Bean BP et al. Protein kinase C modulates glutamate receptor inhibition of Ca²⁺ channels and synaptic transmission. Nature 1993; 361(6408):165-168.
- 77. Swartz KJ. Modulation of Ca²⁺ channels by protein kinase C in rat central and peripheral neurons: disruption of G protein-mediated inhibition. Neuron 1993; 11(2):305-320.
- Barrett CF, Rittenhouse AR. Modulation of N-type calcium channel activity by G-proteins and protein kinase C. J Gen Physiol 2000; 115(3):277-286.
- 79. Berman DM, Wilkie TM, Gillman AG. GAIP and RGS4 are GTPase-activating proteins for the Gi subfamily of G protein α subunits. Cell 1996; 86(3):445-452.
- Boupnik CA, Davidson N, Lester HA et al. RGS proteins reconstitute the rapid gating kinetics of Gβγ-activated inwardly rectifying K^{*} channels. Proc Natl Acad Sci USA 1997; 94(19):10461-10466.
- Berman DM, Gilman AG. Mammalian RGS proteins: barbarians at the gate. J Biol Chem 1998; 273(3):1269-1272.
- 82. Snow BE, Betts L, Mangion J et al. Fidelity of G protein β -subunit association by the G protein γ -subunit-like domains of RGS6, RGS7, and RGS11. Proc Natl Acad Sci USA 1999; 96(11):6489-6494.
- Jeong SW, Ikeda SR. G protein α subunit Gαz couples to couples neurotransmitter receptors to ion channels in sympathetic neurons. Neuron 1998; 21(5):1201-1212.
- 84. Melliti K, Meza U, Fisher R et al. Regulators of G protein signaling attenuate the G protein mediated inhibition of N-type calcium channels. J Gen Physiol 1999; 113(1):97-109.
- Diverse-Pierreluissi MA, Fischer T, Jordan JD et al. Regulators of G protein signaling proteins as determinants of the rate of desensitization of presynaptic calcium channels. J Biol Chem 1999; 274(20):14490-14494.
- Jeong SW, Ikeda SR. Endogenous regulator of G-protein signaling proteins modify N-type calcium channel modulation in rat sympathetic neurons. J Neurosci 2000b; 20(12):4489-4496.
- Mark MD, Witteman S, Herlitze S. G protein modulation of recombinate P/Q type calcium channels by regulators of G protein signalling proteins. J Physiol 2000; 528 (Pt 1):65-77.
- Sheng ZH, Rettig T, Takahashi M et al. Identification of a syntaxin-binding site on N-type calcium channels. Neuron 1994; 13(6):1303-1313.
- Sheng ZH, Rettig J, Cook T et al. Calcium-dependent interaction of N-type calcium channels with the synaptic core complex. Nature 1996; 379(6564):451-454.
- Yokoyama CT, Sheng ZH, Catterall WA. Phosphorylation of the synaptic protein interaction site on N-type calcium channels inhibits interactions with SNARE proteins. J Neurosci 1997; 17(18):6929-6938.
- Stanley EF, Mirotznik RR. Cleavage of syntaxin prevents G-protein regulation of presynaptic calcium channels. Nature 1997; 385(6614):340-343.
- 92. Jarvis SE, Magga J, Beedle AM et al. G protein modulation of N-type calcium channels is facilitated by physical interactions between syntaxin 1A and Gβγ. J Biol Chem 2000; 275(9):6388-6394.
- 93. Jarvis SE, Zamponi GW. Distinct molecular determinants govern syntaxin 1A-mediated inactivation and G-protein inhibition of N-type calcium channels. J Neurosci 2001;21(9):2939-48.
- 94. Jarvis SE, Barr W, Feng ZP et al. Molecular determinants of syntaxin 1 modulation of N-type calcium channels. J Biol Chem 2002; 277(46):44399-407.
- 95. Lu Q, AtKisson MS, Jarvis SE et al. Syntaxin 1A supports voltage-dependent inhibition of alpha1B Ca2+ channels by Gbetagamma in chick sensory neurons. J Neurosci 2001; 21(9):2949-57.
- 96. Sutton KG, McRory JE, Guthrie H et al. P/Q-type calcium channels mediate the activity-dependent feedback of syntaxin-1A. Nature 1999; 401(6755):800-804.
- Michaeleyski I, Chikyashvili D, Tsuk S et al. Modulation of a brain voltage-gated K+ channel by syntaxin 1A requires the physical interaction of Gbetagamma with the channel. J Biol Chem 2002; 277(38):34909-17.
- 98. Magga J, Jarvis SE, Arnot MI et al. Cysteine string protein promotes G protein modulation of N-type calcium channels. Neuron 2000; 28(1):195-204.
- 99. Miller LC, Swayne LA, Kay JG et al. Molecular determinants of cysteine string protein modulation of N-type calcium channels. J Cell Sci 2003; 116(Pt 14):2967-74.
- 100. Blackmer T, Larsen EC, Takahashi M et al. G protein betagamma subunit-mediated presynaptic inhibition: regulation of exocytotic fusion downstream of Ca2+ entry. Science 2001; 292(5515):293-7.
- Beedle AM, McRory JE, Poirot O et al. Agonist-independent modulation of N-type calcium channels by ORL1 receptors. Nat Neurosci 2004; 7(2):118-25.

- 102. Hummer A, Delzeith O, Gomez SR et al. Competitive and synergistic interactions of G protein beta(2) and Ca(2+) channel beta(1b) subunits with Ca(v)2.1 channels, revealed by mammalian two-hybrid and fluorescence resonance energy transfer measurements. J Biol Chem 2003; 278(49):49386-400.
- 103. Sandoz G, Lopez-Gonzalez I, Grunwald D et al. Cavbeta-subunit displacement is a key step to induce the reluctant state of P/Q calcium channels by direct G protein regulation. Proc Natl Acad Sci USA 2004; 101(16):6267-72.
- 104. Wolfe JT, Wang H, Howard J et al. T-type calcium channel regulation by specific G-protein betagarma subunits. Nature 2003; 424(6945):209-13.

CHAPTER 10

Phosphorylation-Dependent Regulation of Voltage-Gated Ca²⁺ Channels

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Overview

Note that the eurotransmitters, hormones, growth factors and extracellular matrix proteins bind to cell membrane receptors that, in turn, activate intracellular signaling cascades. Often, these cascades involve signaling by protein or lipid kinases and protein or lipid phosphatases. Protein kinases add phosphate groups to serine, threonine or tyrosine residues within proteins, and lipid kinases add phosphates to the inositol rings of certain lipids; phosphatases reverse this process. Phosphorylation or dephosphorylation can "switch-on" or "switch-off" protein or lipid activity. It has long been known that voltage-gated Ca²⁺ channels are regulated through signaling events involving phosphorylation. In this chapter, we summarize recent findings in this field. We have attempted to minimize overlap with other recent reviews.¹⁻⁹

Abbreviations

AC= adenylyl cyclase; Akt/PKB= protein kinase B; AKAP= A kinase anchoring protein; β 2AR= beta 2 adrenergic receptor; CaM= calmodulin; CaMKII= Ca²⁺/calmodulin-dependent protein kinase II; GPCR= G-protein-coupled receptor; NCS-1= neuronal calcium sensor-1; nNOS= neuronal nitric oxide synthase; PDE= phosphodiesterase; PI3K= phosphoinositide 3-kinase; PIP₂= phosphatidylinositol 4,5-bisphosphate; PIP₃= phosphatidylinositol 3,4,5-trisphosphate; PKA= protein kinase A; PKC= protein kinase C; PKG= protein kinase G; PLC= phospholipase C; PP2A= protein phosphatase 2A; RTK= receptor tyrosine kinase; sGC= soluble guanylyl cyclase.

Regulation of Ca²⁺ Channels by Protein Kinase A (PKA)

L-type Ca^{2+} channels display several different gating modes upon depolarization.¹⁰ Mode 0 represents a closed state of the channel and is characterized by null sweeps, mode 1 is characterized by brief bursts of channel openings, and mode 2 is characterized by long openings and delayed deactivation upon repolarization. Mode 2 gating of L-type channels can be induced by strong depolarization, PKA-dependent phosphorylation, or some combination thereof (for review see ref. 6). As described by Hess et al¹⁰ mode 2 can also be induced by 1,4-dihydropyridine (DHP) agonists such as Bay K 8644. Wilkens et al¹¹ recently demonstrated that strong depolarization and Bay K 8644 trigger mode 2 gating of cardiac L-type channels through distinct mechanisms. They mutated the DHP binding site within Cav1.2a, and showed that the mutant channel cannot respond to Bay K 8644, but can still respond to depolarization. They also constructed a chimera between Cav1.2a and Cav2.1; the latter is a neuronal P/Q-type channel that does not exhibit mode 2 gating in response to either depolarization. Interestingly, the chimeric channel responded to Bay K 8644, but not to strong depolarization. Interestingly, the

Voltage-Gated Calcium Channels, edited by Gerald Zamponi. ©2005 Eurekah.com and Kluwer Academic / Plenum Publishers. suggesting that the presence of these sites is by itself not sufficient for induction of mode 2 gating by strong depolarization.

Held et al¹² present data indicating that PKA-dependent regulation of skeletal muscle L-type channels (Ca_v1.1) involves the γ_1 subunit. In myotubes from γ_1 -knockout mice (γ_1 -deficient), steady-state inactivation is shifted by +15 mV and current densities are increased relative to wildtype myotubes. Both effects are reversed in γ_1 -deficient myotubes by overexpressing γ_1 . In contrast, overexpressing the distantly related γ_2 subunit (stargazin) had no effect. A membrane permeant cAMP analogue (8-Br-cAMP) increased L-type current amplitudes in wildtype but not in γ_1 -deficient myotubes. Steady-state inactivation was unaffected by 8-Br-cAMP in either phenotype. Rp-cAMPs, an inactive cAMP-analogue that blocks activation of PKA, reduced current amplitude in γ_1 -deficient myotubes without altering steady-state inhibition. Currents in wildtype cells were unaffected by Rp-cAMPs. Altogether, these findings suggest that Ca_v1.1 (or an associated protein, for example β_{1a}) is already phosphorylated by PKA in the absence of γ_1 .

Wu et al¹³ demonstrated that phosphatidylinositol 4,5-bisphosphate (PIP₂) affects the activity of neuronal P/Q-type Ca²⁺ channels (Ca₂2.1) by two different mechanisms. First, application of exogenous PIP₂ slows rundown of Ca₂2.1 channels in giant inside-out patches pulled from *Xenopus* oocytes. Rundown is also slowed by intracellular ATP, but surprisingly, PKA-dependent phosphorylation does not mediate this effect. Instead, ATP is thought to replenish PIP₂ by activating membrane-associated lipid kinases. Second, PIP₂ causes voltage-dependent (VD) inhibition of Ca₂2.1. Thus, PIP₂ inhibits currents evoked by weak depolarizations more strongly than currents evoked by strong depolarizations. Interestingly, VD inhibition by PIP₂ is alleviated by PKA-dependent phosphorylation. The authors propose that Ca₂2.1 has two distinct binding sites for PIP₂. Binding of PIP₂ to a high-affinity site stabilizes channel activity (i.e., slows rundown), whereas binding of PIP₂ to a second, lower-affinity site shifts the channel into a "reluctant" gating mode. Binding of PIP₂ to the second site is thought to be antagonized by PKA-dependent phosphorylation.

AKAPs and Ca²⁺ Channel Regulation

A-kinase anchoring proteins (AKAPs) act as scaffolds that mediate colocalization of PKA and its substrates, including L-type Ca²⁺ channels (for review see ref. 14). AKAPs are thought to enhance PKA-dependent regulation of native L-type channels.¹⁵⁻¹⁸ Using a heterologous expression system (TsA-201 cells), Gao et al¹⁶ showed that PKA-mediated regulation of Ca.1.2a could be reconstituted by coexpression of AKAP79. The reconstituted channel stimulation was considerably less robust than PKA-mediated stimulation of native L-type current in cardiac myocytes, however, suggesting that AKAPs may not be solely responsible for coupling PKA to L-type channels. Subsequent studies of AKAPs have generally supported an emerging model of ion channel regulation wherein scaffolding proteins coassemble molecular components of signal transduction cascades.^{19,20} For example, coimmunoprecipitation assays demonstrate that AKAP15 and Ca_v1.1 form a complex in skeletal muscle.¹⁷ From data obtained using a yeast two-hybrid system and coimmunoprecipitation from transfected TsA-201 cells, Hulme et al²¹ proposed that AKAP15 interacts with Cav1.1 via a leucine-zipper (LZ) motif. An LZ motif within the carboxyl-terminus of Ca, 1.1 binds to a corresponding motif within AKAP15. Mutations within the LZ motifs of either AKAP15 or Cav1.1 disrupt this interaction. In mouse MM14 myotubes, dialysis of a peptide corresponding to residues 38-54 of AKAP15 blocks voltage-dependent facilitation of Cav1.1 as effectively as PKI (a pseudosubstrate inhibitor of PKA) or AP2 (a specific peptide inhibitor of the AKAP15 – PKA interaction). Interestingly, it has long been known that the carboxyl-terminal portion of Ca_v1.1 (the region that binds AKAP15, i.e., amino acids 1774-1821) is proteolytically cleaved from the rest of the Cav1.1 polypeptide.²² This would seem to preclude close association between Ca_v1.1 and AKAP15. However, the corresponding region of the cardiac channel $Ca_v 1.2a$, which is also thought to be proteolytically cleaved, remains associated with Cav1.2a at the plasma membrane and regulates its function.^{23,24} Thus, the cleaved carboxyl-terminus of the skeletal muscle Ca_v1.1 may also remain associated with the channel and thereby mediate its colocalization with AKAP15.

Davare et al²⁵ showed that cAMP-dependent stimulation of hippocampal L-type channels involves highly localized signaling. Previously, this group had reported that microtubule-associated protein 2B (an AKAP) coprecipitates with PKA and Ca_v1.2.²⁶ More recently, Davare et al²⁷ showed that phosphatase 2A (PP2A) is also constitutively associated with Ca_v1.2 and reverses stimulation of this channel by PKA. The new data of Davare et al²⁵ indicate that Ca_v1.2, PKA and PP2A form a macromolecular signaling complex with β_2 -adrenergic receptors, G\alphas and adenylyl cyclase. Thus, in cell-attached recordings from hippocampal neurons, endogenous L-type currents were enhanced only when β_2 -receptor agonist was applied through the pipette, and not when it was bath applied. Importantly, these findings from neurons are consistent with demonstrations that cAMP signaling is tightly localized in cardiac myocytes.²⁸⁻³⁰

Recent evidence indicates that AKAPs may perform other important functions in addition to colocalizing PKA and its substrates. For example, Altier et al³¹ showed that AKAP79 increases expression of Ca_v1.2c at the cell surface. Unexpectedly, this effect of AKAP79 did not involve PKA. The increased surface expression of Ca_v1.2c requires a polyproline region within its II-III linker, but direct binding of AKAP79 to this sequence was not detected. Altier et al³¹ proposed that the polyproline region antagonizes surface trafficking of Ca_v1.2c, and that AKAP79 somehow counteracts this effect, possibly by interacting with Ca_v1.2c through an unidentified adaptor protein.

Other Examples of PKA-Dependent Ca²⁺ Channel Regulation

Relatively little is known about regulation of Ca₄1.3 (α 1D), a neuroendocrine L-type channel. Chik et al³² used RT-PCR to show that rat pinealocytes express primarily Ca₄1.3. Although whole-cell Ba²⁺ currents were small (~50 pA), they were clearly inhibited in response to 8-Br-cAMP or activation of receptors (β -adrenergic or PACAP) that elevate intracellular cAMP. Channel inhibition was blocked by Rp-cAMPS. Even less is known about regulation of Ca₄1.4 (α _{1F}), which has not yet been expressed in heterologous systems. However, Stella et al³³ showed that adenosine, acting through A₂ adenosine receptors, stimulates PKA to produce inhibition of L-type currents in salamander retinal rod cells. This effect was blocked by Rp-cAMPs. The L-type current in vertebrate retinal photoreceptors is presumably mediated by Ca₄1.4³⁴

Pemberton et al³⁵ reported that M3 muscarinic acetylcholine receptors stimulate native T-type channels in NIH 3T3 cells through PKA. Lenglet et al³⁶ presented evidence that 5-HT₇ receptors, G α s, adenylyl cyclase, and PKA stimulate endogenous T-type Ca²⁺ currents and aldosterone secretion in rat adrenal glomerulosa cells.

In freshly-dissociated rat amygdalar neurons, pharmacologically isolated P-type currents are potentiated by agents (isoproterenol or forskolin) that elevate cAMP.³⁷ When expressed in *Xenopus* oocytes from cerebellar mRNA, P/Q-type channels are increased by injection of cAMP.³⁸ Similar cAMP-dependent stimulation of P/Q-type current was observed by Fukuda et al³⁹ and Kaneko et al⁴⁰ in oocytes expressing Ca.2.1. In each of the above studies, cAMP-dependent stimulation of P/Q-type currents was prevented by inhibitors of PKA. Stimulation of P/Q-type channels by PKA may be important in certain forms of neuronal plasticity.^{37,41}

When expressed in *Xenopus* oocytes, N-type channels (Ca_v2.2; α_{1B}) are only weakly potentiated by treatments that elevate cAMP.^{39,40} However, such subtle PKA-dependent modulation of N-type channels may be physiologically important. For example, Herring and Paterson⁴² showed that secretion of acetylcholine (ACh) by vagal nerve is increased by the nitric oxide donor sodium nitroprusside (SNP). This effect of SNP was blocked by ω -conotoxin GVIA and by inhibitors of guanylyl cyclase or PKA, but not by a PKG inhibitor. The effect of SNP was also occluded by an inhibitor of phosphodiesterase 3 (PDE3). These results suggest that NO can stimulate N-type channels mediating vagal ACh secretion through a pathway involving (sequentially) NO, guanylyl cyclase, cGMP, PDE3, cAMP and PKA. Activation of G α s-coupled D1 dopamine receptors inhibits both N-type and P-type currents in rat nucleus acumbens medium spiny neurons.⁴³ Inhibition is mimicked by 8-Br-cAMP and is blocked by either PKI or okadaic acid. The authors suggest that channel inhibition results from dephosphorylation by a PKA-activated phosphatase. In summary, activation of PKA may produce either stimulation or inhibition of L-type, N-type, P/Q-type and T-type Ca²⁺ channels. Additionally, there appears to be significant crosstalk between NO and cGMP-dependent signaling pathways and PKA-dependent pathways.

Regulation of Ca²⁺ Channels by Protein Kinase C (PKC)

A variety of membrane receptors activate phospholipase C (PLC), leading to production of 1,2-diacylglycerol (DAG). This signaling lipid activates both conventional (α , β I, β II, γ) and novel (δ , ϵ , η , θ) isozymes of PKC.⁴⁴ DAG is mimicked by phorbol esters such as 12-myristate, 13-acetate (PMA), and for this reason phorbol esters have been extensively used to activate PKC experimentally. However, it has recently become apparent that enzymes other than PKC are also activated by DAG.^{45,46} Thus, effects of phorbol esters should always be confirmed using specific PKC inhibitors.

PKC-dependent regulation of cardiac and smooth muscle Ca²⁺ channels has been the topic of numerous investigations (for reviews see refs. 5 and 8). Furthermore, "crosstalk" between PKC-dependent phosphorylation and G protein-dependent modulation of neuronal Ca²⁺ channels has received considerable attention (see ref. 2 and Chapter 9 of this volume). We therefore limit coverage here to papers that have appeared since these previous reviews.

In nerve growth factor-differentiated PC-12 cells, neuropeptide Y inhibits L-type currents through a PKC-dependent pathway.⁴⁷ Using *Xenopus* oocytes, Blumenstein et al⁴⁸ expressed a human splice-variant of Ca_v1.2a having a long amino-terminus. This L-type channel is stimulated by PMA through a pathway that is blocked by bisindolylmaleimide I (Bis I), a specific inhibitor of PKC. Love et al⁴⁹ demonstrated PKC-dependent stimulation of L-type channels in HIT-T15 cells, a clonal pancreatic β -cell line. Presumably, these channels are Ca_v1.3, because Scholze et al⁵⁰ cloned Ca_v1.3 from HIT-T15 cells and expressed it in *Xenopus* oocytes. Scholze et al⁵⁰ then demonstrated channel stimulation through a PKC-dependent pathway linked to coexpressed μ -opioid receptors. Thus, under some conditions both Ca_v1.2 and Ca_v1.3 channels can be stimulated by PKC.

PMA stimulates R-type Ca^{2*} currents mediated by rat brain $Ca_v 2.3$ expressed in *Xenopus* oocytes^{51,52} or human brain $Ca_v 2.3$ expressed in HEK 293 cells.⁵³ Rat brain $Ca_v 2.3$ is also stimulated through activation of coexpressed metabotropic glutamate receptors (mGluR) that couple to PKC.⁵¹ In these experiments, receptor-mediated stimulation of $Ca_v 2.3$ was occluded by PMA, and staurosporine blocked channel stimulation by either PMA or mGluR activation. $Ca_v 2.3$ cloned from rabbit brain, which contains a longer amino-terminus than the rat clone and is consequently susceptible to voltage-dependent inhibition by G $\beta\gamma$ dimers,⁵⁴ is also stimulated by either PMA or M2 muscarinic acetylcholine receptors.⁵⁵ Both rat and rabbit $Ca_v 2.3$ channels are strongly stimulated through M1 muscarinic acetylcholine receptors⁵⁶ which couple strongly to PKC. Bannister et al^{56a} showed that muscarinic stimulation of $Ca_v 2.3$ involves signaling by $G\alpha q/11$, diacylglycerol, and a Ca^{2+} -independent PKC isozyme. Muscarinic stimulation of rabbit $Ca_v 2.3$ decreases inhibition of these channels by $G\beta\gamma$ subunits, similar to the "crosstalk" previously reported for N-type ($Ca_v 2.2$) Ca^{2+} channels.

Wu et al¹³ showed that Ca₂2.1 channels expressed in *Xenopus* oocytes are biphasically modulated by PKC. Application of PMA initially produces a modest stimulation of Ca₂2.1 currents, followed by a more substantial inhibition. Both effects are blocked by Bis I.

Morita et al⁵⁷ have identified a nifedipine-insensitive, rapidly-inactivating Ca²⁺ current (NI-*ICa*) in guinea pig arteriole smooth muscle cells. Although NI-*ICa* is clearly not an L-type, N-type, P/Q-type or T-type channel, the authors argue that it is also not R-type (i.e., encoded by Ca₂2.3). Recently, Morita et al⁵⁸ showed that NI-*ICa* is stimulated through a purinergic pathway involving PKA, and inhibited through a separate purinergic pathway involving PKC.

PKC Can Regulate Ca²⁺ Channels Indirectly by Triggering Receptor Desensitization

Garcia et al⁵⁹ demonstrated that PKC phosphorylates, and thereby downregulates CB1 cannabinoid receptors in AtT-20 cells. PKC-dependent receptor downregulation significantly attenuates agonist-dependent inhibition of endogenous P/Q-type channels in these cells. Similarly, Wu et al⁶⁰ showed that a low concentration (10 nM) of PMA, which submaximally activates PKC, desensitizes 5-HT_{1A} receptors and attenuates receptor-mediated inhibition of N-type channels in F11 rat dorsal root ganglion x mouse neuroblastoma hybrid cells. The attenuation of channel inhibition was mediated by a conventional PKC isozyme as it was prevented by the inhibitor Gö6976. Furthermore, mutation of a single PKC phosphorylation site (T149A) within the second intracellular loop of the 5-HT_{1A} receptor abolished desensitization in response to 10 nM PMA.

Regulation of Ca²⁺ Channels by Protein Kinase G (PKG)

Protein kinase G (PKG) is activated by cyclic GMP (cGMP), which is generated by guanylyl cyclase (GC). Nitric oxide (NO) stimulates soluble guanylyl cyclase, 9,61 which can lead to Ca2+ channel regulation by PKG. In an early study, Chen and Schofield⁶² showed that NO donors (SNP and SNAP) increase whole-cell Ca2+ currents (mostly N-type) in rat SCG neurons, but the involvement of cGMP was not documented in this study. NO donors or membrane-permeable cGMP analogues (e.g., 8-Br-cGMP) also stimulate whole-cell Ca²⁺ currents (which include N-type) in rat DRG neurons.⁶³ In contrast, N-type currents in human neuroblastoma (IMR32) cells are inhibited by NO donors acting through cGMP and PKG.⁶⁴ Native L-type currents in NIH 3T3 fibroblast cells are inhibited by 8-Br-cGMP, and inhibition is prevented by KT-5823, a specific PKG inhibitor.⁶⁵ SNP also inhibits endogenous L-type channels in bovine adrenal chromaffin cells through a pathway involving cGMP.⁵⁶ Abi-Gerges et al⁶⁷ found that high concentrations of the NO donor DEANO (100 μ M) antagonized β-adrenergic stimulation of cardiac L-type current through a pathway involving guanylyl cyclase, PKG and pertussis-toxin sensitive G proteins. Other NO donors (SIN-1, SNAP, SPNO) did not have the same effects as DEANO. In a subsequent paper, Abi-Gerges et al⁶⁸ reported that lower concentrations (1 pM – 1 μ M) of both DEANO and SNAP potentiate, rather than inhibit, β -adrenergic stimulation of L-type current. This potentiating effect of NO donors appears to involve the adenylyl cyclase pathway, and to be independent of cGMP.

It is important to note that NO may also modulate Ca^{2+} channel function through direct S-nitrosylation of Ca^{2+} channels or their regulatory proteins. S-nitrosylation is independent of PKG and other enzymes. For an excellent review of this topic, see Ahern et al.⁹

It is worth mentioning here that internal perfusion with cGMP may produce effects not mediated by PKG. For example, Vandecasteele et al⁶⁹ showed that a low concentration (0.5 μ M) of intracellular cGMP stimulated basal L-type currents in human atrial myocytes by inhibiting PDE3, a cGMP-inhibited phosphodiesterase. Inhibition of PDE3 results in elevated intracellular cAMP and activation of PKA, which enhances L-type current. In contrast, a high concentration of intracellular cGMP (5 μ M) inhibited basal L-type currents by activating PDE2, a cGMP-activated phosphodiesterase.

In summary, regulation of Ca²⁺ channels by cGMP may be complex, because in addition to altering the activity of PKG, changes in intracellular [cGMP] can alter the activity of PDEs, which can then produce changes in [cAMP] and PKA-dependent phosphorylation.

Regulation of T-Type Ca²⁺ Channels by Ca²⁺/ Calmodulin-Dependent Protein Kinases (CaM Kinases)

Chen et al⁷⁰ showed that angiotensin II activates CaMKII in adrenal glomerulosa cells, and CaMKII also produces a hyperpolarizing shift in the activation of native T-type Ca²⁺ channels. This hyperpolarizing shift results in enhanced Ca²⁺ influx and enhanced aldosterone secretion in response to elevated serum [K⁺]. In the same cell type, Barrett et al⁷¹ showed that

Ca²⁺-dependent increases in T-type current were blocked by inhibitors of CaMKII, and mimicked by constitutively-active mutant CaMKII. Wolfe et al⁷² found that coexpression of CaMKII γ c stimulates recombinant T-type channels (Ca₄3.2; α_{1H}) expressed in HEK 293 cells. CaMKII γ c increased channel activation at negative potentials without altering channel inactivation. Importantly, a closely-related T-type channel (Ca₄3.1; α_{1G}) was not modulated by CaMKII γ c. These results indicate that some but not all T-type channels are stimulated through CaMKinases.

Regulation of Ca²⁺ Channels by Tyrosine Kinases

Regulation of ion channels through tyrosine kinases was recently reviewed by Davis et al.⁷ Tyrosine kinases may be receptor tyrosine kinases such as the epidermal growth factor (EGF) receptor, or nonreceptor tyrosine kinases such as Src. Studies concerning tyrosine kinases typically employ pharmacological inhibitors. Notably, certain inhibitors of tyrosine kinases block Ca²⁺ channels directly.^{55,73-75} For this reason, it is critical to employ control compounds that are chemically closely-related but which do not inhibit tyrosine kinase activity. Otherwise, direct channel block could be misinterpreted as basal channel regulation by tyrosine kinases.

Activation of α -adrenergic receptors antagonizes β -adrenergic stimulation of cardiac L-type Ca²⁺ current (" α -adrenergic antagonism"). Belevych et al⁷⁶ showed that a tyrosine kinase-dependent signaling pathway underlies α -adrenergic antagonism in adult guinea pig ventricular myocytes. Intriguingly, Hool⁷⁷ presented evidence that α -adrenergic antagonism only involves tyrosine kinases under nonhypoxic conditions. During hypoxia, α -adrenergic antagonism appears to involve phospholipase A₂ instead.

Several growth factors are thought to signal through receptor tyrosine kinases. Long-term exposure to EGF increases the density of high voltage-activated Ca²⁺ currents in pituitary GH3 cells without altering channel biophysical properties.⁷⁸ Exposure to nerve growth factor (NGF) maintains N-type and L-type current densities at their preisolation levels during long-term culture (6-15 days) of bullfrog SCG neurons.⁷⁹ Exposure to either NGF or brain-derived neurotrophic factor (BDNF) increases L-type currents in PC12 cells, but surprisingly, this effect is quite fast, requiring only 3-5 minutes.⁸⁰ These results imply that receptor tyrosine kinases can increase Ca²⁺ channel expression and/or activity.

In chick DRG neurons, inhibition of N-type channels through GABA_B receptors can be divided into two components: a voltage-independent, steady-state component (SSI) and a voltage-dependent kinetic slowing component (KS). Diversé-Pierliussi et al⁸¹ showed that SSI could be selectively blocked by either genistein or srcKI (a specific peptide inhibitor of Src). These results suggest that Src mediates SSI but not KS.

Fitzgerald and Dolphin⁸² showed that injection of the monomeric G protein p21-Ras or its downstream effector pp60^{c-Src} increased whole-cell Ca²⁺ current density in neonatal rat DRG neurons. Current density was also decreased by an antibody (Y13-259) directed against p21-Ras or a phosphopeptide (Trk490) that blocks Ras activation. Ca²⁺ currents were also decreased following incubation of cells in serum-free media or media containing anti-NGFR antibody. Finally, currents were decreased by genistein but not its inactive analogue genistin. These results suggest that p21-Ras signals through the tyrosine kinase pp60^{c-Src} to increase Ca²⁺ current density in rat DRG neurons.

Blair et al⁸³ showed that native L-type channels in rat cerebellar granule neurons are potentiated by insulin-like growth factor-1 (IGF-1), which binds to a receptor tyrosine kinase. IGF-1 activates a signaling pathway involving the lipid kinase, phosphoinositide 3-kinase (PI3K) and the serine/threonine kinase Akt (also known as PKB). They show that Akt is responsible for potentiating L-type channels in these cells.

Regulator of G-protein signaling (RGS) proteins serve as GTPase-activating proteins or as effector antagonists for certain heterotrimeric G-proteins.^{56,84-86} By accelerating GTP hydrolysis by G α or by blocking interactions of G α with downstream effectors, RGS proteins may influence signaling events that involve kinases or phosphatases. RGS proteins can significantly influence Ca²⁺ channel regulation (see Chapter 9). Recently, Schiff et al⁸⁷ reported that RGS12

can directly associate with N-type Ca^{2+} channels in chick DRG neurons. Intriguingly, this interaction appears to require channel phosphorylation by a tyrosine kinase. Experiments also indicate that RGS proteins themselves may be regulated through phosphorylation,⁸⁶ suggesting another indirect route by which kinases and phosphatases could influence Ca^{2+} channel activity.

Strauss et al⁸⁸ showed that pp60^{c-src} coprecipitates with neuroendocrine L-type channels (Ca_v1.3) isolated from rat brain or retinal pigmented epithelial (RPE) cells. In electrophysiological experiments in RPE cells, intracellular dialysis of pp60^{c-src} produced a modest increase in L-type current. Thus, Ca_v1.3 is apparently stimulated through a pathway involving pp60^{c-src}. Similarly, Rosenthal et al⁸⁹ found that the fibroblast growth factor receptor 2 (FGFR2) mediates stimulation of L-type current in RPE cells and in central neurons. Stimulation is blocked by lavendustin A, implicating tyrosine kinases. Additionally, FGFR2 coprecipitate with Ca_v1.3, and vice versa.

 Ca^{2*} channels in bovine adrenal chromaffin cells are tonically inhibited through autocrine release of ATP and opioids. These agonists of G protein-coupled receptors inhibit P/Q-type channels through both voltage-dependent (VD) and voltage-independent (VI) mechanisms. Weiss and Burgoyne⁹⁰ showed that suramin and naxolone (purinergic and opioid receptor antagonists, respectively) increase P/Q-type current by relieving tonic autocrine inhibition. Relief from inhibition is not prevented by Bis I nor occluded by PMA, indicating that PKC is not involved. However, relief from VI inhibition is blocked by coexpression of a mutant, dominant-negative Neuronal Calcium Sensor-1 (NCS-1) protein; the effect of NCS-1 E120Q suggests that wildtype NCS-1 (also known as Frequenin) is somehow necessary for tonic inhibition. Furthermore, inhibition of Src (by PP1 or srcKI) relieves tonic VI inhibition as effectively as suramin and naloxone. Weiss and Burgoyne⁹⁰ also demonstrated that Src-containing cell extracts support direct phosphorylation of Ca_v2.1 channels. Altogether, their results suggest that both NCS-1 and Src mediate autocrine VI inhibition of Ca_v2.1 in adrenal chromaffin cells.

Tyrosine kinases may also be involved in signaling pathways not traditionally associated with ion channel regulation. For example, vascular smooth muscle L-type Ca²⁺ channels (Ca_{*}1.2b) are stimulated through activation of $\alpha_5\beta_1$ integrins.⁹¹ Channel stimulation is reduced by broad-spectrum tyrosine kinase inhibitors or by intracellular application of antibodies directed against focal adhesion kinase (FAK) or pp60^{c-Src}. In a related study, Waitkus-Edwards et al⁹² found that a peptide (leucin-aspartate-valine; LDV) that mimics the integrin binding sequence of a fibronectin triggers vasoconstriction of rat skeletal muscle arterioles. Vasoconstriction is mediated by L-type current, and L-type currents are potentiated by LDV through a pathway blocked by PP2, another inhibitor of Src. These studies suggest that integrins activate a tyrosine kinase pathway that stimulates L-type channels, leading to smooth muscle contraction.

Wu et al¹³ showed that Ca,2.1 channels expressed in *Xenopus* oocytes are biphasically modulated by nerve growth factor (NGF) acting through TrkA, a receptor tyrosine kinase that activates phospholipase C- γ . Application of NGF initially produces a mild enhancement of Ca,2.1 currents that is thought to reflect depletion of membrane PIP₂ and an accompanying shift of Ca,2.1 channels from "reluctant" to "willing" gating modes. Subsequent inhibition of Ca,2.1 in response to NGF is thought to reflect channel rundown arising from continuing depletion of membrane PIP₂. These effects of NGF are not prevented by Bis I, suggesting that PKC is not involved.

Regulation of Ca²⁺ Channels by Mitogen-Activated Protein (MAP) Kinases

MAP kinases can be activated by a wide variety of signaling pathways (for reviews, see refs. 93 and 94). Wilk-Blaszczak et al⁹⁵ reported that bradykinin receptors activate a particular MAP kinase (p38-2) in NG108-15 cells. They also presented pharmacological evidence that p38-2 inhibits N-type channels. Thus, bradykinin-mediated channel inhibition was blocked

by SB203580, an inhibitor of p38 MAP kinases, but not by its inactive analogue SKF106978. Inhibition was similarly not blocked by PD98059, which inhibits MAP kinases in the ERK pathway. In another study, Lei et $a1^{96}$ showed that longterm exposure to PD98059 prevents NGF from maintaining Ca²⁺ channel density in bullfrog sympathetic neurons kept in culture. Their results suggest that NGF may signal through MAP kinases in controlling Ca²⁺ channel expression.

As mentioned above, Fitzgerald and Dolphin⁸² showed that p21-Ras increases Ca²⁺ currents in rat DRG neurons. Extending this observation, Fitzgerald⁹⁷ presented evidence that Ras increases Ca²⁺ currents by signaling through MAP kinases. In her experiments, currents were potentiated by a mutant Ras protein (V12S35Ras) that specifically activates Raf-1 and a MAP kinase signaling pathway. Current density was decreased by UO126, a specific inhibitor of MEK, but not by UO124, its inactive control compound. More recently, Fitzgerald⁹⁸ showed that UO126 (but not UO124) decreases N-type currents produced by expression of Ca_v2.2 in COS-7 cells, suggesting that Ca_v2.2 activity is tonically stimulated by MAP kinases under these conditions.

Regulation of Ca²⁺ Channels by Lipid Kinases

Lipid kinases play important roles in a variety of cellular processes, including but not limited to cell survival, cell transformation, vesicle budding, cytoskeletal assembly, and activation of serine/threonine kinases such as PKC and Akt/PKB (for reviews see refs. 99 and 100). The roles of lipid kinases and phosphatases in Ca²⁺ channel regulation are just beginning to be explored. Most existing studies have focused on the role of phosphoinositide 3-kinases (PI3Ks). PI3Ks can be activated by ligand binding to receptor tyrosine kinases, to G protein-coupled receptors, or by integrin-dependent cell adhesion. Activated PI3K converts plasma membrane phosphatidylinositol 4,5-bisphosphate (PIP₂) into phosphatidylinositol 3,4,5-trisphosphate (PI(3,4,5)P₃), otherwise known as PIP₃. A wide variety of signaling proteins contain domains that specifically bind PIP₃, resulting in protein translocation to the plasma membrane and interaction with effectors.¹⁰⁰ Significantly, certain PI3Ks (e.g., PI3K α and PI3K γ) can also phosphorylate serine or threonine residues within proteins. Inhibitors of PI3K activity, such as wortmannin and LY294002, cannot be used to distinguish between lipid and protein kinase activity.⁹⁹

Evidence indicates that PI3Ks regulate L-type channel activity in smooth muscle cells. Thus, in rat portal vein myocytes, activation of AT1A angiotensin II receptors stimulates L-type channels through a pathway involving G $\beta\gamma$ released from G α_{13} . Channel stimulation is blocked by intracellular dialysis with an antibody against GB, or by overexpression of a GB γ -sequestering peptide.¹⁰¹ Viard et al¹⁰² showed that L-type current is also stimulated in these cells following dialysis with purified GBy. Channel stimulation by either purified GBy or angiotensin II is blocked by nanomolar wortmannin. Dialysis with activated, recombinant, $G\beta\gamma$ -sensitive PI3K γ also stimulated L-type channels. The stimulating effects of GBY or recombinant PI3KY were reduced, but not blocked, by inhibitors of PKC. These results indicate that PKC is involved in, but not completely responsible for, channel stimulation by GBY and PI3KY.¹⁰² Quignard et al¹⁰³ subsequently showed that stimulation of L-type channels through the G protein-coupled AT_{1A} angiotensin II receptor involves signaling by PI3Ky. On the other hand, Macrez et al¹⁰⁴ reported that a different isozyme, PI3KB, mediates stimulation of L-type channels through the platelet-derived growth factor receptor, which is a receptor tyrosine kinase. The above studies demonstrate that PI3Ks stimulate vascular L-type Ca2+ channels. However, the mechanism by which they act remains unclear: possibilities include direct effects of PIP3 on Ca2+ channels or proteins that regulate them, PIP3-dependent activation of PDK1 and subsequent activation of PKC or Akt/PKB, direct channel phosphorylation by PI3K, or some combination thereof.99

Several recent studies indicate that lipid kinases can modulate ion channels by altering the concentrations of membrane phospholipids. Specifically, changes in membrane PIP₂ concentration following PLC activation have been implicated in regulation of several different ion

channel types.¹⁰⁵ It was recently proposed¹⁰⁶ that phosphoinositide 4-kinase (PI4K) restores membrane PIP₂ following its depletion by PLC, and that restoration of PIP₂ is necessary for recovery of M-type K⁺ channels from slow muscarinic inhibition. This same signaling pathway is thought to produce slow muscarinic inhibition of neuronal L-type and N-type Ca²⁺ channels.¹⁰⁷ As described earlier, other recent evidence supports the idea that membrane PIP₂ plays important roles in Ca²⁺ channel regulation.¹³

Regulation of Ca²⁺ Channels by Cyclin-Dependent Kinase 5 (Cdk5)

Cdk5 has important neuronal functions and its absence or dysfunction may contribute to neurodegenerative diseases such as Alzheimer's and amyotrophic lateral sclerosis.¹⁰⁸ Liu et al¹⁰⁹ presented evidence that Cdk5 stimulates Ca²⁺ currents in dissociated mouse neostriatal neurons. Activation of mGluRs stimulated whole-cell Ca²⁺ currents in these cells, and stimulation was blocked by butyrolactone, an inhibitor of Cdk5. Subsequently, Tomizawa et al¹¹⁰ reported that p35, a neuron-specific activator of Cdk5, inhibits neurotransmitter release in rat hippocampus by disrupting interactions between P/Q-type channels and SNARE proteins. Their conclusion was based in part on the finding that roscovitine, which at that time was thought to be a specific inhibitor of Cdk5, potentiates synaptic transmission mediated by P/Q-type channels. They¹¹⁰ showed that Ca_v2.1 is phosphorylated in vitro by Cdk5, and that such phosphorylation effectively blocks interactions between Cav2.1 and SNAP-25 or synaptotagmin I. These findings led to a model in which Cdk5-mediated phosphorylation of P/Q-type channels uncouples Ca²⁺ influx from neurosecretion. However, Yan et al¹¹¹ have more recently demonstrated that roscovitine is a direct agonist of P/Q-type channels. Extracellular roscovitine slows channel deactivation, thereby potentiating tail currents and Ca2+ influx. This effect is independent of Cdk5, because roscovitine is ineffective when applied intracellularly, and roscovitine slows P/Q-type current deactivation in neurons from mice lacking p35 as much as in neurons from wildtype mice. Cdk5 activity is largely eliminated in neurons from mice lacking p35.

Regulation of Ca²⁺ Channels by Calcineurin

Protein and lipid phosphatases are activated through various membrane receptors and cell signaling mechanisms (for review see ref. 4). The concept that dephosphorylation activates Ca^{2+} channel activity has been relatively neglected, and most information concerning the effects of phosphatases on Ca²⁺ channel activity is derived from purely pharmacological studies. Protein phosphatase 2B, or calcineurin (CaN), has been of special interest to Ca2+ channel physiologists because it is abundantly expressed in brain and is activated by Ca²⁺ influx. CaN, like PKA and PKC, is thought to be tethered nearby its activators and substrates by AKAPs.¹¹² Zhu and Yakel¹¹³ found that calcineurin inhibitory fragment (CIF) reduced the voltage-dependent (VD) inhibition of N-type channels in rat major pelvic ganglion cells through endogenous α_2 -adrenergic and somatostatin receptors. Inhibition through α_2 -adrenergic receptors was also reduced by CaN inhibitors (cyclosporin A and cyclophilin), but not by okadaic acid which does not inhibit CaN. Additionally, CIF relieved kinetic slowing and accelerated inactivation in cells dialyzed with GTPYS. Thus, CaN-dependent dephosphorylation may participate in the "crosstalk" between kinases and G proteins in the modulation of N-type, P/ Q-type and R-type channels. Lukyanetz et al¹¹⁴ also presented evidence for regulation of L-type and N-type channels by CaN in NG108-15 cells. They showed that both L-type and N-type currents are decreased by high-frequency trains of stimulation that elevate intracellular Ca²⁺. This effect was blocked by FK-506, an inhibitor of CaN. Transfection with CaN antisense increased calcium currents, whereas overexpression of CaN triggered tonic channel inhibition that was partially relieved by FK-506 or EGTA. Their results suggest that basally phosphorylated L-type and N-type channels are inhibited through dephosphorylation by CaN in these cells.



Figure 1. In this figure, we have attempted to graphically depict many of the phosphorylation-dependent interactions discussed in this chapter. Voltage-gated Ca^{2+} channels are represented by transmembrane barrels, with penetrating arrows to indicate Ca^{2+} influx. Arrows within the cell represent established or hypothesized interactions, which may be either stimulatory or inhibitory. The circled Ps represent phosphorylation of Ca^{2+} channel proteins or associated molecules.

In rat striatal neurons, activation of D2 dopamine receptors produces inhibition of L-type channels through a pathway that includes, sequentially, $G\beta\gamma$, PLC β_1 , elevated intracellular Ca²⁺ and activation of CaN.¹¹⁵ More recently, Day et al¹¹⁶ showed that currents mediated by Ca_v1.2 in rat prefrontal pyramidal neurons are inhibited through an almost identical signaling cascade activated by 5-HT₂ receptors.

Summary

Recent experiments indicate that a wide variety of protein and lipid kinases can regulate voltage-gated Ca^{2+} channels. The examples summarized herein are mostly limited to the relatively well known kinases such as PKA, PKC, CaMKII, tyrosine kinases and PI3K (see also Fig. 1). However, the human genome encodes approximately 500 different protein kinases.¹¹⁷ It therefore seems likely that voltage-gated Ca^{2+} channels are regulated through many additional kinase-dependent signaling pathways. Furthermore, the potential for crosstalk between different kinase-involving pathways seems enormous. However, crosstalk may be highly restricted within living cells, because an emerging theme seems to be that Ca^{2+} channels, receptors, G proteins and scaffolding proteins are tightly colocalized within "signaling complexes" that include kinases and phosphatases. Future studies will undoubtably strive toward a better understanding of the composition and function of such signaling complexes. Future work will also be required to elucidate the physiological roles of membrane phospholipids in Ca^{2+} channel function. It will also be of interest to more fully understand how alternative splicing of Ca^{2+} channel proteins their participation in signaling networks, and ultimately, their physiological roles.

References

- 1. Dolphin AC. L-type calcium channel modulation. Adv Second Mess Phos Res 1999; 33:153-177.
- 2. Bean BP. Modulating modulation. J Gen Physiol 2000; 115:273-275.
- Catterall WA. Structure and regulation of voltage-gated Ca²⁺ channels. Annu Rev Cell Dev Biol 2000; 16:521-555.
- 4. Herzig S, Neumann J. Effects of serine/threonine protein phosphatases on ion channels in excitable membranes. Physiol Rev 2000; 80:173-210.
- 5. Kamp TJ, Hell JW. Regulation of cardiac L-type calcium channels by protein kinase A and protein kinase C. Circ Res 2000; 87:1095-1102.
- 6. Carbone E, Carabelli V, Cesetti T et al. G-protein- and cAMP-dependent L-channel gating modulation: A manyfold system to control calcium entry in neurosecretory cells. Pflügers Arch 2001; 442:801-813.
- 7. Davis MJ, Wu X, Nurkiewicz TR et al. Regulation of ion channels by protein tyrosine phosphorylation. Am J Physiol 2001; 281:H1835-H1862.
- Keef KD, Hume JR, Zhong J. Regulation of cardiac and smooth muscle Ca²⁺ channels (Ca_v1.2a,b) by protein kinases. Am J Physiol 2001; 281:C1743-C1756.
- 9. Ahern GP, Klyachko VA, Jackson MB. cGMP and S-nitrosylation: Two routes for modulation of neuronal excitability by NO. Trends Neurosci 2002; 25:510-517.
- Hess P, Lansman JB, Tsien RW. Different modes of Ca²⁺ channel gating behaviour favoured by dihydropyridine Ca²⁺ agonists and antagonists. Nature 1984; 311:538-544.
- Wilkens CM, Grabner M, Beam KG. Potentiation of the cardiac L-type Ca²⁺ channel (α1C) by dihydropyridine agonist and strong depolarization occur via distinct mechanisms. J Gen Physiol 2001; 118:495-507.
- 12. Held B, Freise D, Freichel M et al. Skeletal muscle L-type Ca²⁺ current modulation in γ 1-deficient and wildtype murine myotubes by the γ 1 subunit and cAMP. J Physiol (Lond) 2002; 539:459-468.
- Wu L, Bauer CS, Zhen X et al. Dual regulation of voltage-gated calcium channels by PtdIns(4,5)P₂. Nature 2002; 419:947-952.
- Michel JJ, Scott JD. AKAP mediated signal transduction. Annu Rev Pharmacol Toxicol 2002; 42:235-257.
- Johnson BD, Scheuer T, Catterall WA. Voltage-dependent potentiation of L-type Ca²⁺ channels in skeletal muscle cells requires anchored cAMP-dependent protein kinase. Proc Natl Acad Sci USA 1994; 91:11492-11496.
- Gao T, Yatani A, Dell'Acqua ML et al. cAMP-dependent regulation of cardiac L-type Ca²⁺ channels requires membrane targeting of PKA and phosphorylation of channel subunits. Neuron 1997; 19:185-196.
- 17. Gray PC, Johnson BD, Westenbroek RE et al. Primary structure and function of an A kinase anchoring associated with calcium channels. Neuron 1998; 20:1017-1026.
- Zhong J, Hume JR, Keef KD. Anchoring protein is required for cAMP-dependent stimulation of L-type Ca²⁺ channels in rabbit portal vein. Am J Physiol 1999; 277:C840-C844.
- 19. Tsunoda S, Sierralta J, Sun Y et al. A multivalent PDZ-domain protein assembles signaling complexes in a G-protein-coupled cascade. Nature 1997; 388:243-249.
- Marx SO, Kurokawa J, Reiken S et al. Requirement of a macromolecular signaling complex for β-adrenergic receptor modulation of the KCNQ1-KCNE1 potassium channel. Science 2002; 295:496-499.
- 21. Hulme JT, Ahn M, Hauschka SD et al. A novel leucine zipper targets AKAP15 and cyclic AMP-dependent protein kinase to the C terminus of the skeletal muscle Ca²⁺ channel and modulates its function. J Biol Chem 2002; 277:4079-4087.
- 22. De Jongh KS, Warner C, Colvin AA et al. Characterization of the two size forms of the α1 subunit of skeletal muscle L-type calcium channels. Proc Natl Acad Sci USA 1991; 88:10778-10782.
- 23. Gerhardstein BL, Gao T, Bünemann M et al. Proteolytic processing of the C terminus of the α_{1C} subunit of L-type calcium channels and the role of a proline-rich domain in membrane tethering of proteolytic fragments. J Biol Chem 2000; 275:8556-8563.
- 24. Gao T, Cuadra AE, Ma H et al. C-terminal fragments of the α 1C (Cav1.2) subunit associate with and regulate L-type calcium channels containing truncated α 1C subunits. J Biol Chem 2001; 276:21089-21097.
- 25. Davare MA, Avdonin V, Hall DD et al. A β_2 adrenergic receptor signaling complex assembled with the Ca²⁺ channel Ca_v1.2. Science 2001; 293:98-101.
- Davare MA, Dong F, Rubin CS et al. The A-kinase anchor protein MAP2B and cAMP-dependent protein kinase are associated with class C L-type calcium channels in neurons. J Biol Chem 1999; 274:30280-30287.

- Davare MA, Horne MC, Hell JW. Protein phosphatase 2A is associated with class C L-type calcium channels (Ca,1.2) and antagonizes channel phosphorylation by cAMP-dependent protein kinase. J Biol Chem 2000; 275:39710-39717.
- Jurevicius J, Fischmeister R. cAMP compartmentation is responsible for a local activation of cardiac Ca²⁺ channels by β-adrenergic agonists. Proc Natl Acad Sci USA 1996; 93:295-299.
- Chen-Izu Y, Xiao R-P, Izu LT et al. G₁-dependent localization of β₂-adrenergic receptor signaling to L-type Ca²⁺ channels. Biophys J 2000; 79:2547-2556.
- 30. Zaccolo M, Pozzan T. Discrete microdomains with high concentration of cAMP in stimulated rat neonatal cardiac myocytes. Science 2002; 295:1711-1715.
- 31. Altier C, Dubel SJ, Barrère C et al. Trafficking of L-type calcium channels mediated by the postsynaptic scaffolding protein AKAP79. J Biol Chem 2002; 37:33598-33603.
- 32. Chik CL, Liu Q-Y, Li B et al. αID L-type Ca²⁺-channel currents: Inhibition by a β-adrenergic agonist and pituitary adenylate cyclase-activating polypeptide (PACAP) in pinealocytes. J Neurochem 1997; 68:1078-1087.
- 33. Stella Jr SL, Bryson EJ, Thoreson WB. A₂ adenosine receptors inhibit calcium influx through L-type calcium channels in rod photoreceptors of the salamander retina. J Neurophysiol 2002; 87:351-360.
- 34. Bech-Hansen NT, Naylor MJ, Maybaum TA et al. Loss-of-function mutations in a calcium-channel α1-subunit gene in Xp11.23 cause incomplete X-linked congenital stationary night blindness. Nat Genet 1998; 19:264-267.
- Pemberton KE, Hill-Eubanks LJ, Jones SVP. Modulation of low-threshold T-type calcium channels by the five muscarinic receptor subtypes in NIH 3T3 cells. Pflügers Arch 2000; 440:452-461.
- 36. Lenglet S, Louiset E, Delarue C et al. Activation of 5-HT₇ receptor in rat glomerulosa cells is associated with an increase in adenylyl cyclase activity and calcium influx through T-type calcium channels. Endocrinol 2002; 143:1748-1760.
- Huang C-C, Wang SJ, Gean PW. Selective enhancement of P-type calcium currents by isoproterenol in the rat amygdala. J Neurosci 1998; 18:2276-2282.
- Fournier F, Bourinet E, Nargeot J et al. Cyclic AMP-dependent regulation of P-type calcium channels expressed in Xenopus oocytes. Pflügers Arch 1993; 423:173-180.
- 39. Fukuda K, Kaneko S, Yada N et al. Cyclic AMP-dependent modulation of N- and Q-type Ca²⁺ channels expressed in Xenopus oocytes. Neurosci Lett 1996; 217:13-16.
- Kaneko S, Akaike A, Satoh M. Differential regulation of N- and Q-type Ca²⁺ channels by cyclic nucleotides and G-proteins. Life Sci 1998; 62:1543-1547.
- Robbe D, Alonso G, Chaumont S et al. Role of P/Q-Ca²⁺ channels in metabotropic glutamate receptor 2/3-dependent presynaptic long-term depression at nucleus accumbens synapses. J Neurosci 2002; 22:4346-4356.
- 42. Herring N, Paterson DJ. Nitric oxide—cGMP pathway facilitates acetylcholine release and bradycardia during vagal stimulation in the guinea-pig in vitro. J Physiol (Lond) 2001; 535:507-518.
- Zhang X-F, Cooper DC, White FJ. Repeated cocaine treatment decreases whole-cell calcium current in rat nucleus accumbens neurons. J Pharmacol Exp Ther 2002; 301:1119-1125.
- 44. Newton AC. Regulation of protein kinase C. Curr Opin Cell Biol 1997; 9:161-167.
- 45. Brose N, Rosenmund C. Move over protein kinase C, you've got company: Alternative cellular effectors of diacylglycerol and phorbol esters. J Cell Science 2002; 115:4399-4411.
- 46. Kazanietz MG. Novel "nonkinase" phorbol ester receptors: The C1 domain connection. Mol Pharmacol 2002; 61:759-767.
- 47. McCullough LA, Egan TM, Westfall TC. Neuropeptide Y inhibition of calcium channels in PC-12 pheochromocytoma cells. Am J Physiol 1998; 274:C1290-1297.
- 48. Blumenstein Y, Kanevsky N, Sahar G et al. A novel long N-terminal isoform of human L-type Ca²⁺ channel is upregulated by protein kinase C. J Biol Chem 2002; 277:3419-3423.
- Love JA, Richards NW, Owyang C et al. Muscarinic modulation of voltage-dependent Ca²⁺ channels in insulin-secreting HIT-T15 cells. Am J Physiol 1998; 274:G397-G405.
- 50. Scholze A, Plant TD, Dolphin AC et al. Functional expression and characterization of a voltage-gated Ca_v1.3 (α1D) calcium channel subunit from an insulin-secreting cell line. Mol Endocrinol 2001; 15:1211-1221
- 51. Stea A, Soong TW, Snutch TP. Determinants of PKC-dependent modulation of a family of neuronal calcium channels. Neuron 1995; 15:929-940.
- 52. Kamatchi GL, Tiwari SN, Durieux ME et al. Effects of volatile anesthetics on the direct and indirect protein kinase C-mediated enhancement of $\alpha 1E$ -type Ca²⁺ currents in Xenopus oocytes. J Pharmacol Exp Ther 2000; 293:360-369.
- 53. Shekter LR, Taussig R, Gillard SE et al. Regulation of human calcium channels by G protein βγ subunits expressed in human embryonic kidney 293 cells. Mol Endocrinol 1997; 52:282-291.

- 54. Page KM, Canti C, Stephens GJ et al. Identification of the amino terminus of neuronal Ca^{2+} channel α 1 subunits α 1B and α 1E as an essential determinant of G-protein modulation. J Neurosci 1998; 18:4815-4824.
- 55. Meza U, Bannister RA, Melliti K et al. Biphasic, opposing modulation of cloned neuronal α1E Ca²⁺ channels by distinct signaling pathways coupled to M2 muscarinic acetylcholine receptors. J Neurosci 1999; 19:6806-6817.
- 56. Melliti K, Meza U, Adams BA. Muscarinic stimulation of α1E Ca²⁺ channels is selectively blocked by the effector antagonist function of RGS2 and PLCβ₁. J Neurosci 2000; 20:7167-7173.
- 56a. Bannister RA, Melliti K, Adams BA. Differential modulation of Ca.2.3 Ca²⁺ channels by Gαq/ 11-coupled muscarinic receptors. Mol Pharmacol 2004; 65:381-388.
- 57. Morita H, Cousins H, Onoue H et al. Predominant distribution of nifedipine-insensitive, high voltage-activated Ca²⁺ channels in the terminal mesenteric artery of guinea pig. Circ Res 1999; 85:596-605.
- Morita H, Sharada T, Takewaki T et al. Multiple regulation by external ATP of nifedipineinsensitive, high voltage-activated Ca²⁺ current in guinea-pig mesenteric terminal arteriole. J Physiol (Lond) 2002; 539:805-816.
- 59. Garcia DE, Brown S, Hille B et al. Protein kinase C disrupts cannabinoid actions by the phosphorylation of the CB1 cannabinoid receptor. J Neurosci 1998; 18:2834-2284.
- 60. Wu X, Kushwaha N, Albert PR et al. A critical protein kinase C phosphorylation site on the 5-HT_{1A} receptor controlling coupling to N-type calcium channels. J Physiol (Lond) 2002; 538:41-51.
- 61. Hofmann F, Ammendola A, Schlossmann J. Rising behind NO: cGMP-dependent protein kinases. J Cell Sci 2000; 113:1671-1676.
- 62. Chen C, Schofield GG. Nitric oxide modulates Ca²⁺ channel currents in rat sympathetic neurons. Eur J Pharmacol 1993; 243:83-86.
- 63. Kim SJ, Song S-K, Kim J. Inhibitory effect of nitric oxide on voltage-dependent calcium currents in rat dorsal root ganglion cells. Biochem Biophys Res Commun 2000; 271:509-514.
- 64. D'Ascenzo M, Martinotti G, Azzena et al. cGMP/protein kinase G-dependent inhibition of N-type Ca²⁺ channels induced by nitric oxide in human neuroblastoma IMR32 cells. J Neurosci 2002; 22:7485-7492.
- Pemberton KE, Jones SVP. Inhibition of the L-type calcium channel by the five muscarinic receptors (m1-m5) expressed in NIH 3T3 cells. Pflügers Arch 1997; 433:505-514.
- 66. Carabelli V, D'Ascenzo M, Carbone E et al. Nitric oxide inhibits neuroendocrine Ca,1 L-type channel gating via cGMP-dependent protein kinase in cell-attached patches of bovine chromaffin cells. J Physiol (Lond) 2002; 541:351-366.
- 67. Abi-Gerges N, Fischmeister R, Méry P-F. G protein-mediated inhibitory effect of a nitric oxide donor on the L-type Ca²⁺ channel in rat ventricular myocytes. J Physiol (Lond) 2001; 531:117-130.
- 68. Abi-Gerges N, Szabo G, Otero AS et al. NO donors potentiate the β -adrenergic stimulation of $I_{Ca,L}$ and the muscarinic activation of $I_{K,ACh}$ in rat cardiac myocytes. J Physiol (Lond) 2002; 540:411-424.
- 69. Vandecasteele G, Verde I, Rücker-Martin C et al. Cyclic GMP regulation of the L-type Ca²⁺ channel current in human atrial myocytes. J Physiol (Lond) 2001; 533:329-340.
- 70. Chen XL, Bayliss DA, Fern RJ et al. A role for T-type Ca²⁺ channels in the synergistic control of aldosterone production by ANG II and K^{*}. Am J Physiol 1999; 276:F674-F683.
- Barrett PQ, Lu H-K, Colbran R et al. Stimulation of unitary T-type Ca²⁺ channel currents by calmodulin-dependent protein kinase II. Am J Physiol 2000; 279:C1694-C1703.
- Wolfe JT, Wang H, Perez-Reyes E et al. Stimulation of recombinant Ca_v3.2, T-type, Ca²⁺ channel currents by CaMKIIγ_c. J Physiol (Lond) 2002; 538:343-355.
- 73. Gutiérrez LM, Viniegra S, Quintanar JL et al. Calyculin A blocks bovine chromaffin cell calcium channels independently of phosphatase inhibition. Neurosci Lett 1994; 178:55-58.
- 74. Bannister RA, Melliti K, Adams BA. Reconstituted slow muscarinic inhibition of neuronal (Ca_v1.2c) L-type Ca²⁺ channels. Biophys J 2002; 83:3256-3267.
- 75. Belevych AE, Warrier S, Harvey RD. Genistein inhibits cardiac L-type Ca²⁺ channel activity by a tyrosine kinase-independent mechanism. Mol Pharmacol 2002; 62:554-565.
- 76. Belevych AE, Nulton-Persson A, Sims C et al. Role of tyrosine kinase activity in α-adrenergic inhibition of the β-adrenergically regulated L-type Ca²⁺ current in guinea-pig ventricular myocytes. J Physiol (Lond) 2001; 537:779-792.
- 77. Hool LC. Hypoxia alters the sensitivity of the L-type Ca^{2*} channel to α -adrenergic receptor stimulation in the presence of β -adrenergic receptor stimulation. Circ Res 2001; 88:1036-1043.
- 78. Meza U, Avila G, Felix R et al. Long-term regulation of calcium channels in clonal pituitary cells by epidermal growth factor, insulin, and glutocorticoids. J Gen Physiol 1994; 104:1019-1038.

- 79. Lei S, Dryden WF, Smith PA. Regulation of N- and L-type Ca²⁺ channels in adult frog sympathetic ganglion B cells by nerve growth factor in vitro and in vivo. J Neurophysiol 1997; 78:3359-3370.
- 80. Jia M, Li M, Liu X-W et al. Voltage-sensitive calcium currents are acutely increased by nerve growth factor in PC12 cells. J Neurophysiol 1999; 82:2847-2852.
- 81. Diversé-Pierliussi M, Remmers AE, Neubig RR et al. Novel form of crosstalk between G protein and tyrosine kinase pathways. Proc Natl Acad Sci USA 1997; 94:5417-5421.
- Fitzgerald EM, Dolphin AC. Regulation of rat neuronal voltage-dependent calcium channels by endogenous p21-ras. Eur J Neurosci 1997; 9:1252-1261.
- Blair LAC, Bence-Hanulec KK, Mehta S et al. Akt-dependent potentiation of L channels by insulin-like growth factor-1 is required for neuronal survival. J Neurosci 1999; 19:1940-1951.
- 84. Berman DM, Gilman AG. Mammalian RGS proteins: Barbarians at the gate. J Biol Chem 1998; 273:1269-1272.
- Melliti K, Meza U, Adams BA. RGS2 blocks slow muscarinic inhibition of N-type Ca²⁺ channels reconstituted in a human cell line. J Physiol (Lond) 2001; 532:337-347.
- 86. Hollinger S, Hepler JR. Cellular regulation of RGS proteins: Modulators and integrators of G protein signaling. Pharmacol Rev 2002; 54:527-559.
- Schiff ML, Siderovski DP, Jordan JD et al. Tyrosine-kinase-dependent recruitment of RGS12 to the N-type calcium channel. Nature 2000; 408:723-727.
- 88. Strauss O, Buss F, Rosenthal R et al. Activation of neuroendocrine L-type channels (α1D subunits) in retinal epithelial cells and brain neurons by pp60^{c-src}. Biochem Biophys Res Commun 2000; 270:806-810.
- Rosenthal R, Thieme H, Strauss O. Fibroblast growth factor receptor 2 (FGFR2) in brain neurons and retinal pigment epithelial cells act via stimulation of neuroendocrine L-type channels (Ca_{*}1.3). FASEB J 2001; 15:970-977.
- 90. Weiss JL, Burgoyne RD. Voltage-independent inhibition of P/Q-type Ca²⁺ channels in adrenal chromaffin cells via a neuronal Ca²⁺ sensor-1-dependent pathway involves Src family tyrosine kinases. J Biol Chem 2001; 276:44804-44811.
- 91. Wu X, Davis GE, Meininger GA et al. Regulation of the L-type calcium channel by α5β1 integrin requires signaling between focal adhesion proteins. J Biol Chem 2001; 276:30285-30292.
- 92. Waitkus-Edwards KR, Martinez-Lemus LA, Wu X et al. $\alpha_4\beta_1$ integrin activation of L-type calcium channels in vascular smooth muscle causes arteriole vasoconstriction. Circ Res 2002; 90:473-480.
- 93. Gutkind JS. Regulation of mitogen-activated protein kinase signaling networks by G protein-coupled receptors. Sci STKE 2001; 2000(40):RE1.
- 94. Johnson GL, Lapadat R. Mitogen-activated protein kinase pathways mediated by ERK, JNK, and p38 kinases. Science 2002; 298:1911-1912.
- 95. Wilk-Blaszczak MA, Stein B, Xu S et al. The mitogen-activated protein kinase p38-2 is necessary for the inhibition of N-type calcium current by bradykinin. J Neurosci 1998; 18:112-118.
- 96. Lei S, Dryden WF, Smith PA. Involvement of Ras/MAP kinase in the regulation of Ca²⁺ channels in adult bullfrog sympathetic neurons by nerve growth factor. J Neurophysiol 1998; 80:1352-1361.
- 97. Fitzgerald EM. Regulation of voltage-dependent calcium channels in rat sensory neurons involves a ras-mitogen-activated protein kinase pathway. J Physiol (Lond) 2000; 527:433-444.
- 98. Fitzgerald EM. The presence of Ca^{2*} channel β subunit is required for mitogen-activated protein kinase (MAPK)-dependent modulation of $\alpha 1B$ Ca^{2*} channels in COS-7 cells. J Physiol (Lond) 2002; 543:425-437.
- 99. Steinberg SF. PI3King the L-type calcium channel activation mechanism. Circ Res 2001; 89:641-644.
- 100. Cantley LC. The phosphoinositide 3-kinase pathway. Science 2002; 296:1655-1657.
- 101. Macrez N, Morel J-L, Kalkbrenner F et al. A βγ dimer derived from G₁₃ transduces the angiotensin AT₁ receptor signal to stimulation of Ca²⁺ channels in rat portal vein myocytes. J Biol Chem 1997; 272:23180-23185.
- 102. Viard P, Exner T, Maier U et al. Gβγ dimers stimulate vascular L-type Ca²⁺ channels via phosphoinositide 3-kinase. FASEB J 1999; 13:685-694.
- 103. Quignard J-F, Mironneau J, Carricaburu V et al. Phosphoinositide 3-kinase γ mediates angiotensin II-induced stimulation of L-type calcium channels in vascular myocytes. J Biol Chem 2001; 276:32545-32551.
- 104. Macrez N, Mironneau C, Carricaburu V et al. Phosphoinositide 3-kinase isoforms selectively couple receptors to vascular L-type Ca²⁺ channels. Circ Res 2001; 89:692-699.
- 105. Hilgemann DW, Feng S, Nasuhoglu C. The complex and intriguing lives of PIP₂ with ion channels and transporters. Sci STKE 2001; (111):RE19.
- 106. Suh B-C, Hille B. Recovery from muscarinic modulation of M current channels requires phosphatidylinositol 4,5-bisphosphate synthesis. Neuron 2002; 35:507-520.

- 107. Hille B. Modulation of ion channels by G-protein-coupled receptors. Trends Neurosci 1994; 17:531-536.
- 108. Dhavan R, Tsai LH. A decade of CDK5. Nat Rev Mol Cell Biol 2001; 2:749-759.
- 109. Liu F, Ma XH, Ule J et al. Regulation of cyclin-dependent kinase 5 and casein kinase 1 by metabotropic glutamate receptors. Proc Natl Acad Sci USA 2001; 98:11062-11068.
- 110. Tomizawa K, Ohta J, Matsushita M et al. Cdk5/p35 regulates neurotransmitter release through phosphorylation and downregulation of P/Q-type voltage-dependent calcium channel activity. J Neurosci 2002; 22:2590-2597.
- 111. Yan Z, Chi P, Bibb JA et al. Roscovitine: A novel regulator of P/Q-type calcium channels and transmitter release in central neurons. J Physiol (Lond) 2002; 540:761-770.
- 112. Dell'Acqua ML, Dodge KL, Tavalin SJ et al. Mapping the protein phosphatase-2B anchoring site on AKAP79. Binding and inhibition of phosphatase activity are mediated by residues 315-360. J Biol Chem 2002; 277:48796-48802.
- 113. Zhu Y, Yakel JL. Calcineurin modulates G protein-mediated inhibition of N-type calcium channels in rat sympathetic neurons. J Neurophysiol 1997; 78:1161-1169.
- 114. Lukyanetz EA, Piper TP, Sihra TS. Calcineurin involvement in the regulation of high-threshold Ca²⁺ channels in NG108-15 (rodent neuroblastoma x glioma hybrid) cells. J Physiol (Lond) 1998; 510:371-385.
- 115. Hernández-López S, Tkatch T, Perez-Garcia E et al. D₂ Dopamine receptors in striatal medium spiny neurons reduce L-type Ca²⁺ currents and excitability via a novel PLCβ₁-IP₃-calcineurin-signaling cascade. J Neurosci 2000; 20:8987-8995.
- 116. Day M, Olson PA, Platzer J et al. Stimulation of 5-HT₂ receptors in prefrontal pyramidal neurons inhibits Ca. 1.2 L-type Ca²⁺ currents via a PLC/IP₃/calcineurin signaling cascade. J Neurophysiol 2002; 87:2490-2504.
- 117. Manning G, Whyte DB, Martinez R et al. The protein kinase complement of the human genome. Science 2002; 298:1912-1934.

CHAPTER 11

Ca²⁺-Dependent Modulation of Voltage-Gated Ca²⁺ Channels

Amy Lee and William A. Catterall

Abstract

The passage of Ca^{2+} ions through voltage-gated Ca^{2+} channels triggers a wide range of signaling pathways but also fundamentally regulates further Ca^{2+} influx through these channels. $Ca_v 1.2$ (L-type) and $Ca_v 2.1$ (P/Q-type) channels undergo a dual feedback regulation by Ca^{2+} , which is manifested as enhanced facilitation and inactivation of Ca^{2+} currents compared to Ba^{2+} currents. Ca^{2+} -dependent facilitation and inactivation are distinct biophysical processes but are linked through a common molecular mechanism. The ubiquitous Ca^{2+} -sensing protein calmodulin binds directly to multiple sequences in the Ca^{2+} channel α_1 subunit, causing Ca^{2+} -dependent conformational changes that favor facilitated or inactivated states of the channel. In the nervous system, Ca^{2+} binding proteins related to CaM also contribute to modulation of Ca^{2+} channels, which may diversify Ca^{2+} signaling in different neurons. In all excitable cells, Ca^{2+} -dependent facilitation and inactivation of voltage-gated Ca^{2+} channels may be a general mechanism for fine-tuning Ca^{2+} entry to protect against toxic Ca^{2+} overloads and to control the specificity with which Ca^{2+} -dependent signaling pathways are activated.

Introduction

Voltage-gated Ca²⁺ channels (VGCCs) couple membrane depolarization to the influx of Ca²⁺ ions, which initiate gene transcription, muscle contraction, and neurotransmitter release. While Ca²⁺ is critical as a second messenger, excess Ca²⁺ entry can cause cell death. Thus, the activity of VGCCs is tightly controlled by a number of factors. Of these, perhaps the most fundamental is a feedback regulation by the Ca²⁺ ions that permeate the channel itself. Based on different properties of Ca²⁺ and Ba²⁺ currents (I_{Ca} and I_{Ba}) through the same channels, it has been proposed that some VGCCs have a Ca²⁺-sensing mechanism that promotes inactivation, and in some cases, also causes facilitation of further Ca²⁺ entry. Such Ca²⁺-dependent regulation of VGCCs may enhance excitation-contraction coupling in the heart and contribute to synaptic plasticity in the nervous system. Elucidating the molecular mechanisms mediating Ca²⁺-dependent inactivation and facilitation has been the focus of intense research, culminating in the recent identification of calmodulin and related Ca²⁺-binding proteins as Ca²⁺ sensors that directly associate with and modulate various VGCC family members. This chapter summarizes the findings that have led to current views and remaining controversies about Ca²⁺-dependent regulation of VGCCs.

Feedback Regulation of VGCCs by Ca²⁺ in Paramecium and Aplysia

The influx of Ca²⁺ ions through VGCCs in the plasma membrane of *Paramecium* initiates the reorientation and beating of cilia to allow the organism to swim in reverse.¹ Voltage-clamp

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Figure 1. Ca^{2*} -dependent inactivation and facilitation of $Ca_v 1.2$. A) $Ca_v 1.2$ currents evoked by 400-ms test pulses from -90 to +20 mV using Ca^{2*} or Ba^{2*} as the permeant ion. B) Facilitation of Ca^{2*} but not Ba^{2*} currents evoked by repetitive depolarizations at the indicated frequencies in $Ca_v 1.2$ channels containing the I/A mutation. (From Zuhlke et al, 1999).

studies of this Ca^{2+} current in *P. caudatum* first characterized a major role for Ca^{2+} ions in accelerating inactivation of a voltage-gated Ca²⁺ conductance.^{2,3} In these experiments, several lines of evidence favored a Ca²⁺-dependent mechanism for inactivation that was distinct from the conventional mechanism for voltage-dependent inactivation. First, inactivation of test currents correlated with the amplitude of the peak Ca²⁺ current. A plot of the amount of inactivation of ICa vs. test voltage was U-shaped, with the greatest inactivation occurring at the voltage eliciting the maximal inward Ca²⁺ current. By contrast, inactivation that depended solely on membrane potential should increase monotonically with the applied voltage. Second, the use of Ba²⁺ rather than Ca²⁺ as the permeant ion significantly reduced the amount of inactivation of test currents. Finally, chelating intracellular Ca²⁺ by injection of EGTA greatly slowed inactivation of I_{Ca}, suggesting that Ca²⁺ influx and accumulation in the cell was necessary for Ca2+-dependent inactivation. Parallel experiments in giant neurons in the marine snail, Aplysia californica, revealed similar Ca2+-dependent inactivation of ICa that was prevented with Ba2+ substitution for Ca^{2+} and by injection of EGTA.^{4,5} These classical studies defined standards for characterizing Ca²⁺-dependent inactivation (CDI) of VGCCs, which would prove to be a fundamental form of negative feedback regulation in a diverse range of cell types and organisms.^{6,7}

Ca²⁺-Dependent Modulation of Ca_v1.2 (L-Type) Channels

Ca²⁺-Dependent Inactivation

Dihydropyridine-sensitive Ca_v1.2 (L-type) channels mediate Ca²⁺ influx required for the contraction of the heart in response to membrane depolarization. Electrophysiological recordings of cardiac myocytes revealed that inactivation of these channels is jointly regulated by both Ca²⁺ ions and voltage.⁸⁻¹¹ An example of CDI measured for cloned and expressed Ca_v1.2 is illustrated in Figure 1A. ¹² Unlike the feedback regulation of Ca²⁺ channels in *Paramecium* and *Aplysia* neurons, CDI in heart cells is only partially removed by intracellular Ca²⁺ chelators,¹³ which led to the hypothesis that the underlying mechanism involved very local increases in Ca²⁺ either in or near the channel pore.¹⁴⁻¹⁷ Single-channel analyses of rat myocytes supported a model in which Ca²⁺ entry through Ca_v1.2 channels shifts their gating to a mode with lower open probability.^{18,19} In parallel whole-cell recordings, calmidazolium, a calmodulin inhibitor, did not block Ca²⁺-dependent inactivation, suggesting that perhaps Ca²⁺-binding directly to

the channel was the molecular switch that altered channel gating. However, calmidazolium does not competitively inhibit all CaM-target interactions, particularly those involving constitutive association of CaM,²⁰ which may explain its inefficacy in this case.

Ca²⁺-Dependent Facilitation

In addition to enhancing inactivation, Ca2+ ions cause a positive feedback regulation of further Ca2+ entry through Ca, 1.2 channels in cardiac myocytes, which may be important in amplifying intracellular Ca²⁺ signals leading to contraction of the heart.^{21,22,23} While CDI is evident during prolonged depolarizations, Ca2+-dependent facilitation (CDF) of Cav1.2 currents is revealed in repetitive pulse protocols. In whole-cell recordings of cardiac myocytes, Ca²⁺ currents during a train of depolarizations progressively increase in amplitude, reaching a steady state by the fifth pulse.²⁴ An example of CDF of the cloned and expressed Ca_v1.2 channel is illustrated in Figure 1B.¹² The facilitation of Ca²⁺ currents is Ca²⁺-dependent in that it can be induced by photolysis of caged-Ca²⁺ compounds²⁵ and is abolished by substitution of extracellular Ca²⁺ with Ba²⁺ or Sr^{2+, 24} CDF can still be observed with 20 mM EGTA or 5 mM BAPTA in intracellular recording solutions, suggesting that like CDI, CDF may depend on very local increases in Ca²⁺ near the channel.²⁴ Interestingly, while both CDF and CDI characterize Cav1.2 channels in cardiac myocytes, recombinant Cav1.2 channels expressed in Xenopus oocytes and HEK 293 cells show primarily CDI and comparatively little CDF.¹² These results suggest that the mechanism for CDF may depend on cell-type specific differences in the processing of Ca, 1.2 channels or on cellular factors, such as Ca^{2+} -dependent kinases or phosphatases, which are more abundant in cardiac cells than in heterologous expression systems.

Molecular Determinants of Ca²⁺-Dependent Modulation in Ca_v1.2 Channels

Efforts to identify the molecular structures important for Ca²⁺-dependent modulation of Ca_v1.2 have focused on the C-terminal domain of the pore-forming α_1 subunit of these channels $(\alpha_1 1.2)^{26-28}$ (Fig. 2). Alternative splicing of exons 40-42 of the human $\alpha_1 1.2$ gene $(\alpha_1 1.2_{86})$ gives rise to channels in which I_{Ba} inactivates rapidly with no further enhancement of inactivation of I_{Ca}²⁹ Further analyses revealed that this loss of CDI depended on multiple sequences within the alternately spliced region of $\alpha_1 1.2_{86}$ (amino acids 1572-1651). Substitution of 1572 IKTEG¹⁵⁷⁶ and 1600 LLDQV¹⁶⁰⁴ of $\alpha_1 1.2$ with the corresponding residues of $\alpha_1 1.2_{86}$ eliminated CDI.³⁰ In addition, deletion of a more distal sequence (aa 1624-1631) also caused fast Ca²⁺-independent inactivation of $\alpha_1 1.2$.³¹ This region partially encompassed the IQ-domain, a consensus site for CaM-binding.

The Role of Ca^{2+} and CaM in CDI of $Ca_v 1.2$.

The emergence of CaM as a critical element in the Ca²⁺-dependent regulation of many ion channels³² foreshadowed the discovery that CaM binding to the IQ-domain was important for CDI of Ca_v1.2 channels. Peptides corresponding to the IQ-domain bind CaM in a Ca²⁺-dependent manner and mutations of residues in the IQ-domain that prevent CaM binding also impair CDI.^{12,33,34} Furthermore, CaM mutants in which at least three of the four Ca²⁺-binding EF-hand motifs are rendered dysfunctional prevent CDI of coexpressed Ca_v1.2 channels.^{12,34} Interestingly, inactivating mutations restricted to the C-terminal but not the N-terminal EF-hands of CaM block CDI.³⁴ The C-terminal lobe of CaM binds Ca²⁺ ions with higher affinity than the N-terminal lobe,³⁵ which may be functionally significant for initiating CDI of Ca_v1.2 channels.

Although CaM binding to the IQ-site was Ca^{2+} -dependent , the ability of the CaM mutants to cause dominant negative inhibition of CDI suggested that Ca^{2+} binding to CaM is not required for interaction with the channel, and that apoCaM must somehow be tethered to the channel, similar to the interaction of CaM with Ca^{2+} -activated K⁺ channels.²⁰ Such constitutive association of CaM with Ca_v1.2 channels would explain the millisecond kinetics of CDI



Figure 2. Molecular determinants for Ca²⁺-dependent regulation of Ca_v1.2. Schematic showing α_1 1.2 subunit with EF-hand and sites involved in CaM tethering (A and C) and the Ca²⁺/CaM binding sites in the N- and C- terminal (IQ) domains.

and was confirmed in living cells using fluorescence resonance energy transfer (FRET) and in biochemical experiments.^{36,37} Although peptides corresponding to the IQ-domain do not bind CaM at or below 10 nM Ca²⁺, non-contiguous sequences upstream of the IQ-domain bind CaM at these levels of Ca²⁺, which approximate the resting Ca²⁺ concentration in cells.³⁶ These separate "A" and "C" peptides contain the ¹⁵⁷²IKTEG¹⁵⁷⁶ and ¹⁶⁰⁰LLDQV¹⁶⁰⁴ sequences, respectively, shown previously to bind CaM and to contribute to CDI of Ca_v1.2 channels.^{30,31,38,39} Based on analyses of the Ca²⁺-dependence of CaM interactions with A, C, and IQ-peptides, Pitt and colleagues (2001) propose a model in which CaM is tethered by the A and C peptides at resting Ca²⁺ levels and elevations in Ca²⁺ to the micromolar range cause a conformational change in CaM and/or α_1 1.2 that results in additional contacts of CaM with the IQ-domain. In this way, the IQ-domain would act as a Ca²⁺-dependent effector site. It is also proposed that CaM tethering to the A and C sites slows inactivation of Ca_v1.2 channels when Ca²⁺ is low. This would neatly explain the unexpected enhancement of I_{Ba} inactivation when either A or C sites may also control Ca²⁺-independent mechanisms for inactivation, such that mutations in these regions would enhance both I_{Ba} and I_{Ca} inactivation regardless of whether CaM was bound.^{40,41}

In addition to the CaM-binding sites in the cytoplasmic C-terminal domain of $\alpha_1 1.2$, other molecular determinants may play a significant role in CDI of Ca_v1.2 channels (Fig. 2). For example, CaM binds also to a site in the intracellular N-terminal domain of $\alpha_1 1.2$ and deletion of this site attenuates CDI.⁴² Furthermore, a number of studies indicate a major role for a EF-hand motif upstream of the CaM-binding sites in the C-terminal domain of $\alpha_1 1.2$.^{26,31,43} While the Ca²⁺-binding capability of this EF-hand is clearly not required for CDI,^{28,43} deletion of the entire EF-hand and mutations of residues other than those that would coordinate Ca²⁺ ions severely limit CDI.^{31,43} Other mutational analyses of the EF-hand indicate the importance of this region for voltage- as well as Ca²⁺-dependent mechanisms for Ca_v1.2 inactivation.⁴⁴

CaM, CaM Kinase II and CDF of Cav1.2 Channels

Although CDI and CDF were thought to be distinct processes both kinetically and mechanistically, structure-function studies of the IQ-domain uncovered a surprising role for CaM binding to this site in both processes.¹² In *Xenopus* oocytes, facilitation of Ca,1.2 channels is evident as a faster recovery from inactivation for I_{Ca} compared to I_{Ba} . While mutating ¹⁶²⁴Ile to glutamate abolished CDI as well as the Ca²⁺-dependent enhancement of recovery from inactivation, substituting alanine for ¹⁶²⁴Ile prevented CDI, but greatly enhanced CDF.¹² These results suggested that CDF was partially obscured in wild-type channels due to the strength of CDI. Although it is still not apparent how CaM binding to the IQ domain leads to both forms of modulation, exhaustive substitutions of ¹⁶²⁴Ile with various amino acids indicate the importance of a bulky hydrophobic side-chain at this residue for CDI but not CDF.⁴⁵ It could be that minute changes in contacts between CaM and ¹⁶²⁴Ile accompany transitions to inactivated and facilitated states. Clarification of this issue awaits crystallization of the CaM-IQ complex, as has been done for Ca²⁺-activated K^{*} channels.⁴⁶

In addition to CaM binding to the IQ domain, other studies support a role for CaM kinase II (CaMK) in CDF of Cav1.2. In single-channel recordings of inside-out patches excised from cardiac myocytes, bath application of a constitutively active form of CaMK caused a marked increase in the probability of channel opening. This effect was blocked by a specific inhibitor of CaMK and by perfusion with non-hydrolyzable forms of ATP, suggesting that phosphorylation of the channel or some regulatory protein is essential for the facilitation.⁴⁷ CaMK not only enhanced ICa but also reduced Ca2+ release from, and increased Ca2+ content of, the sarcoplasmic reticulum in cardiac myocytes, suggesting a role for CaMK and CDF of Cav1.2 channels in excitation-contraction coupling.⁴⁸ Moreover, CDF was not observed upon treating myocytes with thapsigargin, ryanodine, or caffeine, supporting a dependence of CDF on Ca²⁺ from intracellular stores in these cells.⁴⁹ While it is not clear how CaMK might interact with CaM binding to the IQ-domain in promoting CDF, the prominence of CDF of Cav1.2 currents in cardiac cells compared to transfected cells may result from the stronger effects of CaMK regulation in the former compared to the latter system. These studies demonstrate the importance of studying CDI and CDF in native systems, in which the physiological regulation of Cav1.2 channels may be considerably more complex than in transfected cell lines.

Ca²⁺-Dependent Regulation of Ca₂.1 (P/Q-Type) Channels

 Ca^{2+} influx through presynaptic $Ca_v 2.1$ (P/Q-type) channels initiates neurotransmitter release at many central synapses. Compared to the prominent CDI of $Ca_v 1.2$ channels, early experiments indicated that $Ca_v 2.1$ channels expressed in Xenopus oocytes show relatively little regulation by Ca^{2+} . However, fluorometric analysis of Ca^{2+} influx in rat brain synaptosomes revealed Ca^{2+} -dependent inactivation of $Ca_v 2.1$ channels that could be suppressed by decreasing the extracellular Ca^{2+} concentration.⁵⁰ CDI of presynaptic Ca^{2+} channels was further supported in patch clamp recordings of presynaptic nerve terminals in the rat neurohypophysis⁵¹ and at the calyx of Held synapse in the rat brainstem.⁵²

Presynaptic Ca^{2+} currents at the Calyx of Held are unusual in that their functional and pharmacological properties are consistent solely with Ca_v2.1 channels and not a mixed population of VGCCs.⁵² During tetanic stimulation, Ca_v2.1 currents at this synapse undergo an initial facilitation followed by progressive inactivation. Both the facilitation and inactivation are diminished by intracellular perfusion with BAPTA and by Ba²⁺ rather than Ca²⁺ as the permeant ion.^{53,54} Because of the steep dependence of neurotransmitter release on presynaptic Ca²⁺ concentrations, this dual feedback regulation of Ca_v2.1 channels by Ca²⁺ ions could significantly affect synaptic efficacy. Indeed, simultaneous recording of excitatory postsynaptic responses showed that CDF and CDI of Ca_v2.1 channels could lead to synaptic enhancement and depression, respectively.⁵²⁻⁵⁴ CDF and CDI are also observed for cloned and expressed Ca_v2.1 channels expressed in mammalian cells, as illustrated in Figure 3.⁵⁵ Due to the general importance of presynaptic Ca_v2.1 channels in regulating neurotransmitter release throughout



Figure 3. Ca^{2+} -dependent inactivation and facilitation of $Ca_*2.1$. A) $Ca_*2.1$ currents evoked by 1-s test pulses from -80 to +10 mV using Ca^{2+} or Ba^{2+} as the permeant ion. B) Facilitation of Ca^{2+} but not Ba^{2+} currents through $Ca_*2.1$ channels upon repetitive depolarizations given at 100-Hz.

the central nervous system, these results suggested a role for Ca^{2+} -dependent regulation of $Ca_v 2.1$ channels in mechanisms of activity-dependent synaptic plasticity.

CaM Binding Domains in the C-Terminal Region of $\alpha_1 2.1$

A major clue to the mechanism underlying the Ca^{2^*} -dependent regulation of presynaptic $Ca_v 1.2$ channels in neurons came from the identification of a novel CaM-binding site in the C-terminal domain of the pore-forming $\alpha_1 2.1$ subunit of $Ca_v 2.1$ channels using yeast two-hybrid as well as in vitro binding and immunoprecipitation methods.⁵⁵ This CaM-binding domain (CBD) (Fig. 4) is located on the C-terminal side of the sequence in $\alpha_1 2.1$ that corresponds to the IQ-domain of $Ca_v 1.2$ channels.^{12,33,34} The modified IQ domain of $\alpha_1 2.1$ contains IM instead of IQ and has other changes that would also be predicted to substantially reduce its affinity for CaM.

Although CaM binding to the CBD was found to be Ca²⁺-dependent,⁵⁵ the physiological significance of this interaction was not clear since Ca_v2.1 channels showed little Ca²⁺-dependent regulation when expressed in heterologous cells.⁵⁶ With a relatively low (0.5 mM) concentration of EGTA in intracellular recording solutions, I_{Ca} through transfected Ca_v2.1 channels inactivates significantly faster than I_{Ba}.⁵⁵ CDI is particularly evident in channels containing the auxiliary β_{2a} subunit, in which voltage-dependent inactivation is minimal.⁵⁷ Moreover, Ca_v2.1 channels also show prominent CDF, which is evident as a significant increase in I_{Ca} amplitude above initial levels during recovery from inactivation, in paired-pulse protocols, and during repetitive depolarizations designed to mimic trains of action potentials.^{55,57} The enhanced facilitation and inactivation of I_{Ca} are not seen for I_{Ba} or for cells in which intracellular Ca²⁺ is buffered with 10 mM BAPTA, and both CDF and CDI are blocked by coexpression of a CaM inhibitor peptide. The slower Ca²⁺ sensitivity due to faster binding or higher affinity binding of Ca²⁺.⁵⁷ These results strongly suggested that the Ca²⁺-dependent modulation of Ca_v2.1 channels in neurons is caused by two sequential interactions with CaM or perhaps a related Ca²⁺-sensing protein.

As for Ca_v1.2 channels, the mechanism for CDI and CDF of Ca_v2.1 channels involves more than just CaM binding to a single site. Deletion of the CBD from the C-terminal domain of α_1 2.1 decreases but does not completely abolish Ca²⁺-dependent regulation of transfected Ca_v2.1 channels.⁵⁷ CaM also binds to peptides corresponding to the modified IQ-domain of α_1 2.1, and mutation of the I and M residues of this motif to alanines prevents CDF, but not CDI.⁵⁸ (Lee, Scheuer, and Catterall, unpublished). This result is surprising if CaM binding to



Figure 4. Molecular determinants for Ca²⁺-dependent regulation of Ca_v2.1. Schematic showing α_1 2.1 subunit with EF-hand and sites involved in binding Ca²⁺/CaM and CaBP1.

the IQ-domain is essential for CDI since the first two residues of this motif are critical for virtually all target interactions with CaM.⁵⁹ Mutation of IM to negatively charged glutamate residues accelerates inactivation 40-fold⁵⁸ so that CDI is no longer detected as an increase over the much more rapid voltage-dependent inactivation. A similar effect was observed for Ca_v2.1 channels containing β 1b subunits, which inactivate rapidly in the absence of Ca²⁺ and have little CDI.⁵⁷ Thus, the apparent loss of CDI in the IM/EE mutant does not provide evidence for an essential role of the modified IQ motif in CDI, but does show clearly that these amino acid residues have crucial effects on the rate of voltage-dependent inactivation in the absence of Ca²⁺. Overall, the results to date indicate that both the CBD and the modified IQ domain of Ca_v2.1 channels have significant roles in regulation by Ca²⁺ and CaM, with the potential for different actions of these two distinct CaM binding motifs in CDF and CDI.

Mechanism for Dual-Feedback Regulation by CaM

Alanine substitutions in the IQ-domain disrupt CDF but not CDI, while deletion of the CBD preferentially suppresses CDI.^{57,58} These findings suggest that the CBD and modified IQ-domains may be important for CDI and CDF, respectively. Moreover, DeMaria et al have provided evidence that distinct molecular determinants for these two processes reside in the CaM molecule itself. CaM mutants containing inactivating mutations in the N-terminal lobe EF-hands (CaM 1,2) block CDI but spare CDF, while CaM mutants with the corresponding C-terminal mutations (CaM 3,4) prevent CDF but not CDI.⁵⁸ These results are consistent with the higher Ca²⁺ sensitivity of CDF than CDI because the C-terminal EF hands have higher affinity for Ca²⁺. binding than those in the N-terminus of CaM. The ability of these CaM mutants to compete successfully with the endogenous pools of CaM in the cell suggests that apoCaM may be tethered to Ca₂2.1. As for Ca₂1.2, FRET studies indicate that apoCaM can indeed bind to Car2.1 channels in intact cells.³⁷ While regulatory interactions with other proteins depend on either the N- or C-terminal Ca²⁺-binding capability of CaM, Ca₂2.1 channels would be the first example of lobe-specific bi-directional modulation within a single molecular target by CaM. An interesting hypothesis is that the two lobes of CaM interact differentially with the modified IQ domain and the CBD in order to effect bi-directional regulation, perhaps with the C-terminal lobe primarily controlling interactions with the modified IQ domain and the N-terminal lobe primarily controlling interactions with the CBD.

Differential Modulation of Ca_v2.1 by CaM and Neuronal Ca²⁺-Binding Proteins

CaM is the most well-characterized member of a superfamily of Ca²⁺-binding proteins, many members of which differ from CaM in neuron-specific localization and/or amino acid substitutions that prevent Ca²⁺ binding to one or more of the EF-hands.^{60,61} Although the physiological significance of many neuronal Ca²⁺ binding proteins (NCBPs) remains elusive, some NCBPs have emerged as key regulators of ion channel function and synaptic transmission. Recent evidence indicates that NCBPs may confer Ca²⁺-dependent and Ca²⁺-independent regulation to VGCCs that differs significantly from their modulation by CaM.

Neuronal Ca²⁺ Sensor-1

Since its discovery in *Drosophila* mutants with aberrant synaptic function,⁶² neuronal Ca²⁺ sensor-1 (NCS-1) has been implicated in the regulation of neurosecretion, synapse formation, and neuronal circuits controlling associative learning.⁶³⁻⁶⁵ NCS-1 acts indirectly through *src* tyrosine kinase activity to inhibit P/Q-type Ca²⁺ channels in chromaffin cells, but enhances the activity of presynaptic Ca₂2.2 channels in cultured frog spinal cord neurons.⁶⁵⁻⁶⁷ NCS-1 is localized in presynaptic nerve terminals at the calyx of Held synapse, and injection of purified recombinant NCS-1 into these nerve terminals causes a facilitation of I_{Ca} that is blocked by intracellular perfusion with BAPTA and a dominant-negative NCS-1 inhibitor peptide.⁶⁸ Although a direct interaction between NCS-1 and the Ca²⁺ channel was not demonstrated, these findings raise the possibility that NCS-1 rather than CaM may mediate activity-dependent facilitation of Ca_x2.1 channel at this, and potentially other, central synapses.

CaBP1

Ca²⁺-binding protein 1 (CaBP1) represents a novel family of NCBPs identified in retina and the brain.^{69,70} Of all the NCBPs, CaBP1 and its variants show the highest degree of sequence homology with CaM, reflecting a potential to interact with and modulate CaM targets. Intriguingly, CaBP1 binds to the CBD and not the IQ-domain of $\alpha_1 2.1$, but unlike the inter-action with CaM, CaBP1 binding does not require Ca^{2+,71} This Ca²⁺-independent binding of CaBP1 causes a strong enhancement of the rate of inactivation, a positive shift in the voltage-dependence of activation, and a loss of Ca²⁺-dependent facilitation of Ca₂.1 channels in transfected cells.⁷¹ All of these effects would combine to reduce the activity of Ca.2.1 channels. These effects of CaBP1 do not depend on Ca²⁺, but they are absent in channels lacking the CBD, consistent with the hypothesis that CaBP1 displaces CaM from this site in a way that stabilizes closed conformations of the channel. This idea is also supported by the loss of CaM-dependent facilitation when CaBP-1 is co-expressed.⁷¹ The differences in modulation of Cav2.1 channels by CaBP1 and CaM may result from the structural differences between the two Ca²⁺ binding proteins, which include an inactivated Ca²⁺ binding site, a lipid anchor, and an extended central helix connecting the two lobes of CaBP-1.⁶⁹ For example, inactivation of the Ca²⁺ binding activity of EF hand 1 in CaBP-1 may allow it to assume an active conformation and accelerate the rate of inactivation of Ca.2.1 channels without Ca²⁺ binding. Since it co-immunoprecipitates and co-localizes with Ca₂.1 channels in the brain,⁷¹ CaBP1 may be an important determinant of Ca₂.1 channel function in neurons and may contribute to the diversity of function of these channels in the nervous system.

Conclusion and Perspectives

Although Ca²⁺-dependent regulation of VGCCs seems an elegantly simple way to control further Ca²⁺ entry into cells, the underlying mechanism has proven deceptively complex. At resting levels of intracellular Ca²⁺, CaM is prebound to regions upstream of the IQ-domain in

 $Ca_v 1.2$, and Ca^{2*} permeating the channel orchestrates Ca^{2*} -dependent conformational shifts in the CaM binding pocket to include the IQ-domain, which leads to enhanced facilitation and/or inactivation of further Ca^{2*} entry. CaM can also cause CDI and CDF of $Ca_v 2.1$ channels, but the underlying mechanism appears to be fundamentally different from that for $Ca_v 1.2$. First, the determinants for CaM binding and modulation of $Ca_v 2.1$ function are unique. CaM binds in a Ca^{2*} -dependent manner to the modified IQ-domain and the CBD of $\alpha_1 2.1$, which both contribute to CDI and CDF, but are distinct from the corresponding sequences in $\alpha_1 1.2$. The modified IQ-domain of $\alpha_1 2.1$ differs from conventional IQ-motifs, including that in $\alpha_1 1.2$, in that the second residue is methionine rather than glutamine. Moreover, mutating the critical first two residues of $\alpha_1 2.1$ to alanine spares CDI for $Ca_v 2.1$ but abolishes CDI in $Ca_v 1.2$. By the same token, the CBD of $\alpha_1 2.1$ is not conserved in $\alpha_1 1.2$ and the A and C CaM tethering sites in $\alpha_1 1.2$ are not present in $\alpha_1 2.1$. How CaM binding to such distinct sites is transduced into similar forms of channel modulation is an intriguing question to resolve in comparative structure/function analyses.

Despite the remarkable advances in understanding how CaM interacts with VGCCs, in the nervous system, other Ca²⁺ sensors may be physiologically more relevant than CaM in terms of channel modulation. NCBPs such as NCS-1 and CaBP1 may interact with and regulate Ca₂.1 channels in neurons in ways that are distinct from CaM. Differences in subcellular targeting, Ca²⁺ dependence of binding, or binding affinity may confer some NCBPs an advantage over CaM in competing for interaction with the same sites in the α_1 subunit. Given that CaBP1, CaM, and potentially other NCBPs may be colocalized with VGCCs in neurons, it will be necessary to determine which Ca²⁺-binding proteins preferentially regulate VGCCs and to understand the importance of these forms of VGCC modulation in vivo. Given the pathological consequences of VGCC defects, which include migraine, congenital deafness, and absence epilepsy, clarifying the physiological significance of Ca²⁺-dependent modulation of VGCCs by CaM or other Ca²⁺ sensors may reveal novel insights for the development of alternative therapeutic strategies for treating these and other disorders of aberrant VGCC function.

References

- 1. Naitoh Y. Ionic control of the reversal response of cilia in Paramecium caudatum. A calcium hypothesis. J Gen Physiol 1968; 51:85-103.
- 2. Brehm P, Eckert R. Calcium entry leads to inactivation of calcium channel in Paramecium. Science 1978; 202:1203-6.
- 3. Brehm P, Eckert R, Tillotson D. Calcium-mediated inactivation of calcium current in Paramecium. J Physiol 1980; 306:193-203.
- Tillotson D. Inactivation of Ca conductance dependent on entry of Ca ions in molluscan neurons. Proc Natl Acad Sci USA 1979; 76:1497-500.
- 5. Eckert R, Tillotson, DL. Calcium-mediated inactivation of the calcium conductance in caesiumloaded giant neurones of Aplysia californica. J Physiol 1981; 314:265-80.
- 6. Eckert R, Chad JE. Inactivation of Ca channels. Prog Biophys Mol Biol 1984; 44: 215-267.
- 7. Byerly L, Hagiwara S. Calcium channel diversity. In: Grinnell AD, Armstrong D, Jackson M, eds. Calcium and Ion Channel Modulation. New York: Plenum Press, Inc., 1990.
- Kass RS, Sanguinetti MC. Inactivation of calcium channel current in the calf cardiac Purkinje fiber. Evidence for voltage- and calcium-mediated mechanisms. J Gen Physiol 1984; 84:705-26.
- 9. Mentrard D, Vassort G, Fischmeister R. Calcium-mediated inactivation of the calcium conductance in cesium- loaded frog heart cells. J Gen Physiol 1984; 83:105-31.
- 10. Lee KS, Marban E, Tsien RW. Inactivation of calcium channels in mammalian heart cells: joint dependence on membrane potential and intracellular calcium. J Physiol 1985; 364:395-411.
- 11. Hadley RW, Hume JR. An intrinsic potential-dependent inactivation mechanism associated with calcium channels in guinea-pig myocytes. J Physiol 1987; 389:205-22.
- 12. Zühlke RG, Pitt GS, Deisseroth K et al. Calmodulin supports both inactivation and facilitation of L-type calcium channels. Nature 1999; 399:159-161.
- 13. Bechem M, Pott L. Removal of Ca current inactivation in dialysed guinea-pig atrial cardioballs by Ca chelators. Pflugers Arch 1985; 404:10-20.
- 14. Chad JE, Eckert R. An enzymatic mechanism for calcium current inactivation in dialysed Helix neurones. J Physiol 1986; 378:31-51.

- Sherman A, Keizer J, Rinzel J. Domain model for Ca²⁺-inactivation of Ca2+ channels at low channel density. Biophys J 1990; 58: 985-95.
- Imredy JP, Yue DT. Submicroscopic Ca²⁺ diffusion mediates inhibitory coupling between individual Ca²⁺ channels. Neuron 1992; 9:197-207.
- Keizer J, Maki LW. Conditional probability analysis for a domain model of Ca²⁺- inactivation of Ca²⁺ channels. Biophys J 1992; 63:291-295.
- 18. Yue DT, Backx PH, Imredy JP. Calcium-sensitive inactivation in the gating of single calcium channels. Science 1990; 250:1735-1738.
- Imredy JP, Yue DT. Mechanism of Ca²⁺-sensitive inactivation of L-type Ca²⁺ channels. Neuron 1994; 12:1301-1318.
- 20. Xia XM, Fakler B, Rivard A et al. Mechanism of calcium gating in small-conductance calcium-activated potassium channels. Nature 1998; 395:503-507.
- 21. Marban E, Tsien RW. Enhancement of calcium current during digitalis inotropy in mammalian heart: positive feed-back regulation by intracellular calcium? J Physiol 1982; 329:589-614.
- Mitra R, Morad M. Two types of calcium channels in guinea pig ventricular myocytes. Proc Natl Acad Sci 1986; 83:5340-4.
- McCarron JG, McGeown JG, Reardon S et al. Calcium-dependent enhancement of calcium current in smooth muscle by calmodulin-dependent protein kinase II. Nature 1992; 357:74-77.
- 24. Zygmunt AC, Maylie J. Stimulation-dependent facilitation of the high threshold calcium current in guinea-pig ventricular myocytes. J Physiol (Lond) 1990; 428:653-671
- Gurney AM, Charnet P, Pye JM et al. Augmentation of cardiac calcium current by flash photolysis of intracellular caged-Ca²⁺ molecules. Nature 1989; 341:65-68.
- 26. De Leon M, Wang Y, Jones L et al. Essential Ca²⁺-binding motif for Ca²⁺-sensitive inactivation of L-type Ca²⁺ channels. Science 1995; 270:1502-1506.
- 27. Adams B, Tanabe T. Structural regions of the cardiac Ca channel alpha subunit involved in Ca-dependent inactivation. J Gen Physiol 1997; 110:379-89.
- 28. Zhou JM, Olcese R, Qin N et al. Feedback inhibition of Ca²⁺ channels by Ca²⁺ depends on a short sequence of the C terminus that does not include the Ca²⁺-binding function of a motif with similarity to Ca²⁺-binding domains. Proc Natl Acad Sci USA 1997; 94:2301-2305.
- 29. Soldatov NM, Zühlke RD, Bouron A et al. Molecular structures involved in L-type calcium channel inactivation-Role of the carboxyl-terminal region encoded by exons 40-42 in α_{1C} subunit in the kinetics and Ca²⁺ dependence of inactivation. J Biol Chem 1997; 272:3560-3566.
- 30. Soldatov NM, Oz M, O'Brien KA et al. Molecular determinants of L-type Ca²⁺ channel inactivation-Segment exchange analysis of the carboxyl-terminal cytoplasmic motif encoded by exons 40-42 of the human α_{1C} subunit gene. J Biol Chem. 1998; 273: 957-963.
- Zühlke RD, Reuter H. Ca²⁺-sensitive inactivation of L-type Ca²⁺ channels depends on multiple cytoplasmic amino acid sequences of the α_{1C} subunit. Proc Natl Acad Sci USA 1998; 95:3287-3294.
- 32. Saimi Y, Kung C. Calmodulin as an ion channel subunit. Annu Rev Physiol 2002; 64:289-311.
- Qin N, Olcese R, Bransby M et al. Ca²⁺-induced inhibition of the cardiac Ca²⁺ channel depends on calmodulin. Proc Natl Acad Sci 1999; 96:2435-2438.
- Peterson BZ, DeMaria CD, Yue DT. Calmodulin is the Ca²⁺ sensor for Ca²⁺-dependent inactivation of 1-type calcium channels. Neuron 1999a; 22:549-558.
- James P, Vorherr T, Carafoli E. Calmodulin-binding domains: just two faced or multi-faceted? Trends Biochem Sci 1995; 20:38-42.
- 36. Pitt GS, Zuhlke RD, Hudmon A et al. Molecular basis of calmodulin tethering and Ca²⁺-dependent inactivation of L-type Ca²⁺ channels. J Biol Chem 2001; 276:30794-802.
- 37. Erickson MG, Alseikhan BA, Peterson BZ et al. Preassociation of calmodulin with voltage-gated Ca²⁺ channels revealed by FRET in single living cells. Neuron 2001; 31:973-85.
- Pate P, Mochca-Morales J, Wu Y et al. Determinants for calmodulin binding on voltage-dependent Ca²⁺ channels. J Biol Chem 2000; 275:39786-39792.
- Romanin C, Gamsjaeger R, Kahr H et al. Ca²⁺ sensors of L-type Ca²⁺ channel. FEBS Lett 2000; 487:301-6.
- 40. Ferreira G, Yi J, Rios E et al. Ion-dependent inactivation of barium current through L-type calcium channels. J Gen Physiol 1997; 109:449-461.
- 41. Patil PG, Brody DL, Yue DT. Preferential closed-state inactivation of neuronal calcium channels. Neuron 1998; 20:1027-1038.
- 42. Ivanina T, Blumenstein Y, Shistik E et al. Modulation of L-type Ca²⁺ channels by G $\beta\gamma$ and calmodulin via interactions with N and C termini of α_{1C} . J Biol Chem 2000; 275:39846-54.
- 43. Peterson BZ, Lee JS, Mulle JS et al. Individual amino acids within a consensus EF-hand motif are critical for calcium-dependent inactivation of α_{1C} calcium channels. Biophys J 1999b; 76:A340.

- 44. Bernatchez G, Talwar D, Parent L. Mutations in the EF-hand motif impair the inactivation of barium currents of the cardiac alpha1C channel. Biophys J 1998; 75:1727-39.
- 45. Zuhlke RD, Pitt GS, Tsien RW et al. Ca²⁺-sensitive inactivation and facilitation of L-type Ca²⁺ channels both depend on specific amino acid residues in a consensus calmodulin- binding motif in the α_{1C} subunit. J Biol Chem 2000; 275:21121-9.
- 46. Schumacher MA, Rivard AF, Bachinger HP et al. Structure of the gating domain of a Ca²⁺-activated K⁺ channel complexed with Ca²⁺/calmodulin. Nature 2001; 410:1120-4.
- 47. Dzhura I, Wu Y, Colbran RJ et al. Calmodulin kinase determines calcium-dependent facilitation of L-type calcium channels. Nat Cell Biol 2000; 2:173-7.
- 48. Wu Y, Colbran RJ, Anderson ME. Calmodulin kinase is a molecular switch for cardiac excitationcontraction coupling. Proc Natl Acad Sci USA 2001a; 98:2877-81.
- Wu Y, Dzhura I, Colbran RJ et al. Calmodulin kinase and a calmodulin-binding 'IQ' domain facilitate L- type Ca2+ current in rabbit ventricular myocytes by a common mechanism. J Physiol 2001b; 535:679-87.
- Tareilus E, Schoch J, Breer H. Ca²⁺-dependent inactivation of P-type calcium channels in nerve terminals. J Neurochem 1994; 62:2283-91.
- Branchaw JL, Banks MI, Jackson MB. Ca²⁺ and voltage-dependent inactivation of Ca²⁺ channels in nerve terminals of the neurohypophysis. J Neurosci 1997; 17:5772-5781.
- 52. Forsythe ID, Tsujimoto T, Barnes-Davies M et al. Inactivation of presynaptic calcium current contributes to synaptic depression at a fast central synapse. Neuron 1998; 20:797-807.
- 53. Borst JG, Sakmann B. Facilitation of presynaptic calcium currents in the rat brainstem. J Physiol 1998; 513:149-155.
- 54. Cuttle MF, Tsujimoto T, Forsythe ID et al. Facilitation of the presynaptic calcium current at an auditory synapse in rat brainstem. J Physiol 1998; 512:723-729.
- 55. Lee A, Wong ST, Gallagher D et al. Ca²⁺ /calmodulin binds to and modulates P/Q-type calcium channels. Nature 1999; 339:155-159.
- 56. Cens T, Mangoni ME, Nargeot J et al. Modulation of the α1A Ca²⁺ channel by β subunits at physiological Ca²⁺ concentration. FEBS Lett 1996; 391:232-237.
 57. Lee A, Scheuer T, Catterall WA. Ca²⁺ calmodulin-dependent facilitation and inactivation of P/
- Lee A, Scheuer T, Catterall WA. Ca²⁺ (calmodulin-dependent facilitation and inactivation of P/ Q-type Ca²⁺ channels. J Neurosci 2000; 20:6830-6838.
- DeMaria CD, Soong T, Alseikhan BA et al. Calmodulin bifurcates the local Ca²⁺ signal that modulates P/Q-type Ca²⁺ channels. Nature 2001; 411:484-489.
- 59. Bahler M, Rhoads A. Calmodulin signaling via the IQ motif. FEBS Lett 2002; 513:107-13.
- 60. Polans A, Baehr W, Palczewski K. Turned on by Ca²⁺! The physiology and pathology of Ca²⁺-binding proteins in the retina. Trends Neurosci 1996; 19:547-554.
- 61. Burgoyne RD, Weiss JL. The neuronal calcium sensor family of Ca²⁺-binding proteins. Biochem J 2001; 353:1-12.
- 62. Pongs O, Lindemeier J, Zhu XR et al. Frequenin-a novel calcium-binding protein that modulates synaptic efficacy in the Drosophila nervous system. Neuron 1993; 11:15-28.
- McFerran BW, Graham ME, Burgoyne RD. Neuronal Ca²⁺ sensor 1, the mammalian homologue of frequenin, is expressed in chromaffin and PC12 cells and regulates neurosecretion from dense-core granules. J Biol Chem 1998; 273: 22768-22772.
- 64. Gomez M, De Castro E, Guarin E et al. Ca²⁺ signaling via the neuronal calcium sensor-1 regulates associative learning and memory in C. elegans. Neuron 2001; 30:241-248.
- 65. Wang C-Y, Yang F, He X et al. Ca²⁺-binding protein frequenin mediates GDNF-induced potentiation of Ca²⁺ channels and transmitter release. Neuron 2001; 32:99-112.
- 66. Weiss JL, Archer DA, Burgoyne RD. Neuronal Ca²⁺ sensor-1/frequenin functions in an autocrine pathway regulating Ca²⁺ channels in bovine adrenal chromaffin cells. J Biol Chem 2000; 275:40082-40087.
- 67. Weiss JL, Burgoyne RD. Voltage-independent inhibition of P/Q-type calcium channels in adrenal chromaffin cells via a neuronal calcium sensor-1 dependent pathway involves src family tyrosine kinase. J Biol Chem 2001; 276:44804-44811.
- 68. Tsujimoto T, Jeromin A, Saitoh N et al. Neuronal calcium sensor 1 and activity-dependent facilitation of p/q- type calcium currents at presynaptic nerve terminals. Science 2002; 295:2276-9.
- 69. Hacseleer F, Sokal I, Verlinde CLMJ et al. Five members of a novel Ca²⁺-binding protein (CABP) subfamily with similarity to calmodulin. J Biol Chem 2000; 275:1247-1260.
- 70. Haeseleer F, Imanishi Y, Sokal I et al. Calcium-binding proteins: intracellular sensors from the calmodulin superfamily. Biochem Biophys Res Commun 2002; 290:615-23.
- Lee A, Westenbroek RE, Haeseleer F et al. Differential modulation of Ca_v2.1 channels by calmodulin and Ca²⁺-binding protein 1. Nat Neuroscience 2002; 5:210-217.

Voltage-Dependent Inactivation of Voltage Gated Calcium Channels

Mary T. An and Gerald W. Zamponi

Summary

The fast inactivation of voltage-dependent calcium channels is an important, intrinsic regulatory mechanism that helps to precisely control the amount of calcium entering excitable cells during membrane depolarizations. The association with ancillary β subunits regulates the inactivation characteristics of the α_1 subunit through functional (and possibly direct) interactions between the β subunit and N-terminal region of the α_1 subunit. Moreover, palmitoylation of the β subunit N-terminus has emerged as a key regulatory mechanism of inactivation kinetics. Recent advances have provided novel insights into the calcium channel α_1 subunit structural determinants of inactivation, revealing key roles for the S6 transmembrane regions, as well as intracellular linker such as the domain I-II and II-II linkers, and the C-terminus region. Current models include a mechanism of inactivation in which cytoplasmic loops may act as a gating particle that docks to the cytoplasmic end of the S6 transmembrane segments to block calcium flux. Here, we review the calcium channel structural determinants of fast, voltage-dependent inactivation of these channels.

Introduction

The inactivation of ion channels is a fundamental biological process that prevents the breakdown of ionic gradients, and determines action potential duration and the refractory period of excitable tissues. It can be defined as a transition into a nonconducting state following channel opening. At the whole cell level, inactivation is seen as a decay of current levels during the course of the membrane depolarization, and a decreased availability for channel opening at more depolarized membrane potentials. In calcium channels, inactivation serves several unique purposes. It is a key mechanism by which cells are able to tightly control intracellular calcium levels. Such regulation of the temporal precision of calcium signals is of particular significance in view of the pivotal role of calcium as a cytoplasmic messenger in processes such as gene transcription or synaptic transmission.¹⁴ For example, in nerve terminals, the inactivation of calcium currents may contribute to the short term depression of neurosecretion.⁵⁻⁶ Conversely, calcium channel inactivation also helps to prevent the accumulation of excessive, cytotoxic levels of intracellular calcium.⁷⁻⁹ Calcium channel inactivation also regulates cellular excitability. For example, in T-type Ca2+ channels, voltage-dependent inactivation is of added significance as it is a key determinant of pattern behaviour and pacemaker activity in neurons. Calcium influx through T-type calcium channels during prolonged high frequency stimulation is critically dependent on the inactivation characteristics of the channels.¹⁰⁻¹¹ Changes in the inactivation properties of P/Q-type calcium channels are induced by naturally occurring mutations in the Ca_v2.1 α_1 subunit (see Fig. 1),¹²⁻¹⁴ raising the possibility that inappropriate inactivation of certain types of calcium channels may result in CNS malfunction. Finally, the

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Figure 1. Schematic representation of the calcium channel α_1 subunit depicting the loci of naturally occurring point mutations¹²⁻¹⁴ and CAG repeats⁸⁶ that have been shown to affect inactivation properties of various types of voltage-gated calcium channels.

inactivated calcium channel conformation can result in dramatic increases in the affinity of the channel for a number of pharmacological agents, including many clinically used calcium channel therapeutics (see also Chapter 18).¹⁵⁻¹⁷

In principle, voltage gated calcium channels are capable of undergoing multiple types of inactivation processes. Calcium dependent inactivation can be observed predominantly with L-type channels,¹⁸⁻¹⁹ although more recent evidence suggests that other types of high voltage-activated channels also undergo changes in inactivation kinetics in response to calcium entry.²⁰ This is reviewed in detail in Chapter 11, and will not be discussed further here. Slow inactivation occurs only after very prolonged membrane depolarizations (~1 minute) and remains poorly understood.²¹⁻²² Here, we shall discuss aspects of fast voltage dependent inactivation.

What Have We Learnt from Other Types of Voltage Gated Cation Channels?

It has been known for more than two decades that the exposure of sodium channels to cytoplasmically applied proteolytic enzymes results in a loss of inactivation.²³ Based on these initial findings, Armstrong et al²³ coined the "ball and chain mechanism of inactivation", in which inactivation was proposed to occur via occlusion of the channel pore by a cytoplasmic gating particle that was assumed to be physically tethered to the channel. Additional evidence for such a mechanism came from experiments that involved an anti-peptide antibody directed towards the short intracellular segment connecting sodium channel domains III and IV. Application of these antibodies to excised inside out patches resulted in the inhibition of inactivation.²⁴⁻²⁵ The first conclusive molecular biological confirmation of the ball and chain mechanism was derived from experiments on the Shaker B potassium channels.²⁶⁻²⁷ The amino terminus of the Shaker B α subunit contains a 22 amino acid cluster comprised

of hydrophobic and polar domains. Tryptic cleavage of this cluster, or deletion of the region by molecular biological means results in a dramatic slowing of inactivation kinetics.²⁶ But more strikingly, the application of synthetic peptides corresponding to the deleted regions restores the fast inactivation of mutated channels lacking the amino terminal,²⁷ with characteristics resembling those of typical open channel block with regard to concentration dependence of the open times.²⁸ Interestingly, the Shaker B amino terminal "ball" peptide is capable of inducing inactivation-like pore block of other types of potassium channels that do not inactivate under normal conditions.²⁹ Taken together, these results suggest a simple structural basis for the "ball and chain" inactivation model, with the N-terminus acting as the gating ball, and the remainder of the N-terminus serving as a ~50 amino acid long "chain" like tether for the ball.

Since voltage gated potassium channels are tetramers, each channel contains as many as four inactivation particles, but it is believed that only one may block the pore at a given time.³⁰ Less information is available on the exact binding site for the ball region, although functional studies indicate that the cytoplasmic linker between the fourth and fifth transmembrane segment of the α subunit may be involved.³¹ However, the inactivation mechanism in potassium channels is complicated by the fact that certain types of potassium channel β subunits (e.g., Kv β 1.1 and Kv β 3) contain regions that structurally and functionally resemble gating balls. Indeed, coexpression of these ancillary subunits with certain types of noninactivating Kv α subunits (i.e., Kv1.1, Kv1.2 or Kv1.5, but not Kv 1.6) produces rapidly inactivating currents.³²⁻³³

In the sodium channel field, it is more difficult to provide unequivocal evidence for the existence of a gating particle structure. It was shown that expression of the α subunit as two separate proteins (i.e., one corresponding to the first three domains, and one corresponding to the fourth domain) resulted in functional channels which inactivated, however, only very slowly.³⁴ Together with the antibody experiments mentioned earlier, this suggested a critical involvement of the domain III-IV linker region of the sodium channel α subunit in sodium channel inactivation. Indeed, site-directed mutagenesis of three adjacent hydrophobic amino acid residues in this region (I1488, F1489, M1490) to glutamine abolished fast inactivation, 35 which could be partially restored by cytoplasmic application of a pentapeptide containing the IFM motif.³⁶ This resembles in many ways the findings obtained with potassium channels, with the exception that a cytoplasmic loop rather than the N-terminal region is involved. Thus, the domain III-IV linker might act as a "hinged lid" that can dock to the pore and prevent current flow. There is evidence suggesting that the "hinge" might be formed by glycine and proline residues flanking the III-IV linker,³⁷ whereas the docking site for the "lid" structure may include the intracellular regions between the fourth and fifth transmembrane segments in domains III³⁸ and IV,³⁹ and the sixth transmembrane segment in domain IV.⁴⁰ The inactivation properties of the sodium channel α subunit are also modified through the noncovalent association of the auxiliary β_1 subunit which results in acceleration of inactivation kinetics, a speeding of the recovery from inactivation, and a negative shift in the voltage dependence of inactivation in both brain and skeletal muscle sodium channels.⁴¹ Although the exact mechanism by which this occurs is not understood, it has been suggested that part of the effects of the β subunits may be due to a switch in gating modes of the channel.⁴²

Both sodium and potassium channels undergo a second, often slower inactivation process (termed slow inactivation in sodium channels and C-type inactivation in potassium channels) which is thought to occur via global conformational changes in channel structure in response to depolarization. For both sodium and potassium channels, this process appears to depend on regions flanking the pore⁴³⁻⁴⁷ and may involve pore constriction.

In summary, in sodium and potassium channels, there is a common fast inactivation mechanism involving physical occlusion of the pore by an intracellular channel structure. Moreover, both sodium and potassium channel inactivation is regulated by ancillary subunits. As we will outline below, these two general principles may also apply to voltage gated calcium channels, although the molecular details are somewhat different.

α_1 Subunit Structural Inactivation Determinants in High Voltage Activated Channels

Based on work carried out in transient expression systems, the ability of voltage dependent calcium channels to inactivate appears to be an intrinsic feature of the α_1 subunit, since expression of this subunit alone produces inactivating currents. Unlike in sodium and potassium channels, there have been no reports that show a loss of inactivation following intracellular application of proteolytic enzymes such as pronase or trypsin, suggesting the possibility that inactivation in calcium channels could perhaps be fundamentally different from that of other voltage-gated channels. This idea was supported by work of Zhang et al⁴⁸ who created a series of chimeric calcium channels that combined the structural features of rat Ca.2.1 and marine ray Ca_v2.3 calcium channel α_1 subunits (Zhang et al 1994). Based on functional studies carried out with these chimeras in Xenopus oocytes, the authors concluded that the differences in inactivation kinetics observed between the wild type channels could be attributed to the domain I S6 region. The apparent lack of involvement of a cytoplasmic loop led the authors to suggest the possibility that calcium channel inactivation might occur via a pore collapse mediated by the S6 segment, similar to what has been proposed for slow inactivation of potassium channels.⁴⁹⁻⁵¹ A similar possibility was raised by Spaetgens and Zamponi⁵² based on chimera studies with hybrid Ca, 1.2 - Ca, 2.3 channels, which showed that all four transmembrane domains contributed to the rate and/or voltage-dependence of inactivation, with domains II and III mediating the largest effects. To test the hypothesis that the S6 segments might control inactivation in Ca_v2.3 channels, Stotz et al⁵³ exchanged the domain IIS6 and IIIS6 segments between Cav1.2 and Cav2.3 channels individually, or in combination. Consistent with the hypothesis, transfer of the domain IIS6 or the domain IIIS6 regions from the Ca₂.3 channel onto the normally slowly inactivating Cav1.2 channel could confer the rapid inactivation kinetics seen with the rapidly inactivating wild type Ca_v2.3 channel. However, the converse experiment (i.e., slowing of inactivation of Ca₂2.3 with Ca₂1.2 sequence) did not alter inactivation rates, even when both the domain IIS6 and IIIS6 region were substituted concomitantly, suggesting that there had to be other structures that could independently maintain rapid inactivation kinetics. Indeed, only when the IIS6, IIIS6 and I-II linker regions were substituted together could Ca_v2.3 channel inactivation be slowed. Conversely, replacement of the Ca_v1.2 I-II linker with that of Cav2.3 conferred faster inactivation kinetics, suggesting that the domain I-II linker acts as a key structure in the inactivation process.⁵³ It is peculiar, however, that substitution of only the first two thirds of the Cav1.2 linker with Cav2.3 sequence mediates the opposite effect, namely a complete disruption of inactivation, yielding ultraslow inactivation kinetics (see also Fig. 2).⁵⁴⁻⁵⁵ This may indicate that the structural integrity of this region may be critical for appropriate function. It is interesting to note that the domain IS6 chimera described by Zhang et al⁴⁸ involved a short stretch of the domain I-II linker being substituted, a notion that may perhaps serve to reconcile the apparently contradictory results with those of Spaetgens and Zamponi.⁵² An involvement of the domain I-II linker region in calcium channel inactivation is also supported by a number of other studies on mutant calcium channels, 56-57 as well as from data obtained with a naturally occurring splice variant of Ca_v2.1 in which a single valine residue is inserted in this region which results in virtually complete loss of inactivation.⁵⁸ Indeed, this splicing event effectively converts Cav2.1 between a P-type and Q-type channel. Finally, Cens et al⁵⁹ reported that overexpression of peptides corresponding the domain I-II linker of Ca.2.1 speeds the inactivation kinetics of transiently expressed Ca.2.1 channels, which is consistent with the possibility of the domain I-II linker acting as a gating particle.

The involvement of the domain IIS6 and IIIS6 regions in calcium channel inactivation is supported by several other studies based on artificial mutants⁶⁰⁻⁶¹ and, perhaps more interestingly, based on naturally occurring mutations linked to disorders such as familial hemiplegic migraine (see Fig. 1).¹²⁻¹⁴ A systematic investigation of residues involved in inactivation has been carried out for the domain II and IVS6 region of voltage gated calcium channels. Berjukov et al⁶² reported that substitution of reissue M1811 in the domain IV S6 region of Ca_v2.1



Figure 2. Regions of the calcium channel α_1 subunits that have been implicated in inactivation (shown in dark gray—blue in online version). Inset: Current traces obtained from wild type Ca_v1.2 calcium channels, a Ca_v1.2 mutant in which residue T823 in IIS6 was replaced by alanine, and a Ca_v1.2 channel carrying part of Ca_v2.3 sequence in the domain I-II linker. Note that the S6 mutant shows dramatically faster inactivation, whereas substitution of the first two thirds of the I-II linker with Ca_v2.3 sequence (Cav1.2-CecCCC) completely disrupts inactivation.⁵⁴ A color version of this figure is available online at www.Eurekah.com.

calcium channels with glutamine results in a 75-fold increase in inactivation rates. Conversely, the authors showed that inactivation kinetics could be slowed by substitution of residue V1818. Stotz and Zamponi⁵⁴ systematically examined inactivation determinants in the IIS6 region of the Ca_v1.2 channel. The authors showed that replacement of two out of seven of amino acids in this region that were not conserved between Ca_v1.2 and Ca_v2.3 could mimic the effect of exchanging the entire domain IIS6 segment between these channels. Moreover, a systematic replacement of these residues with a variety of different amino acids revealed that increasing size in position 823 slowed inactivation kinetics, whereas hydrophobicity was a more important determinant in position 829. Indeed, replacing F823 with alanine induced rapid inactivation kinetics resembling those typically only seen with T-type calcium channels, but neither recovery from inactivation, nor the voltage-dependence of inactivation were affected. These results indicate that only the rate of entry into the inactivated conformation, but not its stability was controlled by these residues. Taken together, the data of Berjukov et al,⁶² Stotz et al,⁵³ Zhang et al,⁴⁸ and Stotz and Zamponi⁵⁴ suggest that all four S6 segments of the calcium channel α_1 subunit contribute to inactivation.

Besides the domain I-II linker, three other cytoplasmic regions have been implicated in inactivation. Data from Soldatov et al⁶³ and Sandoz et al⁶⁴ have implicated the C-terminal region in voltage dependent inactivation of calcium channels, whereas Stephens et al⁶⁵ reported the N-terminal as an important regulator if inactivation. However, in both of these instances, this may be secondarily due to altered β subunit interactions with the pore forming

 α_1 subunit. More recently, Geib et al⁶⁶ have reported that inactivation of Ca_v2.1 channels is regulated by an intramolecular interaction between the domain I-II and the domain III-IV linker regions. Site-directed mutagenesis, or intracellular application of peptides designed to disrupt this interaction slows the inactivation kinetics of the channel, provided that the channel complex does not contain a β subunit. In follow up work, the authors⁶⁷ suggested that the domain III-IV linker region might structurally resemble the G_γ subunit, and that this loop physically interacts with the G_{βγ} binding site⁶⁸⁻⁶⁹ in the domain I-II linker. The only remaining major intracellular loop, i.e., that connecting domains II and III, does not appear to be a major determinant of inactivation rate, since deletion of most of this region in a naturally occurring splice variant of the N-type channel produces normal current kinetics.⁷⁰ However, in these splice variants, the half-inactivation voltage is shifted towards more depolarized potentials compared to full length channels. This is consistent with the effects of syntaxin 1A and SNAP25, which bind to this region and induce hyperpolarizing shifts in the voltage dependence of inactivation (see Chapter 8).

Taken together, the inactivation of high-activated calcium channels is a complex process that involves a number of α_1 subunit structural determinants (see Fig. 2), comprised predominantly of the S6 transmembrane segments. In addition, the domain I-II linker appears to be a key structure involved in this process, but its role in inactivation may be modulated by other cytoplasmic loops.

Members of the family of T-type calcium channels have only recently been cloned, therefore inactivation determinants have not yet been systematically examined for these channels. To date, there is conflicting information about what may be key structural requirements. Staes et al⁷¹ reported that the C-terminus region of the Ca_v3.1 channel is important for inactivation. In contrast, Marksteiner et al⁷² implicated the domain IIIS6 segment as a major inactivation determinant of these channels. Despite some apparent overlap in the structural determinants of inactivation, it remains at this point difficult to determine as to whether inactivation in low and high voltage activated calcium channel occurs via a functionally conserved mechanism. The fact that T-type calcium channel do not associate with calcium channel β subunits,⁷³ and the low degree of sequence identity in the I-II linker regions of high versus low voltage activated channels may perhaps suggest that T-type channels could be unique among voltage-dependent calcium channels in terms of their inactivation mechanism. Future chimeric approaches will certainly shed light on this issue.

Role of Ancillary Subunits in Calcium Channel Inactivation

Although α_1 subunits can inactivate when expressed alone, the ancillary β subunits are major modulators of the inactivation process.⁷⁴⁻⁷⁵ For many types of high voltage activated channels, coexpression with β_3 or β_{1b} tends to increase the rate of inactivation, whereas β_4 , and particularly, the rat isoform of β_{2a} slow inactivation kinetics.⁷⁶⁻⁷⁷ Using a chimeric approach, Olcese et al and coworkers⁷⁸ showed that the N-terminal region of the rat β_{2a} subunit was responsible for this subunit's dramatic slowing effect on inactivation. Deletion of the first 18 amino acids of the N-terminus removes the slowing effect.⁷⁹ What is unique about the N-terminus of the rat β_{2a} subunit is the presence of two cysteine residues that form sites for palmitoylation. Replacement of the cysteines with serines,^{77,80} or the block of palmitoylation via tunicamycin⁸¹ blocks the kinetic slowing effect of the rat β_{2a} subunit. Replacement of the N-terminus with a transmembrane region such as the CD8 receptor can restore the ability of the β_{2a} subunit to slow calcium channel inactivation.⁸² This is consistent with the role of palmitoylation, and suggests that membrane association of the N-terminus region is involved in regulating inactivation kinetics. Besides the N -terminus, additional interactions between the second variable region of the β_{2a} subunit⁷⁹ and the N-terminus of the calcium channel α_1 subunit⁶⁵ appear to contribute to the regulation of inactivation. Finally, for β_4 subunits, it has been shown that the highly variable C-terminal region can interact with the Ca₂2.1 carboxy terminus to regulate inactivation kinetics.

The effects of α_2 - δ and γ subunit on inactivation have been less completely addressed, but the evidence to date suggests that both the α_2 - δ^{83} subunits and the γ^{84} subunits can regulate inactivation. Coexpression of Ca_v1.2 and Ca_v2.3 calcium channels with different α_2 - δ subunits shifts voltage dependence of inactivation, and alters inactivation kinetics.⁸³ The γ subunit appears to be able to regulate inactivation kinetics by enhancing a slowly inactivating current component seen with Ca_v2.1 calcium channels.⁸⁴ The mechanisms that underlie these effects have, however, not yet been fully explored.

Overall, of the ancillary calcium channel subunits, the β subunit has by far the most profound effects on calcium channel inactivation. The picture emerges that these β subunits interact in multiple ways with the calcium channel α_1 subunit to regulate inactivation. Along these lines, the effect of mutagenesis of residues in the α_1 subunit N-terminus⁶⁵ or C-terminus⁶³⁻⁶⁴ may arise secondarily from a loss of β subunit regulation rather than indicating a direct involvement of these regions in the core inactivation process.

Possible Molecular Mechanism of Calcium Channel Inactivation

From the collective body of structure function studies, the picture emerges that the key structural determinants of inactivation are the domain I-II linker and the S6 segments in the four major transmembrane domains (see also ref. 85). The involvement of the a cytoplasmic domain and of transmembrane helices lining the inner vestibule of the pore is consistent with a pore blocking mechanism of inactivation similar to that seen with sodium and potassium channels. In such a hinged-lid mechanism, the domain I-II linker may act as the inactivation lid that may dock to the S6 segments to prevent current flow through the channels.⁵³⁻⁵⁴ The intramolecular interaction with the domain III-IV loop,⁶⁶ or the association of the I-II linker with a membrane associated calcium channel β subunit (such as rat β_{2a}) may restrict the mobility of this putative inactivation gate, thus modulating the inactivation kinetics. The additional interactions between regions on the β subunit and the N-terminus⁶⁵ and C-terminus⁶⁴ regions of the α_1 subunit may indirectly affect I-II linker function. Finally, a role of the I-II linker as an inactivation particle is consistent with the effects of overexpressed I-II linker peptides on inactivation rates.⁵⁹

The observation that mutations in the domain IIS6 segment of Ca, 1.2 channels (i.e., F823, T829) modify the rate of inactivation, but not the recovery from inactivation suggests that only the rate of entry into the inactivated state is affected and once the channel is inactivated, the stability of the inactivated conformation does not involve these residues. Accordingly, Stotz and Zamponi⁵⁴ proposed that in response to membrane depolarization, residues 823 and 829 may be involved in a conformational change in the II S6 segment that culminates in the availability of a docking site for the inactivation gate. Once docking has occurred, the lifetime of the docked state would then no longer be influenced by these two residues (see Fig. 3). Based on work by several other groups,^{62,48} the authors proposed that this principle would likely apply to all four S6 segments, suggesting a concerted action of the four pore lining transmembrane segments in the inactivation process. It is worth noting that at their cytoplasmic ends, these four transmembrane helices carry several highly conserved residues, which when mutated, result in slowing of inactivation.²² Mutations in additional S6 segments produce incremental, additive effects. This raises the strong possibility that the S6 segments per se may form the docking site for the I-II linker region, but whether all four S6 segments act cooperatively to form a single site, or whether the inactivation gate has a choice of 4 different docking sites remains to be determined.

Taken together, the model proposed by Stotz and Zamponi⁵⁴ can account for the bulk of the structure function data reported in the literature to date. However, it is important to remember that this is merely a model whose validity is difficult to confirm without detailed structural information.



Figure 3. A) Possible model for calcium channel inactivation. Following membrane deploarization, the S6 segments undergo a conformational channel that unmasks a docking site for the inactivation gate formed by the domain I-II linker. B) Reconciliation of the model presented in panel A with data by a number of other laboratories (see main text). a: Membrane insertion of the palmitoylated N-terminus of the rat β_{2a} subunit restricts the mobility of the inactivation gate. b: Interactions between the calcium channel β subunit with the N-terminus and/or the C-terminus region of the α_1 subunit indirectly affects I-II linker function as the inactivation gate. c: Interactions between the III-IV linker that occur in the absence of the β subunit directly regulate inactivation.

Concluding Remarks

Many structural determinants of high voltage activated calcium channel inactivation have been identified over the past 8 years. To date, the model that is most consistent with the currently available literature is that of a hinged-lid mechanism of inactivation, in which the mobility of the lid is regulated by other intracellular loops and ancillary subunits. The basic mechanism of calcium channel inactivation therefore appears to be a common feature to voltage gated sodium and potassium channels, which reaffirms the fundamental importance of the inactivation process in the physiology of excitable cells.

References

- 1. Wheeler DB, Randall A, Tsien RW et al. Roles of N-type and Q-type Ca²⁺ channels in supporting hippocampal synaptic transmission. Science 1994; 264:107-111.
- 2. Dunlap K, Luebke JL, Turner TJ et al. Exocytotic Ca²⁺ channels in mammalian central neurons. Trends Neurosci 1995; 18:89-98.
- 3. Sutton KG, McRory JE, Guthrie H et al. P/Q-type calcium channels mediate the activity-dependent feedback of syntaxin-1A. Nature 1999; 401:800-804.
- 4. Dolmetsch RE, Pajvani U, Fife K et al. Signaling to the nucleus by an L-type calcium channel-calmodulin complex through the MAP kinase pathway. Science 2001; 294:333-9.
- 5. Branchaw JL, Banks MI, Jackson MB et al. Ca²⁺- and voltage-dependent inactivation of Ca²⁺ channels in nerve terminals of the neurohypophysis. J Neurosci 1997; 17:5772-5781.
- 6. Forsythe ID, Tsujimoto T, Barnes-Davies M et al. Inactivation of presynaptic calcium current contributes to synaptic depression at a fast central synapse. Neuron 1998; 20:797-807.
- 7. Choi DW. Calcium-mediated neurotoxicity: Relationship to specific channel types and role in ischemic damage. Trends Neurosci 1988; 11:465-9.
- Orrenius S, McConkey DJ, Bellomo G et al. Role of Ca²⁺ in toxic cell killing. Trends Pharmacol Sci 1989; 10:281-5.
- 9. Orrenius S, Nicotera P. The calcium ion and cell death. J Neural Transm Suppl 1994; 43:1-11.
- Chemin J, Monteil A, Dubel S et al. The alpha1 T-type calcium channel exhibits faster gating properties when overexpressed in neuroblastoma/gliama NG 108-15 cells. Eur J Neurosci 2001; 14:1678-86.
- 11. Chemin J, Monteil A, Perez-Reyes E et al. Specific contribution of human T-type calcium channel isotypes (alpha(1G), alpha(1H) and alpha(1I)) to neuronal excitability. J Physiol 2002; 540:3-14.
- 12. Kraus RL, Sinnegger MJ, Glossmann H et al. Familial hemiplegic migraine mutations change alpha1A Ca²⁺ channel kinetics. J Biol Chem 1998; 273:5586-90.
- Kraus RL, Sinnegger MJ, Koschak A et al. Three new familial hemiplegic migraine mutants affect P/Q-type Ca(2+) channel kinetics. J Biol Chem 2000; 275:9239-43.
- 14. Wappl E, Koschak A, Poteser M et al. Functional consequences of P/Q-type Ca²⁺ channel Cav2.1 missense mutations associated with episodic ataxia type 2 and progressive ataxia. J Biol Chem 2002; 277:6960-6.
- 15. Sun J, Triggle DJ. Calcium channel antagonists: Cardiovascular selectivity of action. J Pharmacol Exp Ther 1995; 274:419-426.
- Jimenez C, Bourinet E, Leuranguer V et al. Determinants of voltage-dependent inactivation affect Mibefradil block of calcium channels. Neuropharmacology 2000; 39:1-10.
- Roullet JB, Spaetgens RL, Burlingame T et al. Modulation of neuronal voltage-gated calcium channels by farnesol. J Biol Chem 1999; 274:25439-46.
- Peterson BZ, DeMaria CD, Adelman JP et al. Calmodulin is the Ca²⁺ sensor for Ca²⁺-dependent inactivation of L=type calcium channels. Neuron 1999; 22:549-558.
- 19. Zuhlke RD, Pitt GS, Deisseroth K et al. Calmodulin supports both inactivation and facilitation of L-type calcium channels. Nature 1999; 399:159-162.
- Lee A, Wong A, Gallagher D et al. Ca²⁺/calmodulin binds to and modulates P/Q-type calcium channels. Nature 1999; 399:155-159.
- Sokolov S, Weiss RG, Timin EN et al. Modulation of slow inactivation in class A Ca²⁺ channels by β-subunits. J Physiol 2000; 527:445-454.
- Shi C, Soldatov NM. Molecular determinants of voltage-dependent slow inactivation of the Ca²⁺ channel. J Biol Chem 2002; 77:6813-21.
- Armstrong CM, Bezanilla F, Rojas E. Destruction of sodium conductance inactivation in squid axons perfused with pronase. J Gen Physiol 1973; 62:375-391.
- 24. Vassilev PM, Scheuer T, Catterall WA. Identification of an intracellular peptide segment involved in sodium channel inactivation. Science 1988; 241:1658-1661.
- 25. Vassilev P, Scheuer T, Catterall WA. Inhibition of inactivation of sodium channels by a site-directed antibody. Proc Natl Acad Sci USA 1989; 86:8147-81.
- 26. Hoshi T, Zagotta WN, Aldrich RW. Biophysical and molecular mechanisms of Shaker potassium channel inactivation. Science 1990; 250:533-53.
- 27. Zagotta WN, Hoshi T, Aldrich RW. Restoration of inactivation in mutants of Shaker potassium channels by a peptide derived from ShB. Science 1990; 250:506-507.
- Demo SD, Yellen G. The inactivation gate of the Shaker potassium channel behaves like an open-channel blocker. Neuron 1991; 7:743-753.
- 29. Toro L, Stefani E, Latorre R. Internal blockade of a Ca(2+)-activated K⁺ channel by Shaker B inactivating "ball" peptide. Neuron 1992; 9:237-245.
- MacKinnon R, Aldrich RW, Lee AW. Functional stoichiometry of Shaker potassium channel inactivation. Science 1993; 262:757-759.
- Isacoff EY, Jan YN, Jan LY. Putative receptor for the cytoplasmic inactivation gate in the Shaker potassium channel. Nature 1991; 353:86-90.
- 32. Heinemann SH, Rettig J, Graack HR et al. Functional characterization of Kv channel b-subunits for rat brain. J Physiol 1996; 493:623-633.
- Robertson B. The real life of voltage-gated K^{*} channels: More than model bahavior. Trends Pharmacol Sci 1997; 18:474-483.
- 34. Stuhmer W, Conti F, Suzuki H et al. Structural parts involved in activation and inactivation of the sodium channel. Nature 1989; 339:597-603.
- 35. West JW, Patton DE, Scheuer T et al. A cluster of hydrophobic amino acid residues required for fast sodium channel inactivation. Proc Natl Acad Sci 1992; 89:10910-10914.

- Eaholtz G, Scheuer T, Catterall WA. Restoration of inactivation and block of open sodium channels by an inactivation gate peptide. Neuron 1994; 12:1041-1048.
- 37. Kellenberger S, West JW, Catterall WA et al. Molecular analysis of potential hinge residues in the inactivation gate of brain type IIA Na+ channels. J Gen Physiol 1997; 109:607-617.
- Smith MR, Goldin AL. Interaction between the sodium channel inactivation linker and domain III S4-S5. Biophys J 1997; 73:1885.
- 39. McPhee JC, Ragsdale DS, Scheuer T et al. A critical role of the S4-S5 intracellular loop in domain IV of the sodium channel α subunit in fast inactivation. J Biol Chem 1998; 273:1121-1129.
- 40. McPhee JC, Ragsdale DS, Scheuer T et al. A mutation in segment IVS6 disrupts fast inactivation of sodium channels. Proc Natl Acad Sci USA 1994; 91:12346-12350.
- McCormick KA, Srinivasan J, White K et al. The extracellular domain of the beta1 subunit is both necessary and sufficient for β1-like modulation of sodium channel gating. J Biol Chem 1999; 274:32638-32646.
- Isom LL, De Jongh KS, Catterall WA. Auxilliary subunits of voltage-gated calcium channels. Neuron 1994; 12:1183-1194.
- 43. Vilin YY, Makita N, George Jr AL et al. Structural determinants of slow inactivation in human cardiac and skeletal muscle sodium channels. Biophys J 1999; 77:1384-1393.
- 44. Richmond JE, Featherstone DE, Hartmann HA et al. Slow inactivation in human cardiac sodium channels. Biophys J 1998; 74:2945-2952.
- 45. Hoshi T, Zagotta WN, Aldrich RW. Two types of inactivation in Shaker potassium channels: Effects of alterations in the carboxyl terminal. Neuron 1991; 7:547-556.
- 46. Lopez GA, Jan YN, Jan LY. Evidence that the S6 segments of the Shaker voltage-gated potassium channel comprises part of the pore. Nature 1994; 367:179-182.
- 47. Lopez-Barneo J, Hoshi T, Heinemann SH et al. Effects of external cations and mutations in the pore region on C-type inactivation of Shaker potassium channels. Receptors & Channels 1993; 1:61-71.
- 48. Zhang JF, Elinor PT, Aldrich RW et al. Molecular determinants of voltage-dependent inactivation in calcium channels. Nature 1994; 372:97-100.
- Durell SR, Hao Y, Guy HR. Structural models of the transmembrane region of voltage-gated and other K⁺ channels in open, closed, and inactivated conformations. Struct Biol 1998; 121:263-284.
- Liu Y, Jurman ME, Yellen G. Dynamic rearrangement of the outer mouth of a K^{*} channel during gating. Neuron 1996; 16:859-867.
- Ogielska EM, Zagotta WN, Hoshi T et al. Cooperative subunit interactions in C-type inactivation of K channels. Biophys J 1995; 69:2449-57.
- Spaetgens RL, Zamponi GW. Multiple structural domains contribute to voltage-dependent inactivation of rat brain α1E calcium channels. J Biol Chem 1999; 274:22428-22436.
- Stotz SC, Hamid J, Spaetgens RL et al. Fast inactivation of voltage-dependent calcium channels. A hinged-lid mechanism? J Biol Chem 1999; 274:5483-5490.
- Stotz SC, Zamponi GW. Identification of inactivation determinants in the domain IIS6 region of high voltage-activated calcium channels. J Biol Chem 2001; 276:33001-10.
- Beedle AM, Hamid J, Zamponi GW. Inhibition of transiently expressed low- and high-voltage-activated calcium channels by trivalent metal cations. J Membr Biol 2002; 187:225-38.
- 56. Herlitze S, Hockerman GH, Scheuer T et al. Molecular determinants of inactivation and G protein modulation in the intracellular loop connecting domains I and II of the calcium channel alpha1A subunit. Proc Natl Acad Sci USA 1997; 94:1512-6.
- 57. Berrou L, Bernatchez G, Parent L. Molecular determinants of inactivation within the I-II linker of alpha1E (CaV2.3) calcium channels. Biophys J 2001; 80:215-228.
- Bourinet E, Soong TW, Sutton K et al. Splicing of a1A subunit gene generates phenotypic variants of P- and Q-type calcium channels. Nat Neurosci 1999; 2:407-415.
- 59. Cens T, Restituito S, Galas S et al. Voltage and calcium use the same molecular determinants to inactivate calcium channels. J Biol Chem 1999; 274:5483-5490.
- 60. Hering S, Aczel S, Grabner M et al. Transfer of high sensitivity for benzothiazepines from L-type to class A (BI) calcium channels. J Biol Chem 1996; 271:24471-24475.
- 61. Hering S, Berjukow S, Aczel S et al. Ca²⁺ channel block and inactivation: Common molecular determinants. Trends Pharmacol Sci 1998; 19:439-443.
- 62. Berjukow S, Marksteiner R, Sokolov S et al. Amino acids in segment IVS6 and beta-subunit interaction support distinct conformational changes during Ca(v)2.1 inactivation. J Biol Chem 2001; 276:17076-17082.
- 63. Soldatov NM, Oz M, O'Brien KA et al. Molecular determinants of L-type Ca²⁺ channel inactivation. Segment exchange analysis of the carboxyl-terminal cytoplasmic motif encoded by exons 40-42 of the human α1C subunit gene. J Biol Chem 1998; 273:957-963.

- 64. Sandoz G, Bichet D, Cornet V et al. Distinct properties and differential beta subunit regulation of two C-terminal isoforms of the P/Q-type Ca(2+)-channel alpha(1A) subunit. Eur J Neurosci 2001; 14:987-997.
- 65. Stephens GJ, Page KM, Bogdanov Y et al. The a1B Ca²⁺ channel amino terminus contributes determinants for b subunit-mediated voltage-dependent inactivation properties. J Physiol 2000; 525:377-390.
- 66. Geib S, Sandoz G, Cornet V et al. The interaction between the I-II loop and the III-IV loop of Cav2.1 contributes to voltage-dependent inactivation in a beta -dependent manner. J Biol Chem 2002; 277:10003-13.
- 67. Fathallah M, Sandoz G, Mabrouk K et al. Modelling of the III-IV loop, a domain involved in calcium channel Ca(v)2.1 inactivation, highlights a structural homology with the gamma subunit of G proteins. Eur J Neurosci 2001; 16:219-28.
- 68. Zamponi GW, Bourinet E, Nelson D et al. Crosstalk between G proteins and protein kinase C mediated by the calcium channel α1 subunit. Nature 1997; 385:442-446.
- 69. De Waard M, Liu H, Walker D et al. Direct binding of G-protein betagamma complex to voltage-dependent calcium channels. Nature 1997; 385:446-50.
- 70. Kaneko S, Cooper CB, Nishioka N et al. Identification and characterization of novel human Ca(v)2.2 (alpha 1B) calcium channel variants lacking the synaptic protein interaction site. J Neurosci 2002; 22:82-92.
- 71. Staes M, Talavera K, Klugbauer N et al. The amino side of the C-terminus determines fast inactivation of the T-type calcium channel alpha1G. J Physiol 2001; 530:35-45.
- Marksteiner R, Schurr P, Berjukow S et al. Inactivation determinants in segment IIIS6 of Ca(v)3.1. J Physiol 2001; 537:27-34.
- 73. Lambert RC, Maulet Y, Mouton J et al. T-type Ca²⁺ current properties are not modified by Ca²⁺ channel beta subunit depletion in nodosus ganglion neurons. J Neurosci 1997; 17:6621-6628.
- 74. Lacerda AE, Kim HS, Ruth P et al. Normalization of current kinetics by interaction between the α1 and β subunits of the skeletal muscle dihydropyridine-sensitive Ca²⁺ channel. Nature 1991; 352:527-530.
- 75. Varadi G, Lory P, Schultz D et al. Acceleration of activation and inactivation by the β subunit of the skeletal muscle calcium channel. Nature 1991; 352:159-162.
- Isom LL, De Jongh KS, Catterall WA. Auxiliary subunits of voltage-gated ion channels. Neuron 1994; 12:1183-1194.
- 77. Qin N, Platano D, Olcese R et al. Unique regulatory properties of the type 2a Ca²⁺ channel β subunit caused by palmitoylation. Proc Natl Acad Sci USA 1998; 95:4690-4695.
- 78. Olcese R, Qin N, Schneider T et al. The amino terminus of a calcium channel b subunit sets rates of channel inactivation independently of the subunit's effect on activation. Neuron 1994; 13:1433-1438.
- 79. Qin N, Olcese R, Zhou J et al. Identification of a second region of the b-subunit involved in regulation of calcium channel inactivation. Am J Physiol 1996; 271:C1539-C1545.
- Feng ZP, Arnot MI, Doering CJ et al. Calcium channel beta subunits differentially regulate the inhibition of N-type channels by individual Gbeta isoforms. J Biol Chem 2001; 276:45051-45058.
- Hurley JH, Cahill AL, Currie KP et al. The role of dynamic palmitoylation in Ca²⁺ channel inactivation. Proc Natl Acad Sci USA 2000; 97:9293-9298.
- Restituito S, Cens T, Barrere C et al. The [beta]2a subunit is a molecular groom for the Ca²⁺ channel inactivation gate. J Neurosci 2000; 20:9046-9052.
- Klugbauer N, Lacinova L, Marais E et al. Molecular diversity of the calcium channel alpha2delta subunit. J Neurosci 1999; 19:684-691.
- 84. Rousset M, Cens T, Restituito S et al. Functional roles of gamma2, gamma3 and gamma4, three new Ca²⁺ channel subunits, in P/Q-type Ca²⁺ channel expressed in Xenopus oocytes. J Physiol 2001; 532:583-593.
- Shi C, Soldatov NM. Molecular determinants of voltage-dependent slow inactivation of the Ca²⁺ channel. J Biol Chem 2002; 277:6813-6821.
- 86. Matsuyama Z, Wakamori M, Mori Y et al. Direct alteration of the P/Q-type Ca²⁺ channel property by polyglutamine expansion in spinocerebellar ataxia 6. J Neurosci 1999; 19:RC14.

Selective Permeability of Voltage-Gated Calcium Channels

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Abstract

A dvances based on experiment and theory are converging upon a structural description of the selectivity mechanism of voltage-gated calcium channels. The emerging description differs from that for potassium channels, which make use of a stiff filter lined with main chain carbonyl oxygens that snugly fit K⁺ ions. Instead, calcium channels use a selectivity filter composed of the side chain carboxylate oxygen atoms of a cluster of four glutamate residues (EEEE locus). These carboxylate-bearing side chains are thought to project into the aqueous lumen of the pore where they sort Ca²⁺ from other would-be permeant ions. The EEEE locus is evidently flexible: it can tightly bind a single Ca²⁺ ion in order to block Na⁺ flux but rearranges to accommodate multiple Ca²⁺ ions in order to allow high Ca²⁺ flux. The four glutamates are not functionally equivalent, an observation that is suspected to be important for Ca²⁺ passage through the selectivity filter. This chapter summarizes the experimental results that support these conclusions and the theoretical models that have been proposed to explain how calcium channels can be at once highly selective and yet readily permeated.

Introduction

The selective permeability of voltage-gated calcium channels is essential for transduction of cellular electrical activity into cytosolic Ca^{2+} signals used by cells to initiate such processes as neurotransmitter release, contraction of cardiac muscle, and alteration of gene transcription. By opening in response to membrane depolarization, voltage-gated calcium channels permit Ca^{2+} in the extracellular solution, which has a Ca^{2+} concentration on the order of a few millimolar, to enter the cell and raise cytosolic Ca^{2+} concentration above its resting level of -0.1 micromolar.

Rapid transit of Ca^{2+} through the pore of voltage-gated calcium channels is required to produce the cytosolic Ca^{2+} transients that are necessary for release of neurotransmitter or contraction of cardiac muscle. Coincident with rapid Ca^{2+} transit, voltage-gated calcium channels must be able to distinguish Ca^{2+} ions from similarly sized Na⁺ ions. Because Na⁺ ions are much more abundant in the extracellular solution as compared to Ca^{2+} ions, voltage-gated calcium channels have necessarily evolved a selectivity mechanism that places them among the most highly selective ion channels known.

As a consequence of their robust selective permeability, voltage-gated calcium channels have become a favored model system for investigation of ion selectivity mechanisms. Analysis of selective permeability in calcium channels has benefited from the wealth of information regarding structure of Ca²⁺ binding sites in a variety of proteins and organic molecules. In addition, parallel study of calcium channels and potassium channels has greatly enriched the comparative biology of ion channel selectivity, with progress for each channel enhancing understanding of selective permeation in both. The present chapter considers the importance for selectivity of Ca^{2+} binding within the pore, evidence that multiple ion occupancy of the pore is essential for rapid Ca^{2+} throughput, what tinkering with pore structure has revealed about selectivity filter structure, and how theoretical approaches contribute to understanding selective permeability of Ca^{2+} channels.

Selectivity by Ion Binding Affinity

Some ions are simply too large to pass through a channel's selectivity filter: in calcium channels, cations larger than tetramethylammonium are too big to pass.¹ Among ions smaller than tetramethylammonium, various metal cations (Ba^{2+} , Sr^{2+} , Li^+ , Na^+ , K^+ and Cs^+ , in addition to Ca^{2+}) will pass through the pore of a calcium channel under certain experimental conditions.²⁻⁵ However, calcium channels strongly select among these cations when more than one of them is present. Most pertinent to the physiological situation, calcium channels reliably discriminate between Ca^{2+} and the 100-fold more abundant Na^+ despite the fact that these two ions are nearly identical in diameter (2 Å). How does this happen?

In general, a selectivity filter must be able to stabilize permeant ions much as water stabilizes them in solution. In calcium channels, selective permeability is based on the fact that Ca^{2+} ions are more effectively stabilized in the filter than are other ions, particularly Na⁺ ions. This ideathat relative ion binding affinity underlies calcium channel selectivity among small metal cations-was first suggested by the finding that Ca^{2+} reduced the amplitude and upstroke velocity of action potentials supported by Sr^{2+} current through calcium channels, as though Ca^{2+} blocked Sr^{2+} current by competing with Sr^{2+} for a binding site in the channel.⁶ Other early evidence for the importance of binding affinity was the observation that Co^{2+} blocks Ca^{2+} current through calcium channels less potently than it blocks Ba^{2+} current through these same channels: the greater resistance of Ca^{2+} current to block by Co^{2+} can be understood if the pore binds Ca^{2+} more tightly than Ba^{2+} .⁷

Bi-ionic reversal potentials provide one means of estimating the relative permeability for divalent and monovalent cations.⁸⁻¹¹ From these kinds of measurements, the relative permeability sequence has been found to be $Ca^{2+} > Ba^{2+} > Li^+ > Na^+ > K^+ > Cs^+$. Ca^{2+} is selected over Na⁺ by >1000:1, which explains why Ca^{2+} current is little influenced by extracellular Na⁺ concentration.^{12,13}

A permeability sequence can also be derived from measurements of single-channel conductance: a smaller conductance corresponds to a slower rate of ion passage through the pore and lower permeability. Single-channel conductance for Ca^{2+} is small, indicating that this ion passes slowly through the pore, whereas conductance for Na^+ is larger because this ion passes through more rapidly. The permeability sequence obtained from single-channel conductance, $Ca^{2+} < Ba^{2+} < Li^+ < Na^+ < K^+ < Cs^+$, is opposite in order to that obtained from reversal potentials and seems to indicate that Ca^{2+} is less permeant than, for example, Na^+ .^{12,14,15} However, this seeming contradiction can be resolved by considering the consequences of binding permeant ions in the pore. Permeant ions that bind with higher affinity will reside, on average, for a longer period of time on the binding site and will therefore travel through the pore more slowly, yielding smaller single-channel conductance.¹⁶ This "sticky pore" concept thus predicts that ions with higher binding affinity (Ca^{2+}) have high relative permeability but small conductance, whereas ions with lower affinity (Na^+) have low relative permeability but high conductance.

A Multi-Ion Pore Confers High Flux

For a single-file pore that cannot contain more than one ion, selection by affinity is ineffective.¹⁶ If such a pore is confronted with an equimolar mixture of two permeant ions which differ by, for example, 1000-fold in affinity, the higher affinity ion traverses the pore 1000-fold slower, but it also blocks passage of the lower affinity, faster-throughput ion 99.9% of the time. The result is that the two ion species cross the pore at the same net rate and they are thus equally permeant. Pores that can contain more than one ion are not restricted in this way: intrapore interactions between ions allow one high-affinity ion to elute another and so selectivity with high flux is achieved.

Three experimental observations indicate that calcium channels function as multi-ion pores. First, single-channel conductance is smaller in a mixture of Ca^{2+} and Ba^{2+} than in Ba^{2+} or Ca^{2+} alone.^{4,17} The phenomenon is much larger for mixtures of Ca^{2+} and Na^{+} .¹⁸ This anomalous mole-fraction behavior¹⁹ has been attributed to reciprocal, partial block by one ion species of flux by the other, which presupposes that the pore contains multiple ion binding sites and that ions move from site to site in single file.^{4,18,20,21} The second line of evidence indicating that calcium channels are multi-ion pores follows from the fact that calcium channels bind Ca^{2+} with two distinct affinities: Ca^{2+} blocks Na⁺ movement through calcium channels with a 1 μ M dissociation constant (K_D), whereas single-channel Ca^{2+} current saturates with a 14 mM K_D.^{4,18} The two affinities have been thought to correspond to two Ca^{2+} binding sites, and hence Ca^{2+} channels appear able to contain at least two Ca^{2+} ions.

The third and strongest piece of evidence that calcium channels can contain at least two divalent cations comes from study of the kinetics of Cd^{2+} block of single-channel Ba^{2+} currents.²² Cd^{2+} blocks calcium channel current by binding to a site in the pore that more usually binds Ca^{2+} or other permeant ions, including Ba^{2+} . The rate of Cd^{2+} unbinding (unblock) has been shown to depend upon the concentration of Ba^{2+} in the bathing solution, so that raising Ba^{2+} in the bathing solution—and thereby increasing the probability of Ba^{2+} occupying the pore—speeds unbinding of Cd^{2+} . The ability of Ba^{2+} to speed Cd^{2+} exit must reflect an intrapore interaction between these ions because this is where the blocking Cd^{2+} ion is located. The pore therefore seems able to accommodate at least two divalent cations. Moreover, the enhancement of Cd^{2+} exit rate by Ba^{2+} brings to mind the elution of one Ca^{2+} ion by another, hypothesized to be the key feature supporting large Ca^{2+} flux through the high-affinity selectivity filter.

How advantageous for flux is a multi-ion pore? Consider a one-site pore, for which the theoretical upper limit on flux is given by the rate of unbinding of the permeant ion: $k_{off} = k_{on}/k_{off}$ K_D (Fig. 1A). In calcium channels, 1 μ M Ca² half-blocks Na⁺ current (K_D = 10⁻⁶ M). This concentration is so low that only a single Ca^{2+} ion would be bound in the selectivity filter during block, making this a one-ion situation. With this K_D , and assuming that Ca^{2+} ions arrive at the site as fast as diffusion allows ($k_{on} - 10^9 \text{ M}^{-1}\text{s}^{-1}$), the maximal off-rate and hence flux is only 10^3 Ca²⁺ ions per second. In Figure 1A, arrow 2 indicates the size of the jump that a Ca²⁺ ion must make in order to get out of a high-affinity, one-site pore. The large size of the jump explains the low rate of movement over the barrier and small flux through the one-site pore. But open calcium channels pass roughly 10⁶ Ca²⁺ ions per second. One way high flux with high Ca^{2+} binding affinity might work is based on interaction between pairs of Ca^{2+} ions bound in the pore. Figure 1B illustrates such a scenario. When one Ca²⁺ ion is bound tightly in either of the two postulated high-affinity sites, Na⁺ flux is stopped, but when both sites are occupied by Ca²⁺, electrostatic repulsion between the Ca²⁺ pair decreases net affinity for pore and high flux results.^{4,18} In this model, tight binding of one Ca²⁺ ion maintains high selectivity while electrostatic repulsion provides the energy to push Ca2+ ions through the avid selectivity filter 1000x faster than would be allowed in a one-ion, high-affinity pore.

Although high flux seems to require a multi-ion pore, such a pore need not necessarily possess more than one high-affinity site in order to support high flux. Indeed, the voltage-dependence of Ca^{2+} block of monovalent cation current indicates that high-affinity binding occurs just within the extracellular entrance of calcium channels, as if only one high-affinity binding region is present in calcium channels.^{14,15} But how do ions get out of this site? One possibility is that low-affinity sites flank the high-affinity region, and these might act as stair steps to allow an ion to climb out of the central high-affinity site.²³ Figure 1C illustrates this idea. Experimental evidence for such low-affinity sites has been obtained.¹⁴ Another useful way of viewing the role of the low-affinity sites is that they act to increase the probability that the pore is multiply occupied, because ions reside in the high-affinity site, and though more briefly, at the low-affinity sites too. Calculations with the model show that substantial



Figure 1. Three rate theory models for pores that have high affinity for Ca²⁺. The fraction of the electric field (V_M) experienced by a Ca2+ ion as it passes through the pore is indicated on the horizontal axis (0 = extracellular end, 1 = intracellular end). Chemical potential energy is indicated on the vertical axis. Ca²⁺ ions are represented by solid black circles, and the energy profile along the permeation pathway is represented by solid lines. Lengths of vertical arrows represent (arrow 1) strength of the highest affinity site and (arrow 2) the size of the barrier that Ca²⁺ must hurdle to exit the pore. The length of arrow 1 corresponds to the ability of Ca2+ to block flux of foreign ions, and the length of arrow 2 corresponds to Ca2+ flux, with a shorter arrow 2 indicating greater flux. In a one-site pore A), flux is very low because the energy barrier for exit is large (-22kT; arrow 2). In multi-ion pores, Ca²⁺ flux is increased because the size of the rate-limiting barrier is reduced: in B), ion-ion interactions lower binding affinity, whereas in C) low-affinity sites flanking the selectivity site provide stair steps out of the central energy well. Modified with permission from: Dang TX, McCleskey EW. Journal of General Physiology 1998; 111:185-193. © 1998 The Rockefeller University Press.

occupancy of the low-affinity sites is required to achieve significant flux. Thus even with a single high-affinity site, the pore preserves high flux through multiple ion occupancy. Other models of a high-flux pore with a single high-affinity site have been developed as well.²⁴

Summarizing ideas regarding binding and flux in calcium channels yields the following view. Ions move in single file through the pore, but several species of divalent and monovalent metal cations are able to pass through. Relative binding affinity determines, for a mixture of permeant ions, which will be permeant; higher affinity ions block flux by lower affinity ones. Multiple ion occupancy seems essential for high flux. These ideas also apply to potassium channels, for which ideas of single-file, multi-ion behavior were first developed.²⁴⁻²⁹ For potassium channels, crystal structure shows a single file, multiply occupied pore.³⁰

Amino Acid Residues of the Selectivity Filter

The cloning of L-type calcium channels from skeletal^{31,32} and cardiac³³ muscle allowed identification of structural features underlying ion binding and multi-ion behavior. Figure 2 illustrates the pore lining sequences of calcium channels.

The most obvious candidate binding site in the P-loops was a conserved cluster of four glutamate residues (0 position; Fig. 2) referred to as the EEEE locus. Each of the four P-loops



Figure 2. Membrane organization and amino acid residues that form the pore lining for an L-type calcium channel. In the four pore-lining loops (P-I through P-IV), the EEEE locus glutamate is designated as the 0 position. Amino acid sequence number is marked to the left of each EEEE locus glutamate.³¹ Reprinted with permission from: Wu XS, Edwards HD, Sather WA. J Biol Chem 2000; 275:31778-31785. ©2000 The American Society for Biochemistry and Molecular Biology, Inc.

contributes a glutamate to the locus, and in analogy to Ca^{2+} binding by chelators like EGTA³⁴, a tetracarboxylate binding site formed from the glutamate side chains was an immediately attractive idea. The first experimental evidence supporting the importance of the EEEE locus was obtained using a mutant sodium channel engineered to possess a DEEE locus: micromolar Ca^{2+} blocked Na⁺ current carried by this mutant and Ca^{2+} was permeant, both hallmarks of calcium channels.³⁵ Single point mutations introduced into the EEEE locus of calcium channels severely compromised ion selectivity: measurement of bi-ionic reversal potentials revealed that the relative permeability of Ca^{2+} was decreased in EEEE locus mutants, and block experiments showed that binding affinity for Ca^{2+} was also decreased.³⁶⁻³⁸

Among calcium channel mutants in which only one EEEE locus glutamate was replaced, even relatively conservative substitutions such as aspartate or glutamine significantly decreased Ca^{2+} binding affinity.³⁸ This finding, unexpected at the time, strongly suggested that calcium channels contain one—not two—high-affinity (K_D ~ 1 µM) binding sites. Whether the EEEE locus represents the sole region of high-affinity interaction with Ca^{2+} was therefore tested using constructs in which the entire EEEE locus was replaced with four glutamine or four alanine residues.³⁹ In these quadruple mutants (QQQQ or AAAA), half-block of monovalent current occurred at ~1 mM Ca²) (Fig. 3). This weakened Ca²⁺ block strongly implies that all high-affinity binding between Ca²⁺ and the pore occurs in a region defined by the EEEE locus; there is apparently no other high-affinity site in the pore.

A potential loose end in this argument is that divalent cations are unable to carry currents of detectable size through the pore of the QQQQ or AAAA mutants.³⁹ Could the absence of potent block by Ca^{2+} of monovalent current be attributed to an inability of Ca^{2+} to pass through a hydrophobic QQQQ or AAAA locus and bind with high affinity to a putative second, and



Figure 3. EEEE locus quadruple mutants lack high-affinity binding of divalent cations. The graph illustrates the concentration-dependence of block by Ca²⁺ of normalized Li⁺ current carried by calcium channels expressed in Xenopus oocytes. WT = wild type, Q4 = quadruple glutamine mutant, A4 = quadruple alanine mutant. Fitted curves are 1:1 binding functions. Modified with permission from: Ellinor PT, Yang J, Sather WA, et al. Neuron 1995; 15:1121-1132. ©1995 Cell Press.



Figure 4. Recordings of single-channel currents in inside-out excised patches show that Ca^{2+} applied to the intracellular pore entrance does not block monovalent current carried through EEEE locus quadruple mutants. WT = wild-type, AAAA = quadruple alanine mutant. The blocking ion (Ca^{2+}) and Li⁺ current flow in the same, outward, direction (diagram at upper right). In the absence of Ca^{2+} , wild-type and mutant channel openings are long owing to the action of the dihydropyridine Bay K 8644. In the presence of 10 mM Ca^{2+} , Bay K 8644-prolonged openings of wild-type are interrupted at high frequency by brief Ca^{2+} block events (top, middle). Openings of the quadruple alanine mutant are unaffected at up to 1 mM Ca^{2+} . Reproduced with permission from: Cibulsky SM, Sather WA. Journal of General Physiology 2000; 116:349-362. ©2000 The Rockefeller University Press.

more distally located high-affinity site? In pursuit of this idea, inside-out excised patches were used to examine whether Ca^{2+} entering from the intracellularly-disposed pore entrance could block monovalent current.⁴⁰ As illustrated in Figure 4, these experiments failed to reveal high-affinity block by Ca^{2+} entering from the intracellular pore mouth. The results thus support the conclusion, as first thought, that the EEEE locus constitutes the only region of high-affinity Ca^{2+} binding in the pore.



Figure 5. The EEEE locus does not house two high-affinity binding sites. Ca^{2+} block of Li⁺ current for channels with two alanine substitutions in the EEEE locus. Half-block values are compared for wild-type (WT), all six double alanine mutants (motifs bearing alanine substitutions are indicated by roman numerals), and the quadruple alanine mutant (AAAA). Ca^{2+} block—binding affinity—was severely reduced in each of the six double alanine mutants, indicating that none of the pairs of EEEE locus glutamates forms a high-affinity binding site. Modified with permission from reference: Modified with permission from: Ellinor PT, Yang J, Sather WA, et al. Neuron 1995; 15:1121-1132. ©1995 Cell Press.

A Single High-Affinity Locus

The attractiveness of the two-site model^{4,18} was such that although mutagenesis experiments showed that no high-affinity site exists outside the EEEE locus, it was important to determine whether the EEEE locus might house two high-affinity sites itself. It was specifically postulated that the locus might be functionally subdivided into two working pairs of glutamates, with each pair forming a high-affinity site.³⁹ This seems sensible because each pair of glutamates would bear a charge of -2, exactly the charge needed to electrostatically balance one Ca²⁺ ion. Pursuing this idea, pairs of alanine substitutions were introduced into the EEEE locus, on the idea that some of the double alanine mutations would knock out one putative high-affinity site (functional glutamate pair) but leave the other intact. Among the six ways that the glutamates might be paired, double alanine substitution would in two cases leave high-affinity binding intact, according to the hypothesis. The experimental results showed, however, that Ca²⁺ block, and hence binding affinity, was severely reduced (>100x) in each of the six double alanine mutants (Fig. 5). The EEEE locus apparently does not contain two high-affinity sites.

In fact, even single point mutations in the EEEE locus significantly weaken Ca^{2+} binding, by up to 50-fold for single alanine substitutions.^{38,39} These results, combined with the fact that block of monovalent current occurs when only one Ca^{2+} ion is bound in the pore, imply that each glutamate interacts with the single Ca^{2+} ion in the EEEE locus. In other words, all four EEEE locus glutamates are involved in high-affinity binding, forming one high-affinity site.

From the standpoint of pore structure, how might Ca^{2+} pass through this single high-affinity site at upwards of a million ions per second? One suggestion is that the EEEE locus is physically flexible, so that it can bind one Ca^{2+} ion tightly or two Ca^{2+} ions more loosely.³⁸ Figure 6 schematizes this view. Each of the EEEE locus glutamates contributes to tight binding of one Ca^{2+} ion, the configuration underlying Ca^{2+} block of Na⁺ flux and ion selectivity. The glutamates can rapidly rearrange to hold more loosely two Ca^{2+} ions, the configuration supporting high single-channel conductance. The EEEE locus is supposed to switch back and forth between these two configurations in response to the type of ion entering the pore, Na⁺ or Ca^{2+} in most instances. Figure 6 also suggests that additional conformational states may be important in



Figure 6. Cartoon depicting the hypothesized structural flexibility of the EEEE locus. Forks represent glutamate side chains. Adapted with permission from: Yang J, Ellinor PT, Sather WA, et al. Nature 1993; 366:158-161. ©2003 Nature Publishing Group.

fostering passage of Ca^{2+} through the locus, with the glutamates working like a bucket brigade for Ca^{2+} . The behavior illustrated in Figure 6 is somewhat fanciful for calcium channels, but X-ray crystallographers have recently caught potassium channels in the act: images suggest that an ion can enter a pore already occupied by two ions, seeming to push one of the occupying ions out the other side.⁴¹

Despite the dominating importance of the EEEE locus, other regions of the channel do appear to have a role to play in ion conduction. Near the extracellular entrance of the channel and outside the narrow pore, site-directed mutagenesis work has identified a putative Ca²⁺ binding domain that regulates calcium channel conductance, perhaps via allosteric interaction with the selectivity filter.⁴² Other evidence that regions outside the EEEE locus are involved in control of ion conduction has been obtained by studying chimeras constructed between calcium channel isotypes that differ in single-channel conductance.^{43,44} P-loops, S5 and S6 segments were swapped and single-channel conductance measured. Based on these experiments, regions that may form part of the external pore entrance or that compose much of the lining of the pore closer to the intracellular exit³⁰ are, in ways yet to be understood, involved in determining ion conduction. For selectivity, however, the EEEE locus appears to be the only structure of importance.

Non-Equivalence of EEEE Locus Glutamates

The effect of an amino acid substitution in the EEEE locus depends upon which glutamate has been replaced. ^{36,38,39,45} Figure 7 presents examples of Cd²⁺ block of single channel currents from four single alanine substitution mutants. The principal effect of the mutations, for the case of Cd²⁺ versus Li⁺, was reduced blocker on-rate (lower panels). The functional non-equivalence of the EEEE locus glutamates is evidenced by the differences between the four mutants in on-rate. Replacement of the glutamate in motif III (E_{III}) caused the largest change in on-rate. This fits the general pattern that substitution at E_{III} has the greatest impact on block kinetics, reversal potential, or single-channel conductance^{38,39} Substitution at E_{II} typically follows replacement of E_{III} in severity of effect; replacement of E_I or E_{IV} has lesser impact on function.

The significance of non-equivalence among EEEE locus glutamates is unknown, but an intriguing possibility is that it is important for high flux.³⁸ Figure 6 captures the idea: entry of



Figure 7. EEEE locus glutamates differ from one another in their interactions with divalent cations, as illustrated by the differing size of effect of single alanine substitutions on Cd^{2*} block kinetics. Single-channel currents were carried by Li⁺; dashed lines indicate closed level. The substituted glutamate is indicated by motif number (roman numerals), e.g., EtA indicates replacement by alanine of the EEEE locus glutamate in motif I. Lower panels show the concentration dependence of Cd^{2*} block ($1/t_{open}$) and unblock ($1/t_{shut}$). Fitted lines represent Cd^{2*} on-rate (k_{on} , through filled symbols) and off-rate (k_{off} through open symbols). Reproduced from: Cloues RK, Cibulsky SM, Sather WA. The Journal of General Physiology 2000; 116:569-586. ©2000 The Rockefeller University Press.

a second Ca^{2+} ion into an occupied locus, and departure of the first Ca^{2+} ion, may rely upon distinctive interactions that each glutamate makes with Ca^{2+} ions. In this view, each glutamate has a specialized role in transporting Ca^{2+} . The suggestion that some glutamates specialize in facilitating Ca^{2+} entry into the locus or departure from it, and that other glutamates preferentially contribute to high-affinity binding of Ca^{2+} recalls the stair steps model (low-affinity sites flanking a high-affinity site) described in Figure 1C. According to this thinking, the EEEE locus contains the central high-affinity site and the low-affinity flanking sites.

The non-equivalence of EEEE locus glutamates must originate from differences in structure between the four channel motifs. Focusing upon P-loop neighbors of the EEEE locus, residues that help determine the unique behavior of particular glutamates have been identified by exploiting differences between Ca^{2+} channel isotypes in P-loop sequence and ion conduction. Site-directed mutagenesis at these positions has shown that neighbor residues can control ion conduction through cooperative interaction with the EEEE locus.⁴⁶

Functional Groups that Bind Ca²⁺

The crystal structure of the KcsA potassium channel shows that high-affinity binding of permeant ions, potassium in this case, can be mediated by rings of carbonyl oxygen atoms projecting from the polypeptide main chain.³⁰ Although the EEEE locus carboxylates had generally been assumed to coordinate Ca²⁺, the evolutionary relationship of calcium channels to potassium channels suggested that main chain carbonyl oxygens, rather than side chain carboxylates, might bind permeant ions in calcium channels as well. However, two kinds of experiments indicate that selectivity filter structure is different between calcium channels and potassium channels.



Figure 8. Contrasting models of selectivity filter structure for calcium and potassium channels. Only two of four pore lining regions are illustrated. Left, carboxylate oxygens from the EEEE locus glutamate side chains form a Ca²⁺ binding locus in calcium channels. Right, carbonyl oxygen atoms from the polypeptide backbone form a series of high affinity K⁺ binding sites. Pore helices³⁰ predicted from sequence analysis are illustrated as cylinders. Reprinted with permission from: Sather WA, McCleskey EW. Annual Review of Physiology, Volume 65 ©2003 by Annual Reviews.

The first experimental test was based upon the ability of protons to reduce the rate of ion conduction through calcium channels. The logic was this: if protonation of EEEE locus glutamate carboxylates underlies the proton-induced reduction in single-channel conductance, then site-directed mutation of the EEEE locus is predicted to alter proton action. Conversely, if EEEE locus substitutions affect proton action, then carboxylate oxygen atoms would seem to project into the pore.⁴⁷⁻⁴⁹ The experimental results showed that the ability of protons to reduce single-channel conductance differed from one EEEE locus mutant to the next. The duration of single protonation events also varied according to the mutation introduced. These findings indicate that protonation within the EEEE locus is responsible for proton-induced reduction of single-channel conductance, and hence that locus carboxylate groups are solvent-accessible. The results also showed that multiple glutamate residues interact with a single proton,⁴⁸ much as they interact with a single Ca²⁺ ion.

The second experimental approach to determining whether glutamate carboxylates reside in the pore lumen was based on the method of substituted cysteine accessibility.⁵⁰ In this approach, cysteine was serially substituted at P-loop positions and the susceptibility of the substituted-cysteine mutants to modification by methanethiosulfonate reagents was examined (Fig. 2; diamonds enclose substituted positions).^{51,51} Methanethiosulfonates react very selectively with thiolate groups ($-S^{-}$), including the ionized sulfhydryl groups of solvent-exposed cysteine side chains. The thiolate form exists only in a high dielectric medium, such as saline, and thus only solvent-exposed sulfhydryl groups are susceptible to methanethiosulfonate modification. The reaction is covalent and results in attachment of moieties that can impede ion passage through narrow regions of a pore. Irreversible block by methanethiosulfonates thus reports the presence of cysteine side chains in the pore. The results of these experiments showed that consecutive P-loop residues were modifiable by methanethiosulfonates, including the substitutions made at the EEEE locus. Assuming that the cysteine mutants preserved basic pore structure, the conclusion is that carboxylate-bearing side chains of the EEEE locus project into the pore. Presumably, EEEE locus interaction with Ca²⁺ is carried out by these carboxylates.

The picture of a tetracarboxylate-based high-affinity Ca²⁺ binding domain in the calcium channel pore contrasts sharply with the known carbonyl-based structure of potassium channel selectivity filters (Fig. 8).^{30,53} This difference in structure between channels sharing common

ancestry and exhibiting similarly high ion selectivity likely derives from the differing demands of binding divalent versus monovalent cations. In general, carboxylate groups make up binding sites selective for divalent metal ions, including in chelating agents like EGTA or EF hand domains of proteins. In these kinds of structures, Ca²⁺ binds within a pocket of seven or eight oxygen atoms, many or all from carboxylate groups. Negatively charged binding sites such as these discriminate strongly against monovalent cations because these ions have an inadequate amount of positive charge to stabilize the closely packed carboxylate oxygens. Divalent metal cations, having greater positive charge, are able to overcome electrostatic repulsion among the carboxylate oxygens and hold such high-affinity sites intact.^{34,54} A similar rationale may underlie the carboxylate-based selectivity filter of calcium channels.

Structure-Based Selectivity Models

Rate theory models, of the sort illustrated in Figure 1, describe ion movement through pores using little information regarding pore structure. This was advantageous in the era prior to the cloning, and now crystallographic imaging, of ion channels. In counterpoint, however, rate theory has little to offer in linking channel structure to the energetics of selective ion permeation. Newer methods, considered below, promise greater insight into this issue. Two kinds of models are considered: ones using pores with simplified structure, and ones using predicted structure.

For model pores with simplified structure, both drift-diffusion and Brownian dynamics have been used. Drift-diffusion, developed originally to describe ion movement through semiconductors, represents ion movement as smooth diffusion through a homogeneous medium. Using experimental results to constrain pore dimensions (6 Å diameter, 10 Å length), and assuming reasonable values for the diffusion constant of Ca^{2+} in the pore, the drift-diffusion model closely mimics most of the defining properties of ion permeation in real Ca²⁺ channels.⁵⁵ An alternative approach of using Brownian dynamics considers ions as spheres that move according to Brownian motion. The ions are influenced by electrostatic forces in the pore. Water is considered a continuous, not particulate, medium of fixed dielectric value. The model pore used to analyze the calcium channel with Brownian dynamics starts with the wide filter known for calcium channels,¹ and the rest of the hourglass-shaped model pore is borrowed from the KcsA channel.⁵⁶ The charges of the EEEE locus glutamates are, in this model, buried in the wall of the selectivity filter rather than projecting into the pore lumen. Building into the model an ad hoc assumption that prevents ions from passing one another in the wide selectivity filter, the model is able to reproduce nearly all features of selective permeation in calcium channels.

Theory also suggests a structural basis for the ability of calcium channels to discriminate between Na⁺ and Ca²⁺. To approach this issue, the selectivity filter was modeled with the eight EEEE locus carboxylate oxygen atoms in the pore lumen. Each oxygen has a charge of -0.5 and is allowed to diffuse within the estimated volume of the selectivity filter. Metal cations entering the model filter must attempt to neutralize the charged locus. Na⁺ has half the neutralizing power of Ca²⁺ but the same size, and because space in the filter is limited, too few Na⁺ ions can be fit inside to produce electroneutrality.^{57,58} According to the model, this explains how calcium channels select with such fidelity between two different ions of essentially identical size.

Using predicted pore structure, structural biologists have addressed three fundamental questions for calcium channel pores: (i) is the selectivity filter flexible, (ii) does the pore contain more than one ion, and (iii) what force expels Ca^{2+} from the high-affinity locus? Two approaches have been taken to answer these questions. One is static in nature, and considers the summed forces exerted by the channel on pore-localized ions at one instant.⁵⁹ The other has utilized molecular dynamics.⁶⁰ In this approach, the Newtonian forces exerted on each atom in a structure cause atoms to move a tiny amount. The new location of each atom is calculated, and then based on these new atomic coordinates, the calculation is carried out again. Each iteration corresponds to one picosecond in the journey of a Ca^{2+} ion through the pore. The selectivity filter is flexible, according to both approaches. The model pores show that in the absence of Ca²⁺, the EEEE locus glutamates repel one another and open up a passageway 6 Å across. This is just the size needed to pass tetramethylammonium ions, the largest ion that passes rapidly through calcium channels.¹ When Ca²⁺ enters the EEEE locus, however, the surrounding carboxylates are drawn close by electrostatic attraction, making a tight fit around the 2 Å ion. Using molecular dynamics or the static approach, both predicted structure models also find that a calcium channel can contain multiple ions within its pore.

Regarding forces that expel Ca^{2+} from the locus during high flux, the models suggest that several ideas developed using rate theory may be involved. Molecular dynamics simulations using a pore of predicted structure reveal that Na⁺ cannot displace Ca^{2+} within the EEEE locus over a short time interval. Ca^{2+} can displace Ca^{2+} over the same time interval, however, suggesting ion-ion interaction may be involved in Ca^{2+} flux.⁶⁰

Using the static approach, several factors seem to be involved in mediating high Ca^{2+} flux.⁵⁹ At millimolar (physiological) Ca^{2+} , three Ca^{2+} ions are arranged in single file in the pore, one in the middle of the EEEE locus and the other two interacting with low-affinity sites located on the periphery of the EEEE locus. The low affinity interactions with Ca^{2+} are mediated by two of the four EEEE locus glutamates. This arrangement of two low-affinity sites flanking a central high affinity site has experimental support¹⁴ and corresponds to the stair steps rate theory model of Figure 1.²³ The stair steps appear to be involved in exit of Ca^{2+} from the locus, but another factor is important as well. A region of strong negative electrostatic potential, or an "electrostatic trap," was found to surround the single bound Ca^{2+} ion, preventing it from escaping from the EEEE locus. The situation changes when the pore becomes multiply occupied: in this case, the aligned positive charges of the ions in the EEEE locus push aside the webbing of the electrostatic trap. In this novel manner, Ca^{2+} overcomes high-affinity binding and high Ca^{2+} flux is permitted.

Summary

Calcium channels use high-affinity binding for ion selectivity, and a multi-ion pore for high flux. The selectivity filter of calcium channels is composed of a cluster of four glutamate residues. This EEEE locus is organized as a single locus that supports high-affinity Ca^{2+} binding but allows high Ca^{2+} flux. Switching between configurations mediating high-affinity binding and high flux, the EEEE locus appears to have high structural flexibility. Functional non-equivalence of EEEE locus glutamates may be important in supporting high flux, with some glutamates providing stair steps for Ca^{2+} passage through the locus. The selectivity filter of calcium channels differs in structure from that of related potassium channels: calcium channels use charged carboxylate oxygens of the EEEE locus to bind Ca^{2+} , whereas potassium channels use neutral carbonyl oxygens to bind K⁺. Models of calcium channel selectivity suggest mechanisms that simultaneously allow selectivity by high-affinity binding and high ion throughput. More modern theories have begun to explain how pore structure may specify the selective permeability properties of calcium channels.

Acknowledgements

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References

- 1. McCleskey EW, Almers W. The Ca channel in skeletal muscle is a large pore. Proc Natl Acad Sci USA 1985; 82:7149-7153.
- Kostyuk PG, Mironov SL, Shuba YM. Two ion-selecting filters in the calcium channel of the somatic membrane of mollusc neurons. J Membr Biol 1983; 76:83-93.
- Almers W, McCleskey EW, Palade PT. A non-selective cation conductance in frog muscle membrane blocked by micromolar external calcium ions. J Physiol 1984; 353:565-583.
- 4. Hess P, Tsien RW. Mechanism of ion permeation through calcium channels. Nature 1984; 309:453-456.

- 5. Fukushima Y, Hagiwara S. Currents carried by monovalent cations through calcium channels in mouse neoplastic B lymphocytes. J Physiol 1985; 358:255-284.
- Vereecke J, Carmeliet E. Sr action potentials in cardiac Purkinje fibres. II. Dependence of the Sr conductance on the external Sr concentration and Sr-Ca antagonism. Pflugers Arch 1971; 322:73-82.
- 7. Hagiwara S, Fukuda J, Eaton DC. Membrane currents carried by Ca, Sr, and Ba in barnacle muscle fiber during voltage clamp. J Gen Physiol 1974; 63:565-578.
- Reuter H, Scholz H. A study of the ion selectivity and the kinetic properties of the calcium dependent slow inward current in mammalian cardiac muscle. J Physiol 1977; 264:17-47.
- Fenwick EM, Marty A, Neher E. Sodium and calcium channels in bovine chromaffin cells. J Physiol 1982; 331:599-635.
- Lee KS, Tsien RW. High selectivity of calcium channels in single dialysed heart cells of the guinea-pig. J Physiol 1984; 354:253-272.
- Hess P, Lansman JB, Tsien RW. Calcium channel selectivity for divalent and monovalent cations. Voltage and concentration dependence of single channel current in ventricular heart cells. J Gen Physiol 1986; 88:293-319.
- 12. Matsuda H, Noma A. Isolation of calcium current and its sensitivity to monovalent cations in dialysed ventricular cells of guinea-pig. J Physiol 1984; 357:553-573.
- Polo-Parada L, Korn SJ. Block of N-type calcium channels in chick sensory neurons by external sodium. J Gen Physiol 1997; 109:693-702.
- 14. Kuo CC, Hess P. Ion permeation through the L-type Ca²⁺ channel in rat phaeochromocytoma cells: two sets of ion binding sites in the pore. J Physiol 1993; 466:629-655.
- Kuo CC, Hess P. Characterization of the high-affinity Ca²⁺ binding sites in the L-type Ca²⁺ channel pore in rat phaeochromocytoma cells. J Physiol 1993; 466:657-682.
- 16. Bezanilla F, Armstrong CM. Negative conductance caused by entry of sodium and cesium ions into the potassium channels of squid axons. J Gen Physiol 1972; 60:588-608.
- 17. Friel DD, Tsien RW. Voltage-gated calcium channels: direct observation of the anomalous mole fraction effect at the single-channel level. Proc Natl Acad Sci USA 1989; 86:5207-5211.
- Almers W, McCleskey EW. Non-selective conductance in calcium channels of frog muscle: calcium selectivity in a single-file pore. J Physiol 1984; 53:585-608.
- Eisenman G, Sandblom JP, Walker JL. Membrane structure and ion permeation. Study of ion exchange membrane structure and function is relevant to analysis of biological ion permeation. Science 1967; 155:965-974.
- Hille B, Schwarz W. Potassium channels as multi-ion single-file pores. J Gen Physiol 1978; 72:409-442.
- Urban BW, Hladky SB, Haydon DA. Ion movements in gramicidin pores. An example of single-file transport. Biochim Biophys Acta 1980; 602:331-354.
- 22. Lansman JB, Hess P, Tsien RW. Blockade of current through single calcium channels by Cd²⁺, Mg²⁺, and Ca²⁺. Voltage and concentration dependence of calcium entry into the pore. J Gen Physiol 1986; 88:321-347.
- Dang TX, McCleskey EW. Ion channel selectivity through stepwise changes in binding affinity. J Gen Physiol 1998; 111:185-193.
- Armstrong CM, Neyton J. Ion permeation through calcium channels. A one-site model. Ann N Y Acad Sci 1991; 635:18-25.
- 25. Hodgkin A, Keynes R. The potassium permeability of a giant nerve fibre. J Physiol 1955; 128:61-88.
- Begenisich T, De Weer P. Potassium flux ratio in voltage-clamped squid giant axons. J Gen Physiol 1980; 76:83-98.
- Neyton J, Miller C. Discrete Ba²⁺ block as a probe of ion occupancy and pore structure in the high-conductance Ca²⁺-activated K⁺ channel. J Gen Physiol 1988; 92:569-586.
- 28. Neyton J, Miller C. Potassium blocks barium permeation through a calcium-activated potassium channel. J Gen Physiol 1988; 92:549-567.
- Korn SJ, Ikeda SR. Permeation selectivity by competition in a delayed rectifier potassium channel. Science 1995; 269:410-412.
- Doyle DA, Morais-Cabral J, Pfuetzner RA et al. The structure of the potassium channel: molecular basis of K⁺ conduction and selectivity. Science 1998; 280:69-77.
- 31. Tanabe T, Takeshima H, Mikami A et al. Primary structure of the receptor for calcium channel blockers from skeletal muscle. Nature 1987; 328:313-318.
- 32. Ellis SB, Williams ME, Ways NR et al. Sequence and expression of mRNAs encoding the α_1 and α_2 subunits of a DHP-sensitive calcium channel. Science 1988; 241:1661-1664.
- 33. Mikami A, Imoto K, Tanabe T et al. Primary structure and functional expression of the cardiac dihydropyridine-sensitive calcium channel. Nature 1989; 340:230-233.

- 34. Schauer CK, Anderson PP. Calcium-selective ligands. 2. Structural and spectroscopic studies on calcium and cadmium complexes of EGTA⁴⁻. J Am Chem Soc 1987; 109:3646-3656.
- 35. Heinemann SH, Terlau H, Stuhmer W et al. Calcium channel characteristics conferred on the sodium channel by single mutations. Nature 1992; 356:441-443.
- 36. Kim MS, Morii T, Sun LX et al. Structural determinants of ion selectivity in brain calcium channel. FEBS Lett 1993; 318:145-148.
- 37. Tang S, Mikala G, Bahinski A et al. Molecular localization of ion selectivity sites within the pore of a human L-type cardiac calcium channel. J Biol Chem 1993; 268:13026-13029.
- 38. Yang J, Ellinor PT, Sather WA et al. Molecular determinants of Ca²⁺ selectivity and ion permeation in L-type Ca²⁺ channels. Nature 1993; 366:158-161.
- 39. Ellinor PT, Yang J, Sather WA et al. Ca²⁺ channel selectivity at a single locus for high-affinity Ca²⁺ interactions. Neuron 1995; 15:1121-1132.
- 40. Cibulsky SM, Sather WA. The EEEE locus is the sole high-affinity Ca²⁺ binding structure in the pore of a voltage-gated Ca²⁺ channel: block by Ca²⁺ entering from the intracellular pore entrance. J Gen Physiol 2000; 116:349-362.
- 41. Jiang Y, MacKinnon R. The barium site in a potassium channel by x-ray crystallography. J Gen Physiol 2000; 115:269-272.
- 42. Feng ZP, Hamid J, Doering C et al. Amino acid residues outside of the pore region contribute to N-type calcium channel permeation. J Biol Chem 2001; 276:5726-5730.
- 43. Dirksen RT, Nakai J, Gonzalez A et al. The S5-S6 linker of repeat I is a critical determinant of L-type Ca²⁺ channel conductance. Biophys J 1997; 73:1402-1409.
- 44. Cibulsky SM, Sather WA. Control of ion conduction in L-type Ca²⁺ channels by the concerted action of S5-6 regions. Biophys J 2003; 84:1709-1719.
- Cloues RK, Cibulsky SM, Sather WA. Ion interactions in the high-affinity binding locus of a voltage-gated Ca²⁺ channel. J Gen Physiol 2000; 116:569-586.
- 46. Williamson AV, Sather WA. Nonglutamate pore residues in ion selection and conduction in voltage-gated Ca²⁺ channels. Biophys J 1999; 77:2575-2589.
- Chen XH, Bezprozvanny I, Tsien RW. Molecular basis of proton block of L-type Ca²⁺ channels. J Gen Physiol 1996; 108:363-374.
- 48. Chen XH, Tsien RW. Aspartate substitutions establish the concerted action of P-region glutamates in repeats I and III in forming the protonation site of L- type Ca²⁺ channels. J Biol Chem 1997; 272:30002-30008.
- Klockner U, Mikala G, Schwartz A et al. Molecular studies of the asymmetric pore structure of the human cardiac voltage- dependent Ca²⁺ channel. Conserved residue, Glu-1086, regulates proton-dependent ion permeation. J Biol Chem 1996; 271:22293-22296.
- Karlin A, Akabas MH. Substituted-cysteine accessibility method. Methods Enzymol 1998; 293:123-145.
- 51. Koch SE, Bodi I, Schwartz A et al. Architecture of Ca²⁺ channel pore-lining segments revealed by covalent modification of substituted cysteines. J Biol Chem 2000; 275:34493-34500.
- 52. Wu XS, Edwards HD, Sather WA. Side chain orientation in the selectivity filter of a voltage-gated Ca²⁺ channel. J Biol Chem 2000; 275:31778-31785.
- 53. Zhou Y, Morais-Cabral, JH, Kaufman A et al. Chemistry of ion coordination and hydration revealed by a K* channel-Fab complex at 2.0 Å resolution. Nature 2001; 414:43-48.
- Falke JJ, Drake SK, Hazard AL et al. Molecular tuning of ion binding to calcium signaling proteins. Q Rev Biophys 1994; 27:219-290.
- Nonner W, Eisenberg B. Ion permeation and glutamate residues linked by Poisson-Nernst-Planck theory in L-type calcium channels. Biophys J 1998; 75:1287-1305.
- Corry B, Allen TW, Kuyucak S et al. Mechanisms of permeation and selectivity in calcium channels. Biophys J 2001; 80:195-214.
- 57. Nonner W, Catacuzzeno L, Eisenberg B. Binding and selectivity in L-type calcium channels: a mean spherical approximation. Biophys J 2000; 79:1976-1992.
- Boda D, Busath D, Henderson D et al. Monte Carlo simulations of the mechanism for channel selectivity: the competition between volume exclusion and charge neutrality. Journal of Physical Chemistry 2000; 104:8903-8910.
- 59. Lipkind GM, Fozzard HA. Modeling of the outer vestibule and selectivity filter of the L-type Ca²⁺ channel. Biochemistry 2001; 40:6786-6794.
- 60. Barreiro G, Guimaraes CR, de Alencastro RB. A molecular dynamics study of an L-type calcium channel model. Protein Eng 2002; 15:109-122.

CHAPTER 14

The Run-Down Phenomenon of Ca²⁺ Channels

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Introduction

The activity of many types of calcium channels decreases rapidly when contact between membrane and cytosol is disrupted. This phenomenon, called run-down, is wide spread among voltage gated calcium channels and appears to be related to regulatory factors present in the cytosol, which are rapidly lost upon patch excision. Even in whole cell experiments Ca²⁺ currents exhibit a slow run-down, suggesting that endogenous cytoplasmic factors are subject to wash-out.^{1,2} It is now generally recognized that run-down of ion channel activity is not due to an artificial artefact.³ Run-down is time-dependent and generally fast, so that the complete closure of the channel occurs within a few minutes. Run-down has never been reported so far to show any voltage dependence. The loss of channel activity does not result from a lack of Ca²⁺ channel integrity.^{4,5} because of the following reasons:

- a. The single channel current amplitude remains stable during run-down
- b. The run-down in excised patches corresponds to the spontaneous drops in either the channel open probability (*P*₀) or the number of channels (*N*) present in multi-channel patches or both

After run-down, calcium channels can be re-activated excluding a proteolytic process interfering with channel activity.

Abbreviations

- LVA low voltage activated
- HVA high voltage activated
- PKA protein kinase A
- PKI protein kinase inhibitor

Which Native Calcium Channel Types Exhibit Run-Down?

There are many studies reporting from run-down of several calcium channel types. However, very few of them are dealing with the run-down phenomenon by itself. Low voltage activated (LVA)¹ T-type calcium channels do not show any run-down.⁶⁻⁸ The high voltage activated (HVA) N-type calcium channels have been also found to lack run-down in the presence of ATP.^{9,10} R-type HVA channels in hair cells exhibit a run-down,¹¹ whereas R-type calcium currents in smooth muscle cells¹² show a markedly reduced run-down. L-type calcium channels in general and particularly from cardiac cells exhibit run-down in the whole-cell and especially in the inside-out configuration.^{4,13}

The mechanisms underlying run-down of calcium channel activity are not fully understood but are best studied on L-type channels. Hence we will focus here on the run-down phenomenon of L-type calcium channels.



Figure 1. Prevention of run-down of cardiac Ca^{2+} channel activity in single channel experiments after patch excision in the presence cytosol plus ATP and GTP (A) and treated with calpastatin plus ATP (B). Reproduced with permission from references 4 and 5.

Prevention and Reversal of Channel Run-Down

Since the discovery of the run-down phenomenon, a lot of mechanisms have been proposed¹⁴ which possibly are involved in the regulation of channel activity including direct ATP binding to, or phosphorylation/dephosphorylation of the Ca²⁺ channels¹⁵⁻¹⁸ and proteolysis by calcium dependent proteases of constituents involved in the regulation of Ca²⁺ channel activity.^{4,19,20} Kameyama et al¹³ and Romanin et al⁴ demonstrate that run-down of L-type channel activity in inside-out patches is prevented or can be reversed by cytoplasm prepared from cardiac tissue (Fig. 1A). A minimal solution containing the protease inhibitor calpastatin and ATP was equally effective in the prevention of run-down as cardiac cytosolic solution (Fig. 1B; Seydl et al).⁵

The Nucleotides ATP and ADP

The modulatory effect of ATP on the activity of Ca^{2+} channels has been discovered a long time ago.²¹ In the sole presence of MgATP; run-down of L-type calcium channel activity is not prevented in the inside-out patch.^{5,17} Hence, study of the effect of ATP requires the continuous presence of cytosolic solution. Yazawa et al²² have examined recovery of calcium channel activity by the use of cytoplasmic preparations containing various levels of ATP. A reduced content of ATP (0.12 mM) in the cytoplasm results only in a recovery of 12 % of channel activity of that previously observed in the cell-attached patch, whereas 10 mM ATP restored activity to the same level as in the cell-attached configuration (Fig. 2). A similar result has been obtained when MgATP levels are varied in a cytoplasm fractionated on a diethylaminoethyl-sepharose (DEAE-sepharose) column (Cp_{DEAE}). Reduction of ATP to 0.055 mM markedly reduces the capability to recover channel openings. The same cytoplasm containing 10 mM MgATP increased channel activity to 60 % of that seen in cell-attached patches. Thus MgATP greatly increase the ability of cytoplasm to recover calcium channel activity in inside-out patches.

Replacing MgATP by K₂ATP does not significantly change the efficiency of ATP to restore channel activity²² suggesting a minor role of Mg in the regulation of calcium channels. Moreover, substitution of ATP by the non-hydrolysable AMP-PNP or AMP-PCP restored channel activity after run-down to 39 % of that observed in the cell-attached configuration,²² suggesting that hydrolysis of ATP is only partially required in the regulation of channel activity.

In whole-cell patch clamp recordings, Elhamdani et al²³ have used bovine chromaffin cells with a mixed population of Ca^{2+} channels (composed of about 50% current through L-type channels and 50% through N- and P-type channels) to study the effect of ATP in the regulation of calcium current run-down. They report that the presence of both ATP and Mg²⁺ prevents run-down for recordings up to 60 min (Fig. 3A). This effect requires the presence of



Figure 2. Restoration of calcium channel activity by cytoplasm is dependent on the presence of ATP. Channel activity (NP_0) under each condition (CA: cell-attached; IO: inside-out) as indicated is normalized to those obtained in the cell-attached patch. Reproduced with permission from reference 22.

 Mg^{2^+} and is not mimicked by the non-hydrolysable ATP analogues AMP-PNP. This set of experiments suggests that hydrolysis of ATP seems to be essential to prevent Ca^{2^+} current run-down. The stabilizing effect of ATP on whole-cell Ca^{2^+} currents is not prevented by protein kinase inhibitors (a synthetic peptide inhibiting PKA; H7; calmidazolium; staurosporine). Furthermore, substitution of ATP by the cAMP analogue 8-Br-cAMP fails to reproduce the stabilizing effect of ATP. Additional experiments reveal that ADP is able to mimic the stabilizing effect of ATP in the presence of Mg^{2^+} (Fig. 3B). Conversion of ADP to ATP by adenylate kinase has been excluded by a lack of effect of the adenylate kinase blocker AP5A (di-(adenosine-5')-pentaphosphate). Although the results of Elhamdani et al²³ are somewhat contrary to those of Yazawa et al,²² they are consistent in that point that at least one effect of ATP in the regulation of L-type channel activity is independent of phosphorylation.



Figure 3. ATP or ADP stabilizes whole-cell calcium currents in the presence of Mg. A) A lack of run-down is observed in the presence of both ATP and MgCl₂ (Δ), whereas a fast run-down occurs in the absence of Mg²⁺ (O) or when ATP is replaced by AMP-PNP (\oplus). B) Mg-ADP at a concentration of 0.5 mM (\Box , 2 mM Mg²⁺) and 1.5 mM (\oplus , 3.5 mM Mg²⁺) largely prevents calcium channel run-down, whereas 1.5 mM ADP and in the absence of Mg²⁺ fails to prevent run-down (\blacktriangle). Reproduced with permission from reference 22.

Regulation by Phosphorylation/Dephosphorylation

It has been reported that up-regulation of L-type Ca^{2+} currents is mediated by phosphorylation that involves distinct protein kinases (see ref. 57) such as protein kinases A, C as well as G and $Ca^{2+}/calmodulin-dependent protein kinase.$ Functionally important phosphorylation sites have been already identified in L-type Ca^{2+} channel forming proteins.²⁴⁻²⁷ Dephosphorylation as possible mechanism underlying L-type Ca^{2+} channel run-down is based on the finding that run-down of the channel can be slowed or prevented by agents that promote phosphorylation particularly cAMP or PKA.^{16,17,28} L-type Ca^{2+} channel activity that runs down within one minute following patch excision can be transiently restored by applying the catalytic subunit of PKA together with MgATP.¹⁷ The stabilizing action of MgATP and PKA is inhibited by protein kinase inhibitor (PKI), and addition of PKI to the solution during stabilization abruptly stops channel activity. Okadaic acid, a protein phosphatase inhibitor, substantially slows the run-down process.

In summary, the effect of ATP in prevention of calcium channel run-down is apparently on the one hand a direct effect that appears to involve binding of ATP to the channel, and on the other hand an indirect effect via promotion of calcium channel phosphorylation.

Is Calpastatin the Regulatory Protein in the Cytoplasm?

It has been extensively studied that channel activity in inside-out patches can be stabilized by superfusing cytosolic preparations.^{1,2,4,29} Comparison of the stabilizing effect of different cytoplasmic preparations from various other tissues reveals that cytoplasm from skeletal muscle, brain and liver in contrast to that of kidney restores channel activity after run-down.¹ Partial purification of the relevant component(s) in the cytoplasm by ion-exchange chromatography yields a fraction, which is able to recover channel activity after run-down. This fraction subjected to two-dimensional electrophoresis shows several spots, of which the major has a Mr of about 100 kDa and an isoelectric point of 4.8. These properties resemble those of calpastatin (Table 1), an endogenous inhibitor of the protease calpain. The Ca²⁺ dependent protease system³⁰ comprises μ -calpain, requiring μ M [Ca²⁺] and m-calpain, requiring mM [Ca²⁺] for their activation and their specific inhibitor calpastatin. Reduction of the amount of calpastatin in the cytoplasm decreases the potency of maintaining Ca²⁺ channel activity in the excised patch configuration, suggesting calpastatin as an important endogenous component regulating L-type Ca²⁺ channels. Furthermore, a high molecular weight protein (>300 kDa) has been characterized that is required together with calpastatin and ATP to obtain long-term stabilization of L-type calcium channel activity similar to the efficiency of crude cytoplasm.³¹

, #, *	Factor	Calpastatin	
Gel filtration ^a	250–300 kDa	260–300 kDa	
SDS-PAGE ^b	~100 kDa	110–120, 70 (RBC) kDa	
pl ^c	4.8	4.7, 4.8 (RBC)	
DEAE column ^d	100-360 mM (KCl)	100-150 mM (NaCl)	
Heat stability ^e	Partially stable	Stable	

Table	e 1.	Com	parison	of pro	perties	of the	cytop	lasmic	factor	' and	calp	astati	n
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^a Apparent molecular mass estimated by gel filtration. ^b Apparent molecular mass estimated by sodium dodecylsulphate-polyacrylamide gel electrophoresis. ^c pl, isoelectric point. ^d Concentration range of salts for elution in diethylaminoethyl-ion exchange chromatography. ^e Heat stability of effect on channel activity (for the cytoplasmic factor, heated at 60°C for 10 min. and replenished with 3 mM MgATP [30]) and inhibitory effect on calpain (for calpastatin). Properties of calpastatin are taken from Takano and Murachi, 1982; Takano et al, 1986; Maki et al, 1987; Takano et al, 1988.⁵³⁻⁵⁶ RBC refers to erythrocyte type, others are tissue type. Reproduced with permission from reference 29.

Molecular Determinants of Calpastatin in the Regulation of Calcium Channel Activity

Calpastatin is composed of five domains containing an N-terminal L domain and four mutually homologous regions called domains 1-4.³² Each of these domains 1 - 4 of calpastatin can inhibit calpain indicating that calpastatin can inhibit up to four calpain molecules at once. However, the domains in calpastatin, which interact with calpain, may not necessarily be required for the action on the Ca²⁺ channel, particularly as the action of calpastatin in the regulation of calcium channel activity occurs independent of the inhibition of the calpains.⁵ This has been tested by substitution of calpastatin by specific, synthetic calpain inhibitors.^{33,34} Three inhibitors (calpain inhibitor I, II and MDL 28,170) that have been studied are clearly not able to substitute for calpastatin in the prevention of calcium channel run-down. Hence, calpastatin exerts an additional effect on L-type calcium channels, besides its inhibition of calpains.

Erythrocyte calpastatin, which lacks the N-terminal domains L and 1^{35,36} is not efficient in the recovery of L-type calcium channel activity from run-down,³⁷ suggesting the importance of domains L and 1 for channel restoration. Among the different domains of calpastatin that were tested³⁷ for their ability to maintain channel activity, calpastatin domain L produces channel recovery that is similar to that of full-length calpastatin. Domain 1, however, is not sufficient to restore calcium channel activity, indicating that domain L rather than domain 1 of calpastatin is involved in calcium channel regulation.

Which Subunits of the L-Type Calcium Channel Are Involved in the Run-Down Process?

The cardiac L-type calcium channel has emerged as a heteropentametric complex consisting of α_1 , β and α_2 - δ subunits. The α_1 subunits of calcium channels are able to serve as voltage gated ion channels when expressed alone. Although significant biophysical diversity of native Ca²⁺ channels is conferred by the α_1 subunits, tertiary structure and channel properties are modulated by associated auxiliary subunits, resulting in an enormous potential for functional and structural diversity.³⁸ A study by Hao et al focuses on different subunit compositions of the L-type calcium channel and their effect on channel activity and run-down. Ca²⁺ channels in CHO cells stably expressing α_{1C} , $\alpha_{1C}\beta_{1a}$, $\alpha_{1C}\beta_{1a}\alpha_{2-}\delta\gamma$ subunits have been studied in the inside-out patch configuration using the patch clamp technique. As observed with native Ca²⁺ channels in guinea-pig cardiac myocytes, ^{1,4,13,29} excision of membrane patches results in run-down of calcium channel activity is not dependent on coexpression of auxiliary subunits, suggesting that the molecular determinant(s) for run-down is located in the α_{1C} subunit.

Molecular Determinants for Run-Down in the α_{1C} Subunit

The pore forming α_1 subunit consists of four homologous transmembrane domains, each composed of six transmembrane segments linked by variable cytoplasmic loops, and cytoplasmic domains of amino- and carboxy termini.^{38,39,40} Alternative splicing of the human α_{1C} subunit generates multiple isoforms of the channel, including those with a structurally altered carboxyl terminal tail. Two human splice variants of the principal 2138 amino acid pore-forming α_{1C} subunit, an ubiquitous isoform $\alpha_{1C,77}$ and a hippocampal isoform $\alpha_{1C,86}$, show differences in their carboxyl terminal tail.^{41,42} Due to alternative splicing 80 amino acid residues in the second quarter of the carboxyl tail are replaced with 81 non-identical amino acids yielding the $\alpha_{1C,86}$ splice variant (Table 2). In an attempt to analyze the role of these 80 amino acids, Kepplinger et al (2000)⁴³ studied the $\alpha_{1C,77}$ and $\alpha_{1C,86}$ subunits and the two sub-segmental mutants, $\alpha_{1C,77K}$ and $\alpha_{1C,77L}$ (Table 2; Soldatov et al)⁴⁴ expressed in HEK-tsA201 cells.

The $\alpha_{1C,77}$ channel exhibits a remarkably and significantly faster run-down compared to the $\alpha_{1C,86}$ channel (Fig. 5). The whole-cell data were substantiated by single-channel experiments in which $\alpha_{1C,86}$ shows a significantly slowed rundown within 1.5 - 2.5 min following patch excision, in contrast to a rapid rundown of $\alpha_{1C,77}$ within the same time period (Fig. 6).



Figure 4. Run-down of Ca²⁺ channels composed of different subunits. The *NP*₀ values of patches of α_{1C} (A), $\alpha_{1C}\beta_{1a}$ (B) and $\alpha_{1C}\beta_{1a}\alpha_{2}\delta\gamma$ (C) channels are summated, taking 0 min as the point of inside-out patch formation (indicated by I.O. and arrow). The decline in *NP*₀ is fitted to double exponential curves. τ_{s} and τ_{f} are the time constants. Reproduced with permission from BBRC, 1998; 247:844-850.

Table 2. Structure of the variable parts in the carboxyl terminal tail of the α_{1C} subunits under investigation

a1c, 77	I KT EGNL EQANEELRAI I KKIWKRTSHKLLDQVVPPAGDDEVTVGKFYATFL-I QEYFRKFKRKEQGLVGKP9QRNALSL	(1572-1651)
a1c, 77L	et elssovoyoakeasllerrrksshp	(1572-1598)
a10, 77K	SSEPKSSTKPNKLLSSGGSTGWVEDÅRALEGQVLARGCGWLGSLEERERGPEEPPLGF	(1595-1652)
C1C, 86	${\tt etelssovoyoakeasllerrrksshpksstkpikllssogstowved aralegovlargcowlgsleerergphhpplgf$	(1572-1652)

Amino acid sequences of $\alpha_{1C,77}$ (1572 - 1651) and $\alpha_{1C,86}$ (1572 - 1652) are shown in the top and bottom rows, respectively. Indicated amino acids of $a_{1C,86}$ replace the respective residues in the amino acid sequence of $\alpha_{1C,77}$. In $\alpha_{1C,77L}$ and $\alpha_{1C,77K}$ subunits, indicated segments of $\alpha_{1C,86}$ replace the respective motifs L (1572 - 1598) and K (1595 - 1651) of the $\alpha_{1C,77}$ subunit. Residues in bold are located in identical positions between α_{1C} subunits. Reproduced with permission from reference 43.



Figure 5. Time dependence of whole-cell Ba²⁺ currents through $\alpha_{1C,77}$ and $\alpha_{1C,86}$ channels. Peak currents are generated by repetitive depolarizations to 25 mV ($\alpha_{1C,77}$) and 35 mV ($\alpha_{1C,86}$). Comparison of currents at 4 min indicated a significant (P < 0.01) difference in current size between the $\alpha_{1C,77}$ and $\alpha_{1C,86}$ channels. Reproduced with permission from reference 43.



Figure 6. Time dependence of single channel currents of $\alpha_{1C,77}$ and $\alpha_{1C,86}$ channels in cell-attached and inside-out patch configurations. Average channel activity (*NP*₀) of $\alpha_{1C,77}$ (A) and $\alpha_{1C,86}$ channels (B) recorded in the cell-attached (c.a.) patch followed by inside-out (i.o.) patch configuration. Inset in A shows mean channel activity reached 1-5 - 2-5 min after patch excision normalized to the previous activity in the cell-attached patch. Consecutive single channel traces corresponding to the experiments in A and B are depicted in C and D both in the cell-attached and inside-out patch. Dotted lines indicate zero current level. Reproduced with permission from reference 43.



Figure 7. Time dependence of whole-cell currents of $\alpha_{1C,77K}$ and $\alpha_{1C,77L}$ channels. Peak currents normalized to initial currents are shown as dependent on time for $\alpha_{1C,77K}$ and $\alpha_{1C,77L}$ channels recorded at test potentials of 35 mV. Comparison of currents at 4 min indicated no significant (P > 0.05) difference in current size between the $\alpha_{1C,77K}$ and $\alpha_{1C,77L}$ channels. Reproduced with permission from reference 43.

As rundown has not been completely abolished, other structures within the α_{1C} subunit might additionally contribute to this process. In both whole-cell (Fig. 7) and single-channel experiments the segmental mutants $\alpha_{1C,77K}$ and $\alpha_{1C,77L}$ exhibit a similar and substantial rundown which resembles more that of the $\alpha_{1C,77}$ channel, indicating that a large stretch of the 81 amino acid sequence of the $\alpha_{1C,86}$ subunit is required to markedly reduce rundown of L-type Ca²⁺ channels. As this sequence also determines channel inactivation,^{44,45} both channel properties may be interdependent. However, the segmental mutants in contrast to the $\alpha_{1C,86}$ channel displayed a fast rundown, though they all showed rapid Ba²⁺ current inactivation. In addition, the inactivation rate did not change during rundown. Thus, the mechanism of rundown seems to be different from that governing channel inactivation.

Summary of the Molecular Mechanisms and Determinants of Run-Down

Dephosphorylation and washout of a regulatory factor have been suggested as prime mechanisms responsible for channel rundown. Proteolysis of the calcium channel protein can be excluded, as run-down has been shown to be fully reversible. Reversal of rundown by PKA is controversial. While Ono and Fozzard¹⁷ reported a clear recovery from rundown by PKA application, Costantin et al⁸ observed an effect only in a subset of patches, and Yazawa et al²² as well as Elhamdani et al²³ found a stabilization of calcium channel activity by ATP, yet essentially independent of PKA. The functionally important PKA phosphorylation site^{24,46} is not present within the sequence 1572 - 1651 in the $\alpha_{1C,77}$ channel, whereas a putative motif (R/KRXS) is found in the $\alpha_{1C,86}$ channel within the L segment (amino acids 1592 - 1595). However, a role of this putative PKA site in the sensitivity of Ca²⁺ channels to rundown is rather unlikely as the $\alpha_{1C,77L}$ contains this motif and shows a rapid rundown similar to the $\alpha_{1C,77}$ channel. Hence, the major role of ATP in the regulation of calcium channel run-down is apparently a direct binding to the calcium channel, where the site of this interaction remains to be identified.



Figure 8. Effect of calpastatin + ATP on the activity of single $\alpha_{1C,77}$ and $\alpha_{1C,86}$ channels in the inside-out patch. Time-course of average channel activity (N,p) of $\alpha_{1C,77}$ (A) and $\alpha_{1C,86}$ (B) in the cell-attached (c.a.) and inside-out (i.o.) patch before and after addition of calpastatin (2 U/ml) + Na₂ATP (1 mM). Single channel activity of $\alpha_{1C,77}$ almost completely recovered from run-down in the inside-out (i.o.) patch, whereas almost no effect was observed with channel activity of $\alpha_{1C,86}$ which was resistant to run-down in the i.o. patch. C, D) depict single channel traces for the corresponding experiments in A and B, respectively, recorded under the indicated conditions. Dotted lines denote zero current level. Reproduced with permission from reference 43.

Washout of a regulatory factor has been suggested as the second mechanism of rundown. It has been reported that the ubiquitous protein calpastatin is an important cytoplasmic factor regulating L-type Ca²⁺ channel activity.^{2,4,5,31} Calpastatin has been also detected in oocytes,⁴⁷ and HEK 293 cells,⁴³ where overexpression of calpastatin was found to increase L-type Ca²⁺ channel activity (Leitner and Romanin, unpublished observations). Indeed, the activity of the $\alpha_{1C,77}$ channel subject to rundown following inside-out patch formation recovers by addition of calpastatin + ATP to the intracellular face of the membrane (Fig. 8). Among the five domains of calpastatin the N-terminal domain L may be particularly important in the regulation of calcium channel activity.³⁷

Run-down has been reported to occur without changes in the gating currents^{18,48} suggesting a disruption of the linkage between the voltage sensor and the opening of the ionic gate.¹⁸ Thus it is tempting to speculate that the sequence 1572 - 1651 that determines run-down properties, represents the target site for the modulatory effects of calpastatin + ATP, which then restore coupling of the ionic gate to the voltage sensor, resulting in channel opening upon depolarization. It has been reported that L-type Ca^{2+} channel activity, enhanced by intracellular application of trypsin, still exhibits the usual run-down, which is reversed by calpastatin



Figure 9. Molecular mechanism and determinants for regulating calcium channel run-down.

plus ATP.⁴⁹ Thus the molecular determinants for run-down and its reversal are not affected by the action of trypsin. The cleavage site of trypsin has been localized to the carboxyl terminus of $\alpha_{1C,77}$ distal to amino acid 1653 consistent with the involvement of the sequence 1572–1651 in the regulation and reversal of run-down. Further, a calmodulin binding IQ region (1624–1635) within this sequence 1572–1651 has been recently reported as a critical site for Ca²⁺-induced inactivation.^{50,51,52} Hence, a cross-talk between Ca²⁺ channel regulation by calpastatin + ATP and Ca²⁺ appears possible and remains to be investigated in future studies.

References

- 1. Kameyama A, Yazawa K, Kaibara M et al. Run-down of the cardiac Ca²⁺ channel: Characterization and restoration of channel activity by cytoplasmic factors. Pflugers Arch 1997; 433:547-556.
- 2. Kameyama M, Kameyama A, Takano E et al.Run-down of the cardiac L-type Ca²⁺ channel: Partial restoration of channel activity in cell-free patches by calpastatin. Pflugers Arch 1998b; 435:344-349.
- 3. Becq F. Ionic channel rundown in excised membrane patches. Biochim Biophys Acta 1996; 1286:53-63.
- 4. Romanin C, Grosswagen P, Schindler H. Calpastatin and nucleotides stabilize cardiac calcium channel activity in excised patches. Pflugers Arch 1991; 418:86-92.
- Seydl K, Karlsson JO, Dominik A et al. Action of calpastatin in prevention of cardiac L-type Ca²⁺ channel run-down cannot be mimicked by synthetic calpain inhibitors. Pflugers Arch 1995; 429:503-510.
- Fenwick EM, Marty A, Neher E. Sodium and calcium channels in bovine chromaffin cells. J Physiol 1982; 331:599-635.
- 7. Nilius B, Hess P, Lansman JB et al. A novel type of cardiac calcium channel in ventricular cells. Nature 1985; 316:443-446.
- 8. Perez-Reyes E, Cribbs LL, Daud A et al. Molecular characterization of a neuronal low-voltage-activated T-type calcium channel. Nature 1998; 391:896-900.
- 9. Hockberger PE, Nam SC. High-voltage-activated calcium current in developing neurons is insensitive to nifedipine. Pflugers Arch 1994; 426:402-411.

- Tombaugh GC, Somjen GG. Differential sensitivity to intracellular pH among high- and low-threshold Ca²⁺ currents in isolated rat CA1 neurons. J Neurophysiol 1997; 77:639-653.
- 11. Martini M, Rossi ML, Rubbini G et al. Calcium currents in hair cells isolated from semicircular canals of the frog. Biophys J 2000; 78:1240-1254.
- 12. Morita H, Cousins H, Onoue H, et al. Predominant distribution of nifedipine-insensitive, high voltage-activated Ca²⁺ channels in the terminal mesenteric artery of guinea pig. Circ Res 1999; 85:596-605.
- Kameyama M, Kameyama A, Nakayama T et al. Tissue extract recovers cardiac calcium channels from 'run-down'. Pflugers Arch 1988; 412:328-330.
- 14. Kameyama M, Kameyama A, Kaibara M et al. Mechanisms of rundown of cardiac calcium channels. In: Yamada K, Shibata S, eds. Recent Advances on Calcium Channels and Antagonists. New York: Pergamon Press, 1990:3-10.
- 15. Kostyuk PG. Intracellular perfusion of nerve cells and its effects on membrane currents. Physiol 1984; Rev 64:435-454.
- Armstrong D, Eckert R Voltage-activated calcium channels that must be phosphorylated to respond to membrane depolarization. Proc Natl Acad Sci USA 1987; 84:2518-2522.
- Ono K, Fozzard HA. Phosphorylation restores activity of L-type calcium channels after rundown in inside-out patches from rabbit cardiac cells. J Physiol 1992; 454:673-688.
- Costantin JL, Qin N, Waxham MN, et al. Complete reversal of run-down in rabbit cardiac Ca²⁺ channels by patch-cramming in Xenopus oocytes; Partial reversal by protein kinase A. Pflugers Arch 1999; 437:888-894.
- 19. Chad JE, Eckert R. An enzymatic mechanism for calcium current inactivation in dialysed Helix neurones. J Physiol 1986; 378:31-51.
- Belles B, Hescheler J, Trautwein W et al. A possible physiological role of the Ca-dependent protease calpain and its inhibitor calpastatin on the Ca current in guinea pig myocytes. Pflugers Arch 1988; 412:554-556.
- 21. Levitan IB. Phosphorylation of ion channels. J Membr Biol 1985; 87:177-190.
- Yazawa K, Kameyama A, Yasui K et al. ATP regulates cardiac Ca²⁺ channel activity via a mechanism independent of protein phosphorylation. Pflugers Arch 1997; 433:557-562.
- Elhamdani A, Bossu JL, Feltz A. ADP exerts a protective effect against rundown of the Ca²⁺ current in bovine chromaffin cells. Pflugers Arch 1995; 430:401-409.
- 24. De Jongh KS, Murphy BJ, Colvin AA et al. Specific phosphorylation of a site in the full-length form of the alpha 1 subunit of the cardiac L-type calcium channel by adenosine 3',5'-cyclic monophosphate-dependent protein kinase. Biochemistry 1996; 35:10392-10402.
- Leach RN, Brickley K, Norman RI. Cyclic AMP-dependent protein kinase phosphorylates residues in the C-terminal domain of the cardiac L-type calcium channel alpha1 subunit. Biochim Biophys Acta 1996; 1281:205-212.
- Mitterdorfer J, Froschmayr M, Grabner M et al. Identification of PK-A phosphorylation sites in the carboxyl terminus of L-type calcium channel alpha 1 subunits. Biochemistry 1996; 35:9400-9406.
- Perets T, Blumenstein Y, Shistik E et al. A potential site of functional modulation by protein kinase A in the cardiac Ca²⁺ channel alpha 1C subunit. FEBS Lett 1996; 384:189-192.
- Sperelakis N. Regulation of ion channels by phosphorylation. In: Sperelakis N, ed. Cell Physiology Source Book. 2nd ed. San Diego: Academic Press, 1998:499-509.
- 29. Kameyama A, Hao LY, Takano E et al. Characterization and partial purification of the cytoplasmic factor that maintains cardiac Ca²⁺ channel activity. Pflugers Arch 1998a; 435:338-343.
- Croall DE, DeMartino GN. Calcium-activated neutral protease (calpain) system: Structure, function, and regulation. Physiol Rev 1991; 71:813-847.
- Hao LY, Kameyama A, Kameyama M. A cytoplasmic factor, calpastatin and ATP together reverse run-down of Ca²⁺ channel activity in guinea-pig heart. J Physiol 1999; 514 (Pt 3):687-699.
- 32. Ma H, Yang HQ, Takano E et al. Requirement of different subdomains of calpastatin for calpain inhibition and for binding to calmodulin-like domains. J Biochem (Tokyo) 1993; 113:591-599.
- 33. Wang KK. Developing selective inhibitors of calpain. Trends Pharmacol Sci 1990; 11:139-142.
- 34. Mehdi S. Cell-penetrating inhibitors of calpain. Trends Biochem Sci 1991;16:150-153.
- 35. Emori Y, Kawasaki H, Imajoh S et al. Endogenous inhibitor for calcium-dependent cysteine protease contains four internal repeats that could be responsible for its multiple reactive sites. Proc Natl Acad Sci USA 1987; 84:3590-3594.
- 36. Imajoh S, Kawasaki H, Emori Y et al. Calcium-activated neutral protease inhibitor from rabbit erythrocytes lacks the N-terminal region of the liver inhibitor but retains three inhibitory units. Biochem Biophys Res Commun 1987;146:630-637.

- 37. Hao LY, Kameyama A, Kuroki S et al. Calpastatin domain L is involved in the regulation of L-type Ca²⁺ channels in guinea pig cardiac myocytes. Biochem Biophys Res Commun 2000; 279:756-761.
- 38. Walker D, De Waard M. Subunit interaction sites in voltage-dependent Ca²⁺ channels: Role in channel function. Trends Neurosci 1998; 21:148-154.
- 39. Isom LL, De Jongh KS, Catterall WA. Auxiliary subunits of voltage-gated ion channels. Neuron 1994;12:1183-1194.
- 40. Striessnig J. Pharmacology, structure and function of cardiac L-type Ca²⁺ channels. Cell Physiol Biochem 1999; 9:242-269.
- Soldatov NM. Molecular diversity of L-type Ca²⁺ channel transcripts in human fibroblasts. Proc Natl Acad Sci USA 1992; 89:4628-4632.
- 42. Soldatov NM. Genomic structure of human L-type Ca2+ channel. Genomics 1994; 22:77-87.
- 43. Kepplinger KJ, Forstner G, Kahr H et al. Molecular determinant for run-down of L-type Ca²⁺ channels localized in the carboxyl terminus of the 1C subunit. J Physiol 2000; 529 (Pt 1):119-130.
- 44. Soldatov NM, Oz M, O'Brien KA et al. Molecular determinants of L-type Ca²⁺ channel inactivation. Segment exchange analysis of the carboxyl-terminal cytoplasmic motif encoded by exons 40-42 of the human alpha1C subunit gene. J Biol Chem 1998; 273:957-963.
- 45. Soldatov NM, Zuhlke RD, Bouron A et al. Molecular structures involved in L-type calcium channel inactivation. Role of the carboxyl-terminal region encoded by exons 40-42 in alpha1C subunit in the kinetics and Ca²⁺ dependence of inactivation. J Biol Chem 1997; 272:3560-3566.
- 46. Gao T, Yatani A, Dell'Acqua ML et al. cAMP-dependent regulation of cardiac L-type Ca²⁺ channels requires membrane targeting of PKA and phosphorylation of channel subunits. Neuron 1997; 19:185-196.
- 47. Lorca T, Galas S, Fesquet D et al. Degradation of the proto-oncogene product p39mos is not necessary for cyclin proteolysis and exit from meiotic metaphase: requirement for a Ca²⁺-calmodulin dependent event. Embo J 1991; 10:2087-2093.
- Josephson IR, Varadi G. The beta subunit increases Ca²⁺ currents and gating charge movements of human cardiac L-type Ca2+ channels. Biophys J 1996; 70:1285-1293.
- Schmid R, Seydl K, Baumgartner W et al. Trypsin increases availability and open probability of cardiac L-type Ca²⁺ channels without affecting inactivation induced by Ca²⁺. Biophys J 1995; 69:1847-1857.
- 50. Peterson BZ, DeMaria CD, Adelman JP et al. Calmodulin is the Ca²⁺ sensor for Ca²⁺-dependent inactivation of L-type calcium channels. Neuron 1999; 22:549-558.
- Qin N, Olcese R, Bransby M et al. Ca²⁺-induced inhibition of the cardiac Ca²⁺ channel depends on calmodulin. Proc Natl Acad Sci USA 1999; 96:2435-2438.
- 52. Zuhlke RD, Pitt GS, Deisseroth K et al. Calmodulin supports both inactivation and facilitation of L-type calcium channels. Nature 1999; 399:159-162.
- 53. Takano E, Murachi T. Purification and some properties of human erythrocyte calpastatin. J Biochem (Tokyo) 1982; 92:2021-2028.
- 54. Takano E, Kitahara A, Sasaki T et al. Two different molecular species of pig calpastatin. Structural and functional relationship between 107 kDa and 68 kDa molecules. Biochem J 1986; 235:97-102.
- 55. Takano E, Maki M, Mori H et al. Pig heart calpastatin: identification of repetitive domain structures and anomalous behavior in polyacrylamide gel electrophoresis. Biochemistry 1988; 27:1964-1972.
- 56. Maki M, Takano E, Mori H et al. Repetitive region of calpastatin is a functional unit of the proteinase inhibitor. Biochem Biophys Res Commun 1987; 143:300-308.
- 57. Yakel JL. Inactivation of the Ba²⁺ current in dissociated Helix neurons: Voltage dependence and the role of phosphorylation. Plugers Arch 1992; 420:470-478.

Calcium Channels As Therapeutic Targets

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Voltage-dependent calcium channels link membrane potential changes of excitable cells to important intracellular processes, including regulated secretion of neurotransmitters and hormones, muscle contraction and gene transcription (see Chapters 1,8,20-22). This critical role makes them attractive targets to develop novel pharmacological agents for a broad variety of diseases originating from excitable tissues, from the central and peripheral nervous systems to the endocrine and cardiovascular apparatus. Currently, calcium channel-blockers are most widely used to treat cardiovascular ailments. Moreover, these agents act largely via block of just one type of calcium channel, the L-type (Table 1). Recent advances in the molecular and biophysical understanding of calcium channels (see Chapters 3-5) now make it possible to rationally design drugs that are selective for a particular molecular class of calcium channel. This chapter briefly reviews the established roles of L-type drugs and then focuses on the potential role of each class of channel as a therapeutic target.

L-Type Channels

L-type channels play a unique role in exo- and endocrine secretion, as well as in excitation-contraction coupling in skeletal, smooth and cardiac muscle. Three pore-forming subunits α_{1C} , α_{1D} , α_{1S} are responsible for this type of calcium channel.

In addition to their expression in the myocardium and the vasculature, L-type channels are also expressed in the sinoatrial (SA) node and the atrioventricular (AV) node at the heart where they propagate action potentials. Their central role in controlling the activity of the heart and their regulation of peripheral vascular tone make them ideal targets for therapeutic intervention in the treatment of arrhythmia and hypertension.

Three classes of blockers that are selective for this group of calcium channels, which have been in use clinically for many years, include the dihydropyridines (nifedipine, amlodipine, felodipine; see Table 1), the phenylalkylamines (verapamil) and the benzothiazepines (diltiazem). In vitro experiments have demonstrated that these drugs decrease AV conduction velocity, heart rate and contractility in isolated hearts.⁸ They also act in arterial smooth muscle to decrease peripheral vascular resistance.⁸ The dilation of the vasculature combined with the negative inotropic and chronotropic effects on the myocardium result in decreased myocardial oxygen consumption.

Although these three classes of drugs block L-type calcium channels by interfering with channel gating, they achieve this outcome via different mechanisms. Dihydropyridines preferentially bind to the inactivated state of the channel, and therefore the potency of dihydropyridines increases at less negative membrane potentials.⁸ Phenylalkylamines and benzothiazepines require open channels and their binding slows recovery of the channel from inactivation. Therefore, the inhibition by these drugs increases with stimulation frequency.⁸ Indications for these drugs include hypertension, angina, supraventricular arrhythmia, migraine, and the prevention of vasospasm in subarachnoid hemorrhage. Unfortunately there are a number of limitations of these drugs.³⁻⁶ There is controversy as to whether drugs such as

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Drug	Target	Therapeutic Indications	References
Ziconotide	N-type	chronic pain	See ref. 1
CKGKGAKCSRLM YDCCT GSCRSGKC			
Flunarizine	L-, P/Q-type	migraine	See ref. 2
Nifedipine	L-type	hypertension, angina,	See refs. 3-6
		arrhythmias	
Mibefradił	T-type	hypertension, chronic	See ref. 7
		(withdrawn)	

Table 1. Examples by class of drugs selective for calcium channels

diltiazem, felodipine, isradapine, nicardipine, nifedipine, nisoldipine verapamil and amlodipine, which are approved in the U.S.A. for the treatment of hypertension by lowering diastolic blood pressure, increase the risk of myocardial infarction (MI). A meta-analysis found a 26% increase in MI in patients who used calcium channel blockers compared to other therapies.⁹ An increased sympathetic response seen with some calcium channel blockers may explain the increased risk of MI. Another limitation of L-type calcium channel blockers includes the unavoidable negative inotropic effects, which in turn can precipitate acute cardiac failure. In addition, the compensatory response of the sympathetic system can increase the risk of arrhythmia. These inherent problems have promoted the search of agents with more selective actions (see next section on T-type).

N-Type Channels

The α_{1B} is the pore-forming subunit underlying the N-type current, which is a predominantly neuron-specific current involved in excitation-secretion coupling at many presynaptic terminals. In turn, presynaptic N-type current is extensively regulated by multiple G protein-coupled receptors, including μ -opioid receptors, the site of action of classic opioid analgesics¹⁰ (Table 2).

Indeed, several lines of evidence support the view that the N-type current is prominently involved in the transduction of acute and chronic pain perception.^{1,11-17} Strong, independent support for the critical role of the N-type channel in chronic neuropathic pain has been provided by the recent work with the α_{1B} null mice.¹⁷ The evidence from this line of work concerning the involvement of this channel in inflammatory pain is less compelling, perhaps because of compensatory mechanisms.¹⁷ These observations reinforce the idea that selective blockers of the N-type current might reproduce the analgesic properties of opioids without their side-effects, such as tolerance, addiction, respiratory depression and constipation. The ensuing effort has produced ziconotide, a derivative of the snail venom ω -conotoxin, which is currently awaiting approval by the FDA for use in chronic intractable pain^{1,15} (Table 1). However, as ziconotide is a peptide, it is effective only by intrathecal application. Therefore, second-generation small molecular weight N-type blockers which are orally active for pain are currently under development.^{18,19}

Interestingly, the α_{1B} null mice reportedly display a behavior consistent with lower anxiety levels than wild type animals, ¹⁷ a phenotype opposite to that shown by the α_{1E} null mice. ¹⁷ In retrospect, this finding may not be surprising given the intimate and often specific relationship between presynaptic calcium channels and transmitter release, and the well-established involvement of certain neurotransmitters in mood disorders.^{20,21} More broadly, it is likely that calcium channels will emerge as targets for other psychiatric disorders. The possible link between T-type channels and certain symptoms of schizophrenia is discussed below.

P/Q-Type Channels

The α_{1A} is the pore-forming subunit underlying the P/Q calcium channel. Much like the α_{1B} , it is also involved in presynaptic transmitter release. Several inherited neurological disorders, which include familial hemiplegic migraine, originate from mutations in either the CACNA1A gene (which codes for α_{1A}), or in the accessory subunits of the P/Q channel^{22,23} (see Chapter 16). Many, of these mutations result in an alteration of the P/Q current.²⁴

These observations led to the view that common forms of migraine might also be related to dysfunction of this channel, and might benefit from pharmacological modulation of the P/Q current. A number of linkage studies were conducted to examine the role of the CACNA1A gene in migraine with or without aura. Linkage analysis was performed on four large Australian families with typical migraine and the disease locus was demonstrated to link to the CACNA1A region in one of the families.²⁵ A sibpair analysis looked at the occurrence of shared parental marker alleles in siblings with typical migraine with or without aura and demonstrated increased allele sharing in the CACNA1A gene region on 19p13 consistent with the involvement of this region in migraine.²⁶ However, in a subsequent study, two patients whose initial migraine locus was originally linked to the CACNA1A region were screened for mutations in the CACNA1A gene by sequencing the 47 exons and no mutations were identified.²⁷ Additionally, linkage and association studies in a large case control population and in 82 migraine pedigrees did not support a role for the CACNA1A gene in typical migraine.²⁷ These findings were further supported by a linkage study that demonstrated that chromosome 19p13 contains a locus which contributes to the genetic susceptibility of migraine with aura that is distinct from the CACNA1A gene.²⁸

Linkage studies in classic migraine have not confirmed the involvement of the α_{1A} subunit, but the molecular etiology underlying migraine might involve a number of different genes. However, flunarazine, a P/Q type channel blocker,²⁹ is a proven migraine prophylactic.² This

Drug	Calcium Channel Target(s)	Therapeutic Indications	References
Morphine HO O HO HO HO HO	N-type, via G _{βγ}	acute and chronic pain	See ref. 10, 75
Gabapentin H ₂ N Соон	N-type?	chronic pain, epilepsy	See ref. 75
Ethosuximide $ \begin{array}{c} H \\ V \\ V \\ CH_3 \\ C_2 H_5 \end{array} $	T-type, _{–1G} ?	absence seizures	See refs. 39, 40
Amiodarone O = O = O = O = O = O = O = O = O = O =	L-type	ventricular arrhythmias	See ref. 6
Pimozide	T-type?	negative symptoms of schizophrenia, Tourette's syndrome	See ref. 71

Table 2. Drugs that have partial action on calcium channels

suggests a potential role of P/Q type channels in migraine that is further supported by electrophysiological studies.³⁰ It is believed that the periaqueductal gray matter (PAG) plays an important role in migraine through its role in the descending pain modulation system.³¹ Functional imaging studies have demonstrated that the periaqueductal gray matter is activated in migraine headache³² and lesions of the periaqueductal gray matter have been associated with headache.^{33,34} Facilitation of trigeminal nociceptive activity was reported after injection of the

P/Q type calcium channel blocker ω -agatoxin IVA into the ventrolateral subdivision of the periaqueductal gray matter in rats.³⁰ It has been postulated that in the periaqueductal gray matter the descending inhibitory neurons that target trigeminal regions of the dorsal horn are abnormally regulated by P/Q type calcium channel dysfunction in migraineurs.³⁰ Modulation of the P/Q type calcium channel may prove to be a rational therapeutic target in the treatment of migraine.

A relationship has also been demonstrated between mutations of the α_{1A} subunit and seizures, in particular absence seizures. Absence seizures are a form of non-convulsant childhood epilepsy, which are characterized by 3 Hz spike and wave electroencephalographic (EEG) activity generated by the hypersynchronous firing of neuronal populations in the thalamocortical circuit. A mutation in the P/Q type calcium channel has been associated with absence seizure phenotype in one human subject.³⁵ A heterozygous point mutation (C5733T) in this individual resulted in a premature stop codon. This mutation lies between the last transmembrane segment (IVS6) and the intracellular C terminus. Electrophysiological studies demonstrated that this mutation was non functional and exerted a dominant negative effect. As P/Q type channels are predominantly presynaptic and play a role in neurotransmitter release, it has been hypothesized that a reduction in current may disrupt the balance of excitation and inhibition within the thalamocortical loop.³⁵

There are several animal models for absence epilepsy, which also involve a variety of voltage-dependant calcium channel subunits. The tottering mouse is the result of a mutation in the α_{1A} subunit gene on chromosome 8,³⁶ the lethargic mouse results from a mutation in the β 4 subunit on chromosome 2^{37} and the stargazer mouse from a mutation in the γ_2 subunit gene on chromosome 15.³⁸ Although these mutations are associated with absence seizure it is not clear how this is mediated. Several lines of evidence indicate that expression of this epileptic phenotype requires yet another calcium channel, a member of the low-threshold T-type.

T-Type Channels

Succinimides have long been known as an effective treatment for absence seizures, and block of T-type calcium channels has been shown to be the likely mechanism of action^{39,40} T-type calcium channels play a normal physiological role in the synchronous firing of thalamic neurons during slow wave sleep. This phase-locked synchronous firing, which results from the interplay of rhythmic synaptic inhibition and T-type calcium channel, is also active during absence seizures. Thalamic relay neurons are hyperpolarized by rhythmic inhibitory postsynaptic potentials, which remove the inactivation of the T current. Recently it has been demonstrated that the calcium dependent spike bursts in the thalamic relay neurons play a central role in the generation of absence seizures.⁴¹ This was achieved through studies on α_{IG} T type calcium channel knockout mice. These mice had abolished T type calcium currents and calcium-dependent spike bursts in the thalamic relay neurons with no change in tonic firing. Systemic injection of GABA_B agonists such as baclofen and γ -hydroxybutyrolactone which are known to produce thalamocortical spike wave discharges, did so in wild-type mice but not in the α_{IG} knockout mice. Importantly, α_{IG} -null mice are resistant to absence seizures induced by deletion of the α_{IA} subunit.

Thus the primary mechanism directly responsible for the epileptic phenotype appears to be a T-type, α_{1G} -induced current rather than a P/Q, α_{1A} -generated current. A likely explanation of the absence seizures observed in α_{1A} null or mutant mice is over-expression of T-type currents. This mechanism has been recently confirmed.⁴²

Thus α_{1G} -induced T-type currents are clearly emerging as targets for at least one clinically relevant type of epilepsy. More broadly, because their gating properties are well suited to support rhythmic, high-frequency electrical activity, one can predict that T-type currents are targets in a variety of conditions such as chronic pain and certain cardiovascular disorders.^{43,44}

The α_{1H} subunits (which is responsible for a second subtype of T-type current) might indeed be involved in pain. Support for this hypothesis has recently emerged from studies showing that these subunits are preferentially expressed in the dorsal root sensory neurons, and

Subunit	Phenotype	References
α _{1A}	ataxia, absence seizures	See ref. 76
α ₁₈	higher threshold for neuropathic & inflammatory pain,	
	higher threshold for anxiety, ortostatic hypotension	See ref. 17
α_{1C}	lethal in utero	See ref. 77
α_{1D}	deafness	See ref. 78
α1Ε	altered pain responses, lower threshold for anxiety	See ref. 73
α _{1F}	N/A	
α _{1G}	resistance to absence seizures	See ref. 41
α _{1H}	cardiovascular malformations	See ref. 49
α11	N/A	

Table 3. Calcium channel knock-outs

would then be able to support the repetitive electrical discharges typical of painful stimuli.⁴⁵⁻⁴⁸ However, a direct test of this hypothesis, as well as of the possible involvement of α_{1H} subunits in epilepsy, will have to wait for the development of selective blockers of the neuronal T-type current, or the detailed study of the α_{1H} knock-out mice.⁴⁹

T-type currents are also attractive targets for cardiovascular disease for two sets of reasons. First, they are expressed in the vascular smooth muscle cells (mainly α_{IG} subunits),⁵⁰ and they are thought to contribute to the vascular tone.⁴⁴ Second, expression in cardiac tissues is relatively diffuse early in development and appears to be associated with the rate of growth; but then in adults they become restricted to the sino-atrial node.⁵¹⁻⁵⁵ Re-expression in ventricular myocytes is associated with chronic cardiac failure and cardiomyopathy.⁵⁶⁻⁶⁰ Therefore, a T-type blocker would be an effective antihypertensive agent without some of the side effects of the L-type blockers, such as negative inotropy.⁶¹⁻⁶⁴ Based on data from experimental models, there are also expectations that T-type blockers might be effective in preventing the cardiovascular remodeling that accompany hypertension and chronic heart failure.^{7,65-68} Mibefradil, a partially selective T-type blocker (Table 1), was recently introduced and then withdrawn due to extensive drug interactions.⁶⁹

Some of the clinically available L-type blockers display moderate T-type blocking properties in-vitro, and at least one of them was reported to have antipsychotic properties in one doubleblind clinical study.⁷⁰ Moreover, certain antipsychotic drugs active against the negative symptoms of schizophrenia are also blockers of the T-type current.⁷¹ Taken together, these observations suggest that blockade of T-type currents might represent a novel class of anti-schizophrenic therapeutics without some of the side effects of the current medications. Interestingly, the α_{11} subunit—which defines a third group of T-type currents—is almost exclusively expressed in the CNS and particularly in the striatum.⁷² It will be important to define its role in the striatal dopaminergic system and the effects of the selective ablation and/ or block of this subunit.

Future Directions

We have only started to address the question of the variety of roles and functions originating from the multiple splice variants expressed by each calcium channel gene. Combined with the hetero-multimeric nature of these channels, this information will provide a rich playground for the next generation of high-throughput patch-clamp machines. More importantly, the search for splice variant-specific calcium channel blockers holds the promise of better drugs, active against a variety of neurological and psychiatric disorders and with fewer side effects.

Finally, the present attempt to understand calcium channels as therapeutic targets is based on the assumption that the research aim is to find a blocker. However, if one includes the possibility of developing compounds that open the channels, additional and interesting possibilities can be envisioned. For example, α_{1E} null mice have a threshold for anxiety lower than normal animals:⁷³ thus, a selective opener of α_{1E} channels could be anxiolytic. Moreover, because the α_{1E} null mice are hyperglycemic presumably due to the role of these subunits in insulin secretion,⁷⁴ a selective opener of α_{1E} channels that does not cross the blood-brain barrier might be useful as antidiabetic.

References

- 1. Bowersox SS, Gadbois T, Singh T et al. Selective N-type neuronal voltage-sensitive calcium channel blocker, SNX-111, poduces spinal antinociception in rat models of acute, persistent and neurophatic pain. J Pharmacol Exp Ther 1996; 279:1243-1249.
- Diener HC, Limmroth V. Advances in pharmacological treatment of migraine. Expert Opin Investig Drugs 2001; 10:1831-45.
- Kerins DM, Robertson RM, Robertson D. Drugs used for the treatment of myocardial ischemia. In: Hardman JG, Limbird LE, Gilman AG, eds. Goodman and Gilman's The Pharmacological Basis of Therapeutics, 10th ed. New York: McGraw-Hill, 2001:843-870.
- 4. Oates JA, Brown MJ. Antihypertensive agents and the drug therapy of hypertension. In: Hardman JG, Limbird LE, Gilman AG, eds. Goodman and Gilman's The Pharmacological Basis of Therapeutics, 10th ed. New York: McGraw-Hill, 2001:871-900.
- Ooi H, Colucci WS. Pharmacological treatment of heart failure. In: Hardman JG, Limbird LE, Gilman AG, eds. Goodman and Gilman's The Pharmacological Basis of Therapeutics, 10th ed. New York: McGraw-Hill, 2001:901-932.
- 6. Roden DM. Antiarrhytmic drugs. In: Hardman JG, Limbird LE, Gilman AG, eds. Goodman and Gilman's The Pharmacological Basis of Therapeutics, 10th ed. New York: McGraw-Hill, 2001:933-970.
- Clozel JP, Ertel EA, Ertel SI. Discovery and main pharmacological properties of mibefradil (Ro 40-5967), the first selective T-type calcium channel blocker. J Hypertens Suppl 1997; 15: S17-25.
- Striessnig J. Pharmacology, structure and function of cardiac L-type Ca²⁺ channel. Cell Physiol Biochem 1999; 9:242-269.
- Opie LH. Calcium channel blockers in hypertension: reappraisal after new trials and major meta-analyses. Am J Hypertens 2001; 14:1280.
- Law PY, Wong YH, Loh HH. Molecular mechanisms and regulation of opioid receptor signaling. Annu Rev Pharmacol Toxicol 2000; 40: 389-430.
- Chaplan SR, Pogrel JW, Yaksh TL. Role of voltage-dependent calcium channel subtypes in experimental tactile allodynia. J Pharmacol Exp Ther 1994; 269:1117-1123.
- 12. Malmberg AB, Yaksh TL. Voltage-sensitive calcium channels in spinal nociceptive processing: blockade of N- and P-type channels inhibits formalin-induced nociception. J Neurosci 1994; 14:4882-4890.
- Neugebauer V, Vanegas H, Nebe J et al. Effects of N- and L-type calcium channel antagonists on the responses of nociceptive spinal cord neurons to mechanical stimulation of the normal and the inflamed knee joint. J Neurophysiol 1996; 76:3740-3749.
- Diaz A, Dickenson AH. Blockade of spinal N- and P-type, but not L-type, calcium channels inhibits the excitability of rat dorsal horn neurones produced by subcutaneous formalin inflammation. Pain 1997; 69:93-100.
- 15. Sluka KA. Blockade of N- and P/Q-type calcium channels reduces the secondary heat hyperalgesia induced by acute inflammation. J Pharmacol Exp Ther 1998; 287:232-237.
- Vanegas H, Schaible H. Effects of antagonists to high-threshold calcium channels upon spinal mechanisms of pain, hyperalgesia and allodynia. Pain 2000; 85:9-18.
- Saegusa H, Kurihara T, Zong S et al. Suppression of inflammatory and neuropathic pain symptoms in mice lacking the N-type Ca²⁺ channel. EMBO J 2001; 20:2349-2356.
- 18. Cox B.Calcium channel blockers and pain therapy. Curr Rev Pain 2000; 4: 488-98.
- 19. Snutch TP, Sutton KG, Zamponi GW. Voltage-dependent calcium channels-beyond dihydropyridine antagonists. Curr Opin Pharmacol 2001; 1:11-6.
- Baldessarini RJ. Drugs and the treatment of psychiatric disorders: depression and anxiety disorders. In: Hardman JG, Limbird LE, Gilman AG, eds. Goodman and Gilman's The Pharmacological Basis of Therapeutics, 10th ed. New York: McGraw-Hill, 2001:447-484.
- Baldessarini RJ, Tarazi FI. Drugs and the treatment of psychiatric disorders: psychosis and mania. In: Hardman JG, Limbird LE, Gilman AG, eds. Goodman and Gilman's The Pharmacological Basis of Therapeutics, 10th ed. New York: McGraw-Hill, 2001:485-520.
- 22. Ophoff RA, Terwindt GM, Vergouwe MN et al. Familial hemiplegic migraine and episodic ataxia type-2 are caused by mutations in the Ca²⁺ channel gene CACNL1A4. Cell 1996; 87:543-552.
- Plomp JJ, van den Maagdenberg AM, Molenaar PC et al. Mutant P/Q-type calcium channel electrophysiology and migraine. Curr Opin Investig Drugs 2001; 2:1250-1260.
- 24. Hans M, Luvisetto S, Williams ME et al. Functional consequences of mutations in the human α_{1A} calcium channel subunit linked to familial hemiplegic migraine. J Neurosci 1999; 19:1610-1619.
- 25. Nyholt DR, Lea RAS, Goadsby PJ et al. Familial typical migraine: linkage to chromosome 19p13 and evidence for genetic heterogeneity. Neurology 1998; 50:1428-1432.
- 26. Terwindt GM, Ophoff RA, van Eijk R et al. Involvement of the CACNA1 ge4ne containing region on 19p13 8in migraine with and without aura. Neurology 2001; 56:1028-1032.
- 27. Lea RA, Curtain RP, Huchins C et al. Investigation of the CACNA1A Gene as a candidate for typical migraine susceptibility. Am J Med Genet 2001; 105:707-712.
- Jones KW, Ehm MG, Pericak-Vance MA et al. Migraine with aura susceptibility locus on chromosome 19p13 is distinct from the familial hemiplegic migraine locus. Genomics 2001; 78(3):150-4.
- Panchenko VA, Krishtal OA, Tegtmeier F et al. R56865 as Ca(2+)-channel blocker in Purkinje neurons of rat: comparison with flunarizine and nimodipine. Neuroscience 1993; 54(3):587-94.
- Knight YE, Bartsch, Kaube H et al. P/Q –type calcium channel blockade in the periaqueductal gray facilitates trigeminal nociception: A functional Genetic Link for Migraine? J Neurosci 2002; 22:RC213
- 31. Welch KMA, Nagesh V, Aurora SK et al. Periaqueductal gray matter dysfunction in migraine: cause or the burden of illness? Headache 2001; 41:629-37.
- 32. Bahra A, Matharu MS, Buchel C et al. Brainstem activation specific to migraine headache. Lancet 2001; 357:1016-1017.
- 33. Haas DC, Kent PF, Friedman DI. Headache caused by a single lesion of multiple sclerosis in the periaqueductal gray area. Headache 1993; 33:452-455.
- 34. Raskin NH, Hosobuchi Y, Lamb S. Headache may arise from perturbation of brain. Headache 1987; 27:416-420.
- 35. Jouvenceau A, Eunson LH, Spauschus A et al. Human epilepsy associated with dysfunction of the brain P/Q-type calcium channel. Lancet 2001; 358:801-7.
- 36. Fletcher CF, Lutz CM, O'Sullivan TN et al. Absence epilepsy in tottering mutant mice is associated with calcium channel defects. Cell 1996; 87:607-17.
- 37. Burgess DL, Jones JM, Meisler MH et al. Mutation of the Ca²⁺ channel b subunit gene Cchb4 is associated with ataxia and seizures in the lethargic (Ih) mouse. Cell 1997; 88,385-92.
- 38. Letts VA, Felix R, Biddlecome GH et al. The mouse stargazer gene encodes a neuronal CA ²⁺ channel r subunit. Nature Genetics 1988;19:340-7.
- Coulter DA, Huguenard JR, Prince DA. Specific petit mal anticonvulsants reduce calcium currents in thalamic neurons. Neurosci Lett 1989; 198:74-8.
- 40. Gomora JC, Daud AN, Weiergräber M et al. Block of cloned human T-type calcium channels by succinimide antiepileptic drugs. Mol Pharmacol 2001; 60:1121-1132.
- 41. Kim D, Song I, Keum S et al. Lack of the burst firing of thalamocortical relay neurons and resistance to absence seizures in mice lacking α_{1G} T-type Ca²⁺ channels. Neuron 2001; 31:35-45.
- 42. Zhang Y, Mori M, Burgess DL et al. Mutations in high-voltage-activated calcium channel genes stimulate low-voltage-activated currents in mouse thalamic relay neurons. J Neurosci 2002; 22:6362-71.
- 43. Huguenard JR. Low-threshold calcium currents in central nervous system neurons. Annu Rev Physiol 1996; 58:329-348.
- 44. Ertel SI, Ertel EA, Clozel JP. T-type Ca²⁺ channels and pharmacological blockade: potential pathophysiological relevance. Cardiovasc Drugs Ther 1997;11:723-739.
- Cardenas CG, Del Mar LP, Scroggs RS. Variation in serotonergic inhibition of calcium channel currents in four types of rat sensory neurons differentiated by membrane properties. J Neurophysiol 1995; 74:1870-9
- 46. Talley EM, Cribbs LL, Lee JH et al. Differential distribution of three members of a gene family encoding low voltage-activated (T-type) calcium channels. J Neurosci 1999; 19:1895-1911.
- 47. Todorovic SM, Jevtovic-Todorovic V, Meyenburg A et al. Redox modulation of T-type calcium channels in rat peripheral nociceptors. Neuron 2001; 31:75-85.
- Bilici D, Akpinar E, Gursan N et al. Protective effect of t-type calcium channel blocker in histamine-induced paw inflammation in rat. Pharmacol Res 2001; 44:527-531.
- Chen CC, Lamping KG, Nuno DW et al. Abnormal coronary function in mice deficcient in α_{IH} T-type Ca²⁺ channels. Science 2003; 302:1416-1418.
- Bielefeldt K. Molecular diversity of voltage-sensitive calcium channels in smooth muscle cells. J Lab Clin Med 1999; 133:469-477.
- 51. Xu X, Best PM. Postnatal changes in T-type calcium current density in rat atrial myocytes. J Physiol 1992; 454:657-672.

- 52. Bohn G, Moosmang S, Conrad H et al. Expression of T- and L-type calcium channel mRNA in murine sinoatrial node. FEBS Lett 2000; 481:73-76.
- Leuranguer V, Monteil A, Bourinet E et al. T-type calcium currents in rat cardiomyocytes during postnatal development: contribution to hormone secretion. J Physiol Heart Circ Physiol 2000; 279:H2540-2548.
- 54. Perchenet L, Benardeau A, Ertel EA. Pharmacological properties of Ca(V)3.2, a low voltage-activated Ca2+ channel cloned from human heart. Naunyn Schmiedebergs Arch Pharmacol 2000; 361:590-599.
- 55. Cribbs LL, Martin BL, Schroder EA et al. Identification of the t-type calcium channel (Ca(v)3.1d) in developing mouse heart. Circ Res 2001; 88:403-407.
- 56. Nuss HB, Houser SR. T-type Ca2+ current is expressed in hypertrophied adult feline left ventricular myocytes. Circ Res 1993; 73:777-782.
- 57. Bkaily G, Sculptoreanu A, Jacques D et al. Increases of T-type Ca²⁺ current in heart cells of the cardiomyopathic hamster. Mol Cell Biochem 1997; 176:199-204.
- Clozel JP, Ertel EA, Ertel SI. Voltage-gated T-type Ca²⁺ channels and heart failure. Proc Assoc Am Physicians 1999; 111:429-437.
- Martinez ML, Heredia MP, Delgado C. Expression of T-type Ca(2+) channels in ventricular cells from hypertrophied rat hearts. J Mol Cell Cardiol 1999; 31:1617-1625.
- 60. Huang B, Qin D, Deng L et al. Reexpression of T-type Ca2+ channel gene and current in post-infarction remodeled rat left ventricle. Cardiovasc Res 2000; 46:442-449.
- Triggle DJ. The physiological and pharmacological significance of cardiovascular T-type, voltage-gated calcium channels. Am J Hypertens 1998; 11:80S-87S.
- 62. Noll G, Luscher TF. Comparative pharmacological properties among calcium channel blockers: T-channel versus L-channel blockade. Cardiology 1998; 89(Suppl 1):10-15.
- 63. Hermsmeyer K. Role of T channels in cardiovascular function. Cardiology 1998; 89(Suppl 1):2-9.
- 64. Angus JA, Sarsero D, Fujiwara T et al. Quantitative analysis of vascular to cardiac selectivity of Land T-type voltage-operated calcium channel antagonists in human tissues. Clin Exp Pharmacol Physiol 2000; 12:1019-1021.
- 65. Giles TD. Hypertension and pathologic cardiovascular remodeling: a potential therapeutic role for T-type calcium antagonists. Clin Ther 1997; 19(Suppl A):27-38.
- 66. Sandmann S, Bohle RM, Dreyer T et al. The T-type calcium channel blocker mibefradil reduced interstitial and perivascular fibrosis and improved hemodynamic parameters in myocardial infarction-induced cardiac failure in rats. Virchows Arch 2000; 436:147-157.
- 67. Tzivoni D, Gilula Z, Klutstein MW et al. The effect of mibefradil on ischemic episodes with and without increase in heart rate. Cardiovasc Drugs Ther 2000; 14:503-509.
- 68. Villame J, Massicotte J, Jasmin G et al. Effects of mibefradil, a T- and L-type calcium channel blocker, on cardiac remodeling in the UM-X7.1 cardiomyopathic hamster. Cardiovasc Drugs Ther 2001; 15:41-48.
- 69. Levine TB, Bernink PJ, Caspi A et al. Effect of mibefradil, a T-type calcium channel blocker, on morbidity and mortality in moderate to severe congestive heart failure: the MACH-1 study. Mortality Assessment in Congestive Heart Failure Trial. Circulation 2000; 101:758-764.
- 70. Yamada K, Kanba S, Ashikari I et al. Nilvadipine is effective for chronic schizophrenia in a double-blind placebo-controlled study. J Clin Psychopharmacol 2002;16:437-439.
- 71. Santi CM, Cayabyab FS, Sutton KG et al. Differential inhibition of T-type calcium channels by neuroleptics. J Neurosci 2002; 22:396-403.
- 72. McRory JE, Santi CM, Hamming KS et al. Molecular and functional characterization of a family of rat brain T-type calcium channels. J Biol Chem 2001; 276:3999-4011.
- 73. Saegusa H, Kurihara T, Zong S et al. Altered pain responses in mice lacking α_{1E} subunit of the voltage-dependent Ca²⁺ channel. Proc Natl Acad Sci USA 2000; 97: 6132-6137.
- 74. Matsuda Y, Saegusa H, Zong S et al. Mice lacking Ca(v)2.3 (α_{1E}) calcium channel exhibit hyperglycemia. Biochem Biophys Res Commun 2001; 289:791-795.
- 75. Rose MA, Kam PC. Gabapentin: Pharmacology and its use in pain management. Anaesthesia 2002; 57:451-462.
- 76. Jun K, Piedras-Renteria ES, Smith SM et al. Ablation of P/Q-type Ca²⁺ channel currents, altered synaptic transmission, and progressive ataxia in mice lacking the α_{1A} -subunit. Proc Natl Acad Sci U S A 1999; 96:15245-15250.
- 77. Seisenberger C, Specht V, Welling A et al. Functional embryonic cardiomyocytes after disruption of the L-type alpha1C (Cav1.2) calcium channel gene in the mouse. J Biol Chem 2000; 275:39193-39199.
- Platzer J, Engel J, Schrott-Fischer A et al. Congenital deafness and sinoatrial node dysfunction in mice lacking class D L-type Ca²⁺ channels. Cell 2000; 102:89-97.

Calcium Channelopathies

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M any cellular functions are directly or indirectly regulated by the free cytosolic calcium concentration. Thus, calcium levels must be very tightly regulated in time, space and amount. Intracellular calcium ions are essential second messengers and play a role in many functions including, action potential generation, neurotransmitter and hormone release, muscle contraction, neurite outgrowth, synaptogenesis, calcium-dependent gene expression, synaptic plasticity and cell death. Calcium ions that control cell activity can be supplied to the cytosol of the cell from two major sources: the extracellular space or intracellular stores. Voltage-gated and ligand-gated channels are the primary way in which Ca^{2+} ions enter from the extracellular space. The sarcoplasm reticulum (SR) in muscle and the endoplasmic reticulum in nonmuscle cells are the main intracellular Ca^{2+} stores: the ryanodine receptor (RyR) and inositol-triphosphate receptor channels are the major contributors of calcium release from internal stores.

Mutations of genes encoding calcium have been implicated in the etiology of a diverse group of nerve and muscle diseases. These mutations have been identified in humans, mice and other organisms. In this chapter, we will summarize calcium channelopathies of humans and mice. Of the ten calcium channel α_1 subunits cloned and sequenced (see ref. 1), disease-causing mutations have been found in α_{1A} and α_{1F} in the nervous system, and α_{1C} and α_{1S} in muscle. Mutations in calcium channel auxiliary subunits (α_2 - δ , β and γ) have also been associated with both human and/or mouse neurological diseases. The disease-causing mutations may provide new insight into the cell biological roles of calcium channels as well as into relationships between structure and function. In addition, understanding how the mutations affect the physiology of the cell could lead to advances in disease treatment through relieving symptoms or slowing the progression of the disease. However, due to the multifaceted functions of calcium in the cell, the correlation between molecular mutation, physiological alterations and disease etiology is neither straightforward nor easily understood. Since calcium is an important intracellular signaling molecule, altered calcium channel function can give rise to widespread changes in cellular function. Indeed, serious diseases result from mutations that cause trivial alterations of calcium currents analyzed in vitro.

Calcium Channelopathies of the Nervous System

Neuronal calcium channels have many cellular functions including; control of neurotransmitter release, regulation of gene expression, integration and propagation of postsynaptic signals, and neurite outgrowth. In addition to altering these signaling pathways, calcium channel mutations could in principle cause cytotoxicity. In particular, both increased (reviewed in ref. 2) and decreased^{3,4,5} intracellular Ca²⁺ have been reported to be cytotoxic to neurons. Neuronal calcium channels have been associated with several dominantly-inherited human diseases ranging from visual disorders to migraines, ataxia, and seizures. Mice have been described which have recessively-inherited phenotypes attributable to calcium channel defects. Some symptoms associated with human calcium channelopathies are similar to those observed in the



Figure 1. Mutations in α_{1F} causing incomplete X-linked congenital night blindness. Schematic representation of the α_{1F} subunit membrane topology and locations of mutations. Both the amino and carboxyl terminals are intracellular; Roman numerals indicate the four homologous repeats; each of which contains six putative transmembrane segments (S1-S6). In this and all subsequent figures mutations are indicated by the number of the affected amino acid. Superscript numbers indicate the references in which the mutations were identified and described. Amino acid numbering as in reference 9.

mutant mice; thus, the study of these murine disorders may lead to a better understanding of calcium channel function and etiology of calcium channelopathies in humans.

Mutations of α_{IF}

Based on its amino acid sequence, α_{1F} is an L-type channel, which is highly expressed in retina.^{6,7} Human incomplete X-linked congenital stationary night blindness (incomplete xlCSNB) is a nonprogressive, dominantly-inherited disorder. Afflicted persons can show a range of symptoms including night blindness, decreased visual acuity, myopia, nystagmus, strabismus and abnormal electroretinogram results. These impairments are thought to result from altered synaptic transmission from photoreceptor cells to second-order neurons. Incomplete xlCSNB has been linked to at least 30 mutations in the α_{1F} subunit of a retinal L-type channel. The α_{1F} subunit is expressed only in retina; strongly in outer and inner nuclear layers and weakly in ganglion cells.⁸ Mutations causing incomplete xlCSNB (Fig. 1) include missense changes, deletions, and frameshifts with premature stops.⁶⁻⁹ The effects of these mutations on channel function have not yet been characterized. However, since synaptic transmission from photoreceptor cells to second-order retinal neurons is mediated by L-type current,¹⁰ it seems likely that α_{1F} is at least partially responsible for this transmission and that the α_{1F} mutations may impair transmission.

Mutations in α_{IA}

The α_{1A} channels are expressed in cell bodies, dendrites and presynaptic terminals of most central neurons¹¹ with highest expression in cerebellar neurons.¹¹⁻¹⁵ As a result of alternative splicing, the α_{1A} gene produces both P- and Q-type currents (as defined by current kinetics and sensitivity to ω -Aga-IVA),¹⁶ which mediate synaptic neurotransmitter release in many cell types.^{17,18} (For detailed information regarding the expression, structure and function of α_{1A} channels see chapters 5 and 6) Important in regard to the channelopathies described in this chapter is that alternative splicing of several regions of the α_{1A} gene is known to produce striking alterations in the pharmacology and properties of the channel (Fig. 2). One alternative splicing inserts a value residue in the domain I-II linker and causes alterations in inactivation



Figure 2. Alternative splicing of the α_{1A} subunit. Schematic representation of the α_{1A} subunit membrane topology and locations of 3 sites of alternative splicing. Valine 421, NP 1605-1606 insertion, and carboxyl-terminal sequence approximately 1853. See Bourinet et al¹⁶ for details about these alternatively spliced regions.

and modulation by second messengers. A second alternative splicing inserts an asparagine and proline (+NP) into the S3-S4 extracellular linker in domain IV of α_{1A} . This insertion alters the voltage-dependence of activation and the sensitivity to ω -Aga-IVA. The +NP splice isoforms display differential expression in the CNS.¹⁶ For example, most cerebellar transcripts lack the NP insertion, while in the hippocampus the +NP and –NP isoforms are about equally expressed. The differential expression patterns of α_{1A} isoforms may mean that a particular α_{1A} mutation could have distinct functional consequences in different cell types. In addition, there are a number of alternatively spliced isoforms of the C-terminal domain of the α_{1A} subunit, including two major isoforms that have been designated α_{1A-1} and α_{1A-2} in humans¹⁹ and B1-I and B1-II in rabbits¹² and rats.¹⁴ Because of this alternative splicing, some mutations of α_{1A} are present in certain C-terminal isoforms, as described below for spinocerebellar ataxia-6.

Mutations in the α_{1A} gene have been shown to produce the human autosomal-dominant neurological disorders of familial hemiplegic migraine, episodic ataxia type-2, spinocerebellar ataxia-6, episodic-and-progressive ataxia and generalized epilepsy. Defects in the gene encoding the α_{1A} calcium channel subunit are also responsible for the recessively-inherited phenotypes of *tottering, leaner, rolling Nagoya*, and *rocker* in mice. In each of these diseases, alteration of the α_{1A} gene results in a host of neurological aberrations. In general, α_{1A} mutations have pronounced effects on the cerebellum, which is not surprising given that α_{1A} is highly expressed in cerebellar neurons. In particular, about 90% of rat Purkinje cell calcium current is blocked with high affinity by the toxin ω -Aga-IVA,²⁰ indicating that this large fraction of current arises from α_{1A} .¹⁶ The diseases associated with mutations in the α_{1A} subunit are discussed below.

Familial hemiplegic migraine (FHM) is a dominantly-inherited human disorder with symptoms that include headaches accompanied by aura and hemiparesis (which is typically transient lasting hours to days), ataxia and nystagmus. In some families, cerebellar atrophy may also occur. The onset of this disorder usually occurs in childhood or adolescence. Genetic studies of FHM patients have identified 14 missense mutations causing defects in the α_{1A} subunit²¹⁻²⁷ (Fig. 3), with T666M being the most recurrent mutation.²⁴ These missense mutations affect highly conserved residues²¹ and are widely distributed throughout the protein.

Heterologous expression of α_{1A} containing FHM mutations has revealed changes in both macroscopic P/Q-type current density (which could arise from changes in surface protein expression, single channel conductance or open probability) and specific channel properties. Results from several studies are discussed below. Hans et al²⁸ and Tottene et al²⁹ analyzed human α_{1A-2} coexpressed with α_{2b} - δ and either β_{2e} or β_{3a} in HEK293 cells, whereas Kraus et al^{30,31} ex-



Figure 3. Mutations in α_{1A} causing familial hemiplegic migraine. Schematic representation of the α_{1A} subunit membrane topology and locations of mutations. Superscript numbers indicate the references in which the mutations were identified and described.

pressed rabbit α_{1A} (BI-2) together with α_2 - δ and β_{1a} subunits in Xenopus oocytes or HEK293 cells (for simplicity, the rabbit mutations are renumbered according to the human sequence). Additionally, Tottene et al²⁹ analyzed expression of human α_{1A-2} in α_{1A} null mice cerebellar granule cells. In the human channel studies in HEK293 cells, the density of functional channel currents was increased for R192Q and decreased for T666M, V714A, 11811L²⁸ and V1457L.²⁹ Interestingly, in cerebellar granule cells, all of the five mutations above caused a reduction in the density of whole-cell calcium current.²⁹ At the single channel level (human α_{1A-2} in HEK293 cells), open probability was increased for R192Q, T666M, V714A, I1811L,²⁸ and V1457L.²⁹ Of these five mutations, single channel conductance was decreased for T666M and V714A²⁸ and V1457L.²⁹ Thus, Tottene et al²⁹ suggest that common features of FHM causing mutations are (i) a hyperpolarizing shift in activation and thus an increased po at the single channel level, and (ii) a decrease in maximal current density at the whole cell level. A number of additional changes have been found in both the human and rabbit channel experiments. The mutations R583Q, T666M, V714A, D715E, V1457L, and I1811L all significantly shifted the voltage-dependence of activation to more hyperpolarized potentials (T666M, V714A, I1811L;³⁰ R583Q, D715E, V1457L;³¹ V714A, 11815L;²⁸ V1457L.²⁹ This would result in a decrease in the threshold of calcium channel activation and an increase in the P/Q current in response to weak depolarizations. Two mutations (R583Q and D715E) caused a reduction in calcium channel current during pulse trains (slower recovery from inactivation for R583Q and faster inactivation for D715E), reflecting altered accumulation of channels in the inactivated state.³¹ This could produce changes in calcium influx especially during high, but not low, neuronal activity, thus imposing the episodic nature of FHM with attacks triggered by sensory or emotional stimuli.³¹

Episodic ataxia-2 (EA-2) is a dominantly-inherited human disorder which results in symptoms of ataxia, nystagmus, dysarthria and vertigo. Cerebellar atrophy is common, and 50% of EA-2 patients report migraine-like symptoms. The ataxia is provoked by stress, exercise or fatigue and lasts hours to days. Between attacks, nystagmus on lateral or vertical gaze is the most prominent sign. Acetazolamide responsiveness is a common feature. The onset of this disorder is usually during late childhood or adolescence. Symptomatic mutation carriers show a broad range of phenotypes with appreciable variability in symptoms (including nonataxic manifestations) and severity of episodic as well as permanent neurologic abnormalities.³²⁻³⁴ Jen et al³⁵ described an example of this heterogeneity in which significant variability in symptoms was present in a large pedigree. Some mutation carriers were totally asymptomatic (incomplete penetrance). Other family



Figure 4. Mutations in α_{1A} causing ataxia disorders. Schematic representation of the α_{1A} subunit membrane topology and locations of mutations. The different mutation symbols signify different clinical diseases: circle=episodic ataxia type 2, square= episodic & progressive ataxia, triangle= generalized epilepsy and episodic and progressive ataxia, star= spinocerebellar ataxia 6. The indicated portion of the C-terminal is alternatively spliced. Superscript numbers indicate the references in which the mutations were identified and described. Amino acid numbering as in Ophoff et al²¹ except as described by Denier et al³³ where the amino acid and/ or nucleotide numbers were not described sufficiently for correlation with the Ophoff paper.

members exhibited episodic ataxia of varying severity, and two individuals additionally exhibited hemiplegia during ataxic episodes. Of these two patients, one suffered from migraines while the other did not. In general, males in this pedigree were more severely affected than the females (males showed earlier onset of the disorder and more frequent and severe ataxic episodes). One female showed exacerbation of her symptoms during pregnancy. The great intra-familial variability in penetrance and symptoms suggests that environmental, hormonal, and/or genetic factors other than α_{1A} mutation are important for the phenotype of EA-2.

Sixteen mutations causing EA-2 (Fig. 4) have been identified in the α_{1A} subunit.^{21,33,35-40} Originally, the mutations found were predicted to lead to premature truncation of the protein; however, more recently, missense mutations have also been correlated with this disease. The mutations that cause early truncation of the protein include insertion or deletion mutations with frameshifts, single base mutations introducing premature stops, and aberrant splicing. The missense mutations are single nucleotide substitutions in various parts of the channel protein (F1491S;³⁹ R1666H;³⁷ E1757K³⁸). An additional nontruncating mutation has been associated with EA-2 (A1593D/delY1594³³).

Functional effects of one missense mutation (F1491S, located in IIIS6) have been studied by means of heterologous expression of mutated human α_{1A-2} (with β_4 and α_2 - δ) in HEK293 cells.³⁹ Although immunostaining indicated that the mutant channel protein was expressed, calcium channel activity was abolished. Another study examined the effects of the R1279X and A1593D/ delY1594 mutations on human α_{1A} function (coexpressed with β_{1a} and α_2 - δ) in tsA-201 cells and *Xenopus* oocytes.⁴¹ The R1279X-mutated channel produced no current when expressed either in tsA-201 cells or *Xenopus* oocytes. The A1593D/delY1594 mutant did not mediate current in tsA-201 cells, but did mediate current when expressed in *Xenopus* oocytes. Compared to control α_{1A} currents, the currents from the mutated channel exhibited a depolarizing shift in the voltage-dependence of activation, an increase in inactivation during 3-s test pulses, and a slowing of recovery from inactivation. This latter study thus demonstrates the need to employ more than one type of expression system before concluding that channels are nonfunctional. In addition,

mutations need not lead to a complete loss of function to produce the symptoms of EA-2: dramatic reduction in current can be sufficient to cause these symptoms.

Episodic and progressive ataxia was originally categorized as a distinct clinical entity although its attributes overlap those of EA-2 and SCA6. Distinguishing features include earlier onset (5-15 years of age), more prominent cerebellar atrophy and, unlike EA-2, insensitivity to treatment with acetazolamide. Some family members exhibit severe progressive ataxia without episodic features, while others have a combination of progressive and episodic ataxia. The disease has been associated with a missense mutation (G293R; Fig. 4) of a conserved amino acid in the S5-S6 linker (pore region) of repeat I of α_{1A} .⁴² Heterologously expressed G293R-mutated α_{1A} (coexpressed with β_{1a} and α_2 - δ in *Xenopus* oocytes) displayed a decrease in current density, a depolarizing shift in the voltage-dependence of activation, and enhanced inactivation compared to control α_{1A} currents. The mutant channels exhibited a decrease in mean open time.⁴¹

Primary generalized epilepsy and episodic and progressive ataxia has been associated with an α_{1A} mutation in an 11-year old patient.⁴³ The patient had generalized tonic-clonic seizures and frequent absence attacks. The episodic ataxia was similar to that in EA-2 patients. Molecular screening of α_{1A} identified a heterozygous point mutation (R1820X; Fig. 4) that would produce a premature stop codon and complete loss of the C-terminal region of the channel protein. Expression studies in *Xenopus* oocytes determined that the mutant α_{1A} was nonfunctional (coexpressed with β_4 and α_2 - δ). When coexpressed with wild-type α_{1A} , the mutant α_{1A} exhibited a robust dominant negative interaction with expression of the wild-type subunit.⁴³

Autosomal dominant spinocerebellar ataxia 6 (SCA6) is a dominantly inherited disorder characterized by ataxia, nystagmus, dysarthria, and neuronal loss in the cerebellum (Purkinje and granule cells) and the dentate and inferior olivary nuclei. Symptoms initially appear at 40-50 years of age and become progressively more severe. Cerebella of SCA6 patients exhibit a severe loss of Purkinje cells, especially in the vermis, and various morphological changes in Purkinje cells and their dendritic arbors.⁴⁴

Molecular analyses of patients with SCA6 demonstrated an expanded CAG repeat in exon 47 of the α_{1A} gene. Normal individuals have 4-16 CAGs and affected individuals have 21-27, which is much smaller than the trinucleotide repeat expansions associated with many other neurodegenerative disorders.¹⁹ In addition, the repeat is more stable and anticipation (progressive expansion from generation to generation) is much milder than observed with other trinucleotide repeat disorders. Great clinical variability has been described in SCA6 symptoms. Similar length CAG expansions have been observed in individuals having symptoms of both SCA6 and EA-245 or only of EA-2,32 which may indicate that the two diseases actually represent a continuum of symptoms. Repeat length effects have been found; however, other unknown factors must be important for phenotypic expression of SCA6. In support of this concept is that two sisters homozygous for SCA6 with identical CAG expansion length (25 repeats) and age of onset (27 years old) presented clinically with marked differences in disease progression and severity.⁴⁶ One patient had rapidly progressing ataxia, moderate dysarthria, mild dysphagia, nystagmus and moderate cerebellar atrophy. The other sister presented with milder and far slower progressing ataxia, slightly slurred speech, and moderate cerebellar atrophy, but no other clinical symptoms.

The CAG expansion in SCA6 introduces polyglutamines at a position approximately 100 amino acids from the carboxyl terminal (Fig. 4). Increased repeat size is associated with both greater disease severity and earlier onset. The pathological consequences of many diseases involving trinucleotide repeats are thought to be related to altered stability of the mutant protein, toxic metabolic breakdown products of the glutamines, or the interaction of the CAG repeats with proteins required for processing RNA. Alternatively, the polyglutamine expansion causing SCA6 might alter the biophysical properties, expression or protein-protein interactions of α_{1A} .

One functional study expressed rabbit α_{1A} (BI-1) with 4, 24, 30 and 40 CAG repeats in BHK cells (coexpressed with α_2 - δ and β_{1a}).⁴⁷ Currents from cells expressing α_{1A} -30 CAG or -40 CAG showed a significant (8 mV) hyperpolarizing shift in the voltage-dependence of inactivation. This would considerably decrease the number of available channels at resting potential.⁴⁷ In another study, heterologous expression of rabbit-human chimeric α_{1A} in *Xenopus* oocytes showed β -subunit specific alterations in electrophysiological properties of the mutant channels.⁴⁸ When coexpressed with α_2 - δ and β_4 , the mutated α_{1A} exhibited a loss of regulation by G-proteins, a hyperpolarizing shift in the voltage-dependence of activation and a slowed rate of inactivation, although no changes in activation or inactivation occurred upon coexpression with α_2 - δ and β_2 or β_3 . Similarly, after coexpression in HEK293 cells of human α_{1A} (homologous to the construct used in ref. 48) together with α_2 - δ and β_{1c} , increased surface expression was observed with only small alterations in voltage-dependence of activation and no changes in inactivation.⁴⁹

Although the CAG repeat is in frame for some C-terminal splice isoforms of the α_{1A} subunit, it is out of frame for others.¹⁹ Thus, understanding the consequences of the CAG repeat expansion requires information on the differential expression of the C-terminal splice isoforms. Immunological studies have shown that the exon 47-encoded polyglutamine tract is abundantly expressed in cell bodies and dendrites of cerebellar Purkinje cells, the cells most affected by this disease.⁴⁸ It appears that it will also be important to have additional information regarding the differential expression of isoforms with alternative splicing of regions other than the C-terminal tail. For example, the presence or absence of the NP insertion in repeat IV¹⁶ (see Fig. 2) affected the functional consequences of polyglutamine expansions in channels heterologously expressed in HEK293 cells (coexpressed with α_2 - δ and β_{1a}).⁵⁰ The α_{1A} (-NP) isoforms with 13, 24 and 28 polyglutamines exhibited a hyperpolarizing shift in the voltage-dependence of inactivation, which was proportional to the length of the polyglutamine repeat. However, for α_{1A} (+NP), 13 polyglutamines had no effect on inactivation and 28 polyglutamines caused a depolarizing shift of 5 mV. Thus, in SCA6 patients, altered function of α_{1A} (-NP), which is highly expressed in Purkinje cells, may cause Purkinje cell degeneration due to a decrease in Ca^{2+} influx. Yet, other types of neurons that express both $\alpha_{1A}(-NP)$ and $\alpha_{1A}(+NP)$ (e.g., hippocampal neurons) may survive because a depolarizing shift in activation for $\alpha_{1A}(+NP)$ might compensate for the alterations caused by $\alpha_{1A}(-NP)$.⁵⁰

Tottering (tg) is a recessively inherited neurological disease of mice characterized by seizures (absence and focal motor) and mild ataxia.⁵¹ There is minor diffuse loss of cerebellar granule and Purkinje cells, an increased density of noradrenergic fibers from the locus coeruleus, and abnormal persistence of tyrosine hydroxylase expression in Purkinje cells.⁵² Tottering results from a single nucleotide change that substitutes a leucine for proline (P601L; Fig. 5) in the IIS5-S6 linker of α_{1A} .^{53,54} In BHK cells heterologously expressing the tg mutated channel, gating was unchanged but current density was reduced by 56%; calcium channel currents were also reduced in cerebellar Purkinje cells of tg/tg mice.⁵⁵ The reduction in Purkinje cells α_{1A} mRNA were normal in tg/tg mice⁵⁴ and (ii) the mutation did not affect the amplitude of single channel currents in the BHK cells.⁵⁵ Defects in transmitter release in the neocortex have been observed in tottering mice.⁵⁶ The Ca²⁺ transients in presynaptic terminals of hippocampal Schaffer collaterals exhibited a diminished contribution from P/Q-type currents and an increased contribution from N-type currents.⁵⁷ Concomittantly, neurotransmitter release at these synapses shifted from a predominant reliance on P/Q-type channels to an almost exclusive reliance on N-type channels.

Leaner (tg^{la}) is another recessively inherited murine disorder. The mutant phenotype includes severe ataxia⁵¹ and a substantial loss of cerebellar Purkinje and granule cells.⁵⁸ The surviving Purkinje cells exhibit aberrant morphology⁵⁹ and aberrant tyrosine hydroxylase (TH) expression.⁶⁰ The tg^{la} mutation has been identified as a single nucleotide substitution in a splice donor consensus sequence of the α_{1A} gene, which results either in a short or long isoform. The



Figure 5. Mutations in α_{1A} associated with murine calcium channelopathies. Schematic representation of the α_{1A} subunit membrane topology and locations of mutations. The different symbols signify different mouse disease phenotypes: circle= *rolling Nagoya*, square= *rocker*, star= *tottering*, triangle= *leaner*. The *leaner* mutation predicts a novel sequence starting at 1922 or 1968 depending upon the isoform expressed. Superscript numbers indicate the references in which the mutations were identified and described.

short isoform has altered sequence that begins at amino acid 1922 (Fig. 5; numbered according to the mouse α_{1A}) and terminates 57 amino acids later, and the long isoform has altered sequence that begins at amino acid 1968 and terminates 90 amino acids later.^{53,54}

In Purkinje cells from tg^{la} mice, whole cell calcium current was reduced in amplitude -65%.^{55,61,62} The reduction was specifically in the ω -Aga-IVA-sensitive component of current, and the remaining ω -Aga-IVA-sensitive current had unchanged gating properties.⁶¹ Dove et al⁶² suggest that the reduced current density results from decreased open probability. Interestingly, Wakamori et al⁵⁵ found that the behavior of the short and long tg^{la} isoforms differed. In comparison with wild-type α_{1A} expressed in BHK cells, current density was unchanged for the long isoform although both activation and inactivation were shifted in the depolarizing direction (5-10 mV), whereas current density was reduced for the short isoform without any other changes. Physiological effects of the *leaner* mutation include defective neurotransmitter release at neocortical synapses.⁵⁶ In addition, marked alterations in rapid Ca²⁺ buffering have been observed in *leaner* Purkinje cells. These neurons exhibited a diminished Ca²⁺ buffering ability, attributed to reduced Ca²⁺ uptake by the endoplasmic reticulum and a decrease in Ca²⁺-binding proteins.⁶³

Rolling Nagoya (tg^{rol}) is recessive, and affected mice have some phenotypic characteristics shared with their allelic counterparts *tottering* and *leaner*, and other characteristics that are distinct. *Rolling Nagoya* mice exhibit poor motor coordination of hindlimbs and sometimes stiffness of hindlimbs and tail, but they lack apparent seizures. The severity of the ataxia is between that of *tottering* and *leaner* mice. No significant numbers of apoptotic cells are observed in tg^{rol} cerebella, with normal cell density and no obvious decrease in size of the granule cell layer. Calbindin immunostaining of mutant cerebella is normal (another indication that there is no significant loss of Purkinje cells), but TH expression in tg^{rol} Purkinje cells fails to show the normal, postnatal decrease.⁶⁰

Rolling Nagoya results from a single nucleotide change that substitutes a glycine for arginine 1262, which is located in the IIIS4 segment⁶⁴ (Fig. 5). Functionally, mutant cerebellar Purkinje cells and mutated recombinant rabbit α_{1A} expressed in BHK cells exhibited comparable alterations in electrophysiological properties.⁶⁴ Mutant Purkinje cells showed a reduced calcium current density and a depolarizing shift (8 mV) and reduced slope of the g-V curve. Mutant Purkinje cells recorded in cerebellar slices lacked Ca²⁺ spike activity, displaying only abortive Na⁺ spike activity. The altered voltage sensitivity and reduced activity of α_{1A} channels would significantly impair the integrative properties of cerebellar Purkinje cells, thus resulting in the locomotor deficits in *rolling Nagoya* mice.⁶⁴

Racker (*rkr*) mutant mice exhibit ataxic, unstable gait accompanied by intention tremor, typical of cerebellar dysfunction. The cytoarchitecture and gross morphology of the brain is normal; however, dendritic abnormalities have been found in mature cerebellar cortex. The Purkinje cell dendrites have a reduction in branching and show a "weaping willow" appearance of the secondary branches. This mutant phenotype is recessive and has been associated with a point mutation (T1310K) located between IIIS5-IIIS6 linker of the α_{1A} subunit⁶⁵ (Fig. 5). Functional studies of this mutation in α_{1A} have yet to be published.

α_{1A} Null Mice

Two groups have used gene-knockout to examine the consequences of complete absence of α_{1A} . There is consensus that mice homozygous for null mutation of α_{1A} are viable at birth but develop a rapidly progressive ataxia and dystonia before usually dying at approximately 3-4 weeks of age.^{66,67} However, the electrophysiological correlates of these pathological changes are less clear based on analyses of cerebellar granule cells. Specifically, results from the two studies differed as to whether changes occurred in the density of L-, N- and R-type Ca²⁺ currents in α_{1A} -knockouts and as to whether P/Q-type Ca²⁺ current density was reduced in heterozygotes compared to homozygous normals. One group⁶⁷ reported that occasional homozygous mice survived past weaning and that the cerebella in these animals (at 15 wks.) exhibited a striped pattern of Purkinje cell loss and a graded loss of granule cells, which was more severe in the anterior lobes. This neuronal loss was not observed before postnatal day 40. Thus, the neurodegeneration was similar to that seen in *leaner* cerebella.

Mutations in Auxiliary Subunits of Calcium Channels

In addition to the α_1 subunit, most calcium channels contain the auxiliary subunits, alpha₂-delta (α_2 - δ_{1-3}), beta (β_{1-4}) and gamma (γ_{1-8}). The β subunits are critical for surface expression of these calcium channels and also modulate the kinetics and voltage dependence; the other subunits also influence expression and properties of these channels, but to a lesser degree.⁶⁸ Channelopathies caused by mutations in each of these auxiliary subunits are summarized in Figure 6 and described below.

Mutations in the β_4 Subunit

Juvenile myoclonic epilepsy has been found in the screening of a small pedigree to cosegregate with a single copy of the mutation R482X in the human β_4 subunit.⁶⁹ This mutation would result in a protein with a prematurely truncated C-terminus (thus, eliminating part of an interaction domain for the α_1 subunit). Analysis by coexpression with α_{1A} in *Xenopus* oocytes revealed that rat R482X- β_4 produced calcium current with a small increase in current amplitude and a small acceleration of inactivation compared to control wild-type β_4 . In addition, the R482X mutation would cause the deletion of two consensus phosphorylation sites that could affect channel function.⁶⁹

Generalized epilepsy and praxis-induced seizures and episodic ataxia have been associated with a single missense mutation (C104F) in the human β_4 subunit.⁶⁹ An allele of β_4 bearing the C104F mutation was identified in two families which exhibited different clinical symptoms: one family with generalized epilepsy and seizures induced by playing complex strategic games and a second family with episodic ataxia. When coexpressed in *Xenopus* oocytes with the α_{1A} subunit, the C104F- β_4 subunit produced a calcium current with a small increase in current amplitude but no obvious alterations in channel kinetics compared to control wild-type β_4 . Escayg et al⁶⁹ suggested that this amino acid substitution might affect channel clustering or targeting by disrupting a domain conserved among β isoforms.

Lethargic (*lh*) is a recessive, murine disorder with behavioral traits overlapping those of human and murine α_{1A} diseases (ataxia and absence seizures), but without apparent neuronal degeneration.⁷⁰ The causative mutation is an insertion of four nucleotides into a splice donor site of the β_4 gene.⁷¹ This results in two mutant isoforms of β_4 , both of which are



Figure 6. Mutations in calcium channel auxiliary subunits associated with human and murine channelopathies. Schematic representation of the membrane topology of the α_1 , $\alpha_2\delta$, β and γ subunits. The indicated central portion of β interacts with the α : I-II loop and the C-terminal portion of $\beta4$ interacts with the α_{1A} C-terminal. The mutations depicted in the β subunit are associated with the following diseases: triangle at C104F = human epilepsy and episodic ataxia,⁶⁹ circle= splice site insertion of 4 bp= *lethargic* mouse,⁷¹ star= R482X= human juvenile myoclonic epilepsy.⁶⁹ The mouse mutant *stargazer* has been associated with a disruption in the γ subunit gene resulting in the total absence of the γ subunit protein. The *ducky* mutation in the $\alpha_2\delta$ subunit gene results in 2 different transcripts: one transcript with exons 1-3 and a novel sequence and a second transcript with exons 2-39 that is not translated. The allelic *du*^{2J} is caused by a 2 base pair deletion in exon 9 causing premature truncation of the protein.

lacking the consensus sequence required for binding to α_1 subunits (Fig. 6). McEnery et al⁷² found that the forebrain and cerebellum of *lh* mice lack immunodetectable β_4 and have increased expression of β_{1B} . This upregulation of other β subunits could lead to rescue or compensation of function in cells expressing the mutated β_4 subunit. This mechanism may account for the observation that neither calcium channel subtypes nor calcium-dependent transmitter release were significantly altered at hippocampal synapses in *lethargic* mice.⁵⁷

Mutations in the $lpha_2$ - δ Subunit

Ducky (du) is a recessive murine disorder and is characterized by an ataxic, wide-based gait and paroxysmal dyskinesia. The mice are reduced in size and fail to survive beyond 35 days. In du mice, dysgenesis occurs in the medulla, spinal cord and cerebellum, with the Purkinje cells exhibiting thickened dendrites and reduced dendritic arbors having a "weeping willow" morphology.⁷³ The du mouse has been utilized as a murine model for epilepsy due to its phenotype of spike-wave seizures and ataxia. The du locus was identified as the α_2 - δ_2 calcium channel subunit gene:⁷⁴ du-1 includes exons 1-3 and a novel sequence, and du-2 includes exons 2-39 and is not translated into protein.⁷³ Another ducky strain, du²¹ results from a 2-bp deletion within exon 9 causing premature truncation.⁷⁴

Calcium channel currents in *du/du* cerebellar Purkinje cells were reduced by 35% compared to currents in wild-type cells.⁷⁴ When heterologously expressed in COS-7 cells, wild-type α_2 - δ_2 caused no changes in biophysical parameters except for an increased surface expression of α_{1A} + β_4 .⁷³ Surface expression in COS-7 cells (i.e., peak current) was reduced by 51% when wild-type α_2 - δ_2 was replaced by its *du*-mutant,⁷³ without large changes in other properties at the macroscopic or single channel level. Thus, the *du* mutation appears to cause a reduction of the number of functional α_{1A} channels in the membrane.

Mutations in the γ_2 Subunit

Stargazer (stg) is another recessive murine disorder and is characterized by ataxia, head-tossing and absence seizures.⁷⁵ In stargazer, the γ_2 gene has an insertion of an ETn retrotransposon in intron 2 causing premature transcriptional termination (Fig. 6) and total absence of γ_2 protein.⁷⁶ Although classified as a calcium channel subunit, γ_2 also interacts with AMPA receptors and synaptic PDZ proteins; moreover, cerebellar granule cells in *stargazer* mice lack functional AMPA receptors and voltage-gated calcium currents seem relatively unaffected.⁷⁷ However, heterologous expression indicated that γ_2 may have small effects on channels containing α_{1A} or α_{1B} .^{76,78} Thus, it is unclear whether altered properties of calcium currents contribute to the *stargazer* phenotype.

Calcium Channelopathies of Muscle

Calcium channel defects have been linked to several human skeletal muscle disorders such as: hypokalemic periodic paralysis (HypoPP), malignant hyperthermia (MH) and central core disease (CCD). Recently, calcium channel defects have also been associated with two cardiac diseases, arrhythmogenic right ventricular cardiopmyopathy type-2 (ARVD2) and familial polymorphic ventricular tachycardia (FPVT). Causative mutations have been localized to calcium channel genes involved in excitation-contraction (E-C) coupling. Two key proteins involved in the process of E-C coupling are the dihydropyridine receptor (DHPR; an L-type calcium channel) in the plasmalemma and the ryanodine receptor (RyR) in the sarcoplasmic reticulum (SR). The DHPR expressed in muscle is a voltage-gated calcium channel containing the α_{1S} subunit (in skeletal muscle) or the α_{1C} subunit (in cardiac muscle). The RyR protein (RyR1 isoform in skeletal and RyR2 in cardiac muscle) is a calcium release channel composed of four identical subunits. In skeletal muscle, a depolarization-induced conformational change of the DHPR^{79,80} results in the opening of the skeletal RyR channel in the SR. This activation may involve a direct molecular interaction between these two junctional components since E-C coupling in skeletal muscle does not require the entry of extracellular calcium. In cardiac muscle, opening of the DHPR channel causes calcium entry into the cell; the Ca^{2+} ions then activate the immediately adjacent RyRs by Ca-induced calcium release. (For detailed information regarding E-C coupling see chapter 22)

Muscular dysgenesis (mdg) mice and *dyspedic (dys)* mice lack functional DHPR or RyR1, respectively. Cultured muscle cells from these animals can be used for expression of cDNAs and thus allow analysis of the effects of specific DHPR and RyR mutations in a near native environment. *Mdg* mice have a single nucleotide deletion in the gene encoding α_{1S} (skeletal DHPR) resulting in a truncated channel protein.⁸¹ *Dyspedic* mice contain a targeted disruption of the gene encoding RyR1.^{82,83} In *dyspedic* myotubes, there is a loss of E-C coupling as well as a large reduction in the density of L-type current compared to normal myotubes.^{82,84-87}

Skeletal Muscle Channelopathies

Hypokalemic periodic paralysis (HypoPP) is a dominantly-inherited human disorder presenting as episodic weakness of the trunk and limbs which can last hours to days and is generally accompanied by a reduction in serum K⁺ levels. This disease usually becomes apparent during childhood or early adulthood and has reduced penetrance in females. Attacks can be provoked by rest after exercise and factors that lower serum K⁺ levels (carbohydrate ingestion or insulin injection); other provoking factors include emotion, stress, cold exposure and alcohol ingestion. HypoPP has been associated with three missense mutations in the voltage-sensing (S4) segments of α_{1S} (Fig. 7): R528H located in IIS4,⁸⁸ and R1239H/G in IVS4.^{89,90}

A small number of studies have been carried out on cultured myotubes derived from muscle biopsies of HypoPP patients carrying the R528H mutation. One study (based on three patients) found a small hyperpolarizing shift (-6 mV) in the voltage-dependence of both activation and inactivation of the L-type calcium current (i.e., the calcium current attributable to the α_{1S}), but found no differences in depolarization-induced release of calcium from the SR.⁹¹ A



Figure 7. Mutations in α_{1S} subunit causing hypokalemic periodic paralysis and malignant hyperthermia. The different mutation symbols signify different clinical diseases: circle= hypokalemic periodic paralysis, square= malignant hyperthermia, triangle= *muscular dysgenesis* mouse. Superscript numbers indicate the references in which the mutations were identified and described. The topology of the RyR protein is not known; therefore, the schematic locations of the mutations in this protein are not noted in the diagram. See Table 1 for amino acid locations of the RyR mutations that have been associated with malignant hyperthermia.

second study (based on a single patient) found that the L-type current had a slightly reduced density and greatly (2-fold) slowed activation.⁹²

Analyses by means of heterologous expression have not revealed any consistent functional changes in L-type calcium channels with introduced HypoPP mutations. Compared to wild-type α_{1S} , expression in L-cells of rabbit R528H- α_{1S} produced current with a 70% decrease in density but no significant differences in gating.⁹³ Compared to wild-type α_{1C} , expression in HEK293 cells of R650H α_{1C} (homologous to R528H in α_{1S}) produced current with a 38% reduction in amplitude and a slight (5 mV) hyperpolarizing shift of both activation and inactivation.⁹⁴ In a preliminary report, Gonzales et al⁹⁵ described no significant differences in voltage-dependence or kinetics of either L-type current or calcium release in *dysgenic* myotubes after heterologous expression of rabbit α_{1S} containing the R528H, R1239H or R1239G mutations. Similarly, Jurkat-Rott et al⁹¹ found no differences in calcium currents or calcium release between wild-type and R528H rabbit α_{1S} expressed in immortalized *dysgenic* muscle cells.

Even if heterologous expression had demonstrated consistent effects on calcium currents or E-C coupling, it would be difficult to explain the etiology of HypoPP. Specifically, when bathed in low K⁺ solution, biopsied intercostal muscle fibers of HypoPP patients were depolarized by 20 mV (compared to a 10 mV hyperpolarization in normal muscle).⁹⁶ If a similar depolarization were to occur in vivo, it would inactivate voltage-gated sodium channels and thus induce muscle paralysis.

Because it is not obvious how altered calcium currents or E-C coupling would produce persistent depolarization triggered by low K⁺, indirect mechanisms have been suggested (e.g., ref. 97). For example, a decrease in Ca^{2+} entry could change activation of a Ca^{2+} -sensitive channel with direct control over resting potential (e.g., Ca^{2+} -activated K⁺ channel). Alternatively, the expression or subcellular distribution of channels important for controlling membrane potential might be altered by small but long-term changes in cytoplasmic calcium levels.

Malignant hyperthermia (MH) and central core disease (CCD) are dominantly inherited muscle disorders that arise from altered handling of intracellular calcium [reviewed in ref. 98-100]. Thus, it is most convenient when discussing these diseases to combine the information about etiology and symptomatology. A number of mutations in RyR1 have been associated with these diseases, but mutations in other proteins can also be causal (see below). No matter what the causative mutation, RyRs represent an important trigger point for the pathophysiology, since RyRs play a key role in controlling intracellular calcium. In addition to being regulated via the DHPR, RyRs are activated by elevations in intracellular calcium ("calcium-induced-calcium-release" or "CICR"). This CICR is "overactive" in RyRs bearing MH mutations so that massive calcium release can be triggered by halogenated anesthetics (which decrease the threshold for CICR) or by depolarizing skeletal muscle relaxants (which trigger low amounts of calcium release via the normal E-C coupling pathway). An episode of MH can thus be triggered by pharmacological agents used during surgery. These episodes are characterized by skeletal muscle rigidity, tachycardia, unstable and rising blood pressure, and elevated body temperature. If not treated immediately, patients may die within minutes from ventricular fibrillation, within hours from pulmonary edema or coagulopathy, or within days from post-anoxic neurological damage and cerebral edema or obstructive renal failure, resulting from release of muscle proteins into the circulation [reviewed in ref. 101]. Individuals with CCD [reviewed in ref. 101] typically display a slowly progressive or nonprogressive myopathy (usually presenting in infancy) associated with hypotonia and proximal muscle weakness. Histologically, the central regions (cores) of both type I and type II skeletal muscle fibers display disintegration of the contractile apparatus, ranging from blurring and streaming of Z lines to total loss of myofibrillar structure. Many individuals with CCD also are susceptible to MH.

Thus far, 36 identified missense mutations and four deletion mutations in RyR1 have been associated with MH susceptibility and/or CCD¹⁰²⁻¹²⁶ (see Table 1). While some mutations produce MH alone, other mutations cause both MH and CCD, and still others produce only CCD. The majority of the RyR1 mutations appear to be clustered in the N-terminal amino acids 35-614 (MH/CCD region 1) and the centrally located residues 2163-2458 (MH/CCD region 2).¹²⁷ Other RyR1 mutations located more distally have been associated with CCD. An MH-related porcine disorder [reviewed in ref. 98] is caused by the mutation R615C, which is homologous to the R614C mutation in humans. Swine heterozygous for R615C display increased muscle mass and increased calcium release in response to a variety of agents, whereas animals homozygous for the mutation suffer "porcine stress syndrome" with MH symptoms brought on by physical and emotional stress.¹⁰⁰ A canine form of MH, A547V, is inherited as an autosomal dominant trait and shares most of the clinical manifestations with MH in pigs and humans.¹²⁸ Mutations in genes other than RyR1 may also be responsible for MH. For example, in a single family, MH segregated with a missense mutation (Fig. 7) in the α_{1S} gene (R1086H).¹²⁹ Moreover, the demonstration of linkages between MH and several loci distinct from either RyR1 or α_{1S} indicate the possibility of additional gene targets.^{99,130} The RyR1 mutations causing MH and CCD have been reported to have variable functional consequences. In part, this variability could be due to the study of different disease-causing mutations, which may truly have different effects. However, the variability most likely also arises from the use of a variety of experimental systems (muscle biopsies, myotube cultures obtained from affected individuals, expression of cDNAs in cell lines or dyspedic myotubes).

Muscle bundles biopsied from MH patients contracted in response to lower concentrations of caffeine and halothane than muscle from normal individuals. Muscle biopsies from patients with the deletion mutation, delE2347, exhibited unusually large electrically-evoked contractions compared to nonMH muscle.¹²⁴ Paralleling the contraction results from biopsied muscle, intracellular calcium release in cultured myotubes derived from MH patients showed an increased sensitivity to halothane¹³¹ as well as to ryanodine.¹³² The kinetic properties of the [Ca²⁺]_i rise in cultured human MH (G2435R) muscle differed significantly from controls.¹³²

RyR1 Mutation	Disease	Reference
C35R	мн	Lynch et al. 1997
R163C	MH, CCD	Quane et al.1993
G248R	MH	Gillard et al. 1992
G341R	мн	Quane et al. 1994b
1403M	CCD	Quane et al. 1993
T522S	MH, CCD	Quane et al. 1994a
R552W	мн	Keating et al. 1997
R614C	мн	Gillard et al. 1991
R614L	мн	Quane et al. 1997
D2129E	мн	Rueffert et al. 2001
R2163C	мн	Manning et al. 1998b
R2163H	MH, CCD	Manning et al. 1998b
R2163P	мн	Fortunato et al. 2000
V2168M	мн	Manning et al. 1998b
T2206M	мн	Manning et al. 1998b
T2206R	мн	Brandt et al. 1999
V2214I	мн	Sambuughin et al. 2001b
Del E2347	мн	Sambuughin et al. 2001a
A2367T	мн	Sambuughin et al. 2001b
D2431N	MH	Sambuughin et al. 2001b
G2434R	MH	Keating et al. 1994
R2435H	MH, CCD	Zhang et al. 1993
R2435L	MH	Barone et al. 1999
R2452W	мн	Chamley et al. 2000
R2454H	MH	Barone et al. 1999
R2454C	мн	Brandt et al. 1999, Gencik et al. 2000
R2458C	MH	Manning et al. 1998a
R2458H	MH	Manning et al. 1998a
RQF4214-6del	CCD	Monnier et al. 2001
LS4647-48del	CCD	Monnier et al. 2001
L4793P	CCD	Monnier et al. 2001
Y4796C	MH, CCD	Monnier et al. 2000
R4825C	CCD	Monnier et al. 2001
T4826I	мн	Brown et al. 2000
F4860del	CCD	Monnier et al. 2001
R4861H	CCD	Monnier et al. 2001
R4893W	CCD	Monnier et al. 2001
14898T	CCD	Lynch et al. 1999
G4899E	CCD	Monnier et al. 2001
R4914G	CCD	Monnier et al. 2001

Table 1. Mutations in RyR associated with disease

Calcium release from SR vesicles of MH muscle also exhibited a lower threshold for activation by calcium, an enhanced sensitivity to caffeine, and a reduced sensitivity to inhibitory concentrations of calcium.¹³³ In addition to an increase in Ca-, halothane-, and TFP-induced calcium release, a reduction in the rate and capacity of calcium loading of heavy SR vesicles from MH patients has been observed.¹³⁴ Porcine MH muscle fibers also displayed an increased sensitivity to agonists such as halothane and caffeine¹³⁵ as well as a 15-mV negative shift in Ca²⁺ release

induced by depolarization.¹³⁶ Introduction of a number of MH-causing missense mutations into RyR1 (expressed in HEK293 cells) caused an increased sensitivity to low concentrations of caffeine and halothane.¹³⁷ It has been suggested that the increased sensitivity of RyR1 to activators observed in many studies may result at least in part from elevated, resting intracellular $Ca^{2+.138}$

Two mutations associated with a severe and highly penetrant form CCD have been analyzed by means of heterologous expression. The CCD for one of these mutations (Y4796C) is accompanied by MH susceptibility,¹²¹ whereas for the other (I4898T) it is not.¹¹⁶ Rabbit Y4796C-RyR1 expressed in HEK293 cells exhibited a decreased EC₅₀ for activation by caffeine, a reduced amplitude of the caffeine response and an elevated resting $[Ca^{2+}]_i$, from which it was concluded that this mutation causes RyR1 to be "leaky".¹²¹ Expressed in HEK293 cells, rabbit I4898T-RyR1 also resulted in an increased resting $[Ca^{2+}]_i$ but loss of responses to caffeine and halothane.¹¹⁶ Expression of I4897T-RyR1 in *dyspedic* myotubes resulted in the complete uncoupling between electrical excitation of the plasma membrane and SR Ca²⁺ release, but no change occurred in either resting myoplasmic $[Ca^{2+}]_i$ or in SR Ca²⁺ content.¹³⁹ When I4897T-RyR1 was coexpressed with wild-type RyR1 (mimicking the situation in patients), voltage-gated SR release was depressed by 60%. Based on the studies above, it appears that CCD accompanied by MH may result from hyperactive (and thus leaky) RyRs, whereas CCD without MH can result from hypoactive RyRs.

Cardiac Muscle Channelopathies

Inherited cardiac disorders that are associated with a propensity to malignant ventricular tachyarrhythmias constitute an important cause of sudden death in both young and adult individuals. Two such disorders, arrhythmogenic right ventricular cardiomyopathy type 2 and familial polymorphic ventricular tachycardia, are associated with mutations in RyR2.

Arrhythmogenic right ventricular cardiomyopathy type 2 (ARVD2) is an autosomal dominant disease characterized by partial degeneration of the myocardium of the right ventricle, electrical instability and sudden death. Thus far, four missense mutations in RyR2 have been correlated with ARVD2: R176Q, L433P, N2386I, T2504M.¹⁴⁰ These mutations are located at highly conserved amino acids in the cytosolic region of the protein and cluster in regions where mutations causing MH or CCD in RyR1 also cluster; R176Q exactly corresponds to the R163C mutation in RyR1 causing MH/CCD. The mutations N2386I and T2504M are located in the domain thought to interact with FKBP12.6, a regulatory subunit of RyR2.¹⁴⁰

Familial polymorphic ventricular tachycardia (FPVT) is an autosomal dominant defect. This cardiac disease is characterized by volleys of bidirectional and polymorphic ventricular tachycardias in response to vigorous exercise, with no structural evidence of myocardial disease. This disease has a relatively early onset and a highly malignant course with estimates of mortality ranging from 30-50% by the age of 20-30 years. Thus far, seven mutations in RyR2 have been correlated with this disorder. Priori and colleagues¹⁴¹ described three different missense mutations in the RyR2 gene of three distinct families: P2328S, Q4201R, and V4653F. A second study found four additional missense mutations: S2246L, R2474S, N4104K, and R4497C.¹⁴² These mutations are located in regions of the protein that correlate with RyR1 mutation hot spots for MH and/or CCD.

It is not currently known how these mutations alter RyR2 channel function; however, several hypotheses have been suggested (e.g., ref. 141). These mutations may increase the Ca^{2+} sensitivity of the channel. Thus, intense adrenergic stimulation or increased physical activity may cause massive SR Ca^{2+} release. Alternatively, the mutations may alter the ability of the channel to remain closed, and on physical perturbation allow Ca^{2+} to leak from the channel and promote massive SR Ca^{2+} release. This excessive calcium release might alter the function of ion channels in the plasma membrane and thus cause severe and possibly fatal tachyarrhythmias.

Summary

Mutations of genes encoding calcium channels are rapidly being identified as causing a diverse group of nerve and muscle diseases. Calcium channel mutations in α_{1F} and α_{1A} subunits and β , γ and α_2 - δ auxiliary subunits have been associated with a number of neurological diseases, and defects in α_{1S} and α_{1C} subunits and RyR1 and RyR2 calcium release channels have been associated with several muscle disorders. The majority of the calcium channel mutations are associated with movement disorders (exceptions are night blindness and arrhythmias), perhaps because these are most readily observed. However, it is intriguing to speculate that linkage analysis will eventually establish correlations between calcium channel mutations and subtle behavioral disorders or even personality traits.

The calcium channelopathies differ from those of voltage-gated sodium and potassium channels, in which the disease phenotype is directly attributable to the changes in electrical excitability of nerve and muscle that result from altered biophysical properties of the channels. The only obvious mechanistic correlation for calcium channelopathies is that a given calcium channel mutation has the most profound impact on the organ or brain region in which that channel is most highly expressed (e.g., night blindness, cerebellar disorders, skeletal and cardiac muscle defects). However, there is often no clear link between disease severity and impact on channel function. Indeed, serious diseases can result from mutations that cause trivial alterations of calcium currents analyzed in vitro. In addition, the same disease phenotype can result from hyper- or hypo-activity of a particular calcium channel. Similarly puzzling is that seemingly comparable mutations of α_{1A} produce dominantly inherited diseases in humans and recessively inherited diseases in mice. Overall, the absence of clear phenotype-genotype correlations may reflect the fact that most analyses thus far have focused on the biophysical properties of channel function, whereas the mutations could well affect subcellular distribution of a channel or its association with other proteins important in signaling cascades. Moreover, genetic background is clearly important in determining the phenotypic consequences of channel mutations as evidenced by identical mutations producing very different clinical symptoms (e.g., disparate disease severity and progression in sisters with the same SCA6 mutation).⁴⁶

Understanding genotype-phenotype correlation of calcium channelopathies is complicated by the fact that Ca²⁺ plays such important and diverse roles as an intracellular regulatory molecule. Thus, even small changes in calcium channels may dramatically alter cellular development and homeostasis and thus result in widespread changes in cellular function. An important challenge for the future remains the identification of fundamental mechanisms involved in the calcium channelopathies: electrical behavior, transmitter release, enzyme cascades, channel targeting, or gene expression/development. Besides providing a better understanding of pathogenesis, future research on the disease-causing mutations may provide new insight into cell biological roles of calcium channels and into relationships between structure and function.

Note Added in Proof

Since submission of this chapter, additional relevant studies have appeared.

One study (Neuton 2004; 41:701-710) found multiple gain-of-function effects in knockin mice carrying α_{1A} with the mutation R192Q, which causes familial hemiplegic migaine. These effects included increased current density in cerebellar granule cells, increased neuromuscular ACh release, and reduced threshold for, and increased velocity of, cortical spreading depression. This study illustrates the importance of examining the behavior of ion channels in their native environment rather than only after heterologous expression.

Mutations of a T-type channel (Cav3.2) now also appear to be associated with neurological disease, specifically childhood epilepsy (Ann Neurol 2003; 54:239-243). Effects of some of these mutations have been examined in heterologously expressed channels (J Biol Chem 279:9681-9684). Heterologous expression has now been used to characterized wild-type α_{1F} channels (J Neurosci 2003; 23:6041-6049) as well as channels bearing mutations causing X-linked congenital night blindness (J Neurosci 2004; 24:1707-1718). In the latter study, it was found that α_{1F} channels have a much broader tissue distribution than originally thought.

References

- 1. Ertel EA, Campbell KP, Harpold MM et al. Nomenclature of voltage-gated calcium channels. Neuron 2000; 25:533-535.
- 2. Choi DW. Calcium-mediated neurotoxicity: Relationship to specific channel types and role in ischemic damage. Trends Neurosci 1988; 11:465-469.
- 3. Koh JY, Cotman CW. Programmed cell death: Its possible contribution to neurotoxicity mediated by calcium channel antagonists. Brain Res 1992; 587:233-240.
- 4. Koike T, Martin DP, Johnson Jr EM. Role of Ca²⁺ channels in the ability of membrane depolarization to prevent neuronal death induced by trophic-factor deprivation: Evidence that levels of internal Ca²⁺ determine nerve growth factor dependence of sympathetic ganglion cells. Proc Natl Acad Sci USA 1989; 86:6421-6425.
- McCaslin PP, Smith TG. Low calcium-induced release of glutamate results in autotoxicity of cerebellar granule cells. Brain Res 1990; 53:280-285.
- Bech-Hansen NT, Naylor MJ, Maybaum TA et al. Loss-of-function mutations in a calcium-channel α1-subunit gene in Xp11.23 cause incomplete X-linked stationary night blindness. Nature Genet 1998; 19:264-267.
- Strom TM, Nyakatura G, Apefelstedt-Sylla E et al. A L-type calcium-channel gene mutated in incomplete X-linked congenital stationary night blindness. Nature Genet 1998; 19:260-263.
- Nakamura M, Ito S, Terasaki H et al. Novel CACNA1F mutations in Japanese patients with incomplete congenital stationary night blindness. Investigative Opthalmology & Visual Science 2001; 42(7):1610-1616.
- 9. Boycott KM, Maybaum TA, Naylor MJ et al. A summary of 20 CACNA1F mutations identified in 36 families with incomplete X-linked congenital stationary night blindness, and characterization of splice variants. Hum Genet 2001; 108:91-97.
- 10. Schmitz Y, Witzovsky P. Dependence of photoreceptor glutamate release on a dihydropyridine-sensitive calcium channel. Neuroscience 1998; 78:1209-1216.
- 11. Westenbroek RE, Sakurai T, Elliott EM et al. Immunochemical identification and subcellular distribution of the α_{1A} subunits of brain calcium channels. J Neurosci 1995; 15:6403-6418.
- 12. Mori Y, Friedrich T, Kim M-S et al. Primary structure and functional expression from complementary DNA of a brain calcium channel. Nature 1991; 350:398-402.
- 13. Sather WA, Tanabe T, Zhang J-F et al. Distinctive biophysical and pharmacological properties of Class A (B1) calcium channel α1 subunits. Neuron 1993; 11:291-303.
- Starr TVB, Prystay W, Snutch TP. Primary structure of a calcium channel that is highly expressed in the rat cerebellum. Proc Natl Acad Sci USA 1991; 88:5621-5625.
- 15. Stea A, Tomlinson WJ, Soong TW et al. Localization and functional properties of a rat brain α_{1A} calcium channel reflect similarities to neuronal Q- and P-type channels. Proc Natl Acad Sci USA 1994; 91:10576-10580.
- 16. Bourinet E, Soong TW, Sutton K et al. Splicing of the α_{1A} subunit gene generates phenotypic variants of P- and Q-type calcium channels. Nature Neurosci 1999; 2:407-415.
- 17. Regehr WG, Mintz IM. Participation of multiple calcium channel types in transmission at single climbing fiber to Purkinje cell synapses. Neuron 1994; 12:605-613.
- 18. Wheeler DB, Randall A, Tsien RW. Roles of N-type and Q-type Ca2+ channels in supporting hippocampal synaptic transmission. Science 1994; 264:107-111.
- 19. Zhuchenko O, Bailey J, Bonnen P et al. Autosomal dominant cerebellar ataxia (SCA6) associated with small polyglutamine expansions in the α_{1A} -voltage-dependent calcium channel. Nature Genet 1997; 15:62-69.
- 20. Mintz IM, Adams ME, Bean BP. P-type calcium channels in rat central and peripheral neurons. Neuron 1992; 9:85-95.
- Ophoff RA, Terwindt GM, Vergouwe MN et al. Familial hemiplegic migraine and episodic ataxia type-2 are caused by mutations in the Ca²⁺ channel gene CACNL1A4. Cell 1996; 543-552.
- 22. Battistini S, Stenirri S, Piatti M et al. A new CACNAIA gene mutation in acetazolamide-responsive familial hemiplegic migraine and ataxia. Neurol 1999; 53:38-43.
- Carrera P, Piatti M, Stenirri S et al. Genetic heterogeneity in Italian families with familial hemiplegic migraine. Neurol 1999; 53:26-32.

- 24. Ducros A, Denier C, Joutel A et al. Recurrence of the T666M calcium channel CACNA1A gene mutation in familial hemiplegic migraine with progressive cerebellar ataxia. Am J Hum Genet 1999; 64:89-98.
- 25. Vahedi K, Denier C, Ducros A et al. CACNA1A gene de novo mutation causing hemiplegic migraine, coma, and cerebellar atrophy. Neurol 2000; 55:1040-1042.
- Ducros A, Denier CD, Joutel A et al. The clinical spectrum of familial hemiplegic migraine associated with mutations in a neuronal calcium channel. N Eng J Med 2001; 345:17-24.
- Kors EE, Terwindt GM, Vermeulen FLMG et al. Delayed cerebral edema and fatal coma after minor head trauma: Role of the CACNA1A calcium channel subunit gene and relationship with familial hemiplegic migraine. Ann Neurol 2001; 49:753-760.
- 28. Hans M, Luvisetto S, Williams ME et al. Functional consequences of mutations in the human α_{1A} calcium channel subunit linked to familial hemiplegic migraine. J Neurosci 1999; 19:1610-1619.
- Tottene A, Fellin T, Pagnutti S et al. Familial hemiplegic migraine mutations increase Ca²⁺ influx through single human Ca₂.1 channels and decrease Ca₂.1 current density in neurons. Proc Natl Acad Sci 2002; 99:13284-13289.
- 30. Kraus RL, Sinnegger MJ, Glossmann H et al. Familial hemiplegic migraine mutations change α_{1A} Ca²⁺ channel kinetics. J Biol Chem 1998; 273:5586-5590.
- Kraus RL, Sinnegger MJ, Koschak A et al. Three new familial hemiplegic migraine mutants affect P/Q-type Ca2+ channel kinetics. J Biol Chem 2000; 275:9239-9243.
- 32. Jodice C, Mantuano E, Veneziano L et al. Episodic ataxia type 2 (EA2) and spinocerebellar ataxia type 6 (SCA6) due to CAG repeat expansion in the CACNA1A gene on chromosome 19p. Hum Molec Genet 1997; 6:1973-1978.
- 33. Denier C, Ducros A, Vahedi K et al. High prevalence of CACNA1A truncations and broader clinical spectrum in episodic ataxia type 2. Neurol 1999; 52:1816-1821.
- Tournier-Lasserve E. CACNA1A mutations. Hemiplegic migraine, episodic ataxia type 2, and the others. Neurology 1999; 53:3-4.
- Jen J, Yue Q, Nelson SF et al. A novel nonsense mutation in CACNA1A causes episodic ataxia and hemiplegia. Neurology 1999; 53:34-37.
- 36. Yue Q, Jen JC, Thwe MM et al. De novo mutation in CACNA1A caused acetazolamide-responsive episodic ataxia. Am J Med Genet 1998; 77:298-301.
- 37. Friend KL, Crimmins D, Phan TG et al. Detection of a novel missense mutation and second recurrent mutation in the CACNA1A gene in individuals with EA-2 and FHM. Hum Genet 1999; 105:261-265.
- Denier C, Ducros A, Durr A et al. Missense CACNA1A mutation causing episodic ataxia type 2. Arch Neurol 2001; 58:292-295.
- 39. Guida S, Trettel F, Pagnutti S et al. Complete loss of P/Q calcium channel activity caused by a CACNA1A missense mutation carried by patients with episodic ataxia type 2. Am J Hum Genet 2001; 68:759-764.
- 40. Scoggan KA, Chandra T, Nelson R et al. Identification of two novel mutation in the CACNA1A gene responsible for episodic ataxia type 2. J Med Genet 2001; 38:249-253.
- 41. Wappi E, Koschak A, Poteser M et al. Functional consequences of P/Q-type Ca²⁺ channel Ca₂2.1 missense mutations associated with episodic ataxia type 2 and progressive ataxia. J Biol Chem 2002; 277:6960-6.
- 42. Yue Q, Jen JC, Nelson SF et al. Progressive ataxia due to a missense mutation in a calcium-channel gene. Am J Hum Genet 1997; 61:1078-1087.
- Jouvenceau A, Eunson LH, Spauschus A et al. Human epilepsy associated with dysfunction of the brain P/Q-type calcium channel. Lancet 2001; 358:801-807.
- 44. Yang Q, Hashizume Y, Yoshida M et al. Morphological Purkinje cells changes in spinocerebellar ataxia type 6. Acta Neuropathol 2000; 100:371-376.
- Geschwind DH, Perlman S, Figueroa KP et al. Spinocerebellar ataxia type 6: Frequency of the mutation and genotype-phenotype correlations. Neurology 1997; 49:1247-1251.
- 46. Kato T, Tanaka F, Yamamoto M et al. Sisters homozygous for the spinocerebellar ataxia type 6 (SCA6)/ CACNA1A gene associated with different clinical phenotypes. Clinical Genetics 2000; 58:69-73.
- 47. Matsuyama Z, Wakamori M, Mori Y et al. Direct alteration of the P/Q-type Ca2+ channel property by polyglutamine expansion in spinocerebellar ataxia 6. J Neurosci 1999; 19:RC14.
- Restituito S, Thompson RM, Eliet J et al. The polyglutamine expansion in spinocerebellar ataxia type 6 causes a β subunit-specific enhanced activation of P/Q-type calcium channels in *Xenopus* oocytes. J Neurosci 2000; 20:6394-6403.

- 49. Piedras-Renteria ES, Watase K, Harata N et al. Increased expression of α_{1A} Ca²⁺ channel currents arising from expanded trinucleotide repeats in spinocerebellar ataxia type 6. J Neurosci 2001; 21:9185-9193.
- 50. Toru S, Murakoshi T, Ishikawa K et al. Spinocerebellar ataxia type 6 mutation alters P-type calcium channel function. J Biol Chem 2000; 275:10893-10898.
- Noebels JL. A single gene error of noradrenergic axon growth synchronizes central neurones. Nature 1984; 310:4019-411.
- 52. Hess EJ, Wilson MC. Tottering and leaner mutations perturb transient developmental expression of tyrosine hydroxylase in embryologically distinct Purkinje cells. Neuron 1991; 6:123-132.
- 53. Fletcher CF, Lutz CM, O'Sullivan TN et al. Absence epilepsy in tottering mutant mice is associated with calcium channel defects. Cell 1996; 87:607-617.
- 54. Doyle J, Ren X, Lennon G et al. Mutations in the Cacnl1a4 calcium channel gene are associated with seizures, cerebellar degeneration, and ataxia in tottering and leaner mutant mice. Mamm Genome 1997; 8:113-120.
- Wakamori M, Yamazaki K, Matsunodaira H et al. Single tottering mutations responsible for the neuropathic phenotype of the P-type calcium channel. J Biol Chem 1998; 273:34857-34867.
- 56. Ayata C, Shimizu-Sasamata M, Lo EH et al. Impaired neurotransmitter release and elevated threshold for cortical spreading depression in mice with mutations in the α_{1A} subunit of the P/Q type calcium channels. Neuroscience 1999; 95:639-645.
- Qian J, Noebels JL. Presynaptic Ca2+ influx at a mouse central synapse with Ca²⁺ channel subunit mutations. J Neurosci 2000; 20:163-170.
- Herrup K, Wilczynski SL. Cerebellar cell degeneration in the leaner mutant mouse. Neuroscience 1982; 7:2185-2196.
- Heckroth JA, Abbott LC. Purkinje cell loss from alternating sagittal zones in the cerebellum of leaner mutant mice. Brain Res 1994; 658:93-104.
- 60. Sawada K, Fukui Y. Expression of tyrosine hydroxylase in cerebellar Purkinje cells of ataxic mutant mice: Its relation to the onset and/or development of ataxia. J Med Invest 2001; 48:5-10.
- Lorenzon NM, Lutz CM, Frankel MN et al. Altered calcium channel currents in Purkinje cells of the neurological mutant mouse leaner. J Neurosci 1998; 18:4482-4489.
- Dove LS, Abbott LC, Griffith WH. Whole-cell and single-channel analysis of P-type calcium currents in cerebellar Purkinje cells of leaner mutant mice. J Neurosci 1998; 18:7687-7699.
- Dove LS, Nahm S-S, Murchison D et al. Altered calcium homeostasis in cerebellar Purkinje cells of mutant mice. J Neurophysiol 2000; 84:513-524.
- 64. Mori Y, Wakamori, Oda S-I et al. Reduced voltage-sensitivity of activation of P/Q-type Ca2+ channels is associated with the ataxic mouse mutation rolling Nagoya (tg^{rol}). J Neurosci 2000; 20(15):5654-5662.
- 65. Zwingman TA, Neumann PE, Noebels JL et al. Rocker is a new variant of the voltage-dependent calcium channel gene Cacnala. J Neurosci 2001; 21:1169-1178.
- 66. Jun K, Piedras-Penteria E, Smith SM et al. Ablation of the P/Q-type Ca^{2+} channel currents, altered synaptic transmission, and progressive ataxia in mice lacking the α_{1A} -subunit. PNAS 1999; 96:15245-15250.
- 67. Fletcher CF, Tottene A, Lennon VA et al. Dystonia and cerebellar atrophy in Cacnala null mice lacking P/Q calcium channel activity. FASEB J 2001; 15:1288-1290.
- 68. Walker D, DeWaard M. Subunit interaction sites in voltage-dependent Ca²⁺ channels: Role in channel function. TINS 1998; 21:148-154.
- 69. Escayg A, De Waard M, Lee DD et al. Coding and noncoding variation of the human calcium-channel β4-subunit gene CACNB4 in patients with idiopathic generalized epilepsy and episodic ataxia. Am J Hum Genet 2000; 66:1531-1539.
- Dung HC, Swigart RH. Histo-pathologic observations of the nervous and lymphoid tissues of the "lethargic" mutant mouse. Tex Rep Biol Med 1972; 30:23-39.
- 71. Burgess DL, Jones JM, Meisler MH et al. Mutation of the Ca²⁺ channel β subunit gene Cchb4 is associated with ataxia and seizures in the lethargic (lh) mouse. Cell 1997; 88:385-392.
- 72. McEnery MW, Copeland TD, Vance CL. Altered expression and assembly of N-type calcium channel α_{1B} and β subunits in epileptic lethargic (lh/lh) mouse. J Biol Chem 1998; 273:21435-21438.
- 73. Brodbeck J, Davies A, Courtney J-M et al. The ducky mutation in Cacna2d2 results in altered Purkinje cell morphology and is associated with the expression of a truncated $\alpha_2\delta$ -2 protein with abnormal function. J Biol Chem 2002; 277:7684-7693.
- 74. Barclay J, Balaguero N, Mione M et al. Ducky mouse phenotype of epilepsy and ataxia is associated with mutation in the Cacna2d2 gene and decreased calcium channel current in cerebellar Purkinje cells. J Neurosci 2001; 21:6095-6104.

- 75. Noebels JL, Qiao X, Bronson RT et al. Stargazer: A new neurological mutant on Chromosome 15 in the mouse with prolonged cortical seizures. Epilepsy Res 1990; 7:129-135.
- 76. Kang M-G, Chen C-C, Felix R et al. Biochemical and biophysical evidence for γ_2 subunit association with neuronal voltage-activated Ca²⁺channels. J Biol Chem 2001; 276:32917-32924.
- Chen L, Chetkovich DM, Petralia RS et al. Stargazin regulates synaptic targeting of AMPA receptors by two distinct mechanisms. Nature 2000; 408:936-943.
- 78. Letts VA, Felix R, Biddlecome GH et al. The mouse stargazer gene encodes a neuronal Ca^{2*} channel γ subunit. Nature Genet 1998; 19:340-347.
- 79. Tanabe T, Takeshima H, Mikami A et al. Primary structure of the receptor for calcium channel blockers from skeletal muscle. Nature 1987; 328:313-318.
- Rios E, Brum G. Involvement of dihydropyridine receptors in excitation-contraction coupling in skeletal muscle. Nature 1987; 325:717-720.
- Chaudhari N. A single nucleotide deletion in the skeletal muscle-specific calcium channel transcript of muscular dysgenesis (mdg) mice. J Biol Chem 1992; 267:25636-25639.
- Takeshima H, Iino M, Takekura H et al. Excitation-contraction uncoupling and muscular dysgeneration in mice lacking functional skeletal muscle ryanodine-receptor gene. Nature 1994; 369:556-559.
- Buck ED, Nguyen HT, Pessah IN et al. Dyspedic mouse skeletal muscle expresses major elements of the triadic junction but lacks detectable ryanodine receptor protein and function. J Biol Chem 1997; 272:7360-7367.
- 84. Takeshima H, Yamazawa T, Ikemoto T et al. Ca²⁺-induced Ca²⁺ release in myocytes from dyspedic mice lacking the type-1 ryanodine receptor. EMBO J 1995; 14:2999-3006.
- Fleig A, Takeshima H, Penner R. Absence of Ca2+ current facilitation in skeletal muscle of transgenic mice lacking the type 1 ryanodine receptor. J Physiol 1996; 496:339-345.
- Nakai J, Dirksen RT, Nguyen HT et al. Enhanced dihydropyridine receptor channel activity in the presence of ryanodine receptor. Nature 1996; 380:72-75.
- Avila G, Dirksen RT. Functional impact of the ryanodine receptor on the skeletal muscle L-type Ca²⁺ channel. J Gen Physiol 2000; 115:467-480.
- Jurkat-Rott K, Lehmann-Horn F, Elbaz A et al. A calcium channel mutation causing hypokalemic periodic paralysis. Hum Mol Genet 1994; 56:374-380.
- Ptacek LJ, Tawil R, Griggs RC et al. Dihydropyridine receptor mutations cause hypokalemic periodic paralysis. Cell 1994; 77:863-868.
- 90. Fouad G, Dalakas M, Servidei S et al. Genotype-phenotype correlations of DHP receptor α1-subunit gene mutations causing hypokalemic periodic paralysis. Neuromuscul Disord 1997; 7:33-38.
- Jurkat-Rott K, Uetz U, Pika-Hartlaub U et al. Calcium currents and transients of native and heterologously expressed mutant skeletal muscle DHP receptor α1 subunits (R528H). FEBS Lett 1998; 423:198-204.
- Morrill JA, Brown Jr RH, Cannon SC. Gating of the L-type Ca channel in human skeletal myotubes: An activation defect caused by the hypokalemic periodic paralysis mutation R528H. J Neurosci 1998; 18:10320-10334.
- 93. Lapie P, Goudet C, Nargeot J et al. Electrophysiological properties of the hypokalemic periodic paralysis mutation (R528H) of the skeletal muscle α_{1S} subunit as expressed in mouse L cells. FEBS Lett 1996; 382:244-248.
- Lerche H, Klugbauer N, Lehmann-Horn F et al. Expression and functional characterization of the cardiac L-type calcium channel carrying a skeletal muscle DHP-receptor mutation causing hypokalemic periodic paralysis. Pflugers Arch 1996; 431:461-463.
- 95. Gonzalez A, Nakai J, Beam K. IVS4 mutations which alter inactivation of the skeletal L-type calcium channel without affecting activation. Biophys J 1996; 70:A128.
- Rudel R, Lehmann-Horn F, Ricker K et al. Hypokalemic periodic paralysis: In vitro investigation of muscle fiber membrane parameters. Muscle Nerve 1984; 7:110-120.
- Morrill JA, Cannon SC. Effects of mutations causing hypokalemic periodic paralysis on the skeletal muscle L-type Ca²⁺ channel expressed in Xenopus laevis oocytes. J Physiol 1999; 520(2):321-336.
- 98. Mickelson JR, Louis CF. Malignant hyperthermia: Excitation-contraction coupling, Ca²⁺ release channel, and cell Ca²⁺ regulation defects. Physiol 1996; Rev 76:537-592.
- 99. Loke J, MacLennan DH. Malignant hyperthermia and central core disease: Disorders of Ca²⁺ release channels. Am J Med 1998; 104:470-486.
- Jurkat-Rott K, McCarthy T, Lehmann-Horn F. Genetics and pathogenesis of malignant hyperthermia. Muscle & Nerve 2000; 23:4-17.
- 101. MacLennan DH. Ca²⁺ signalling and muscle disease. Eur J Biochem 2000; 267:5291-5297.
- 102. Gillard EF, Otsu K, Fujii J et al. A substitution of cysteine for arginine 614 in the ryanodine receptor is potentially causative of human malignant hyperthermia. Genomics 1991; 11:751-755.

- 103. Gillard EF, Otsu K, Fujii J et al. Polymorphisms and deduced amino acid substitutions in the coding sequence of the ryanodine receptor (RYR1) gene and individuals with malignant hyperthermia. Genomics 1992; 13:1247-1254.
- 104. Quane KA, Healy JMS, Keating KE et al. Mutations in the ryanodine receptor gene in central core disease and malignant hyperthermia. Nature Genet 1993; 5:51-55.
- 105. Zhang Y, Chen HS, Khanna VK et al. A mutation in the human ryanodine receptor gene associated with central core diseases. Nat Genet 1993; 5:46-49.
- 106. Keating KE, Quane KA, Manning BM et al. Detection of a novel RYR1 mutation in four malignant hyperthermia pedigrees. Hum Mol Genet 1994; 10:1855-1858.
- 107. Quane KA, Keating KE, Healy JMS et al. Mutation screening of the RYR1 gene in malignant hyperthermia: Detection of a novel Tyr to Ser mutation in a pedigree with associated central cores. Genomics 1994a; 23:236-239.
- 108. Quane KA, Keating KE, Manning BM et al. Detection of a novel mutation in a ryanodine receptor gene in malignant hyperthermia: Implications for diagnosis and heterogeneity studies. Hum Mol Genet 1994b; 3:471-476.
- 109. Keating KE, Giblin L, Lynch PJ et al. Detection of a novel mutation in the ryanodine receptor gene in an Irish malignant hyperthermia pedigree: Correlation of the IVCT response with the affected and unaffected haplotypes. J Med Genet 1997; 34:91-296.
- 110. Lynch PJ, Krivosic-Horber R, Reyford H et al. Identification of heterozygous and homozygous individuals with a novel RYR1 mutation in a large kindred. Anesthesiology 1997; 86:620-626.
- 111. Quane KA, Ording H, Keating KE et al. Detection of a novel mutation at amino acid position 614 in the ryanodine receptor in malignant hyperthermia. Br J Anaesth 1997; 79:332-337.
- 112. Manning BM, Quane KA, Lynch PJ et al. Novel mutations at a CpG dinucleotide in the ryanodine receptor in malignant hyperthermia. Hum Mutat 1998a; 11:45-50.
- Manning BM, Quane KA, Ording H et al. Identification of novel mutations in the ryanodine-receptor gene (RYR1) in malignant hyperthermia: Genotype phenotype correlation. Am J Hum Genet 1998b; 62:599-609.
- Barone V, Massa O, Intravaia E et al. Mutation screening of the RyR1 gene and identification of two novel mutations in Italian Malignant Hyperthermia families. J Med Genet 1999; 36:115-118.
- 115. Brandt A, Schleithoff L, Jurkat-Rott K et al. Screening of the ryanodine receptor gene in 105 malignant hyperthermia families: Novel mutations and concordance with the in vitro contracture test. Hum Mol Genet 1999; 8:2055-2062.
- 116. Lynch PJ, Tong J, Lehane M et al. A mutation in the transmembrane/luminal domain of the ryanodine receptor is associated with abnormal Ca²⁺ release channel function and severe central core disease. PNAS 1999; 96:4164-4169.
- 117. Brown RL, Pollock AN, Couchman KG et al. A novel ryanodine receptor mutation and genotype-phenotype correlation in a large malignant hyperthermia New Zealand Maori pedigree. Hum Mol Genet 2000; 9:1515-1524.
- 118. Chamley D, Pollock NA, Stowell KM et al. Malignant hyperthermia in infancy and identification of novel RYR1 mutation. Br J Anaesth 2000; 84:500-504.
- 119. Fortunato G, Berruti R, Brancadoro V et al. Identification of a novel mutation in the ryanodine receptor gene (RYR1) in a malignant hyperthermia Italian family. Eur J Human Genet 2000; 8:149-152.
- 120. Gencik M, Gencik A, Mortier W et al. Novel mutation in the RyR1 gene (R2454C) in a patient with malignant hyperthermia. Hum Mutat 2000; 15:122.
- 121. Monnier N, Romero NB, Lerale J et al. An autosomal dominant congenital myopathy with cores and rods is associated with a neomutation in the RYR1 gene encoding the skeletal muscle ryanodine receptor. Hum Mol Genet 2000; 9:2599-2608.
- 122. Monnier N, Romero NB, Lerale J et al. Familial and sporadic forms of central core disease are associated with mutations in the C-terminal domain of the skeletal muscle ryanodine receptor. Hum Mol Genet 2001; 10:2581-2592.
- 123. Rueffert H, Kraus H, Olthoff D et al. Identification of a novel mutation in the ryanodine receptor gene (RYR1) in patients with malignant hyperthermia. Hum Mutat 2001; 17:238.
- 124. Sambuughin N, McWilliams S, de Bantel A et al. Single-amino-acid deletion in the RYR1 gene, associated with malignant hyperthermia susceptibility and unusual contraction phenotype. Am J Hum Genet 2001a; 69:204-208.
- 125. Sambuughin N, Sei Y, Gallagher KL et al. North American malignant hyperthermia population: Screening of the ryanodine receptor gene and identification of novel mutations. Anesthesiology 2001b; 95:594-599.
- 126. Oyamada H, Oguchi K, Saitoh N et al. Novel mutations in C-terminal channel region of the ryanodine receptor in malignant hyperthermia patients. Jpn J Pharmacol 2002; 88:159-166.

- 127. McCarthy TV, Quane KA, Lynch PJ. Ryanodine receptor mutations in malignant hyperthermia and central core disease. Human Mut 2000; 15:410-417.
- 128. Roberts MC, Mickelson JR, Patterson EE et al. Autosomal dominant canine malignant hyperthermia is caused by a mutation in the gene encoding the skeletal muscle calcium release channel (RyR1). Anesthesiology 2001; 95:716-725.
- 129. Monnier N, Procaccio V, Stieglitz P et al. Malignant-hyperthermia susceptibility is associated with a mutation of the α1-subunit of the human dihydropyridine-sensitive L-type voltage-dependent calcium-channel receptor in skeletal muscle. Am J Hum Genet 1997; 60:1316-1325.
- 130. Schleithoff L, Mehrke G, Reutlinger BL. Genomic structure and functional expression of a human alpha(2)/delta calcium channel subunit gene (CACNA2). Genomics 1999; 61:201-209.
- 131. Censier K, Urwyler A, Zorzato F et al. Intracellular calcium homeostasis in human primary muscle cells from malignant hyperthermia-susceptible and normal individuals. J Clin Invest 1998; 101:1233-242.
- 132. Brinkmeier H, Kramer J, Kramer R et al. Malignant hyperthermia causing Gly2435Arg mutation of the ryanodine receptor facilitates ryanodine-induced calcium release in myotubes. Br J Anaesth 1999; 83:855-861.
- 133. Richter M, Schleithoff L, Deufel T et al. Functional characterization of a distinct ryanodine receptor mutation in human malignant hyperthermia-susceptible muscle. J Biol Chem 1997; 272:5256-5260.
- 134. O'Sullivan GH, McIntosh JM, Heffron JJA. Abnormal uptake and release of Ca²⁺ ions form human malignant hyperthermia-susceptible sarcoplasmic reticulum. Biochem Pharmacol 2001; 61:1479-1485.
- 135. Otsu K, Nishida K, Kimura Y et al. The point mutation Arg615—>Cys in the Ca2+ release channel of skeletal sarcoplasmic reticulum is responsible for hypersensitivity to caffeine and halothane in malignant hyperthermia. J Biol Chem 1994; 269:9413-9415.
- 136. Dietze B, Henke J, Eichinger HM et al. Malignant hyperthermia mutation Arg615Cys in the porcine ryanodine receptor alters voltage dependence of Ca²⁺ release. J Physiol 2000; 526(3):507-514.
- 137. Tong J, Oyamada H, Demaurex N et al. Caffeine and halothane sensitivity of intracellular Ca²⁺ release is altered by 15 calcium release channel (ryanodine receptor) mutations associated with malignant hyperthermia and/or central core disease. J Biol Chem 1997; 272:26332-26339.
- Lopez JR, Contreras J, Linares N et al. Hypersensivity of malignant hyperthermia-susceptible swine skeletal muscle to caffeine is mediated by high resting myoplasmic [Ca²⁺]. Anesthesiology 2000; 92:1799-1806.
- 139. Avila G, O'Brien JJ, Dirksen RT. Excitation-contraction uncoupling by a human central core disease mutation in the ryanodine receptor. PNAS 2001; 98:4215-4220.
- 140. Tiso N, Stephan DA, Nava A et al. Identification of mutations in the cardiac ryanodine receptor gene in families affected with arrhythmogenic right ventricular cardiomyopathy type 2 (ARVD2). Hum Mol Genet 2001; 10:189-194.
- 141. Priori SG, Napolitano C, Tiso N et al. Mutations in the cardiac ryanodine receptor gene (hRyR2) underlie catecholaminergic polymorphic ventricular tachycardia. Circulation 2000; 103:196-200.
- 142. Laitinen PJ, Brown KM, Piippo K et al. Mutations of the cardiac ryanodine receptor (RyR2) gene in familial polymorphic ventricular tachycardia. Circulation 2001; 103:485-490.

CHAPTER 17

The Molecular Basis of Ca²⁺ Antagonist Drug Action-Recent Developments

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Introduction

In the probability of the pharmacotherapeutic actions are mediated by Ca_v1.2 Ca²⁺ channels which are densely expressed in the cardiovascular system.⁵ However, block of Ca_v1.3 channels may be important for their bradycardic effects⁶ (for Ca²⁺ channel series).

Tritiated derivatives of these Ca^{2+} antagonists were found to reversibly bind to LTCCs in membrane preparations of various tissues with dissociation constants in the picomolar or low nanomolar range.⁷ This allowed the biochemical isolation and subsequent cloning of LTCC subunits. Together with fluorescent derivatives it could be shown that these chemically distinct classes of organic Ca²⁺ antagonists affect each others binding to the channel complex⁸ (for review see refs. 9,10). For example, DHPs can slow the association and dissociation kinetics of BTZs for the LTCC complex, whereas verapamil destabilizes binding. Although these interactions are of no clinical relevance, they provided valuable insight into the molecular organization of these drug binding domains. Originally it was believed that separate high affinity, stereoselective binding domains exist for the different chemical classes of Ca²⁺ antagonists ("allosteric model", Fig. 1B). As will be outlined below, such a model does not account for the available structural data which postulate closely associated and even overlapping rather than separate binding domains.

Radioactive photoreactive Ca^{2+} antagonists enabled the covalent labeling of the binding domains. It was found that they exclusively reside on the α_1 subunits of the LTCC complex (Ca^{2+} channel structure is discussed in more detail in other chapters of this series). Photoaffinity labeling experiments could even localize them within the pore-region of the α_1 subunits (Fig. 1A, peptides a,b,c) and thus guided further mutational analysis of these drug binding domains on the single amino acid level. The resulting model of the Ca^{2+} antagonist drug binding domains is at present the most detailed one among the family of voltage-gated ion channels. Further research in this field is warranted because the high structural homology between L-type and non-L-type α_1 subunits may help to develop derivatives of Ca^{2+} antagonists with decreased affinity for L-type (e.g., $Ca_v 1.2\alpha_1$) but increased affinity for non-L-type channels. Small or-

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Figure 1. Transmembrane topology of Ca^{2+} channel $\alpha 1$ subunits and the drug binding domains. A) 24 transmembrane helices (segments S1-S6) are organized in 4 homologous repeats (about 2000 amino acid residues). Proteolytic portions of the drug binding domains (indicated by bold lines and dark segments; fragments a, b, c) were initially identified by photoaffinity labeling. Photoincorporation of DHPs occured into all three fragments, of PAA only into fragment c and of BTZs into fragments b and c. The circles indicate the position of glutamate residues forming a common Ca^{2+} selectivity filter. The segments S5, S6 and the connecting linkers ("pore-loops") assemble in the center of the folded $\alpha 1$ subunit molecule thus creating domains on LTCC $\alpha 1$ subunits. These are modulated by Ca^{2+} . Micromolar Ca^{2+} conentrations stabilize DHP binding (+), whereas millimolar concentrations inhibit binding of all three chemical classes of Ca^{2+} antagonists (-). C) Instead of forming separate "allosterically coupled" domains B), recent structural data indicate that these binding domains overlap within a "multisubsite domain" ^{10,12} involving the photoaffinity labeled regions plus transmembrane segment S5.

ganic modulators of non-L-type channels (e.g., active on $Ca_v 2.1\alpha_1$ or $Ca_v 2.2\alpha_1$ subunits) are urgently needed to test such compounds for their efficacy in the treatment of diseases such as neuropathic pain or migraine.

The process of the antibody-based localization of photoaffinity labeled peptides and mutational analysis of all three LTCC drug binding domains has been reviewed in previous articles.⁹⁻¹² In this chapter we therefore discuss more recent data which nicely extent these previous findings and start to provide a more three-dimensional view of the drug binding pocket.

The L-type amino acid numbering will be according to their position in a rat brain splice variant of $Ca_v 1.2\alpha_1 (\alpha_1 C-II, \text{ genbank accession number M67515}^{13})$.

Abbreviations

BTZ benzothiazepine DHP dihydropyridine LTCC L-type Ca²⁺ channels PAA phenylalkylamine

A Multisubsite Model of the Ca²⁺ Antagonist Drug Binding Domains

Interaction of Drug an Ca²⁺ Binding Sites-How Drug Binding Can Affect Channel Function

In addition to the above mentioned non-competitive interactions between the different chemical classes of Ca^{2+} antagonist drugs, radioreceptor assays also revealed that high affinity DHP binding requires the presence of micromolar concentrations of Ca^{2+8} (Fig.1B). In contrast, millimolar concentrations of divalent cations decreased the affinity for all chemical classes of Ca^{2+} antagonists. This was the first biochemical proof for the presence of a high affinity Ca^{2+} binding site on the channel. From these studies it was clear that a model for drug-channel interaction would also have to incorporate a binding site for Ca^{2+} . A major breakthrough for understanding the drug $-Ca^{2+}$ ion interaction came from the discovery that four conserved glutamate residues form the major determinants of the channel's Ca^{2+} selectivity filter.¹⁴ It could be demonstrated that this selectivity filter represents the high (and low) affinity binding site which modulates drug binding.¹⁵

L-type Ca^{2*} channels require the association with at least a β and an α_2 - δ subunit. Both subunits are required not only for proper plasma membrane targeting but they also stabilize the pore region. Thereby they not only fine-tune the physiological gating properties of α_1 subunits¹⁶ but also Ca^{2*} coordination in the pore.¹⁵ As the drug binding domains interact with the Ca^{2*} binding site and are also localized in the pore region (see below), they are also stabilized by β subunits.¹⁵

Drug Binding Residues Are Associated with the Ion Conducting Pathway in Repeats III and IV

Sequence stretches photoaffinity labeled by radioactive Ca^{2+} antagonists included the domain III pore loop (peptide a in IIIS5-IIIS6 linker, Fig. 1A) and peptides containing transmembrane segments IIIS6 and IVS6 (peptides b and c, Fig. 1A). These regions were therefore the major target of subsequent mutational studies undertaken not only to confirm these biochemical findings but to identify individual amino acid residues participating in drug interaction. For this purpose recombinant α_1 subunits carrying specific mutations or chimeric constructs between L- and non-L-type Ca^{2+} channel α_1 subunits were heterologously expressed in Xenopus laevis oocytes or in mammalian cells. Drug sensitivity was then quantified by either electrophysiological recordings of channel currents in intact cells or by radioligand binding studies (restricted to DHP binding after expression in mammalian cells). "Loss-of-function" mutations/constructs were created in which L-type sequence was systematically changed to alanine ("alanine-scanning mutagenesis") or to the corresponding residues in non-L-type α_1 subunits. In addition, "gain-of-function" mutants were constructed in which L-type sequence was engineered into non-L-type α_1 subunits thereby introducing high Ca^{2+} antagonist sensitivity. The major findings of these experiments can be summarized as follows:

1. Drug binding residues are indeed localized within the photolabeled regions and therefore close to the channel pore: This established the usefulness of photoaffinity labeling techniques and argued against the criticism that the photoreactive side chains photolabeled regions outside the drug binding pocket.¹⁷ In addition, transmembrane segment IIIS5 was discovered as an important determinant of DHP binding.^{4,18,19} Note that the localization of the drug binding pocket within pore forming regions does not allow to conclude that Ca²⁺ antagonists are simply pore blockers which occlude the pore. Instead, all of them can be shown to alter the gating behavior of the channel.²⁰ They are able to preferentially stabilize or promote entry



Figure 2. Individual amino acid residues (blue) participating in the formation of the DHP, PAA and BTZ binding domains. Residues interacting with drugs are highlighted in blue. Dark blue indicates stronger contribution. The numbers indicate the position of some of the residues within the $Ca_v 1.2\alpha 1$ subunit sequence (see text). The arrow in IIIS5 (DHPs) indicate Thr1039 which when replaced to tyrosine removes DHP sensitivity. The domain III and IV glutamate residues forming part of the Ca^{2+} selectivity filter are also shown. They directly contribute to the binding of the cationic PAAs (and maybe also BTZs) and indirectly to DHP binding (conformational stabilization of the DHP binding domain when one Ca^{2+} ion is bound, see text). A color version of this figure is available online at http://www.Eurekah.com.

into the inactivated channel state (channel blockers) or stabilize open channel conformations (channel activators like the DHP BayK 8644 or the benzoyl pyrrole FPL 64176²⁰⁻²²). The amino acid residues participating in the formation of the individual drug binding domains are highlighted in Figure 2. Most of them were already discussed in previous reviews. The discovery of DHP binding residues Ser1115 and Phe1112 in the IIIS5-S6 linker^{23,23a} and more recently discovered BTZ interaction sites^{24,25} will be discussed in more detail below.

2. The drug binding domains are localized close to the Ca^{2+} selectivity filter of the channel: Figure 1 highlights the close localization of drug and Ca^{2+} binding domains which provided the relevant clue for explaining the Ca^{2+} channel modulating effects of these drugs. Ca^{2+} permeation through the channel requires selectivity (i.e., selection by high affinity) but, at the same time, high permeability. These apparently contradictory properties can both be achieved by sequential Ca^{2+} binding to a single Ca^{2+} selectivity filter. When one Ca^{2+} is bound to the four glutamates it does so with high affinity (single occupancy, micromolar K_D). Obviously, the high stability of this complex prevents efficient permeation of the Ca^{2+} ion through the pore into the cytoplasm. This monoliganded state corresponds to the high affinity Ca^{2+} binding site previously found to stabilize the DHP antagonist interaction.⁸ Permeation of Ca^{2+} is initiated by the binding of a second Ca^{2+} ion whose association is driven by the millimolar extracellular Ca²⁺ concentration. When two Ca²⁺ ions are bound they do so with lower affinity (double occupancy, millimolar K_D). This results in the dissociation of one ion which exits on the cytoplasmic face of the open channel. The double occupancy state represents the low affinity Ca²⁺ binding site inhibiting DHP (and also PAA and BTZ) antagonist binding. As the ternary complex of α_1 with a bound Ca2+ ion and a DHP molecule seems very stable, this explains why Ca²⁺ stabilizes high DHP affinity. It also explains why DHP thereby stabilizes the single occupancy of Ca²⁺, i.e., a non-conducting state. Although experimental evidence is lacking it can be proposed that Ca²⁺ channel activators, such as BayK 8644, facilitate double occupancy and thus promote the open channel state.¹²

In contrast to DHPs, PAAs (and most likely also BTZs; both are mainly positively charged at physiological pH) directly interact with the Ca^{2+} selectivity glutamates in domain III and IV.²⁶ Their block of Ca^{2+} channel currents can therefore be explained by a more direct interference with Ca^{2+} binding and permeation.

- 3. As illustrated in Figure 2 the DHP, PAA and BTZ drug binding domains are located in close proximity to each other and even overlap. This is in good agreement with the results of binding experiments with radioactive²⁴ and fluorescent²⁷ DHP and BTZ derivatives demonstrating the presence of steric interactions which occur when two molecules bind simultaneously to the channel. Adjacent binding of DHPs and BTZs could explain e.g., the stabilization of BTZ binding and slowing of its binding kinetics²⁷ by DHPs but also destabilization of DHP binding by bulky BTZ side chains.²⁴ Many residues participate in the formation of more than one binding domain (Fig. 2). The previous "allosteric model" of Ca²⁺ antagonist binding was therefore replaced by a " multisubsite domain" model.^{9,10}
- 4. Ca²⁺ antagonist sensitivity can be transferred to non-L-type Ca²⁺ channel a₁ subunits. Transfer was facilitated by the fact that amino acid residues conserved between L-type and non-LTCC α_1 subunits also participate in drug binding (e.g., Tyr1152 in IIIS6, Asn1472 in IVS6 in the case of DHPs; see also sequence comparison in Fig. 9 below). That means that a portion of these binding domains is already present in non-LTCCs but insufficient to support high affinity interaction. In the case of DHPs this prompted further studies to investigate how the L-type specific residues contribute to drug binding within a non-LTCC environment.

Towards a Three-Dimensional Model of the DHP Binding Domain

The DHP Binding Domain—The Most Attractive Candidate to Understand Ca²⁺ Channel Modulation by Drugs

The most detailed molecular analysis has so far been provided for the DHP binding domain. There are several reasons for this:

- DHPs discriminate more between L-type and non-LTCCs (> 100-fold selectivity⁴ than PAAs and BTZs (about 10-fold selectivity²⁵).
- 2. Mutational consequences on DHP interaction can directly be studied using radioligand binding to heterologously expressed recombinant channels. However, high nonspecific binding components prevent such assays with PAAs or BTZs (I. Huber, J. Striessnig, unpublished observations).
- 3. PAAs and BTZs block LTCCs in a highly use- (or frequency-) dependent manner. Quantification of their channel blocking activity requires repetitive channel stimulation, their apparent IC₅₀ becoming strongly dependent on experimental conditions. Some mutations were found to dramatically decrease the (apparent) sensitivity to PAAs and BTZs but mainly by altering channel kinetics (e.g., voltage-dependent inactivation and recovery from channel block) rather than decreasing binding affinity.^{24,28} Although gating changes can also affect apparent DHP sensitivity it is easier to establish experimental conditions which allow to quantify real changes in binding affinity in functional experiments.²⁹
- 4. Some DHPs, such as (S)-BAYK 8644 or (+)-SDZ202-791, act as Ca²⁺ channel activators. Mutational analysis therefore allows also to identify residues which mediate the stabilization of open channel conformations by these compounds.

Three Dimensional Drug DHP Binding Models: Help Required from K⁺-Channels

Due to the high selectivity of DHPs for LTCC α_1 subunits, the finding that DHP sensitivity could be transferred to non-LTCC Ca_v2.1 α_1 (α_{1A})^{30,31} and Ca_v2.3 α_1 (α_{1E})³² was surprising. This was achieved by transfer of only those 8 -9 DHP binding residues in the transmembrane segments IIIS5, IIIS6 and IVS6 which are L-type-specific (Fig. 2). But did this DHP binding pocket retain all its typical properties? If this would be the case one could argue that the folding structure between L-type and non-LTTCC α_1 subunits must be highly preserved. Otherwise the DHP binding residues could not be arranged appropriately to accomodate the DHP molecule in a non-L-type α_1 environment. A detailed analysis of the DHP-sensitive Ca₂.1 α_1 ($\alpha_1 A^{DHP}$, Ca_v2.10(1^{DHP}) in functional³⁰ and radioligand binding studies³³ showed that most characteristics typical for DHP binding to native LTCCs were preserved in the artificial construct: (i) DHPs still bound with low nanomolar affinity and in a highly stereoselective manner; (ii) (+)-[³H] isradipine binding was stimulated by (+)-cis-diltiazem, (+)-tetrandrine and mibefradil; and (iii) Ca2+ channel currents through Ca₂2.1 a₁ DHP still showed the typical activation by BAYK 8644 (stimulation of peak inward current, slowing of tail currents, hyperpolarizing shift of voltage-dependence of activation). In order to obtain a precise three dimensional model of the DHP binding pocket the folding structure of LTCC α_1 subunits must be known. Despite the enormous progress in solving the X-ray structure of different ion channels,^{34,35} (see also notes added in proofs) no Ca²⁺ channel has yet been analyzed. Therefore Huber et al³³ constructed a three-dimensional model of the DHP binding domain by using the three dimensional structural information of the KcsA K⁺-channel.³⁵ This was the most closely related ion channel published at this time. It is likely that the folding structure of the pore-forming regions of the KcsA channel, at least within its membrane-spanning segments, is similar to Ca²⁺ and perhaps other cation channels.³³ Note that this was the only assumption of this model. After sequence alignment, 12 of the most important DHP binding residues within the transmembrane segments, capable of forming the recombinant high affinity binding pocket^{30,32} were introduced into the corresponding 3D structure of KcsA. No docking experiments with the DHP molecule were performed. Figure 3 shows the resulting model with only the "mutated" (i.e., DHP binding) residue side chains highlighted. Pore loops were not included in the model. KcsA was crystallized as a homotetramer, whereas α 1 subunits consist of four homologous but not identical repeats tethered together by intracellular linkers. So the first question that the model could address was if the α_1 subunit sequence can be assigned to the KcsA tetramer by either a clockwise (Fig. 3A) or counterclockwise (Fig. 3B) arrangement. Figure 3A,B (top view along the axis of the pore) illustrates that the DHP binding residues in IIIS5, IIIS6 and IVS6 can participate in the formation of a single binding pocket only after clockwise arrangement of repeats I-IV. In contrast, in the counterclockwise arrangement (Fig. 3B) IIIS5 and some of the IIIS6 from a very narrow cleft from which IVS6 residues are completely excluded. Therefore one interesting prediction from this model was that the homologous repeats of Ca²⁺ channel α_1 subunits must be arranged in a clockwise manner. Meanwhile a clockwise arrangement has also been predicted for voltage-gated sodium channels.³⁶

The clockwise model can form a binding pocket with dimensions that allow coordination of a DHP. Taking into account the flexibility of their side chains, all amino acids could be oriented towards a common binding pocket. An exception was IIIS6 Phe1159 (Fig. 3A). However, this residue contributes only very weakly to DHP sensitivity.³⁷ The narrow inner portion is formed by residues Met1161 (IIIS6) and Asn1472 (IVS6), whose side chains are approx. 5.5 Å apart. This is close enough to form a hydrogen bond that could participate in the conformational stabilization of the pore region. The interaction of the DHP with these residues could therefore contribute to the modulation of channel gating. The wider outer portion is formed by residues Tyr1152 (IIIS6), Gln1043 (IIIS5), Tyr1463 and Met1464 (IVS6). Gln1043-Met1464 and Gln1043-Tyr1463 are separated by approx. 10 Å. This is not close enough for hydrogen-bonding but both distances can easily be spanned by a DHP molecule (9 Å between the DHP ring nitrogen and the isopropyl side chain).



A more detailed model was provided by Zhorov et al.³⁸ It also exploited the KcsA coordinates but attempted to predict the orientation of the DHP agonist and antagonist molecules within the binding pocket. For this purpose more than one sequence alignment between KcsA and the



Figure 4. Nifedipine docked to different test models according to Zhorov et al.³⁸ Side and top view of nifedipine in test model II^{POPE} and test model II^{III/IV} as described in the text. Shown are the lowest-energy complexes with bound ligand. Transmembrane segments and pore-loops are presented, respectively, by Cα tracing and ribbons whose darkness increases with repeat number. Side chains of DHP-sensing residues are shown as thin sticks, and nifedipine by thick sticks. At side views most of repeats I and II is removed for clarity. Test model II^{POPE} with nifedipine in the pore is better in terms of ligand–receptor energy and the number of ligand contacts with the DHP-sensing residues than test model II^{III/IV} in which nifedipine is placed in the domain III-IV interface. Amino acid numbering is according to their position within the indicated helices. Gln^{1IIS5.18} (18th residue in IIIS5 helix) corresponds to Gln1043 in Figure 2; other examples: Tyr^{IIIS6.10} corresponds to Tyr1152 and Tyr^{IVS6.11} to Tyr1463 in Figure 2. Taken from reference 38 with permission.

L-type α_1 subunits was used to determine the positions at which L-type sequence was introduced. In addition, a portion of the four pore loops containing the selectivity filter glutamates was included in the model which also allowed to test for DHP Ca²⁺ ion interactions. Nifedipine and BayK 8644 enantiomers were then docked into the proposed binding regions at different positions. Monte Carlo minimization was used to search the optimal conformations of drug and amino acid side chains. C α -atoms (with the exception of some pore-loop residues) were restrained to kcsA coordinates. Four models were tested. Using two different alignments the calculated binding energy was calculated either with the DHP placed within the pore or within the domain III/IV interface. When the same alignment was used as in the model described above³³ optimal ligand coordination was obtained when placed in the domain III/IV interface (Fig. 4, model II^{111/IV}). A



Figure 5. Energy minimized complexes of the DHP binding domain with BayK 8644 enantiomers. Monte Carlo-minimized complexes of the binding domain DHP with the enantiomers of BayK 8644 bound portside down. As in the case of nifedipine (not shown) the NH group of the ligand approaches the hydroxy groups of Tyr^{IIIS6.10} and Tyr^{IVS6.11}. Interaction with Tyr^{IVS6.11} stabilizes the portside-down orientation. Ca²⁺ ion is coordinated between the ligand and two conserved glutamates. A) Antagonist (R)-Bay K 8644 approaching the hydrophobic methyl group would stabilize its closed conformations. B) Agonist (S)-Bay K 8644 approaching the hydrophobic gate by the hydrophobic gate by the hydrophobic gate by the hydrophobic gate onformations. C) Structure and activity of DHP ligands. Note designations of the different sides of the boat-like structure. For amino acid numbering in comparison to Figure 2 see legend to Figure 4. The hydrophobic residues forming the bracelet (see text) are illustrated in space-filling style (gray spheres). Taken from reference 38 with permission.

total ligand-receptor energy of -31.4 kcal/mol was obtained through interaction with Gln1043, Met1161, Tyr1463, Met1464 and Ile1471 (for the corresponding amino acid numbering in Figs. 4 and 5 see figure legends). An even more stable complex resulted from a different sequence alignment and with the DHP placed in the pore (Fig. 4, model I^{pore}). Interaction with Tyr1152, Ile1153, Ile1156, Met1161, Tyr1463, Ile1460 and Ile1471 provided a ligand-receptor energy of -38.7 kcal/mol. Therefore the latter model was pursued further and also analyzed with Ca²⁺ ion binding in the pore. Figure 5 illustrates how DHP agonists and antagonists could affect channel function. Like nifedipine in model I^{pore} the (R)-Bayk 8644 (antagonist) molecule (for basic structure see Fig. 5C) is positioned in the pore with the portside facing downwards, i.e., towards the inner opening of the channel.

Based on the KcsA structure the S6 segments form an inverted teepee structure crossing on the inner side of the channel thereby forming an inner barrier for ion permeation.³⁵ In the model this hydrophobic bracelet is formed by Met1161 (IIIS6), Ile1471 (IVS6) and two leucine residues in the corresponding positions of IS6 and IIS6 (Fig. 5). This narrow part of the bracelet keeps the permeation pathway closed. One could speculate that even small rearrangements upon membrane depolarization may be sufficient to open it. The hydrophobic bracelet faces a water filled cavity inside the channel in which the DHP binds. Figure 5A,B shows that the NH groups of the DHP ring of the antagonistic (R) and agonistic (S) enantiomer interact with Tyr1152 and Tyr1463. The aromatic ring of Tyr1463 stabilizes the portside-down conformation. In case of the antagonistic (R)-enantiomer a hydrophobic methyl group of the portside COOMe (Fig. 5C) substituent interacts with residues of the hydrophobic bracelet. This can stabilize its hydrophobic interactions and favor a closed channel conformation. The polar (starboardside) NO₂ substituent faces up and participates in Ca²⁺ ion coordination. In the agonistic (S)-enantiomer the hydrophilic NO₂ group is on the portside and thus faces the bracelet. Thus the closed hydrophobic bracelet becomes unfavorable allowing the agonist to destabilize the closed state. It can be envisaged that the close association of the DHP molecules with the bound Ca²⁺ ion allows the antagonist to stabilize a ternary complex in which a single Ca²⁺ becomes tightly bound and the DHP portside substituent simultaneously favors closure of the channel.

Steric Factors Determine Interactions of DHPs with the IIIS5 Segment

In transmembrane segment IIIS5 only two residues contribute to DHP sensitivity, Thr1039 and Gln1043. Mutation of Thr1039 to tyrosine, the corresponding residue in non-LTCCs α_1 subunits, completely removed high affinity for DHPs.^{18,19} A surprising finding was that replacement by alanine did not affect DHP antagonist sensitivity.²⁹ Therefore the Thr1039 side chain is not required for direct antagonist interaction. Instead, the bulky tyrosine side chain seems to sterically prevent the coordination of the DHP within the binding pocket.²⁹

The contribution of this residue for DHP sensitivity was analyzed in more detail in the gain-of-function mutant $Ca_v 2.1 \alpha_1^{DHP}$.³⁰ 10 μ M isradipine blocked about 70% of the inward current in X. laevis oocytes. Unlike in LTCC α_1 subunits (such as Ca₂1.2 α_1) block was independent of the holding potential. In Thr1039Tyr loss of DHP sensitivity was independent of the holding potential. It was absent at both negative (channels in resting state) and more positive (large fraction of channels in inactivated state) holding potentials.²⁹ When Thr1039 was replaced by a phenylalanine instead of tyrosine an interesting difference became evident. Like Thr1039Tyr, Thr1039Phe also removed block by isradipine at negative holding potentials (-100 mV). However, at more positive potentials Thr1039Phe showed almost normal DHP sensitivity. This suggested that the mutation prevents DHP binding only in resting channels but can exert its blocking effect once the channels inactivate. An interesting observation was that the onset of DHP block at more positive potentials was slower than for $\check{C}a_{v}2.1\alpha_{1}^{DHP}$, as if the phenylalanine side chain would compete for access of the DHP to its site. As Thr1039Phe lacks the side chain hydroxyl of Thr1039Tyr, this must be responsible for the observed difference. It is likely that this hydroxyl can participate in the formation of a hydrogen bond, thereby locking the tyrosine side chain in a position preventing DHP access independent of channel conformation. Using the KcsA based DHP binding model described above,³³ the carbonyl oxygen of a IIIS6 residue (Met1160 in Ca_v1.2 α_1 ; replaced by a phenylalanine in Ca_v2.1 α_1^{DHP}) was identified as a potential candidate (for details see legend to Fig. 6). The absence of the hydroxyl could therefore prevent this stabilization and provide the side chain with more flexibility. In the inactivated (but not resting) channel conformation the flexibility of the side chain would then allow the DHP to slowly overcome its steric hindrance explaining the observed slow onset of DHP block. Taken together these results indicate that Thr1039 is not directly participating in DHP antagonist binding but that no bulky side chains are tolerated in this position. In model I^{pore} a Thr1039 is not close to the ligand and its substitution by tyrosine could only affect DHP coordination via an indirect conformational effect (Fig. 4). Instead, these experimental data fit nicely to model II^{III/IV} in which Thr1039 does not directly contribute to DHP interaction but is located close enough to the DHP to allow steric interference with the bulkier tyrosine side chain (Fig. 4).

A more detailed analysis was also carried out for Gln1043,^{19,29} which was replaced by alanine (to reduce the side chain to a methyl group), methionine (the residue in non-LTCCs), glutamate or aspartate (to remove the amide) and asparagine (to shorten the side chain by a C-atom). Methionine and alanine reduced DHP antagonist sensitivity but glutamate, aspartate



Figure 6. Proposed interaction of tyrosine side chain of mutant Thr1039Tyr in the model of Huber et al.³³ DHP binding residues of the Thr1039Tyr mutant were introduced into the model as described in Figure 3. Only the L-type amino acids Phe1158, Phe1159, Met1161, Gln1043 are highlighted. Possible conformations of the Tyr1039 side chain (which removes high DHP sensitivity in this mutant) were calculated and four representative conformations are shown. Note that this mutant was constructed within the Ca_v2.101 sequence environment. Therefore the side chain of a Ca_v2.101 phenylalanine (which replaces the corresponding Met1160 in Ca_v1.201) was also included in the conformational analysis. Four representative conformations of this Phe1160 are also illustrated (highlighted by yellow asterisks). The Tyr1039 side chain is able to form a hydrogen bond with the carbonyl of Phe1160 in IIIS6. This restriction may fix this side chain in a conformation that prevents DHP coordination independent of channel conformation. Removal of the hydroxyl may restore its flexibility and allow DHPs to overcome its steric hindrance at least when channels inactivate (see text). A color version of this figure is available online at http://www.Eurekah.com.

and asparagine were tolerated.^{18,29} This provided evidence that a carbonyl in this position is required for full antagonist sensitivity. It also questions the validity of model I^{pore} and again favors model II^{III/IV} in which this residue can participate in DHP binding. None of these Gln1043 mutations conferred full agonist sensitivity. The glutamine amide group seems therefore crucial for mediating BayK 8644 effects.

Activation of LTCCs by BAYK 8644 Seems to Be More Sensitive to Structural Changes Than Block by Antagonists

As DHPs act as gating modifiers it is not surprising that some of them, like BAYK 8644, are able to stabilize open rather than closed (inactivated) channel conformations.²¹ Do activators require a special interaction with the channel to accomplish this task? The answer seems to be



Figure 7. Sequence of $Ca_v 1.1\alpha 1$ and $Ca_v 1.2\alpha 1$ within the photolabeled regions in domain III. The positions of DHP photolabeled peptides, DHP binding residue Ser1115 and the domain III pore region glutamate are indicated.

"yes". A number of mutations affect agonist more than antagonist action. These are Gln1043Met, Gln1043Asn, Gln1043Glu (IIIS5), Tyr1152Ala (IIIS6) and Met1161Val (IIIS6) in construct $Ca_v 2.1 \alpha_1^{DHP}$, 29 a combined mutation of Tyr1463/Met1464 to isoleucine/phenylalanine, in $Ca_v 1.2 \alpha_1$, and Ser1115Ala in the IIIS5-S6 linker in $Ca_v 1.2 \alpha_1$ (see below). In some of these mutations the agonistic effect was even converted into an inhibitory one. This inhibitory effect seems to reflect the action of the antagonistic (R)-enantiomer of BayK 8644 in the racemic mixture. Although agonists seem to bind competitively with antagonists they may need to stabilize some amino acid side chains in defined conformations in order to promote open channel states.

Pore Loop Residues Also Contribute to DHP Interaction

As outlined above, the mapping of the position of photoaffinity labeled proteolytic fragments within the α_1 subunit sequence was a powerful tool to localize the drug interaction sites of the channel. Figure 7 illustrates the proteolytic peptides photoaffinity labeled by the DHP isradipine in the pore region of repeat III. In addition to a fragment containing the transmembrane segment IIIS6, isradipine photoincorporation was also mapped to an adjacent tryptic fragment within the IIIS5-S6 linker which contains the domain III selectivity filter glutamate. However, replacement of the L-type sequence stretch with non-L-type α_1 sequence did not change DHP sensitivity.³ More recently a series of nice experiments directly confirmed the contribution of this region to DHP binding. These experiments were prompted by the cloning of two non-mammalian α_1 subunits from Halocynthia roretzi (TuCa₁) and the jelly fish.²³ Both were closely structurally related to mammalian L-type α_1 subunits and also contained all known DHP binding residues in the transmembrane regions. Nevertheless their DHP sensitivity was very low. Yamaguchi et al²³ therefore reasoned that residues could contribute to DHP sensitivity which are conserved among all cloned mammalian α_1 subunits but are replaced by other residues in the TuCa₁ and the jellyfish α_1 . From a series of potential candidates (Fig. 8B) Ser1115 and Phe1112 were found to mediate DHP sensitivity. Mutation of Ser1115 to alanine caused a 57-fold decrease in nitrendipine sensitivity (Fig. 8A,C). Agonist effects were affected even stronger. Stimulation by BayK 8644 was converted to inhibition and the stimulatory effect of FPL 64,176 was dramatically reduced (not illustrated). Mutation to threonine increased nitrendipine IC₅₀ 25-fold but stimulation by Bayk 8644 was almost completely removed (not illustrated). As Ser1115 is located only 3 amino acid residues away from the domain III selectivity filter glutamate, it should participate in conformational changes occurring when Ca^{2+} binds to the selectivity filter (seee above). Thus it is likely that Ser1115 represents the (or part of the) effector mechanism allowing DHPs to allosterically interfer with Ca²⁺ binding and flux (see above). It is also surprising that mutation of this residue did not affect verapamil and diltiazem sensitivity,²³ although at least PAAs directly bind to the domain III and IV selectivity filter glutamates²⁶ (Fig. 2).

A role for Ser1115 for DHP binding was successfully predicted by the DHP model shown in Figure 5.


Figure 8. Voltage-dependent block of Ca^{2+} channel currents by nitrendipine (0.1 μ M) and R-(+)-BayK 8644 (1 μ M). A) Representative current traces of wildtype $Ca_v 1.2\alpha 1$ (rbCII) (a), mutant Ser1115Ala (S1115A) (b), Ser1146Ala (S1146A) (c), and Ala1420Ser (A1420S) (d) elicited by a 100-ms test pulse to 0 mV at 0.1 Hz. Open circles represent control Ca^{2+} channel currents at a holding potential of 270 mV. Gray and black circles represent Ca^{2+} channel currents blocked by nitrendipine (0.1 μ M) at holding potentials of -70 mV and -50 mV, respectively. B) Inhibition of $Ca_v 1.2$ channel currents by nitrendipine at holding potentials of -70 mV and -50 mV. *p < 0.05 versus S1146A, A1420S, and wildtype (rbCII). C) Concentration-response curve for nitrendipine of wildtype, respectively. D) Representative current traces of wildtype (a) and S1115A (b). Open and black circles represent control Ca^{2+} channel currents and their block produced by R-(+)-BayK 8644 (1 μ M), respectively. E) Inhibition by R-(+)-BayK 8644 of Ca^{2+} channel current through wildtype and S1115A. The error bars show S.E. *p , 0.05 versus wildtype. Taken from reference 23 with permission.

PAA and BTZ Binding Residues

Figure 2 shows that, in agreement with photoaffinity labeling studies employing photoreactive verapamil and diltiazem derivatives, 24,40 IIIS6 and IVS6 also harbor residues interacting with PAAs and BTZs. Again their binding determinants overlap considerably. This explains the non-competitive and competitive type of binding interactions observed between these two chemical classes of Ca²⁺ antagonists.⁴¹

As outlined above, changes in the inactivation kinetics of the channel have profound effects on the apparent sensitivity towards use-dependent block by PAAs and BTZs. That means that mutations decreasing inactivation during a depolarization can decrease drug-induced use-dependent block without necessarily changing the affinity of the drug for its binding domain. For example, mutations within segment IVS5, a region unlikely to contribute to the formation of the binding domain according to the available folding models (Figs. 3-5), slow channel inactivation and decrease use-dependent block by diltiazem.²⁸ In binding experiments these mutants did not affect diltiazem stimulation of (+)-[³H]isradipine binding suggesting that the mutations do not cause a decrease of diltiazem binding to its binding pocket.²⁸ Obviously, such effects on channel kinetics complicate the analysis of the PAA and BTZ binding residues in functional studies.

A similar finding was reported when the consequences of alanine mutations of IIIS6 residues Phe1164 and Val1165 on diltiazem sensitivity were investigated. The mutations reduced use-dependent diltiazem block when analyzed in Ca_v1.2 α_1^{25} or in a chimeric construct.²⁴ A detailed kinetic analysis in the latter study revealed that diltiazem was still able to potently interact with the Phe1164Ala mutant. The drug accelerated inactivation of Phe1164Ala during long depolarizations and slowed its recovery from inactivation indistinguishable from wildtype. This demonstrated that the binding domain must still be intact to mediate these actions (this residue was therefore not marked as a potential BTZ interaction site in Fig. 2). In contrast, in Val1165Ala these effects of diltiazem were diminished and the drug only slightly slowed recovery from inactivation. This was interpreted as a lower affinity for the binding domain and/or an accelerated dissociation of the drug from blocked channels.²⁴ A model was proposed in which the Val1165 side chain controls dissociation of the drug from its binding domain such that its removal facilitates diltiazem dissociation. If this was true then bulkier diltiazem derivatives should escape at a lower rate and be less sensitive to this mutation. This was indeed confirmed with the bulky diltiazem derivative benziazem. It is therefore likely that Val1165 interacts with the diltiazem molecule but it remains unclear to which extent it directly contributes binding affinity.

Differences in DHP Sensitivity between Ca_v1.2 , Ca_v1.3 and Ca_v1.4 L-Type Ca²⁺ Channels

Based on recent progress in defining the differential roles of $Ca_v 1.2$, $Ca_v 1.3$ and $Ca_v 1.4$ L-type Ca^{2+} channels (see other chapters in this series) it appears challenging to develop selective modulators of these L-type channels. It is therefore important to determine already existing differences in their Ca^{2+} antagonist sensitivity.

DHP Sensitivity of $Ca_v 1.3\alpha_1$

Work from Ca_v1.3 α_1 -deficient mice (see other chapters in this series) revealed a somewhat lower (but still high) DHP sensitivity for Ca_v1.3 α_1 mediated currents as compared to Ca_v1.2.⁶ This was then proven by systematic comparison of DHP effects on heterologously expressed Ca_v1.3 α_1 and Ca_v1.2 α_1 subunits under identical experimental conditions in functional experiments. Ca_v1.3 α_1 showed an about 10-fold lower sensitivity for block by the DHP antagonist isradipine than Ca_v1.2 α_1 .^{42,43} but see reference 44).

Within the DHP binding regions $Ca_v 1.3\alpha_1$ differs in only one amino acid position from $Ca_v 1.2\alpha_1$ (Fig. 9), corresponding to Ile1156 in segment IIIS6 (Fig. 2). Substitution by a value instead of isoleucine results in a modest reduction of the side chain size. Despite the existence





of contradictory findings³⁷ considerable evidence exists suggesting that the contribution of Ile1156 for DHP sensitivity is small.^{29,45} This is in accordance with radioligand binding experiments demonstrating that the affinity of heterologously expressed Ca_v1.2 α_1 and Ca_v1.3 α_1 subunits for (+)-[³H]isradipine was indistinguishable.⁴² This rules out major differences in the DHP affinity for the Ca₂1.3 α_1 binding pocket⁴² when membrane voltage is absent. Therefore the different DHP sensitivity of Cav1.2 and Cav1.3 channels in functional studies must be due to the presence of membrane voltage. As previously shown for DHP antagonist block of Ca, 1.2 channels,⁴⁶ Ca, 1.3 is also blocked in a voltage dependent manner with higher apparent DHP sensitivity when the holding potential is more depolarized. 42,47 Isradipine sensitivity for Ca, 1.3 was increased by an order of magnitude when the holding potential was changed from -80 mV to -50mV.⁴² The lower sensitivity of Ca_v1.3 for DHP antagonists as compared to Ca_v1.2 α_1 in functional experiments is therefore likely due to a difference in the voltage-dependence of DHP block, as previously described for splice variants of cardiac and smooth muscle $Ca_v 1.2\alpha_1$ L-type Ca²⁺ channels,⁴⁸ also reviewed in reference 1. Differences in their inactivation properties may also affect apparent DHP sensitivity. This is discussed in detail in a separate chapter of this series by S. Hering (Chapter 18).

DHP Sensitivity of $Ca_v 1.4\alpha_1$

Ca₄1.4 is exclusively expressed in retinal neurons and loss-of-function mutations cause incomplete X-linked congenital stationary night blindness in humans.^{49,50} New generations of selective modulators of other L-type channels could cause side effects by modulating Ca₄1.4 α_1 . On the other hand modulation of Ca₄1.4 channels may also be of therapeutic interest. Meanwhile Ca₄1.4 channels have been heterologously expressed in mammalian cells and shown to be DHP agonist and antagonist sensitive. However, their sensitivity for DHP channel blocker, such as isradipine, seems to even lower than for Ca₄1.3 in functional experiments.⁵¹⁻⁵³ Again, one explanation may be a difference in voltage-dependence of block. However, another explanation is that the binding pocket binds DHPs with somewhat lower affinity. So far this has not been tested by radioligand binding.

The amino-acid sequence of $Ca_v 1.4\alpha_1$ is 63% identical to the $Ca_v 1.3\alpha_1$ sequence, and is more than 83% identical in the DHP binding regions of domains III and IV. Most importantly, all residues identified to substantially contribute to DHP sensitivity (Fig. 2) are conserved except for Tyr1463, which is replaced by a phenylalanine in the human sequence (Phe1414 in $Ca_v 1.4\alpha_1$, Fig. 9). Previous studies^{3,37,45} have already quantified the role of Tyr1463 by mutational analysis. In $Ca_v 1.1\alpha_1$ replacement by phenylalanine and alanine caused a 3.5 and 6.1-fold decrease in affinity, indicating that both the hydroxyl and the phenyl ring contribute binding affinity. Similar changes were found for Tyr1463Ala and Tyr1463Ile in $Ca_v 1.2\alpha_1$.^{37,45} Single mutations of Tyr1463 to isoleucine (the non-L-type residue) did also not prevent agonist stimulation.^{39,45} It is therefore unlikely that this substitution would have a major effect on the DHP sensitivity of $Ca_v 1.4\alpha_1$.

An important question is therefore if $Ca_v 1.4\alpha_1$ contains amino acids within the DHP binding regions which are not present in all other L-type channel α_1 subunits and may reduce binding affinity. The sequence alignment illustrates that this is indeed the case: Of special interest are Pro1037 ($Ca_v 1.4\alpha_1$ numbering) and Ala1087 in the IIIS5-IIIS6 pore-loop. L-type specific conserved lysine and serine residues, respectively, are present in the other L-type α_1 subunits. Pro1037 is also present in the barely DHP-sensitive jellyfish α_1 (not shown). Proline is known to act as an α_1 -helix breaker and could introduce conformational changes affecting DHP sensitivity.

Two relevant differences to L-type sequence are also present in the IVS5-IVS6 pore-loop, Ser1380 and Asn1385 (Cav1.4 α_1) which are cysteine and lysine, respectively, in all L-type α_1 subunits.

Summary

Exciting new insight has been obtained into the structure of Ca^{2+} antagonist binding domains within the α_1 subunits of L-type Ca^{2+} channels. On the basis of this structural information the data from earlier binding and functional studies can already be nicely combined to understand the basic molecular mechanism underlying block or activation by DHPs. This was supported by the development of three dimensional models derived from the structural homology of Ca^{2+} with a bacterial K⁺-channel. Due to expected structural differences between these ion channels these models cannot yet account for all experimental findings. However, they can be used to generate new hypotheses which can be tested experimentally in future mutational studies.³⁸ High resolution 3D models of more closely related, voltage-gated cation channels will help to refine these models.

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Notes Added in Proof

After the submission of this manuscript (August 2002) the X-ray structure of a voltagegated bacterial K*-channel has been reported by the MacKinnon group (Jiang et al. Nature 2003; 423:33-41). The folding structure of the pore-forming S5 and S6 segments is almost identical to KcsA.

Appendix

Publication permission of the publishers must be seeked for the following material. The permission of the authors has already been granted to the corresponding author of this book chapter: Figures 4 and 5: material used for book chapter: Figures 3 and 5 of the following article. Authors: Zhorov BS, Folkman EV, Ananthanarayanan VS. Title: Homology model of dihydropyridine receptor: implications for L-type Ca²⁺ channel modulation by agonists and antagonists. Published in: Archives of Biochemistry and Biophysics 2001; 393(1):22-41. Publisher: Academic Press. Contact: http://www.academicpress.com/

Figure 8: material used for book chapter: Figure 4 of the following article. Authors: Yamaguchi S, Okamura Y, Nagao T, Adachi-Akahane S. Title: Serine residue in the IIIS5-S6 linker of the L-type Ca²⁺ channel alpha 1C subunit is the critical determinant of the action of dihydropyridine Ca²⁺ channel agonists. Published in: Journal of Biological Chemistry 2000; 275(52):41504-11. Publisher: American Society for Biochemistry and Molecular Biology. Contact: http://www.jbc.org/misc/terms.shtml

References

- 1. Striessnig J. Pharmacology, Structure and Function of Cardiac L-Type Ca²⁺ Channels. Cell Physiol Biochem 1999; 9:242-269.
- 2. Fleckenstein A. Anonymous Calcium antagonism in heart and smooth muscle. New York, Chichester, Brisbane, Toronto, Singapore: John Wiley & Sons, 1983:
- 3. Peterson BZ, Tanada TN, Catterall WA. Molecular determinants of high affinity dihydropyridine binding in L-type calcium channels. J Biol Chem 1996; 271:5293-5296.
- 4. Grabner M, Wang Z, Hering S et al. Transfer of 1,4-dihydropyridine sensitivity from L-type to class A (BI) calcium channels. Neuron 1996; 16:207-218.
- 5. Takimoto K, Li D, Nerbonne JM et al. Distribution, splicing and glucocorticoid-induced expression of cardiac α_{1C} and α_{1D} voltage-gated Ca²⁺ channel mRNAs. J Mol Cell Cardiol 1997; 29:3035-3042.
- 6. Platzer J, Engel J, Schrott-Fischer A et al. Congenital deafness and sinoatrial node dysfunction in mice lacking class D L-type calcium channels. Cell 2000; 102:89-97.

- 7. Glossmann H, Ferry DR. Assay for calcium channels. Meth Enzymol 1985; 109:513-550.
- 8. Glossmann H, Ferry DR, Goll A et al. Calcium channels and calcium channel drugs: recent biochemical and biophysical findings. Drug Res 1985; 35:1917-1935.
- 9. Mitterdorfer J, Grabner M, Kraus RL et al. Molecular Basis of drug interaction with L-type calcium channels. J Bioenerget Biomembr 1998; 30:319-333.
- Striessnig J, Grabner M, Mitterdorfer J et al. Structural basis of drug binding to L calcium channels. Trends Pharmacol Sci 1998; 19:108-115.
- Catterall WA, Striessnig J. Receptor sites for calcium antagonists. Trends Pharmacol Sci 1992; 13:256-262.
- 12. Hockerman GH, Peterson BZ, Johnson BD et al. Molecular determinants of drug binding and action on L-type calcium channels. Annu Rev Pharmacol Toxicol 1997; 37:361-396.
- 13. Snutch TP, Tomlinson WJ, Leonard JP et al. Distinct calcium channels are generated by alternative splicing and are differentially expressed in the mammalian CNS. Neuron 1991; 7:45-57.
- 14. Yang J, Ellinor PT, Sather WA et al. Molecular determinants of Ca²⁺ selectivity in L-type Ca²⁺ channels. Nature 1993; 366:158-161.
- 15. Mitterdorfer J, Sinnegger MJ, Grabner M et al. Coordination of Ca²⁺ by the pore region glutamates is essential for high-affinity dihydropyridine binding to the cardiac Ca²⁺ channel alpha1 subunit. Biochemistry 1995; 34:9350-9355.
- Birnbaumer L, Qin N, Olcese R et al. Structures and functions of calcium channel β subunits. J Bioenerg Biomembr 1998; 30:357-375.
- 17. Varadi G, Mori Y, Mikala G et al. Molecular determinants of Ca²⁺ channel function and drug action. TIBS 1995; 16:43-49.
- Mitterdorfer J, Wang Z, Sinnegger MJ et al. Two amino acid residues in the IIIS5 segment of L-type calcium channels differentially contribute to 1,4-dihydropyridine sensitivity. J Biol Chem 1996; 271:30330-30335.
- 19. He M, Bodi I, Mikala G et al. Motif III S5 of L-type calcium channels in involved in the dihydropyridine binding site. J Biol Chem 1997; 272:2629-2633.
- Hering S, Berjukov S, Aczel S et al. Calcium channel block and inactivation: common molecular determinants. Trends Pharmacol.Sci. 1998; 19:439-434.
- 21. Hess P, Lansman JB, Tsien RW. Different modes of Ca channel gating behaviour favoured by dihydropyridine Ca agonists and antagonists. Nature 1984; 311:538-544.
- 22. Berjukow S, Marksteiner R, Gapp F et al. Molecular mechanism of calcium channel block by isradipine. Role of a drug-induced inactivated channel conformation. J Biol Chem 2000; 275:22114-22120.
- 23. Yamaguchi S, Okamura Y, Nagao T et al. Serine residue in IIIS5-S6 linker of L- type Ca^{2*} channel α_{1C} subunit is the critical determinant of the action of dihydropyridine Ca^{2*} channel agonists. J Biol Chem 2000; 275: 41504-41511.
- 23a. Yamaguchi S, Zhorov BS, Yoshioka K et al. Key roles of Phe1112 and Ser1115 in the poreforming IIIS5-S6 linker of L-type Ca²⁺ channel alpha1C subunit (Ca_v1.2) in binding of dihydropyridines and action of Ca²⁺ channel agonists. Mol Pharmacol 2003; 64:235-48.
- 24. Kraus RL, Hering S, Grabner M et al. Molecular mechanism of diltiazem interaction with L-type calcium channels. J Biol Chem 1998; 273:27205-27212.
- Hockerman GH, Dilmac N, Scheuer T et al. Molecular determinants of diltiazem block in domains IIIS6 and IVS6 of L-type Ca²⁺ channels. Mol Pharmacol 2000; 58:1264-70.
- Hockerman GH, Johnson BD, Abbott MR et al. Molecular determinants of high affinity phenylalkylamine block of L-type calcium channels in transmembrane segment IIIS6 and the pore region of the alpha1 subunit. J Biol Chem. 1997; 272:18759-18765.
- Brauns T, Prinz H, Kimball SD et al. L-type calcium channels: binding domains for dihydropyridines and benzothiazepines are located in close proximity to each other. Biochemistry 1997; 36:3625-3631.
- 28. Motoike HK, Bodi I, Nakayama H et al. A region in IVS5 of the human cardiac L-type calcium channel is required for the use-dependent block by phenylalkylamines and benzothiazepines. J Biol Chem 1999; 274:9409-20.
- 29. Wappl E, Mitterdorfer J, Glossmann H et al. Mechanism of dihydropyridine interaction with critical binding residues of L-type Ca²⁺ channel α_1 subunits. J Biol Chem 2001; 276:12730-5.
- 30. Sinnegger MJ, Wang Z, Grabner M et al. Nine L-type amino acid residues confer full 1,4-dihydropyridine sensitivity to the neuronal calcium channel α_{1A} subunit: role of L-type methionine-1188. J Biol Chem 1997; 272:27686-27693.

- 31. Hockerman GH, Peterson BZ, Sharp E et al. Construction of a high-affinity receptor site for dihydropyridine agonists and antagonists by single amino acid substitutions in a non-L-type calcium channel. Proc Natl Acad Sci USA 1997; 94:14906-14911.
- 32. Ito H, Klugbauer N, Hofmann F. Transfer of the high-affinity dihydropyridine sensitivity from L-type to non-L-type calcium channel. Mol Pharmacol 1997; 52:735-740.
- Huber I, Wappl E, Herzog A et al. Conserved Ca²⁺ antagonist binding properties and putative folding structure of a recombinant high affinity dihydropyridine binding domain. Biochem J 2000; 347:829-836.
- 34. Dutzler R, Campbell EB, Cadene M et al. X-ray structure of a ClC chloride channel at 3.0 A reveals the molecular basis of anion selectivity. Nature 2002; 415:287-94.
- Doyle DA, Cabral JM, Pfuetzner RA et al. The structure of the potassium channel: molecular basis of K⁺ conduction and selectivity. Science 1998; 280:69-77.
- 36. Dudley SC Jr, Chang N, Hall J et al. mu-conotoxin GIIIA interactions with the voltage-gated Na⁺ channel predict a clockwise arrangement of the domains. J Gen Physiol 2000; 116:679-90.
- Peterson BZ, Johnson BD, Hockerman GH et al. Analysis of the dihydropyridine receptor site of L-type calcium channels by alanine-scanning mutagenesis. J Biol Chem. 1997; 272:18752-18758.
- Zhorov BS, Folkman EV, Ananthanarayanan VS. Homology model of dihydropyridine receptor: implications for L-type Calcium channel modulation by agonists and antagonists. Arch Biochem Biophys 2001; 393:22-41.
- 39. Schuster A, Lacinova L, Klugbauer N et al. The IVS6 segment of the L-type calcium channel is critical for the action of dihydropyridines and phenylalkylamines. EMBO J 1996; 15:2365-2370.
- 40. Kraus R, Reichl B, Kimball SD et al. Identification of benz(othi)azepine-binding regions within L-type calcium channel alpha1 subunit. J Biol Chem 1996; 271:20113-20118.
- 41. Glossmann H, Striessnig J. Molecular properties of calcium channels. Rev Physiol Biochem Pharmacol 1990; 114:1-105.
- 42. Koschak A, Reimer D, Huber I et al. α_{1D} (Ca_v1.3) subunits can form l-type Ca²⁺ channels activating at negative voltages. J Biol Chem 2001; 276:22100-6.
- 43. Xu W, Lipscombe D. Neuronal Ca,1.3α₁ L-type channels activate at relatively hyperpolarized membrane potentials and are incompletely inhibited by dihydropyridines. J Neurosci 2001; 21:5944-51.
- 44. Scholze A, Plant TD, Dolphin AC et al. Functional expression and characterization of a voltage-gated Ca_v1.3 (α_{1D}) calcium channel subunit from an insulin-secreting cell line. Mol Endocrinol 2001; 15:1211-21.
- Bodi I, Yamaguchi H, Harat M et al. Molecular studies on the voltage-dependence of dihydropyridine action on L-type calcium channels. J Biol Chem 1997; 272:24952-24960.
- 46. Sanguinetti MC, Kass RS. Voltage-dependent block of calcium channel current in the calf cardiac purkinje fiber by dihydropyridine calcium channel antagonists. Circ Res 1984; 55:336-348.
- 47. Safa P, Boulter J, Hales TG. Functional properties of Ca₄1.3 (α_{1D}) L-type Ca²⁺ channel splice variants expressed by rat brain and neuroendocrine GH3 cells. J Biol Chem 2001; 276:38727-37.
- 48. Welling A, Ludwig A, Zimmer S et al. Alternatively spliced IS6 segments of the α 1C gene determine the tissue-specific dihydropyridine sensitivity of cardiac and vascular smooth muscle L-type Ca²⁺ channels. Circ Res 1997; 81:526-532.
- 49. Strom TM, Nyakatura G, Apfelstedt-Sylla E et al. An L-type calcium-channel gene mutated in incomplete X-linked congenital stationary night blindness. Nat Genet 1998; 19:260-263.
- Bech-Hansen NT, Naylor MJ, Maybaum TA et al. Loss-of-function mutations in a calcium-channel alpha1-subunit gene in Xp11.23 cause incomplete X-linked congenital stationary night blindness. Nat Genet 1998; 19:264-267.
- 51. Koschak A, Reimer D, Walter D et al. Ca_v1.4 α₁ subunits can form slowly inactivating dihydropyridine-sensitive L-type Ca²⁺ channels lacking Ca²⁺-dependent inactivation. J Neurosci 2003; 23:6041-9.
- 52. Baumann L, Gerstner A, Zong X et al. Functional Characterization of the L-type Ca²⁺ Channel Ca₂1.4α1 from mouse retina. Invest Ophthalmol Vis Sci 2004; 45:708-13.
- McRory JE, Hamid J, Doering CJ et al. The CACNA1F gene encodes an L-type calcium channel with unique biophysical properties and tissue distribution. J Neurosci 2004; 24:1707-18.

Calcium Channel Block and Inactivation: Insights from Structure-Activity Studies

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Introduction

Using an action potential calcium (Ca^{2+}) ions enter the cell through voltage-gated Ca^{2+} channels (Ca_v) . Ca_v channels first open and subsequently close before recovering to the resting state (Fig. 1A). The process of channel closure during maintained membrane depolarization is called "inactivation". During inactivation Ca_v channels undergo several conformational changes: one is mediated by intracellular Ca^{2+} interacting with a channel-calmodulin complex (Ca^{2+} -dependent inactivation), two other conformational changes are voltage-dependent (fast and slow voltage-dependent inactivation, Fig. 1A, see refs. 1,2 for review, and other chapters in this book).

Evolution has designed high-voltage-activated (HVA) Ca_v channel families (also known as L-type [Ca_v1.1, Ca_v1.2, Ca_v1.3, Ca_v1.4], P/Q-type [Ca_v2.1], N-type [Ca_v2.2] and R-type [Ca_v2.3] channels) and low-voltage-activated (LVA) Ca²⁺ channel family Ca_v3.³ The different family members display different inactivation properties.^{1,2} HVA Ca_v channels are heterooligomeric protein complexes composed of an α_1 -subunit, auxiliary β -, α_2 - δ - and in some channels of an additional γ -subunit.⁴ The α_1 -subunits sense the membrane voltage, form the pore and define the basic pharmacological properties of the channels⁵⁻⁸ (Fig. 1C, D). Four β -subunit genes (β_1 , β_2 , β_3 , β_4) and various splice variants have been identified. These subunits modulate the inactivation properties of HVA Ca_v (Fig. 1B).⁶ HVA and LVA Ca_v channels undergo fast and slow voltage-dependent inactivation.⁹⁻¹² Ca²⁺/calmodulin-dependent inactivation is exclusively observed in HVA (Ca_v1.2, Ca_v2.1 and other HVA Ca_v channels).¹³⁻¹⁷

The blocking action of many Ca²⁺ antagonists such as the 1,4-dihydropyridines (DHPs), phenylalkylamines (PAAs), diltiazem (DIL) and mibefradil (MIB) in myocardial, smooth muscle and neuronal cells is enhanced by membrane depolarizations.¹⁸⁻²³ This is conventionally explained by a higher affinity of these drugs for open or inactivated channels (Fig. 1A). The precise mechanisms of channel block by these compounds remains to be elucidated.

Recent studies on chimeric and mutant Ca_v channels provided new insights into the underlying molecular events. In particular the design of channels with different inactivation properties may help us to understand the molecular role of inactivation in channel inhibition by Ca²⁺ antagonists.

Voltage-Dependent Inactivation and Drug Sensitivity of Chimeric Ca_v

First evidence for a link between structural determinants of Ca_v channel inactivation and drug-sensitivity came from studies on chimeric channels. In order to localise the drug-binding determinants for Ca^{2+} antagonists Grabner et al²⁴ inserted various sequence stretches of a PAA, DHP and DIL-sensitive α_1 subunit of an L-type channel into the poorly sensitive $\alpha_12.1$ (Fig.

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Figure 1. Ca²⁺ channel conformational states as potential drug targets. A) Voltage-gated Ca²⁺ (Ca_v) channels reside in closed (resting), activated (open) and several inactivated (\overline{I}) states (i.e., $\overline{Ca^{2+}}$ -dependent inactivation [I-Ca], fast [I-fast] and slow [I-slow] voltage-dependent inactivation). Transitions to I-fast and I-slow occur upon membrane depolarizations, transitions to I-Ca are dependent on the intracellular Ca²⁺ concentration. Negative shifts of the membrane potential promote transitions of open and/or inactivated channels to the resting state. It is hypothesised that some Ca2+ channel blockers (e.g., DHPs) interact with an inactivated channel conformation.^{20,21} Recent data from Berjukow et al³⁴ and Sokolov et al³² suggest that transitions to the fast voltage-dependent inactivated state (I-fast) are of particular importance for the drug-channel interaction. B) $Ca_{\nu}2.1$ inactivation is affected by β -subunit composition and point mutations introduced into the α_1 -subunit. Representative barium and calcium currents through a Ca_v1.2 construct composed of β_{1a} or β_{2a} -subunits³² and currents through a mutant Ca_v1.2(β_{1a}) where a single value in segment IVS6 was substituted by alanine (V1477A³⁴). Holding potential -80 mV, test pulses to 20 mV. C) Putative topology of a Ca, channel α_1 -subunit. β -Subunits modulate Ca, channel properties by interacting with the intracellular linker between domains I and II, carboxy and amino terminus (highlighted in black).⁶ D) Segments IIIS5, IIIS6 and IVS6 of Cav1.2. The putative drug-binding determinants (according to refs. 5,40) are indicated as black dots (L-type channel numbering here and further on according to α_{1C-II} ; accession number: M67515). Amino acids that have been shown to modulate channel inactivation are shown in white circles.

2A). Transfer of Ca_v1.2 segments IIIS5, IIIS6 and IVS6 to Ca_v2.1 confered PAA- and DIL-sensitivity to the resulting construct AL12 (Fig. 2B).²⁵

Analysis of the inactivation of some of the chimeric channels revealed a correlation between inactivation kinetics and drug sensitivity. Substitution of domains IIIS5, IIIS6 and the connecting linker (chimera AL20, Fig. 2C) diminished both inactivation and block by DIL and PAA.²⁵ This was surprising because AL20 carries more than half of the PAA- and DIL-determinants (Fig. 1D). The almost complete loss of drug sensitivity raised the suspicion that the process of channel inactivation might interfere with drug action. This hypothesis was further supported by chimera AL22 lacking all PAA- and DIL-determinants in segment IIIS6 but inactivating significantly faster than AL12 and Cav2.1 (Fig. 2D). This channel exhibited



Figure 2. Inactivation properties of chimeric Ca, affect drug sensitivity. Domains III and IV of wild type Ca, 2.1 and Cav2.1/Cav1 chimeric channels. Cav2.1 sequence is shown in white and L-type sequence as black transmembrane segments, corresponding barium currents in the presence of ditiazem are shown on the right. A) Wild type Cav2.1 are almost insensitive to diltiazem. Drug-sensitivity was estimated as peak current inhibition during a train of 15 depolarizing 100-ms pulses applied at 0.1 Hz from -80 mV to 20 mV in the presence of 100 µM d-cis-diltiazem (same protocol used in B, C and D). B) Transfer of segments IIIS5, IIIS6 and IVS6 from the highly sensitive L-type channel into Ca. 2.1 enhances diltiazem-sensitivity to the level of Ca. 1.2 (see also Fig. 4C). C) Transfer of segments IIIS5 and IIIS6 (chimera AL20) does not enhance channel block as evident from negligible current inhibition during the pulse train. The construct comprises, however, all 6 amino acid determinants of diltiazem-sensitivity from Cav1.2 in segment IIIS6 (Fig. 1D). D) Substitution of segment IVS6 and part of the S5 - S6 linker of Cav2.1 by Cav1.2 sequence (chimera AL22) results in an enhanced rate of inactivation and strong use-dependent channel block by diltiazem. Data reproduced from ref. 25 with permission. E) Substitution of part of the IVS4-S5 linker (a sequence stretch that is unlikely to contribute to the drug receptor) in Cav1.2 by the rat brain sodium channel sequence diminishes inactivation and simultaneously reduces the apparent diltiazem sensitivity (300 µM d-cis diltiazem). Use-dependent block during 0.5 Hz train of 15 pulses from holding potential -60 mV in the presence of DIL for wild type Cav2.1 (left) and the chimera HHT-5371 (right) are reproduced with permission from reference 26.



Figure 3. Single amino acids in segment IVS6 of a diltiazem-sensitive Ca,2.1 mutant affect drug sensitivity and channel inactivation. A) α -Helical representation of Ca,2.1 segment IVS6. Transfer of four Ca,1.2 amino acids (Y, A, I, M, highlighted as black circles, α_{1A} numbering, accession number: P27884) enhances DIL- (and PAA-) sensitivity.²⁵ B) Use-dependent I_{Ba} inhibition by 100 μ M d-cis-diltiazem (DIL) during a train of 15 pulses applied at 0.1 Hz. Wild type Ca,2.1 (upper left traces) is barely drug-sensitive. A triple mutant AL25²⁵ (Y, A, I from Ca,1.2) shows a high sensitivity for d-cis-diltiazem and displays a faster inactivation than wild type (upper right traces). Transfer of an additional L-type residue (F1805M) further increases the rate of inactivation and apparent drug-sensitivity of quadruple mutant (Y,M,A,I; bottom left traces). Mutating A1808 back to S (double mutant Y, I; middle left) or I1811 back to M (double mutant Y, A; middle right) impaires inactivation and apparent DIL-sensitivity. Substitution of Y1804 back to I in double mutant A, I (bottom right) reduces use-dependent block without considerably slowing inactivation kinetics (compared to AL25, top right). Reproduced from reference 25 with permission.

PAA- and DIL-sensitivity comparable to (or even higher) than chimera AL12 and wild type $Ca_v 1.2$.²⁵

A further example of a correlation between inactivation and drug-sensitivity in a chimeric channel comes from the work of Motoike et al^{26} who substituted a small sequence stretch outside the putative drug binding region of Ca_v1.2 in the intracellular loop between IVS4 and IVS5 by the homologous residues from the rat brain Na⁺ channel (chimera HHT-5371). As illustrated in Figure 2E, this substitution simultaneously diminished channel inactivation and DIL-sensitivity.

Amino Acid Residues Located in the Putative Drug-Binding Region Affect Drug-Sensitivity and Channel Inactivation

Deeper insights into the interdependence between inactivation and channel block were enabled by the design of mutant Ca_v channels with different inactivation properties. Hering et al^{25} demonstrated that transfer of only three Ca_v1.2-specific amino acids in segment IVS6 to Ca_v2.1 (Y1804, A1808 and I1811 α_{1A} numbering, named chimera AL25²⁵, Fig. 3A) confers high sensitivity for (-)gallopamil and DIL (Fig. 3B, compare top left and top right traces). The authors paid, however, attention to the fact that these mutations significantly accelerated channel inactivation (Fig. 3B, top left and right traces). Furthermore, mutating either A1808 back to serine or I1811 back to methionine (Fig. 3B, middle panels) reduced not only PAA- and DIL-sensitivities but, simultaneously, the rate of channel inactivation.



Figure 4. Inactivation determinants in Ca_v1.2 segment IVS6 modulate drug-sensitivity. A) α -Helical representation of Ca_v1.2 segment IVS6. Amino acid residues contributing to PAA- and DIL-sensitivity^{5,40} (see Fig. 1D) are shown in black. A hot spot of inactivation determinants close to the inner channel mouth (I1471 and V1477⁴²) and the inactivation determinant in position "-1" (I1478⁴³) from the inner end of the helix are illustrated as white circles. B) Mutating the putative PAA- (I1470A) and DHP- (I1471A) determinants slows channel inactivation. C) Normalised superimposed barium currents of Ca_v1.2 and mutant V1477A. Substitution V1477A strongly reduces voltage-dependent inactivation and use-dependent block by d-cis-diltiazem during a train of 15 pulses (-80 mV to +10 mV, 100 ms) applied at 1 Hz (traces in diltiazem are unpublished data from Berjukow et al). Data reproduced from references 34,42 with permission.

On the other hand, insertion of a fourth $Ca_v 1.2$ residue (M1805) into the corresponding position of AL25 further enhanced inactivation and sensitivity for (-)gallopamil and DIL (Fig. 3B, bottom left). These data confirmed a close relation between the rate of intrinsic inactivation and the apparent sensitivity for Ca^{2*} antagonists. We hypothesise that the augmentation of the use-dependent block at least for some of the mutants is mediated by enhanced inactivation rather than by transfer of specific binding determinants.

Interestingly, mutation Y1804I decreased DIL- (and PAA-) sensitivity without significantly slowing the rate of channel inactivation (Fig. 3B bottom right). Y1804 is, therefore, more likely to contribute drug-binding energy than the other IVS6 residues that could equally modulate drug sensitivity in an indirect manner by affecting inactivation. A possible key role of Y1804 in drug binding is also supported by data from Degtiar et al who demonstrated low PAA-sensitivity of a chimeric construct (AL30) inactivating even faster than AL25 but lacking Y1804.²⁷

It was therefore interesting to study if the putative drug binding determinants in the drug sensitive wild type $Ca_v 1.2$ would affect inactivation. A first analysis of the impact of IVS6 amino acids in equivalent positions (Fig. 4) revealed that substitution of I1470 (corresponding to the $Ca_v 2.1$ M1811, (Fig. 3A) and the adjacent DHP-determinant I1471 by alanine both substantially slow channel inactivation (Fig. 4A,B).



Figure 5. Point mutations in Ca₄1.2 segment IIIS6 reveal correlation between inactivation and PAA-sensitivity. A) α -Helical representation of Ca₄1.2 segment IIIS6 forming part of the highly PAA sensitive Ca₄1.1/Ca₄2.1 chimera AL1.²⁴ IIIS6 amino acid residues contributing to PAA- and DIL-sensitivity^{5.40} (Fig. 1D) are shown in black. Inactivation determinants close to the inner channel mouth (11163, F1164 and V1165 corresponding to IFV-inactivation motif⁹⁹) are highlighted in open circles. B) PAA-sensitivity of chimera AL1 and mutants F1164A and IF1163,1164AA (inactivating at a slower rate) were estimated as use-dependent channel inhibition by 100 µM (-)gallopamil (10 100 ms-pulses from -80 mV to 10 mV at 0.1 Hz). The most rapidly inactivating construct AL1 displays the highest apparent PAA-sensitivity. I1163A and to a greater extend double mutation IF1163,1164AA gradually slow the rate of channel inactivation and channel inhibition by (-)gallopamil (see ref. 41 for a similar role of V1165 in DIL-sensitivity). C) A correlation (R=0.92) between the rate of channel inactivation (current decay during 100 ms) and drug-sensitivity (use-dependent channel block) of various AL1 mutants. Data reproduced from reference 39 with permission.

Drug-Sensitivity Is Affected by Inactivation Determinants Located Outside the Putative Drug-Binding Region

A similar correlation between channel inactivation and apparent sensitivity for Ca^{2+} antagonists was observed for amino acids substitutions outside the putative drug-binding region. As illustrated in Figure 4C, substitution of valine (V1478) in the lower part of segment IVS6 of $Ca_v1.2$ by alanine significantly reduced both inactivation and diltiazem sensitivity. A systematic analysis of amino acids in segment IIIS6 of a $Ca_v1.1/Ca_v2.1$ chimera revealed a strong correlation between the two parameters (Fig. 5C).²⁸ Substitution of two residues in segment IIIS6 localised close to the inner mouth of the channel pore by alanine (I1163A and F1164A, Fig. 5) and to an even greater extent the corresponding double mutation (IF1163,1164AA) gradually reduced the rate of current inactivation and simultaneously diminished use-dependent block by (-)gallopamil (Fig. 5B).

By investigating the effect of a single amino acid substitution in the I-II linker (R387E in $Ca_v 2.1$) Sokolov et al²⁹ observed a similar trend: the slower the channel inactivated the lower was the apparent sensitivity for (-)gallopamil. In addition, Jimenez et al³⁰ reported that ultraslow

inactivation generated by a single value insertion in to the I-II linker of the Ca_v1.2 α_1 subunit strongly reduced use-dependent channel block by MIB. Together these data illustrate that Ca²⁺ channel block is modulated by inactivation determinants that are located inside as well as outside of the putative drug-binding region.

β-Subunits Modulate Inactivation and Channel Inhibition

It is well established that the β -subunit composition of HVA Ca_v channels affects their inactivation properties.⁶ According to a widely accepted hypothesis many Ca²⁺ antagonists bind predominately (with high affinity) to the inactivated channel state.^{20,21} Since β -subunits either enhance or reduce Ca_v channel inactivation, they have emerged as important tools for the analysis of state dependent drug action. Coexpression of the α_1 subunit with 'accelerating' β -subunits (β_1 - or β_3 -) was, therefore, expected to enhance channel block.

In line with this hypothesis Lacinova et al³¹ reported an almost 14-fold higher apparent sensitivity of Ca_v1.2 for the PAA verapamil if the Ca_v1.2 α_1 -subunit was coexpressed with a β_3 -subunit (Ca_v1.2(β_3)).

(-)Gallopamil inhibited Ca_v1.2(β_3) 3.4-fold stronger than Ca_v1.2 α_1 subunits expressed without β -subunits.³¹ Sokolov et al³² studied the underlying molecular mechanism and compared PAA-sensitivity of Ca_v1.2 composed of either an 'accelerating' β_3 -subunits or a 'decelerating' β_{2a} . These studies revealed a relation between the rate of β -mediated inactivation and PAA-sensitivity (Fig. 6A-C).

Jimenez et al³⁰ demonstrated that inhibition of Ca_v2.1, Ca_v2.3 and Ca_v1.2 by MIB is significantly stronger if the corresponding α_1 -subunits are coexpressed with an 'accelerating' β_{1b} rather than with a 'decelerating' β_{2a} -subunit. The concentration of drug required to block Ca_v2.1 and Ca_v2.3 composed of β_{2a} was approximately 10-fold higher (Fig. 6D, left, middle). A smaller difference was observed for Ca_v1.2 (Fig. 6D, right). Further evidence for a role of the β -subunit interaction in Ca²⁺ channel block comes from Zamponi et al³³ who reported that coexpression of the Ca_v2.3 α_1 subunit with β_{2a} impaired channel block by piperidines compared to Ca_v2.3 coexpressed with the 'accelerating' β_{1b} . In summary, these data suggest that a β -subunit-mediated increase or reduction in voltage-dependent inactivation modulates Ca_v channel inhibition by PAAs, MIB and piperidines.

Inactivation Determinants and DHP Sensitivity

Evidence for a key role of inactivation in channel inhibition by DHPs came from the drug-induced shift of Ca_v1.2 availability to hyperpolarized voltages in myocardial and smooth muscle cells. This is conventionally explained as high affinity binding of drugs such as nifedipine or isradipine to the inactivated channel conformation.^{20,21} Ca_v1.2 composed of 'accelerating' β_{1a} - (Ca_v1.2(β_{1a})) or β_3 -subunits (Ca_v1.2(β_3)) were, therefore, expected to enhance DHP-binding and channel block.

However, Lacinova et al³¹ reported almost identical sensitivities of $Ca_v 1.2(\beta_3)$ and $Ca_v 1.2$ channels lacking the β subunit for (+)isradipine, despite the considerable differences in inactivation.

Berjukow et al³⁴ came to a similar conclusion by comparing the DHP sensitivities of Ca_v channels containing either β_{1a} or β_{2a} subunits (Fig. 7). A DHP-sensitive Ca_v2.1 mutant composed of the 'accelerating' β_{1a} ($\alpha_{1A-DHP}/\beta_{1a}$) displayed at -80 mV a 3-fold higher steady-state fraction of channels in an inactivated state compared to slowly inactivating $\alpha_{1A-DHP}/\beta_{2a}$. This larger fraction of hypothetically high affinity drug receptors did, however, not promote additional channel block by (+)isradipine (Fig. 7A). Analogous observations were made for Ca_v1.2, the prime target of DHP in vascular smooth muscle cells (Fig. 7).³⁴

There is, nevertheless, evidence for an important role of the inactivation machinery in channel block by DHPs. The more rapidly inactivating mutant α_{1A-DHP} displays a higher sensitivity for (+)isradipine than the slower inactivating wild-type Ca_v1.2, irrespective whether an 'accelerating' β_{1a} or a 'decelerating' β_{2a} -subunit were coexpressed (Fig. 7A). It is, therefore, tempting to



Figure 6. Auxiliary β -subunits modulate inactivation and apparent sensitivity for gallopamil and mibefradil. A) Representative currents through Ca, 1.2 composed of either β_3 (Ca, 1.2(β_3)) or β_{2a} -subunits (Ca, 1.2(β_3)). Barium currents were elicited by a 3-second depolarizations from -80 mV to +10mV. B) Use-dependent current inhibition of Ca, 1.2(β_3) and Ca, 1.2(β_{2a}) by 10 μ M (-)gallopamil during a train of 10 1s-pulses (-80 mV to +10 mV) applied at 0.5 Hz. C) Apparent (-)gallopamil-sensitivities estimated as a peak current inhibition during the train in %. White bars represent the accumulation of channels in intrinsic inactivation (control, C), black bars show the current inhibition by 10 μ M (-)gallopamil. Data reproduced with permission from ref.³² D) Ca, 2.1, Ca, 2.3 and Ca, 1.2 inhibition by mibefradil is dependent on the β -subunit composition (reproduced from ref. 30 with permission). The 'accelerating' β_{1b} -subunit enhances whereas the 'decelerating' β_{2a} -subunit reduces channel inhibition.

speculate that the higher DHP-sensitivity of α_{1A-DHP} is related to their faster inactivation compared to Ca_v1.2 (Fig. 7B,C).

Furthermore, Berjukow et al³⁴ demonstrated that substitution of the putative DHP-binding determinant 11471 in segment IVS6 (Fig. 1D) by alanine slowed the rate of fast voltage-dependent inactivation (Fig. 8A,B) and additionally accelerated recovery of drug modified channels from inactivation. It appears that mutation 11471A destabilises the intrinsic fast inactivated state and the DHP-induced state.

A detailed study of kinetics of entry into and recovery from inactivation and DHP-inhibition of various Ca_v1.2 and Ca_v2.1 mutants led us to a hypothesis that these drugs promote fast voltage-dependent inactivation without binding selectively to this state. This idea was further supported by (+)-isradipine action on Ca_v1.2 mutant V1477A that is almost completely lacking fast voltage-dependent inactivation. (+)-Isradipine accelerated the current decay in a voltage-dependent manner comparable to voltage dependence of inactivation of wild type Ca_v1.2 (Fig. 8C). The effect of (+)-isradipine on this channel can, therefore, be interpreted as a restoration of fast voltage-dependent inactivation.³⁵



Figure 7. The rapidly inactivating Ca₂2.1 mutant α_{1A-DHP} displays a higher DHP-sensitivity than wild-type Ca₂1.2. A) Concentration-response relationships of peak barium current inhibition of $\alpha_{1A-DHP}(\beta_{1a})$ (open squares), $\alpha_{1A-DHP}(\beta_{2a})$ (filled squares), Ca₂1.2(β_{1a}) (open circles) and Ca₂1.2(β_{2a}) (filled circles) by (+)-isradipine (IC₅₀($\alpha_{1A-DHP}/\beta_{1a}$) = 61 nM, IC₅₀($\alpha_{1A-DHP}/\beta_{2a}$) = 52 nM vs. IC₅₀(Ca₂1.2(β_{1a})) = 327 nM and IC₅₀(Ca₂1.2(β_{2a})) = 198 nM). B) Representative scaled currents of Ca₂1.2 and α_{1A-DHP} (C) of the indicated subunit composition (holding potential -80 mV, test pulse to 20 mV). Data are reproduced from reference 34 with permission.



Figure 8. Onset of DHP-induced inactivation is voltage-dependent and recovery is modulated by inactivation determinants. A) (+)Isradipine (1 μ M) accelerates barium current decay through L-type construct Ca_v1.2(β_{1a}) (traces on the left) and slows recovery from inactivation/block (right panel) about 4,5-fold ($\tau_{recovery,control} = 0.63$ s vs. $\tau_{recovery, isradipine} = 2.85$ s). B) Amino acid residue 11471 is believed to form part of the DHP receptor. Substitution 11471A slows inactivation (Fig. 4B). Traces in the left panel illustrate barium currents through 11471A in control and the presence of (+)isradipine (1 μ M). The right panel illustrates faster recovery of mutant 11471A from inactivation at rest compared to Ca_v1.2(β_{1a}) (compare with A). Recovery of 11471A in drug was faster than in Ca_v1.2 and not significantly different from control ($\tau_{recovery,control} = 0.50$ s, $\tau_{recovery, isradipine} = 0.46$ s compare to A). Data from reference 34 with permission. C) Voltage-dependent acceleration of the barium current decay of slowly inactivating mutant V1477A by 1 μ M (+)isradipine (inset). Voltage-dependencies of the time constant of fast Ca_v1.2(β_{1a}) inactivation and the rate of (+)isradipine (inset). Voltage-dependencies of the time constant of fast Ca_v1.2(β_{1a}) inactivation and the rate of (+)isradipine (inset). Noltage-dependencies of the time constant of fast Ca_v1.2(β_{1a}) inactivation and the rate of (+)isradipine-induced current decay are illustrated. The time constant of current decay of V1477A in the absence of drug (open circles) ranged between 10 and 25 seconds. Data reproduced from reference 35 with permission.



Figure 9. On the role of Ca^{2+} dependent inactivation in (-)gallopapil action. A) Normalised Ca^{2+} currents through $Ca_v 1.2(\beta_{2a})$ elicited by a 0.5 Hz train of 10 pulses (-80 mV to 0 mV) in the presence of 10 μ M (-)gallopamil. B) Use-dependent peak current inhibition with Ca^{2+} or Ba^{2+} as charge carriers (black bars) compared to peak current inhibition in absence of drug (white bars). Note the stronger use-dependent block in Ca^{2+} . C) (-)Gallopamil slows $Ca_v 1.2(\beta_{2a})$ recovery kinetics. Barium current recovery in drug is significantly faster than recovery of calcium currents (measured after 3s conditioning pulses to +10mV (Ba²⁺) or +20mV (Ca²⁺) (Ba²⁺: $\tau_{Control=}1.7\pm0.2$ s (not shown) vs. $\tau_{gallopamil=}2.8\pm0.3$ s; $Ca^{2+}: \tau_{Control=}2.3\pm0.2$ s vs. $\tau_{gallopamil=}15\pm3$ s, reproduced with permission from ref²). Note that Ca^{2+} currents through $Ca_v 1.2$ are more efficiently blocked by (-)gallopamil than Ba²⁺ currents.

On the Role of Ca²⁺-Dependent Inactivation in Drug Sensitivity

 Ca^{2+} -dependent inactivation causes an additional rapid component in current decay through Ca.1.2 channels (Figs. 1B and 9A). Sokolov et al³² reported that accelerated inactivation with Ca²⁺ as charge carrier (compared to Ba²⁺) is accompanied by enhanced use-dependent block by (-)gallopamil (Fig. 9B). This effect was apparently caused by a slower recovery from channel block in the presence of Ca²⁺ (Fig. 9C). Its molecular basis has yet to be elucidated.

Simulation of the Drug-Channel Interaction

Different versions of the "modulated receptor paradigm"³⁶ explain the cumulative Ca²⁺ channel block by PAA, DIL and MIB during a train of test pulses ("use-dependent block", Fig. 10) by selective drug binding to either open or inactivated channels.^{20,21,37}

Such a scenario would imply that during a single pulse the drug "has not enough time" to bind to all channels. Thus, due to the slow drug binding only a small fraction of channels would be blocked. Upon repolarization the channels recover to the low affinity resting state where the drug dissociates from its receptor site (Fig. 10). Drug unbinding is, however, slow as well and a certain fraction of channels will remain blocked until the next pulse is applied leading finally to cumulative (use-dependent) channel inhibition.

Alternatively, drug binding could occur independently of the channel state. In such a scenario that we call "drug inactivation synergism," ³⁸ Ca²⁺ antagonists accelerate channel transitions into the fast inactivated state like 'accelerating' β -subunits or point mutations.

Figure 10 illustrates the two competing models. Both of them satisfactory reproduce the experimental data. In the "drug inactivation synergism" model the effect of (-)gallopamil on $Ca_v 1.2(\beta_3)$ and $Ca_v 1.2(\beta_{2a})$ is simulated by an about 7-fold increase in the on-rate of fast voltage-dependent inactivation (rate α (PAA)) and an 8-fold decrease in recovery from drug-induced inactivation (rate β (PAA)). The difference in use-dependent inhibition of the two β -subunit compositions arise, therefore, solely due to the differences in intrinsic inactivation in $Ca_v 1.2(\beta_3)$ and $Ca_v 1.2(\beta_{2a})$. I.e., the "drug-inactivation synergism" model reproduces the differences in apparent drug sensitivity without the necessity to assume different drug affinities for $Ca_v 1.2(\beta_3)$ and $Ca_v 1.2(\beta_{2a})$.



Figure 10. Simulation of use-dependent inhibition of Ca_v1.2 by (-)gallopamil. A, B) Use-dependent Ca²⁺ channel block of Ca_v1.2(β_3) (A, left panel) and Ca_v1.2(β_{2a}) (B, left panel) by 10µM (-)gallopamil (same experiments as in Fig. 6B). The smooth traces are simulations of the experimental data. The kinetic models of the respective PAA-channel interaction are shown above the simulated current traces. The "open channel block" model assumes high affinity drug binding to the open state (O) ($k_{on}(Ca_v(\beta_3)) = 5^{*10^4} \text{ M}^{-1}\text{s}^{-1}$; $k_{on}(Ca_v(\beta_{2a})) = 1.5^{*10^4} \text{ M}^{-1}\text{s}^{-1}$). The "Drug-Inactivation-Synergism" model assumes that the drug promotes transitions to the (modified) fast inactivated state (rate α : α (control) $\beta_3 = 0.13 \text{ s}^{-1}$, α (PAA) $\beta_3 = 0.85 \text{ s}^{-1}$; α (control) $\beta_{2a} = 0.07 \text{ s}^{-1}$, α (PAA) $\beta_{2a} = 0.5 \text{ s}^{-1}$) and slow recovery from this state (rate β : β (control) $\beta_3 = 0.25 \text{ s}^{-1}$, β (PAA) $\beta_3 = 0.35 \text{ s}^{-1}$; β (Control) $\beta_{2a} = 0.35 \text{ s}^{-1}$; β (control) $\beta_{2a} = 0.35 \text{ s}^{-1}$; β (control) $\beta_{2a} = 0.35 \text{ s}^{-1}$; β (PAA) $\beta_3 = 0.35$

In the "open channel block" model we had to presume a higher affinity of (-)gallopamil for rapidly inactivating $Ca_v 1.2(\beta_3)$ compared to $Ca_v 1.2(\beta_{2a})$ ($k_{on}[D](Ca_v(\beta_3)) = 0.5 \text{ s}^{-1} \text{ vs.}$ $k_{on}[D](Ca_v(\beta_{2a})) = 0.15 \text{ s}^{-1}$). This model reproduces the data only if we postulate a direct effect of the β -subunit on the drug binding process. Moreover, if we hypothesise equal affinities this model predicts enhanced inhibition of slowly inactivating (open) Ca_v channels and not—as observed in most experiments—stronger block of faster inactivating channels (Figs. 2-7).

Summary and Outlook

Point mutations in different parts of the Ca_v α_1 -subunits that either enhance or impair channel inactivation simultaneously increase or reduce channel inhibition by PAA, DIL, MIB and to a certain extent by DHPs. Fast inactivating channels tend to be more efficiently inhibited than slow-inactivating ones. This simple correlation has been confirmed by independent groups for wild type, chimeric or mutant HVA Ca_v.²⁵⁻³³ A similar conclusion can be drawn the drug action on Ca_v channels containing either 'accelerating' (e.g., β_1 or β_3) or 'decelerating' (β_{2a}) β -subunits.^{30,32} Subunit compositions promoting faster channel inactivation increase the apparent drug sensitivity. A possible scenario of a "drug inactivation synergism" is illustrated in (Fig. 10) This model does not exclude state-dependent drug access for partially charged compounds. However, once these drugs dock within their binding pockets they are more likely to promote inactivation than to plug the open channel pore (Fig. 10). Some amino acids (e.g., I1470, I1471 in segment IVS6 and the IFV motif close to the inner channel mouth in segment IIIS6 of Cav1.2 as well as M1464 and A1467 in Cav2.1 environment (Fig. 1D)) are strong inactivation determinants.

It is currently not entirely clear which of the determinants of drug sensitivity in segments IIIS5, IIIS6 and IVS6 form part of the drug binding pocket and which of them affect the drug-channel interaction in an indirect manner via inactivation (Fig. 1D). In functional studies the effects of mutations on PAA-, DIL- and MIB-sensitivity is indistinguishable from mutations localised outside the putative drug-binding region. The respective impact of IIIS5, IIIS6 and IVS6 amino acids in inactivation and drug binding has yet to be thoroughly elucidated.

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References

- 1. Stotz SC, Zamponi GW. Structural determinants of fast inactivation of high voltage-activated Ca²⁺ channels. Trends Neurosci 2001; 24:176-181.
- 2. Hering S, Berjukow S, Sokolov S et al. Molecular determinants of inactivation in voltage-gated Ca^{2+} channels. J Physiol 2000; 528:237-249.
- 3. Ertel EA, Campbell KP, Harpold MM et al. Nomenclature of voltage-gated calcium channels. Neuron 2000; 25:533-535.
- Catterall WA. Structure and regulation of voltage-gated Ca²⁺ channels. Annu Rev Cell Dev Biol 2000; 16:521-555.
- 5. Striessnig J, Grabner M, Mitterdorfer J et al. Structural basis of drug binding to L Ca²⁺ channels. Trends Pharmacol Sci 1998; 9:108-115.
- 6. Walker D, De Waard M. Subunit interaction sites in voltage-dependent Ca²⁺ channels: Role in channel function. Trends Neurosci 1998; 21(4):148-154.
- 7. Stea A, Tomlinson WJ, Soong TW et al. Localization and functional properties of a rat brain alpha 1A calcium channel reflect similarities to neuronal Q- and P-type channels. Proc Natl Acad Sci USA 1994; 91:10576-10580.
- Birnbaumer L, Qin N, Olcese R et al. Structures and functions of calcium channel beta subunits. J Bioenerg Biomembr 1998; 30:357-375.
- 9. Boyett MR, Honjo H, Harrison SM et al. Ultra-slow voltage-dependent inactivation of the calcium current in guinea-pig and ferret ventricular myocytes. Pflugers Arch 1994; 428(1):39-50.
- Hering J, Maulet Y, Feltz A et al. Slow inactivation of the Ca.3.1 isoform of the T-type channel. Biophys J 2001; 80(1)p2:621a.
- Sokolov S, Weiss RG, Timin EN et al. Modulation of slow inactivation in class A Ca²⁺ channels by beta-subunits. J Physiol 2000; 527(3):445-454.
- 12. Degtiar VE, Scheller RH, Tsien RW. Syntaxin modulation of slow inactivation of N-type calcium channels. J Neurosci 2000; 20(12):4355-4367.
- Qin N, Olcese R, Bransby M et al. Ca²⁺-induced inhibition of the cardiac Ca²⁺ channel depends on calmodulin. Proc Natl Acad Sci USA 1999; 96:2435-2438.
- Lee A, Wong ST, Gallagher D et al. Ca²⁺/Calmodulin binds to and modulates P/Q-type calcium channels. Nature 1999; 399:155-159.
- 15. Peterson BZ, DeMaria CD, Yue DT. Calmodulin is the Ca²⁺ sensor for Ca²⁺-dependet inactivation of L-type calcium channels. Neuron 1999; 22:549–558.
- 16. Zuhlke RD, Pitt GS, Deisseroth K et al. Calmodulin supports both inactivation and facilitation of L-type calcium channels. Nature 1999; 399:159-162.
- Erickson MG, Alseikhan BA, Peterson BZ et al. Preassociation of calmodulin with voltage-gated Ca²⁺ channels revealed by FRET in single living cells. Neuron 2001; 31(6):973-985.
- Lee KS, Tsien RW. Mechanism of calcium channel blockade by verapamil, D600, diltiazem and nitrendipine in single dialysed heart cells. Nature 1983; 302(5911):790-794.

- 19. McDonald TF, Pelzer D, Trautwein W. Cat ventricular muscle treated with D600: Characteristics of calcium channel block and unblock. J Physiol 1984; 352:217-241.
- Bean BP. Nitrendipine block of cardiac calcium channels: High-affinity binding to the inactivated state. Proc Natl Acad Sci USA 1984; 81:6388-6392.
- Sanguinetti MC, Kass RS. Voltage-dependent block of calcium channel current in the calf cardiac purkinje fibre by dihydropyridine calcium channel antagonists. Circ Res 1984; 55:336-348.
- Bezprozvanny I, Tsien RW. Voltage-dependent blockade of diverse types of voltage-gated Ca2+ channels expressed in Xenopus oocytes by the Ca²⁺ channel antagonist mibefradil (Ro 40-5967). Mol Pharmacol 1995; 48(3):540-549.
- Aczel S, Kurka B, Hering S. Mechanism of voltage- and use-dependent block of class A Ca²⁺ channels by mibefradil. Br J Pharmacol 1998; 125(3):447-454.
- 24. Grabner M, Wang Z, Hering S et al. Transfer of 1,4-dihydropyridine sensitivity from L-type to class A (BI) calcium channels. Neuron 1996; 16(1):207-218.
- 25. Hering S, Aczel S, Grabner M et al. Transfer of high sensitivity for benzothiazepines from L-type to class A (BI) calcium channels. J Biol Chem 1996; 271(40):24471-24475.
- 26. Motoike HK, Bodi I, Nakayama H et al. A region in IVS5 of the human cardiac L-type calcium channel is required for the use-dependent block by phenylalkylamines and benzothiazepines. J Biol Chem 1999; 274(14):9409-9420.
- 27. Degtiar VE, Aczel S, Doring F et al. Calcium channel block by (-)devapamil is affected by the sequence environment and composition of the phenylalkylamine receptor site. Biophys J 1997; 73(1):157-167.
- Hering S, Aczel S, Kraus RL et al. Molecular mechanism of use-dependent calcium channel block by phenylalkylamines: Role of inactivation. Proc Natl Acad Sci USA 1997; 94(24):13323-13328.
- 29. Sokolov S, Weiss RG, Kurka B et al. Inactivation determinant in the I-II loop of the Ca²⁺ channel α_1 -subunit and beta-subunit interaction affect sensitivity for the phenylalkylamine (-)gallopamil. J Physiol 1999; 519(2):315-322.
- 30. Jimenéz C, Bourinet E, Leuranguer V et al. Determinants of voltage-dependent inactivation affect mibefradil block of calcium channels. Neuropharmacology 2000; 39:1-10.
- 31. Lacinova L, Ludwig A, Bosse E et al. The block of the expressed L-type calcium channel is modulated by the beta 3 subunit. FEBS Lett 1995; 373:103-107.
- 32. Sokolov S, Timin E, Hering S. On the role of Ca²⁺- and voltage-dependent inactivation in Cav1.2 sensitivity for the phenylalkylamine (-)gallopamil. Circ Res 2001; 89:700-708.
- 33. Zamponi GW, Soong TW, Bourinet É et al. Beta subunit coexpression and the alpha1 subunit domain I-II linker affect piperidine block of neuronal calcium channels. J Neurosci 1996; 6:2430-2443.
- 34. Berjukow S, Marksteiner R, Gapp F et al. Molecular mechanism of calcium channel block by isradipine. Role of a drug-induced inactivated channel conformation. J Biol Chem 2000; 275:22114-22120.
- 35. Berjukow S, Hering S. Voltage-dependent acceleration of Cav1.2 channel current decay by (+)- and (-)-isradipine. Br J Pharmacol 2001; 133(7):959-966.
- 36. Hille B. Local anaesthetics: Hydrophilic and hydrophobic pathways for drug-receptor action. J Gen Physiol 1977; 69:497-515.
- 37. Timin EN, Hering S. A method for estimation of drug affinity constants to the open conformational state of calcium channels. Biophys J 1992; 63(3):808-814.
- 38. Hering S. B-Subunits: Fine tuning of calcium channel block. Trends Pharmacol Sci 2002; in press.
- 39. Hering S, Berjukow S, Aczel S et al. Ca²⁺ channel block and inactivation: Common molecular determinants. Trends Pharmacol Sci 1998; 19:439-443.
- Hockerman GH, Dilmac N, Scheuer T et al. Molecular determinants of diltiazem block in domains IIIS6 and IVS6 of L-type Ca²⁺ channels. Mol Pharmacol 2000; 58(6):1264-1270.
- 41. Kraus RL, Hering S, Grabner M et al. Molecular mechanism of diltiazem interaction with L-type Ca2+ channels. J Biol Chem 1998; 273(42):27205-27212.
- 42. Berjukow S, Gapp F, Aczel S et al. Sequence differences between alpha1C and alpha1S Ca²⁺ channel subunits reveal structural determinants of a guarded and modulated benzothiazepine receptor. J Biol Chem 1999; 274(10):6154-6160.
- Shi C, Soldatov NM. Molecular determinants of voltage-dependent slow inactivation of the Ca²⁺ channel. J Biol Chem 2002; 277(9):6813-6821.
- 44. Berjukow S, Marksteiner R, Sokolov S et al. Amino acids in segment IVS6 and β-subunit interaction support distinct conformational changes during Ca_v2.1 inactivation. J Biol Chem 2001; 276:17076-17082.

Block of Voltage-Gated Calcium Channels by Peptide Toxins

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Introduction

Structurally, the calcium channels are closely related to sodium channels, with the main structurally significant difference being the positioning and nature of the residues that line the selectivity filter in the pore of the channel. There are at least six pharmacologically distinct calcium channels types, including L-, N-, P/Q-, T, and R-type calcium channels (Table 1).¹ Within each group are multiple subtypes that are presently less easy to distinguish pharmacologically. In the nervous system, several types of ion channels may contribute to processes such as neurotransmitter release, with the ratio and role for each type varying among different nervous tissues² (see Table 1). A number of different peptide toxins from marine snails (conotoxins) and spiders (agatoxins, grammotoxin and DW13.3 *Filistata hibernalis*) are known to potently inhibit the activities of specific voltage-dependent calcium channels.^{3,4} The conotoxins are usually smaller in size comprising around 22–30 amino acid residues and are believed to act by physically blocking the pore of the channel.⁵ Spider toxins such as ω-Aga IVA⁶ typically larger consisting of 60–90 residues and ω-grammotoxin⁷ around 30–40 residues affect channel gating.⁸

The diversity of peptide toxins provides the possibility for selective modulation of nerve function that may allow the selective treatment of diseases such as pain and stroke. The first examples of calcium channel inhibitors being useful therapeutically are the ω -conotoxins MVIIA (Ziconotide or Prialt, Elan) and ω -CVID (AM336, AMRAD) which target the N-type calcium channel and are currently in clinical trials for chronic pain. ω -Conotoxins are a large family of structurally related peptides with a wide range of specificities for different subtypes of the VSCC (Table 2).9-18 Their high selectivity has made them enormously valuable as physiological tools. A remarkable feature of the six cysteine/four-loop framework exemplified by the ω -conotoxins is the presence of a cystine knot within the structures. This motif consists of an embedded loop in the structure formed by two of the disulfide bonds and their connecting backbone segments. This loop is penetrated by the third disulfide bond in a remarkable example of nature's engineering designs. Although the structure of the core of ω -conotoxins is rigid due to the knotted disulfide structure, NMR studies have revealed conformational flexibility in the exposed loops that might influence receptor binding. This review will describe structural aspects of peptide toxins from cone snails as well as those from snakes and spiders that selectively inhibit different voltage-sensitive calcium channels (VSCCs). Several excellent general reviews describing peptide toxin interactions with voltage-gated ion channels including calcium channels have been published recently. 19-21

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Ca ²⁺ Channel	Ca ²⁺ Current Type	Primary Localisation	Previous Name of α1 Subunit	Specific Blocker	Functions	
Ca _v 1.1	L	Skeletal muscle	α _{1S}	DHPs	Excitation-concentration coupling, Calcium homeostasis	
Ca _v 1.2	L	Cardiac muscle Endocrine cells Neurons	α_{1C}	DHPs	Excitation-concentration coupling, Hormone secretion	
Ca _v 1.3	L	Endocrine cells Neurons	α_{1D}	DHPs	Hormone secretion, Gene regulation	
Ca _v 1.4	L	Retina	α_{1F}		Tonic neurotransmitter release	
Ca _v 2.1	P/Q	Nerve terminals Dendrites	α_{1A}	ω-Agatoxin	Neurotransmitter release Dendritic Ca ²⁺ transients	
Ca _v 2.2	N	Nerve terminals Dendrites	α_{1B}	ω-GVIA	Neurotransmitter release Dendritic Ca ²⁺ transients	
Ca _v 2.3	R	Cell bodies Dendrites Nerve terminals	α_{1E}	SNX-482	Ca ²⁺ -dependent action potentials	
Ca _v 3.1	Т	Cardiac muscle Skeletal muscle Neurons	α_{1G}	None	Repetitive firing	
Ca _v 3.2	Т	Cardiac muscle Neurons	α_{1H}	None	Repetitive firing	
Ca _v 3.3	Т	Neurons	α_{11}	None	Repetitive firing	

Table 1. Subunit composition and function of Ca²⁺ channel types¹

L-Type VSCC Antagonists

Toxins from several species of snails and snakes block the L-type VSCC. For example, ω-conotoxin TxVII from the mollusc hunting Conus textile targets dihydropyridine-sensitive L-type calcium channels.¹⁷ TxVII is similar to other ω -conotoxins, including GVIA, MVIIA and CVID, having 26 residues including six Cys which form three disulphide bonds (Table 2). Thus TxVII shares a similar four-loop framework with the other ω-conotoxins (Fig. 1). However, TxVII is negatively charged and has a large hydrophobic patch unlike other @-conotoxins that target N-and P/Q-type VSCCs which are highly positively charged (+5 to +6), These positive charges contribute to N-type VSCC binding, with Lys2 being the most critical charge²²⁻²⁴ The conserved Lys2 is the only positively charged residue in TxVII and there are several negative charges in the proximity of Lys2. It is also missing a Tyr in position 13, which has been shown by several groups to be crucial for activity at the N-type VSCC.^{22,25,26} Instead TxVII has a hydrophobic Leu13. The hydrophobic patch in TxVII, which includes Phe11 and Trp26, is not found in other w-conotoxins and could be part of the face that interacts with the L-type VSCC. These differences presumably act in concert to explain why TxVII does not bind to the N-type VSCC, despite having the consensus structure of ω -conotoxins. Interestingly, TxVII reversibly inhibits snail but not rat L-type currents,²⁷ indicating that it has evolved to selectively inhibit calcium channels found in its prey. The sequence of TxVII resembles δ -conotoxin TxVIA, an inhibitor of sodium channel inactivation and despite the fact that they act on different ion channels, they share the common

Toxin	Sequence	Target	Net Charge	Ref.
C.geographu	s			
GVIA	CKSOGSSCSOTSYNCCR-SCNOYTKRCY*	N-type VDCC	+5	9
GVIB	CKSOGSSCSOTSYNCCR-SCNOYTKRCYG*	?	+5	10
GVIC	CKSOGSSCSOTSYNCCR-SCNOYTKRC*	?	+5	10
GVIIA	CKSOGTOCSRGMRDCCT-SCLLYSNKCRRY*	?	+7	11
GVIIB	CKSOGTOCSRGMRDCCT-SCLSYSNKCRRY*	?	+7	11
C.magus				
MVIIA	CKGKGAKCSRLMYDCCTGSC-R-SGKC*	N-type VDCC	+6	11
MVIIC	CKGKGAPCRKTMYDCCSG-SCGR~RGKC*	P/Q-type VDCC	+7	12
C.striatus				
SVIA	CRSSGSOCGVTSI-CC-GRC-YRGKCT*	not known	+5	13
SVIB	CKLKGQSCRKTSYDCCSG-SCGR-SGKC*	N- and	+6	13
		P/Q-type		
C.tulipa				
TVIA	CLSOGSSCSOTSYNCCR-SCNOYSRKCR*	?	+4	14
C.consors				
CnVIIA	CKGKGAOCTRLMYDCCHG-SCSSSKGRC*	N-type VDCC	+5	15
C.catus				
CVIA	CKSTGASCRRTSYDCCTG-SCRSGRC*	N-type VDCC	+5	16
CVIB	CKGKGASCRKTMYDCCR-GSCRSGRC*	N- and	+7	16
		P/Q-type		
CVIC	CKGKGQSCSKLMYDCCTG-SCSR-RGKC*	N- and	+6	16
		P/Q-type		
CVID	CKGKGAKCSKLMYDCCSGSCSGTVGRC*	N-type VDCC	+5	16
C.textile				
TxVII	CKQADEPCDVFSLDCCTGICLGV-CMW	L-type VDCC	-3	17
C.radiatus				
RVIA	CKPOGSOCRVSSYNCCS-SCKSYNKKCR*	N-type	+6	18

Table 2. Sequences of native ω-Conotoxins from different Conus species

Cys four loop framework (Fig. 2).^{28,29} Conotoxins with this conserved cysteine framework highlight the cysteine knots as an excellent structural scaffold from which to present different side chains to achieve diverse biological activities.²⁷

Recently a conotoxin member of the Contryphan family, glacontryphan-M from *C. marmoreus* was reported to be the first contryphan peptide containing two γ -carboxylatedglutamic to be a selective L-type calcium channel blocker.³⁰ Interestingly the NMR solution structure of glacontryphan-M superimposes with the backbone of Contryphan-R³¹ and Contryphan-Vn.^{32,33} Similar to Contryphan-Vn, which was recently reported to be a Ca²⁺-dependent K⁺ channel inhibitor, glacontryphan-M requires calcium binding to the N-terminal of the peptide to be active at the L-type calcium channel. The binding of calcium to the peptide induces a structural perturbation in the Gla-containing part of the peptide believed to be important for the activity of the peptide.

The venoms from the snakes of the families *Elapidae* and *Hydrophidae* contain a variety of toxins with distinct pharmacologies. A large portion of these toxins are either neurotoxins³⁴ that act postsynaptically to block the nicotinic acetylcholine receptor causing flaccid paralysis of the muscle,³⁴ or cytotoxins³⁵ which appear to change membrane permeability and/or



Figure 1. Three different ω -conotoxins that inhibit different voltage-sensitive calcium channels. Ribbon diagram and sequnence alignments for A) L-type VSCC inhibitor TxVII from *C. textile*, B) P/Q-type VSCC inhibitor MVIIC from *C. magus* and C) N-type VSCC blocker CVID from *C. catus*. superimposed across the backbone heavy atoms residue 1–12. The three disulfide bonds are in yellow. The cysteine knot disulfide bond connectivity is indicated in the sequence alignment of the three peptides. Yellow boxes indicate residues identified as important for binding to their VSCC target. Sequence homology across two peptides (red) and three peptides (blue) are indicated. O= hydroxyloproline; *= amidated C-terminal.



Figure 2. Superimposition of solution structures of A) ω -conotoxin TxVII, a L-type calcium channel inhibitor from *Conus textile* and B) δ -conotoxin TxVIA, a sodium channel inhibitor. Disulfides are indicated in orange and corresponding residues are indicated in blue. The cysteine framework is boxed in the sequence alignment and sequence homology across the two peptides is shown in blue.



Figure 3. Three different L-type calcium channel blockers from different venomous species. A) TxVII, a 26 residue peptide from the cone snail *C. textile*; B) Calcicludine (CaC), a 60 residue peptide from the green mamba snake *Dendroaspis augusticeps* and C) FS2, a 60 residue peptide isolated from the venom of black mamba snake *Dendroaspis poluepis polyepis*. Stabilising disulfide bonds shown in yellow. Sequence alignments and disulfide bond connectivity are indicated.

membrane organisation. These two very distinct pharmacological classes share a similar structural motif, namely the three-fingered architecture, where four conserved cysteine pairs are organised as a "disulfide β -cross".^{36,37} A third class of postsynaptically active toxins have been isolated from the venom of the mamba snakes (*Dendroaspis* spp). Even though they also have a three-fingered architecture, they show no neurotoxic or cytotoxic activity. Their homology and immunological properties have led to further subdivision into four subgroups^{32,39} of which two have been pharmacologically characterised. Toxins of subgroup I are potent inhibitors of acetylcholine esterases,⁴⁰ whereas subgroup III contains toxins such as FS2 from *Dendroaspis polyepis*, ³⁸ C10S2C2 from *D. augusticepceps* (green mamba)³⁹ and calciseptine from the venom of *D. p. polyepis*. Calciseptine and FS2 differs only in two residue and have similar blocking effect at the L-type VSCC⁴¹ (Fig. 3).

Calciseptine, a 60 residue peptide, has been found to be an antagonist at heart L-type calcium channels, but acts as an agonist at frog and mammalian skeletal muscle L-type calcium currents.⁴² Like ω -agatoxin IIIA from the spider venom,⁴³ calciseptine blocks the L-type VSCC with weak efficacy and low specificity.^{44,45} Flanking proline residues have been proposed to bracket the L-type calcium channel binding site of calciseptine and FS2.^{46,47} In calciseptine they are spaced four residues apart (P-42 TAMWP-47) to present this series of residues in a well-defined loop in the two proteins. Albrand et al (1995)⁴⁸ also proposed that Trp contributes to binding to the L-type channel. In support, an eight residue long peptide containing the P-42 TAMWP-47 motif (L-calchin) retained the parent peptide activity at the L-type calcium channel, but with lower potency.⁴⁶



Figure 4. Ribbon diagrams of three venom peptides with low sequence homology but high structural homology. A) Bovine pancreatic trypsine inhibitor (BPTI) in pink, B) Calcicludine (CaC), a L-type calcium channel inhibitor from the green mamba snake, *Dendroaspis augusticeps* (green), and C) Dendrotoxin I (DTX-I) a potassium channel blocker from a snake (blue). Peptides are superimposed across the backbone and disulfide bonds indicated in orange. Disulfide connectivity for CaC and Dendrotoxin I is indicated in the sequences. Residue important for activity boxed for BPTI and CaC.

Calcicludine (CaC), a 60 amino acid peptide isolated from the green mamba venom (Dendroaspis augusticeps), irreversibly inhibits L-type calcium channels (IC_{50} -90 nM), without affecting the voltage-dependence or kinetics of the current. However, even at saturating toxin concentration, block was incomplete (~60%), indicating either a partial occlusion of the pore or an effect on channel gating. Recent data suggest that CaC interacts with multiple transmembrane domains of the L-type VSCC to mediate either a partial occlusion of the conductance pathway or a reduction in the steady-state open probability of the L-type VSCC.⁴⁵ CaC block is both tissue and species dependent.⁴⁵ Structurally, CaC is unrelated to calcium channel blocking peptides isolated from marine snails, spiders or other snakes. Instead it exhibits structural homology to a number of protease inhibitors such as the bovine pancre-atic trypsin inhibitor (BPTI)^{49,50} and the dendrotoxin family of snake toxins that inhibit the K⁺ channel.⁵¹ The secondary structural features shared by these three peptides include a short 3–10 helix, a hairpin β -sheet twisted 180° and a regular α -helix.⁵¹ Closer examination of the secondary structure of dendrotoxin-I and CaC they differ at the N-terminus. N-terminal chimeras between CaC and dendrotoxin indicate that differences in distribution of N-terminal cationic charges underlies their L-type calcium channel or potassium channel preferences^{51,52} (Fig. 4). Interestingly, three of the four prolines in the CaC are in the N-terminal region, which also includes a tryptophan previously identified to be involved in TxVII,^{17,28} calcispetine and FS2,⁴⁷ affinity for the L-type VSCC. However, the precise role for these residues in CaC remains to be elucidated.



Figure 5. Sequence alignment and ribbon diagrams for selective N-type voltage-sensitive calcium channel blockers from three different cone snail species, A) CVID from *C. catus*, B) GVIA from *C. geographus* and C) MVIIA from *C. magus*. Disulfide bond connectivity (yellow), residues important for activity (yellow boxes) and sequence homology across two peptides (red) and three peptides (blue) are indicated.

DW13.3 is a74 residue peptide isolated from the venom of the spider *Filistata hibernalis* that contains 12 cysteines.⁵³ It causes a potent and reversible inhibition of Ca_v2.1, Ca_v2.2, Ca_v1.2 and Ca_v2.3 expressed in *Xenopus* oocytes with IC₅₀ values of 4.3, 14.4, 26.8 and 96.4 nM, respectively. The dose-response data indicate that the peptide binds in a 1:1 manner, producing different extents of block at saturating concentrations, being most effective at Ca_v1.2. Structurally, DW13.3 differs from other calcium channel peptide toxins, but it has the same broad specificity across different voltage-sensitive calcium channel subtypes as that of ω -Aga IIIA, a 76 residue peptide isolated from the funnel web spider *A. aperta*.⁵⁴⁻⁵⁶ Despite the lack sequence homology, they both have an overall positive charge and a hydrophobic core of 12 cysteine residues forming six disulfide bridges. These six disulfide bonds again appear to maintain a conserved three-dimensional fold from which to present amino acids side chains in specific orientations.

N-Type VSCC Antagonists

Toxins that selectively target the N-type voltage-sensitive calcium channel have mainly been isolated from cone snails (ω -conotoxin), whereas a number of nonselective inhibitors for this channel have been found in both snake and spider venoms. ω -Conotoxin inhibitors have been identified from a number of different fish hunting cone snails, including GVIA from *Conus geographus*,^{57,58} MVIIA from *Conus magus*,⁵⁹ CVID from *Conus catue*¹⁶ and CnVIIA from *Conus consors*¹⁵ (see Table 2). All ω -conotoxins identified to date are 25–27 amino acid residues long but specific variations in primary sequence can be accommodated without affecting potency, selectivity or the structural core of the peptide (Fig. 5). As found for snake and the spider toxins, the lack of sequence homology among ω -conotoxins suggests that the overall three-dimensional structure and charge distribution underpin their interaction with the N-type VSCC. Interestingly, the two ω -conotoxins that display most sequence homology (MVIIA and MVIIC) (Table 2) target quite different VSCCs (Ca_v2.2 and Ca_v2.1, respectively). Whereas ω -conotoxins GVIA and MVIIA inhibit the same calcium channel subtype despite remarkably low sequence homology (Table 2).

All the ω -conotoxins are characterised by a common cysteine scaffold that stabilises the four-loop frame work (Fig. 5). This configuration defines the canonical ω -conotoxin fold, which comprises a triple-stranded β -sheet/inhibitory cysteine-knot frame work^{60,61} that has also been found in peptides such as PVIIA (a K*-channel blocker from *Conus. purpurascens*,^{62,63} and the cyclic cysteine knot peptide Kalata.⁶⁴ Interestingly, independent of sequence or structural homology, the affinity of all ω -conotoxins for the N-type (Ca_x2.2) calcium channel is reduced by the presence of the $\alpha_2\delta$ auxilary subunit.⁶⁵

Structure Activity Studies at the N-Type VSCC

Only limited information is available on the location of the ω -conotoxin binding site on the N-type calcium channel protein. By using a chimeric approach, Ellinor et al⁵ showed that the outer vestivule of the pore region in the third domain of the N-type calcium channel α_1 subunit contained amino acid residues that appeared to contribute to conotoxing block. Additional residues in this region were implicated by Feng et al.⁶⁶ However, it is likely that other parts of the N-type calcium channel are involved in the docking of the blocking molecules.

Several groups have undertaken extensive studies of the structure-activity relationship (SAR) of ω -conotoxins to identify all residues important for binding to the N-type calcium channel (for review see ref. 67). These SAR investigations have mainly consisted of alanine scans and then further probing of positions found to influence binding. Initially these studies were followed by CD-spectroscopy, but more recently NMR studies have been used to identify structural perturbations that may have accompanied residue replacements.

The first and most important residue identified to be crucial for ω -conotoxin binding to the N-type VSCC was the conserved Tyr13. Replacing the Tyr13 with Phe and the binding drops affinity by 2–3 orders of magnitude in GVIA,²² MVIIA²⁶ and CVID,⁶⁸ and Ala replacement decreased binding another order of magnitude.^{22,25} The orientation of Tyr13 is also important, since D-Tyr13 analogues of MVIIA (N-type specific) and MVIIC (P/Q-type selectivie) had 3–4 orders of magnitude lower affinity than the native conotoxin.⁶⁹ In these analogues the shape of loop 2 was severely distorted. The decrease in binding of D-Tyr13-MVIIA for the N-type calcium channel appears to stems from the loss of either (i) a hydrogen bond from the hydroxyl group on Tyr13, (ii) a hydrophobic interaction from Leu11 and/or (iii) a putative electrostatic interaction from Arg10.⁶⁹

Lys2 is another conserved residue in N-type selective ω -conotoxins that contributes to activity. Replacing Lys2 with an alanine in either GVIA,²³⁻²⁵ or MVIIA^{23,26} dramatically reduces affinity. Arginine and ornithine can effectively replace lysine, but bulkier aromatic residues hinder binding.⁷⁰ Leucine and norleucine also reduce binding affinity, indicating that side chain length and charge at position 2 contribute to GVIA binding.⁷⁰ Lys2 may interact with the VSCC in other ω -conotoxins including MVIIA, CVID and CnVIIA. Alternatively, the positive charge in these latter peptides could interact with Asp14 in loop 2 to provide a structural contribution.

Another residue conserved accross ω -conotoxins that target the N-type calcium channel is glycine 5. One study showed that replacing the glycine with the more sterically hindered alanine resulted in difficulty oxidising the peptide and a nonnative disulfide connectivity dominating the oxidised products. This is not surprising since the glycine is an integral part of the type II β -turn that extends across residue 3–6 in the ω -conotoxins, and fixing the ϕ -angle in a negative position is most likely unfavourable for the native conformation.²⁵ However, replacing the glycine with a D-alanine, does not hinder folding in either GVIA²⁵ or CVID (Lewis et al, unpublished data) and these peptides retain activity at the N-type calcium channel.

Loop Integrity in (0-Conotoxins.

A study by Nielsen et al⁷¹ of 14 loop splice hybrids of MVIIA (N-type inhibitor) and MVIIC (P/Q-type inhibitor) revealed that loop 2 and loop 4 make the greatest contribution to subtype selectivity, whereas loops 1 and 3 contributions are negligible. Peptides with homogeneous combinations of loop 2 and 4 display clear selectivity, while those with heterogeneous

combinations of loops 2 and 4 are less discriminatory.⁷¹ The recently published structure of CVID¹⁶ shows that the orientation of loop 2 in relation to loop 4 in this peptide is quite different from previously published structures of ω -conotoxins. Two additional hydrogen bonds were identified in CVID that position loop 4 closer to loop 2 and introduce a "kink"¹⁶ which is not seen in either GVIA⁷²⁻⁷⁶ or MVIIA.⁷⁷⁻⁷⁹ GVIA, having a slightly larger loop 4 instead shows preference for a "kink" in the opposite direction.⁷⁶

Other N-Type VSCC Inhibitors

Peptides belonging to the inhibitory cysteine knot family that inhibit N-type calcium channels have been identified in assassin bug venom. Three novel peptides named Ado1, Ptu1 and Iob1 have been isolated⁸⁰ and the solution structure of Ptu1 determined by NMR.⁸¹ Despite the fact that these peptides have low sequence homology with the ω -conotoxins, they have a similar four-loop framework. The three peptides have quite high sequence homology, despite coming from different *Reduviiae genera*. Ptu1 and Ado1 are basic peptides, whereas Iob1 is neutral. All the three peptides have one or more aspartic acids in the N-terminal region, which is homologous to PnVIB from *C. pennaceus.*⁸² CD spectroscopy indicated that Ptu1 has less β -sheet than ω -conotoxins.⁸⁰ The solution structure confirmed this, with the only secondary structure being a β -sheet region comprising two antiparallel β -strands.⁸¹ Ptu1 lacks most of the residues shown to be important for ω -conotoxin binding to the N-type calcium channel, including equivalents of Tyr13 or Lys2.⁸⁰ Despite these differences, Ptu1 shares pharmacological specificity reminiscent of MVIIA and GVIA, with 300 nM Ptu1 inhibiting ~50% of Ba²⁺ current through N-type VSCCs expressed in BHK cells. However, neither Ado1 nor Ptu1 displace binding of ¹²⁵I-GVIA to N-type calcium channel in rat brain membrane (personal communication).

The spider toxins ω -grammotoxin-SIA⁸ isolated from the Chilean tarantula *Grammostola* spatulata or *Phrixotrichus spatulata*, ω -agatoxinIIIA⁸³ from the funnel web spider Agelenopsis aperta⁸³ and Huwentoxin-I isolated from the chinese spider Selenocosmia huwena⁸⁴ have also been found to block N-type (and P/Q-type) VSCCs. NMR solution of the two peptides ω -grammotoxin-SIA⁸⁵ and Huwentoxin-I,⁸⁶ indicates that these toxins share the 'inhibitory cysteine knot' motif characteristic for the ω -conotoxins. Both peptides contain the antiparallel triple stranded β -sheet stabilised by the cysteine knot.

P/Q-Type VSCC Antagonists

ω-Conotoxins

 ω -Conotoxins MVIIC and MVIID from *C. magus*, and SVIB from *Conus striatus* preferentially target the P/Q-type calcium channel.⁸⁷ Despite this difference in selectivity, they possess the consensus inhibitory cysteine knot structure found in ω -conotoxins selective for the N-type calcium channel.⁷¹ To start to understand VSCC subtype differentiation among ω -conotoxins, we compared the structure of MVIIA to SVIB and a synthetic hybrid, SNX-202, which has altered specificity for both VSCC subtypes.⁷⁹ The secondary structures of the three peptides are almost identical, consisting of a triple-stranded β -sheet and several turns. The three-dimensional structures of SVIB and MVIIA are likewise quite similar, but subtle differences including a change in the relative orientation between loops 2 and 4 are likely to underlie the selectivity differences among the peptides.

From the above structural studies and a large number of other studies of molecules within this family, it is apparent that the ω -conotoxins form a consensus structure despite differences in sequence and VSCC subtype specificity. This indicates that the ω -conotoxin macrosites for the N/P/Q-subfamily of VSCCs are most likely related, with specificity for receptor targets being conferred by the positions of functional sidechains on the surface of the peptides. Structural studies of the type described above are likely to lead to the development of second-generation analogues which may overcome some of the side-effects associated with intrathecal delivery of ω -conotoxins such as MVIIA.



Figure 6. Comparison of two P/Q-type calcium channel inhibitors from a snail and a spider. A) MVIIC from the fish hunting cone snail *C. magus*, and B) ω-Aga IVB from the funnel web spider *Agenelopsis apertal*. Peptides are superimposed over the heavy backbone atoms of residues 5–15 of ω-Aga IVB and residues 1–12 of MVIIC. Disulfide bond connectivity (yellow) and the disordered N- and C-terminal of ω-Aga IVB are indicated. Highlighted residues for MVIIC are believed important for binding to the P/Q-type VSCC.

Spider Toxins

 ω -Aga-IVA and ω -Aga-IVB were the first spider peptides identified to specifically inhibit the P-type calcium current in the brain. These toxins block P-type channel activity by antagonizing activation gating and likely act at a region other than the pore.⁸ Indeed, Bourinet et al⁶ showed that insertion of two amino acid residues (proline and asparagine) through alternate splicing in the extracellular domain IV S4-S4 linker region dramatically reduces ω -Aga-IVA sensitivity of transiently expressed α_{1A} (Ca_v2.1) calcium channels. These residues thus act as a molecular switch between P-type and Q-type calcium channel phenotypes with regard to toxin sensitivity, and indicate a site of action outside of the pore region. Unlike the very poorly reversible pore blocking conotoxins, block by ω -Aga-IVA (and ω -grammotoxin SIA) can be reversed by application of strong membrane depolarisations which are thought to dislodge these toxins from their sites of action.⁸

The solution structure of ω -Aga-IVB shows that apart from a long and disordered N- and C-terminal, the peptide has a well-defined core which again is structurally stabilised with a network of disulfide bonds. This configuration produces a structure strikingly similar to the solution structure of MVIIC (Fig. 6).⁸⁸ One face of the molecule has a cluster of basic residue that has been suggested to be involved in the binding interaction with the channel.^{89,90}

R-Type VSCCC Antagonists

The R-type calcium channel is the least defined of the six identified calcium channels to date. This has partly been due to the lack of selective inhibitors. However, recently a 41 amino acid peptide (SNX-482) was isolated from the venom of the African tarantula, *Hysteraocrates gigas.*⁹¹ SNX-482 was found to be structurally homologous to the spider toxins grammatoxin SIA⁸ and hanatoxin⁹² that block calcium and potassium channels, respectively by affecting channel gating. However, SNX-482 was found to completely and irreversibly inhibit expressed

R-type calcium channel current with an IC_{50} ~20 nM⁹¹ and is now being used as a tool⁹³ to unravel the physiological role of the α_{1E} calcium channel, which is widely distributed in the brain.⁹⁴⁻⁹⁶ Bourinet et al⁹⁷ confirmed that SNX-482 is indeed a gating-modifer reminiscent of grammotoxin SIA, ω -Aga-IVA and hanatoxin, and can be reversed by strong membrane depolarization. They also showed, using chimeric calcium channel α_1 subunits, that the toxin needs to interact with both domain III and IV of the α_{1E} subunit to influence channel gating.⁹⁷ SNX-482 applied to L-type calcium channels caused an incomplete block (~25%) at 200 nM.⁹⁷ Despite the lack of selectivity at the R-type calcium channel, SNX-482 is useful in further characterising the role of an important component of this poorly characterised calcium channel.

T-Type Antagonists

Since the cloning of the T-type calcium channel⁹⁸⁻¹⁰⁰ it has been possible to screen this channel for selective inhibitors. Kuroxin, identified by Chuang and coworkers (1998) in the venom of the South African scorpion *Parabuthus transvaalicus*, inhibits the T-type current by modifying channel gating.¹⁰¹ This 63 amino acid residues peptide has eight Cys and is most likely a member of the cysteine knot family of peptides. Comparing kurtoxin with other previously described toxins suggests that it is closely related to the α -scorpion toxins, a family of toxins that slow inactivation of sodium channels, but are also known as gating modifiers.^{101,102} While kurtoxin acts on the low-threshold α_{1G} and α_{1H} calcium channels, it also partially inhibits the high-threshold N-type, P-type and L-type currents¹⁰³ in rat peripheral and central neurones. Despite lack of selectivity, kurtoxin is a promising tool for functional and structural studies of this low-threshold calcium current.

Conclusions and Future Prospects

Peptide toxins that selectively block voltage sensitive calcium channels have contributed enormously to our understanding of the role of specific calcium channels in normal and pathological conditions. Several members of the ω -conotoxin class of calcium channel blockers are currently in clinical trials for chronic pain. While they are particularly efficacious when delivered intrathecally, side effects may limit their usage. Future advances will come with the discovery of new probes for VSCC subtypes, particularly those that are more selective for pain pathways and disease states.

References

- 1. Catterall WA. Structure and regulation of voltage-gated Ca²⁺ channels. Ann Rev Cell Dev Biol 2000; 16:521-55.
- 2. Olivera BM, Miljanich GP, Ramachandran J et al. Calcium channel diversity and neurotransmitter release: the ω-conotoxins and ω-agatoxins. Annu Rev Biochem 1994; 63:823-67.
- 3. Adams ME, Myers RA, Imperial JS et al. Toxityping rat brain calcium channels with omega-toxins from spider and cone snail venoms. Biochemistry 1993; 32:12566-70.
- 4. Zamponi GW. Antagonist sites of voltage dependent calcium channels. Drug Dev Res 1997; 42:131-143.
- 5. Ellinor PT, Zhang JF, Horne WA et al. Structural determinants of the blockade of N-type calcium channels by a peptide neurotoxin. Nature 1994; 372:272-5.
- 6. Bourinet E, Soong TW, Sutton K et al. Splicing of α_{1A} subunit gene generates phenotypic variants of P- and Q-type calcium channels. Nat Neurosci 1999; 2:407-15.
- 7. Li-Smerin Y, Swartz KJ. Gating modifier toxins reveal a conserved structural motif in voltage-gated Ca^{2+} and K⁺ channels. Proc Natl Acad Sci USA 1998; 95:8585-9.
- McDonough SI, Lampe RA, Keith RA et al., Voltage-dependent inhibition of N- and P-type calcium channels by the peptide toxin ω-grammotoxin-SIA. Mol Pharmacol 1997; 52:1095-104.
- 9. Olivera BM, McIntosh JM, Cruz LJ et al. Purification and sequence of a presynaptic peptide toxin from Conus geographus venom. Biochemistry 1984; 23:5087-90.
- Olivera BM, Gray WR, Zeikus R et al. Peptide neurotoxins from fish-hunting cone snails. Science 1985; 230:1338-43.
- 11. Olivera BM, Cruz LJ, de Santos V et al. Neuronal calcium channel antagonists. Discrimination between calcium channel subtypes using omega-conotoxin from Conus magus venom. Biochemistry 1987; 26:2086-90.

- Hillyard DR, Monje VD, Mintz IM et al. A new Conus peptide ligand for mammalian presynaptic Ca²⁺ channels. Neuron 1992; 9:69-77.
- Ramilo CA, Zafaralla GC, Nadaski L et al. Novel α- and ω-conotoxins from Conus striatus venom. Biochemistry 1992; 31:9919-26.
- Fox JA. Novel ω-conopeptides reduced field potential amplitudes in the rat hippocampal slice. Neurosci Lett 1994; 165:157-60.
- Favreau P, Gilles N, Lamthanh H et al. A new ω-conotoxin that targets N-type voltage-sensitive calcium channels with unusual specificity. Biochemistry 2001; 40:14567-75.
- Lewis RJ, Nielsen KJ, Craik DJ et al. Novel ω-conotoxins from Conus catus discriminate among neuronal calcium channel subtypes. J Biol Chem 2000; 275: 35335-44.
- Fainzilber M, Lodder JC, van der Schors RC et al. A novel hydrophobic ω-conotoxin blocks molluscan dihydropyridine-sensitive calcium channels. Biochemistry 1996; 35:8748-52.
- Abbott JR, Litzinger MJ. Different ω-conotoxins mark the development of Swiss Webster mouse cortex suggesting N-type voltage sensitive calcium channel subtypes. Int J Dev Neurosci 1994; 12:43-7.
- 19. Mouhat S, Jouirou B, Mosbah A, De Waard M, Sabatier J-M. Diversity of folds in animal toxins acting on ion channels. Biochem J 2004; 378:717-726.
- 20. Lewis RJ, Garcia ML. Therapeutic potential of venom peptides. Nature Reviews Drug Discovery 2003; 2:790-802.
- 21. Terlau H, Olivera BM. Conus venoms: A rich source of novel ion channel-targeted peptides. Physiol Rev 2004; 84:41-68.
- 22. Kim JI, Takahashi M, Ogura A et al. Hydroxyl group of Tyr¹³ is essential for the activity of ω-conotoxin GVIA, a peptide toxin for N-type calcium channel. J Biol Chem 1994; 269:23876-8.
- 23. Kim JI, Takahashi M, Martin-Moutot N et al. Tyr¹³ is essential for the binding of ω-conotoxin MVIIC to the P/Q-type calcium channel. Biochem Biophys Res Commun 1995; 214:305-9.
- 24. Sato K, Park NG, Kohno T et al. Role of basic residues for the binding of ω-conotoxin GVIA to N-type calcium channels. Biochem Biophys Res Commun 1993; 194:1292-6.
- Lew MJ, Flinn JP, Pallaghy PK et al. Structure-function relationships of ω-conotoxin GVIA. Synthesis, structure, calcium channel binding, and functional assay of alanine-substituted analogues. J Biol Chem 1997; 272:12014-23.
- Nadasdi L, Yamashiro D, Chung D et al. Structure-activity analysis of a Conus peptide blocker of N-type neuronal calcium channels. Biochemistry 1995; 34:8076-81.
- 27. Sasaki T, Feng ZP, Scott R et al. Synthesis, bioactivity, and cloning of the L-type calcium channel blocker ω-conotoxin TxVII. Biochemistry 1999; 38:12876-84.
- Kobayashi K, Sasaki T, Sato K et al. Three-dimensional solution structure of ω-conotoxin TxVII, an L- type calcium channel blocker. Biochemistry 2000; 39:14761-7.
- Kohno T, Sasaki T, Kobayashi K et al. Three-dimensional structure in solution of the δ-conotoxin TxVIA. J Biol Chem 2002; 277:36387-91.
- Hansson K, Ma X, Eliasson L et al. The first γ-carboxyglutamic acid-containing contryphan. A selective L-type calcium ion channel blocker isolated from venom of Conus marmoreus. Biochem J 2004; 270: 32453-63.
- Jimenez EC, Olivera BM, Gray WR, Cruz LJ. Contryphan is a D-tryptophan containing conus peptide. J Biol Chem 1996; 27:28002-5.
- 32. Eliseo T, Cicero DO, Romeo C et al. Solution structure of the cyclic peptide contryphan- Vn, a Ca²⁺-dependent K⁺ channel modulator. Biopolymers 2004; 74:189-98.
- 33. Grant MA, Hansson K, Furie BC et al. The metal-free and calcium bound structures of a γ-carboxyglutamic acid-containing contryphan from Conus marmoreus, glacontryphan-M. J Biol Chem 2004; 279:32464-73.
- Endo T, Tamiya N. Current view on the structure-function relationship of postsynaptic neurotoxins from snake venoms. Pharmacol Ther 1987; 34:403-451.
- 35. Dufton MJ, Hider RC. Structure and pharmacology of elapid cytotoxins. Pharmacol Ther 1988; 36:1-40.
- 36. Ruoppolo M, Talamo F, Pucci P et al. Slow folding of three-fingered toxins is associated with the accumulation of native disulfide-bonded intermediates. Biochemistry 2001; 40:15257-66.
- Harrison PM, Sternberg MJ. The disulphide β-cross: from cystine geometry and clustering to classification of small disulphide-rich protein folds. J Mol Biol 1996; 264:603-23.
- Strydom DJ. The amino-acid sequence of a short-neurotoxin homolo from Dendroaspis polylepis polylepis (black mamba) venom. Eur J Biochem 1977; 76:99-106.
- Joubert FJ, Taljaard N. The complete primary structures of two reduced and S-carboxymethylated Angusticeps-type toxins from Dendroaspis angusticeps (green mamba) venom. Biochim Biophys Acta 1980; 623:449-56.

- Karlsson E, Mbugua PM, Rodriguez-Ithurralde D. Anticholinesterase toxins. Pharmacol Ther 1985; 30:259-76.
- Spedding M. Assessment of "Ca²⁺-antagonist" effects of drugs in K⁺-depolarized smooth muscle. Differentiation of antagonist subgroups. Naunyn Schmiedebergs Arch Pharmacol 1980; 318:234-40.
- 42. Garcia MC, Hernandez-Gallegos Z, Escamilla J et al. Calciseptine, a Ca²⁺ channel blocker, has agonist actions on L-type Ca²⁺ currents of frog and mammalian skeletal muscle. J Membr Biol 2001; 184:121-9.
- Mintz IM, Venema VJ, Adams ME et al. Inhibition of N- and L-type Ca²⁺ channels by the spider venom toxin ω-Aga-IIIA. Proc Natl Acad Sci USA 1991; 88:6628-31.
- 44. deWeille JR, Schweitz H, Maes P et al. Calciseptine, a peptide isolated from black mamba venom, is a specific blocker of the L-type calcium channel. Proc Natl Acad Sci USA 1991; 88:2437-40.
- Stotz SC, Spaetgens RL, Zamponi GW. Block of voltage-dependent calcium channel by the green mamba toxin calcicludine. J Membr Biol 2000; 174:157-65.
- 46. Kini RM, Caldwell RA, Wu QY et al. Flanking proline residues identify the L-type Ca²⁺ channel binding site of Calciseptine and FS2. Biochemistry 1998a; 37:9058-63.
- 47. Kini RM. Proline brackets and identificatioin of potential functional sites in proteins: toxins to therapeutics. Toxicon 1998b; 36:1659-70.
- Albrand JP, Blackledge MJ, Pascaud F et al. NMR and restrained molecular dynamics study of the three-dimensional solution structure of toxin FS2, a specific blocker of the L-type calcium channel, isolated from black mamba venom. Biochemistry 1995; 34:5923-37.
- 49. Schweitz H, Heurteaux C, Bois P et al. Calcicludine, a venom peptide of the Kunitz-type protease inhibitor family, is a potent blocker of high-threshold Ca²⁺ channels with a high affinity for L-type channels in cerebellar granule neurons. Proc Natl Acad Sci USA 1994; 91:878-82.
- 50. Gilquin B, Lecoq A, Desne F et al. Conformational and functional variability supported by the BPTI fold: solution structure of the Ca²⁺ channel blocker calcicludine. Proteins 1999; 34:520-32.
- Nishio H, Katoh E, Yamazaki T et al. Structure-activity relationships of calcicludine and dendrotoxin-I, homologous peptides acting on different targets, calcium and potassium channels. Biochem Biophys Res Commun 1999; 262:319-21.
- 52. Katoh E, Nishio H, Inui T et al. Structural basis for the biological activity of dendrotoxin-I, a potent potassium channel blocker. Biopolymers 2000; 54:44-57.
- Sutton KG, Siok C, Stea A et al. Inhibition of neuronal calcium channels by a novel peptide spider toxin, DW13.3. Mol Pharmacol 1998; 54:407-18.
- 54. Cohen CJ, Ertel EA, Smith MM et al. High affinity block of myocardial L-type calcium channel gating currents with spider toxin ω-Aga-IIIA: advantages over 1, 4-dihydropyridines. Mol Pharmacol 1992; 42:947-51.
- 55. Ertel EA, Smith MM, Leibowitz MD et al. Isolation of myocardial L-type calcium channel gating currents with the spider toxin ω-Aga-IIIA. J Gen Physiol 1994; 103:731-53.
- 56. Mintz IM. Block of Ca channels in rat central neurons by the spider toxin ω-Aga-IIIA. J Neurosci 1994; 14:2844-53.
- 57. Cruz LJ, Gray WR, Olivera BM et al. Conus geographus toxins that discriminate between neuronal and muscle sodium channels. J Biol Chem 1985; 260:9280-8.
- Cruz LJ, Olivera BM. Calcium channel antagonists. ω-Conotoxin defines a new high affinity site. J Biol Chem 1986; 261:6230-3.
- McCleskey EW, Fox AP, Feldman DH et al. ω-Conotoxin: direct and persistent blockade of specific types of calcium channels in neurons but not muscle. Proc Natl Acad Sci USA 1987; 84:4327-31.
- 60. Pallaghy PK, Nielsen KL, Craik DJ et al. A common structural motif incorporating a cystine knot and a triple-stranded β-sheet in toxic and inhibitory polypeptides. Protein Sci 1994; 3:1833-9.
- 61. Norton RS, Pallaghy PK. The cystine knot structure of ion channel toxins and related polypeptides. Toxicon 1998; 36:1573-83.
- 62. Terlau H, Shon KJ, Grilley M et al. Strategy for rapid immobilization of prey by a fish-hunting marine snail. Nature 1996; 381:148-51.
- 63. Scanlon MJ, Naranjo D, Thomas L et al. Solution structure and proposed binding mechanism of a novel potassium channel toxin κ-conotoxin PVIIA. Structure 1997; 5:1585-97.
- 64. Saether O, Craik DJ, Campbell ID et al. Elucidation of the primary and three-dimensional structure of the uterotonic polypeptide kalata B1. Biochemistry 1995; 34:4147-58.
- 65. Mould J, Yasuda T, Schroeder CI et al. The α₂δ auxiliary subunit reduces affinity of ω-conotoxins for recombinant N-type (Ca₄2.2) calcium channels. J Biol Chem 2004; 279:34705-14.
 66. Feng ZP, Hamid J, Doering CJ et al. Residue Gly¹³²⁶ of the N-type calcium channel α1B subunit
- 66. Feng ZP, Hamid J, Doering CJ et al. Residue Gly¹³²⁰ of the N-type calcium channel α1B subunit controls reversibility of ω-conotoxin GVIA and MVIIA block. J Biol Chem 2001; 276:15728-35.
- 67. Nielsen KJ, Schroeder T, Lewis R. Structure-activity relationships of ω-conotoxins at N-type voltage-sensitive calcium channels. J Mol Recognit 2000; 13:55-70.

- 68. Adams DJ, Smith AB, Schroeder CI et al. ω-Conotoxin CVID inhibits a pharmacologically distinct voltage-sensitive calcium channel associated with transmitter release from preganglionic nerve terminals. J Biol Chem 2003; 278:4057-62.
- 69. Nielsen KJ, Adams DA, Alewood PF et al. Effects of chirality at Tyr¹³ on the structure-activity relationships of ω-conotoxins from Conus magus. Biochemistry 1999; 38:6741-51.
- Flinn JP, Pallaghy PK, Lew MJ. Roles of key functional groups in ω-conotoxin GVIA synthesis, structure, and functional assay of selected peptide analogues. Eur J Biochem 1999; 262:447-55.
- Nielsen KJ, Adams D, Thomas L et al. Structure-activity relationships of ω-conotoxin MVIIA, MVIIC and 14 loop splice hybrids at N and P/Q-type calcium channels. J Mol Biol 1999; 289:1405-21.
- 72. Skalicky JJ, Metzler WJ, Ciesla DJ et al. Solution structure of the calcium channel antagonist ω-conotoxin GVIA. Protein Sci 1993; 2:1591-603.
- Sevilla P, Bruix M, Santoro J et al. Three-dimentional structure of ω-conotoxin GVIA determined by ¹H NMR. Biochem Biophys Res Commun 1993; 192:1238-44.
- 74. Pallaghy PK, Duggan BM, Pennington MW et al. Three-dimentional structure in solution of the calcium channel blocker ω-conotoxin. J Mol Biol 1993; 234:405-20.
- 75. Davis JH, Bradley EK, Miljanich GP et al. Solution structure of ω-conotoxin GVIA using 2-D NMR spectroscopy relaxation matrix analysis. Biochem 1993; 32:7396-405.
- Pallaghy PK, Norton RS. Refined solution structure of w-conotoxin GVIA: Implications for calcium channel binding. J Pept Res 1999; 53:343-51.
- 77. Basus VJ, Nadaski L, Ramachadran J et al. Solution structure of ω-conotoxin MVIIA using 2D NMR spectroscopy. FEBS Lett 1995; 370:163-169.
- Kohno T, Kim JI, Kobayashi K et al. Three-dimentional structure in solution of the calcium channel blocker ω-conotoxin MVIIA. Biochemistry 1995; 34:10256-65.
- Nielsen KJ, Thomas L, Lewis R et al. A consensus structure for ω-conotoxins with different selectivities for voltage-sensitive calcium channel subtypes: comparison of MVIIA, SVIB and SNX-202. J Mol Biol 1996; 263:297-310.
- 80. Corzo G, Adachi-Akahane S, Nagao T et al. Novel peptides from assassin bugs (Hemiptera: Reduviidae): isolation, chemical and biological characterization. FEBS Lett 2001; 499:256-61.
- Bernard C, Corzo G, Mosbah A et al. Solution structure of Ptu1, a toxin from the assassin bug Peirates turpis that blocks the voltage-sensitive calcium channel N-type. Biochemistry 2001; 40:12795-800.
- 82. Kits KS, Lodder JC, van der Schors RC et al. Novel ω-conotoxins block dihydropyridine-insensitive high voltage-activated calcium channels in molluscan neurons. J Neurochem 1996; 67:2155-63.
- 83. Yan L, Adams ME. The spider toxin ω-Aga IIIA defines a high affinity site on neuronal high voltage-activated calcium channels. J Biol Chem 2000; 275:21309-16.
- 84. Peng K, Chen X-D, Liang S-P. The effect of Huwentoxin-I on Ca²⁺ channels in differentiated NG108-15 cells, a patch-clamp study. Toxicon 2001; 39:491-498.
- 85. Takeuchi KK, Park EJ, Lee CW et al. Solution structure of ω -grammotoxin SIA, a gating modifier of P/Q and N-type Ca²⁺ channel. J Mol Biol 2002; 321:517-526.
- Qu Y, Liang S, Ding J et al. Proton nuclear magnetic resonance studies on huwentoxin-I from the venom of the spider Selenocosmia huwena: 2. Three-dimensional structure in solution. J Protein Chem 1997; 16:565-74.
- Miljanich GP, Ramachandran J. Antagonists of neuronal calcium channels: structure, function, and therapeutic implications. Annu Rev Pharmacol Toxicol 1995; 35:707-34.
- Reily MD, Thanabal V, Adams ME. The solution structure of ω-Aga-IVB, a P-type calcium channel antagonist from venom of the funnel web spider, Agelenopsis aperta. J Biomol NMR 1995; 5:122-32.
- 89. Reily MD, Holub KE, Gray WR et al. Structure-activity relationships for P-type calcium channel-selective ω-agatoxins. Nat Struct Biol 1994; 1:853-6.
- 90. Narasimhan L, Singh J, Humblet C et al. Snail and spider toxins share a similar tertiary structure and 'cystine motif'. Nat Struct Biol 1994; 1:850-2.
- 91. Newcomb R, Szoke B, Palma A et al. Selective peptide antagonists of the class E calcium channel from the venom of the Tarantula Hysterocrates gigas. Biochemistry 1998; 37:15353-62.
- 92. Swartz KJ, McKinnon R. An inhibitor of the Kv2.1 potassium channel isolated from the venom of a Chilean tarantula. Neuron 1995; 15:941-949.
- 93. Wang G, Dayanithi G, Newcomb R et al. An R-type Ca²⁺ current in neurohypophysial terminals preferentially regulates oxytocin secretion. J Neurosci 1995; 19:9235-41.
- 94. Soong TW, Stea A, Hodson CD et al. Structure and functional expression of a member of the low voltage-activate calcium channel family. Science 1993; 260:1133-6.

- 95. Williams ME, Marubio LM, Deal CR et al. Structure and functional characterisation of neuronal α_{1E} calcium channel subtypes. J Biol Chem 1994; 269:22347-57.
- 96. Yokoyama CT, Westenbroek RE, Hell JW et al. Biochemical properties and subcellular distribution of the neuronal class E calcium channel α1 subunit. J Neurosci 1995; 15:6419-32.
- 97. Bourinet E, Stotz SC, Spaetgens RL et al. Interaction of SNX-482 with domains III and IV inhibits activation gating of a1E (Ca_v2.3) calcium channels. Biophysical J 2001; 81:79-88.
- 98. Lambert RC, McKenna F, Maulet Y et al. Low-voltage activated Ca²⁺ currents are generated by members of the CavT subunit family (α1G/H) in rat primary sensory neurons. J Neurosci 1998; 18:8605-13.
- 99. Perez-Reyes E, Cribbs LL, Daud A et al. Molecular characterisation of a neuronal low-voltage activated T-type calcium channel. Nature 1998; 391:896-900.
- 100. Lee JH, Daud AN, Cribbs LL et al. Cloning and expression of a novel member of the low-voltage activated T-type calcium channel family. J Neurosci 1999; 19:1912-21.
- 101. Chuang RS, Jaffe H, Cribbs LL et al. Inhibition of T-type voltage-gated calcium channels by a new scorpion toxin. Nat Neurosci 1998; 1:668-74.
- 102. Meves H, Simard JM, Watt DD. Interactions of scorpion toxins with the sodium channel. Ann NY Acad Sci 1986; 479:113-32.
- 103. Sidach SS, Mintz IM. Kurtoxin, a gating modifier of neuronal high- and low-threshold Ca channels. J Neurosci 2002; 22:2023-34.

Calcium Channels in the Heart

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Introduction

In the sixties, the first Ca^{2+} currents were recorded by voltage-clamp techniques on multi-cellular cardiac strips ¹⁻⁴ It is only since 1980 that the development of enzymatic dissociation methods allowed the first electrophysiological recordings on isolated cardiac cells.³ The whole cell patch-clamp technique, developed by E. Neher and B. Sakman in 1976 ⁵ and awarded in 1991 with the Nobel prize, and the micro-electrode technique ⁶ initiated the study of voltage-gated Ca^{2+} channels. The improvement of the technique gave the first opportunity to study the activity of single channels owing to the cell-attached^{7,8-11} and the inside-out configuration.¹² The nystatin- or amphotericine B-perforated patch recordings prevent the leak of cytoplasmic molecules, nucleotides and diffusing agents in the recording pipette and then, preserves the mechanisms of regulations by second messengers.^{13,14}

S. Ringer in 1883 was the first physiologist who evidenced the crucial role of Ca²⁺ in cardiac contraction since Ca²⁺ withdrawal suppresses heart contractility. A century later, A. Fleckenstein reported that "Ca²⁺ antagonists" could mimic Ca²⁺ withdrawal.¹⁵ These drugs selectively block voltage-dependent Ca²⁺ entry through activated L-type Ca²⁺ channels.¹⁶

Influx of Ca^{2+} through voltage-dependent L-type Ca^{2+} channels plays an essential role in cardiac excitability and in coupling excitation to contraction. I_{Ca,L} contributes to the plateau phase of the action potential as well as to pacemaker activity in nodal cells.

Given the essential role of L-type Ca^{2+} channels in multiple cellular functions, it is not surprising that this protein is extensively regulated by a variety of signaling pathways.

I-Cardiac Ca²⁺ Channels in Working Myocardial Cells

Two main classes of voltage-dependent Ca^{2+} channels coexist in cardiac cells: L-and T-types. L-Type Ca^{2+} currents ($I_{Ca,L}$) are characterized by a Large conductance (25 pS) and Long lasting openings. They are activated at Larger depolarizations and highly sensitive to 1,4-dihydropyridines (DHP).

In contrary to $I_{Ca,L}$ which is largely ubiquitous in cardiac myocytes, $I_{Ca,T}$ is not so widely expressed and is more transient. T-type channels are more specific of atrial cells¹⁷ and Purkinje fibers where $I_{Ca,T}$ is the prominent voltage-dependent Ca²⁺ influx.¹⁸

L-Type Ca²⁺ Channels

Structure of L-Type Ca²⁺ Channels

The molecular biology of Ca²⁺ channels has its origins in the biochemical characterization of the skeletal muscle DHP receptor.¹⁹ The cardiac L-type Ca²⁺ channel is a multi-subunit protein complex composed of α_1 , the ion-conducting subunit, and auxiliary subunits including β , and α_2 - δ . The cardiac α_{1C} subunit was cloned from rabbit heart cDNA libraries using low stringency hybridization with the first cloned α_1 -subunit, α_{1S} , as probe.²⁰ Like Na⁺ channels α_1 -subunit, it contains four internal repeats called Domains I, II, III and IV. Each domain
is composed of six membrane spanning segments S1 to S6 (α helix) with one particular, the voltage-sensor S4 which contains positively-charged residues every third residue.²¹ The SS1-SS2 loops (between S5 and S6) of each repeat coassembles in the membrane to constitute the pore.

Although it is generally accepted that α_{1C} is the predominant L-type α_1 in cardiac myocytes, α_{1D} -subunit has also been detected at both the mRNA and protein levels.^{22,23} α_{1D} was originally cloned from neuro-endocrine cells.²⁴

Recently, the nomenclature for voltage-dependent Ca²⁺ channels has changed and the alphabetic descriptor L-type was replaced by Ca_v1. The Ca_v1 family includes Ca²⁺ channel α_1 -subunits encoded by four separate genes Ca_v1.1, Ca_v1.2, Ca_v1.3 and Ca_v1.4 which correspond to α_{1S} , α_{1C} , α_{1D} and α_{1F} respectively.²⁵ The Ca_v1.2 gene encodes for cardiovascular α_{1C} subunits. The cardiac Ca_v1.2a and the smooth muscle Ca_v1.2b α_1 -subunits are splice variants of the same gene. This may account for the differences of DHP-sensitivity between smooth muscle and cardiac muscle L-type Ca²⁺ channels.²⁶

In addition to the pore forming subunit α_1 , there is an intra-cytoplasmic localized β -subunit. These subunits vary from 53 to 71 kDa and are encoded by four distinct genes: β_1 ,²⁷ β_2 ,²⁸ β_3 ,²⁹ and β_4 .³⁰ In cardiac muscle the β_2 -subunit predominates.^{31,32} The β -subunit binds to AID (Alpha subunit Interacting Domain), a specific sequence located in the cytoplasmic linker between Domains I and II of the α_1 -subunit.³³ The α_2 - δ subunit is an extracellularly located complex composed by an α_2 -subunit linked via a disulfide bond to a membrane-spanning δ -subunit. These two subunits are encoded by the same gene.³⁴

Structure-Function of Ca,1.2 Channels

Functional expression in heterologous systems of Ca^{2+} channels, together with structure-function studies have allowed description of the functional role of the different channels subunits. The loop between Domain II and III of α_{1C} subunit plays a key role in cardiac specific excitation-contraction coupling.³⁵ Ca²⁺ selectivity is conferred by the presence in the pore region of glutamate residues.³⁶⁻³⁸ Numerous studies have also attempted to identify the regions involved in Ca²⁺-dependent inactivation. Based on sequence homology with the Ca²⁺-binding motifs of EF hands, one homologous region was identified previously close to IVS6.³⁹ However, most of these regions are located in the carboxy terminus.^{40,41}

When coexpressed with Ca_v1.2 α_1 -subunit, β -subunits are responsible for an increase in Ca_v1.2 -current amplitude,⁴² facilitation^{43,44} and targeting of the α_1 -subunit to the plasma membrane.^{44,45} α_2 - δ seems to also increase Ca²⁺ current amplitude and accelerate the current decay kinetics.^{46,47} The effects of β and α_2 - δ subunits on Ca_v1.2 currents are cumulative.⁴⁸ Interestingly, α_2 - δ abolishes the prepulse facilitation occurring specifically with Ca_v1.2 Ca²⁺ currents.⁴⁹

Molecular determinants for Ca²⁺ antagonists have also been determined. The binding sites for DHP have been mapped in IIIS5, IIIS6 and IVS6.⁵⁰⁻⁵² Residues for phenylalkylamine (PAA) binding are located in IIIS6 and IVS6.⁵³

Auxiliary subunits are also important in the formation of high-affinity drug binding sites and their interactions.⁵⁴

Physiological Role of L-Type Ca²⁺ Channels: Excitation-Contraction Coupling

It is now well established that both the Ca²⁺ from the sarcosplamic reticulum (SR) and the Ca²⁺ entering the cell via L-type Ca²⁺ channels contribute to cardiac contraction. The activation of sarcolemmal L-type Ca²⁺ channels is a prerequisite for the initiation of contraction. ⁵⁵⁻⁵⁷ Ca²⁺ influx through these channels is the trigger of the activation of ryanodine receptors (RyR) and the subsequent release of Ca²⁺ leading to activation of contraction. This mechanism called "Ca²⁺-induced Ca²⁺-release" or CICR was extensively described by the studies of Fabiato on skinned single cardiac myocytes ".⁵⁸⁻⁶⁸ SR Ca²⁺ release is gated by Ca²⁺ current and not by gating charges.⁵⁶ Niggli and Lederer (1990) showed that CICR in cardiac muscle is not dependent on membrane voltage.⁶⁹ The amount of Ca²⁺ released is graded with the amount of Ca²⁺

influx. At high concentrations of Ca^{2+} , the CICR is inactivated and the SR release terminated.⁷⁰ These findings are explained by the existence of two binding sites for Ca^{2+} ions on RyR, an activating site and an inactivating site which turns off the Ca^{2+} release.^{66,68} In turn, SR Ca^{2+} release (in addition to Ca^{2+} entering the cell) causes L-type Ca^{2+} channel inactivation as a negative feedback to limit Ca^{2+} entry.^{71,72}

The "local control" theory of excitation-contraction was first suggested by Lederer in 1990 who mentioned the importance of the local concentrations gradients of Ca²⁺ in the junctional space.⁷³ Stern in 1992 suggested several models which could explain the local control and the graded nature of CICR.⁷⁴ He considered the colocalization of one DHPR with a cluster of RyR to form a "cluster bomb". The stoichiometry of this association was confirmed later: one single L-type Ca²⁺ channel triggers a cluster of 4 to 10 molecules of RyR₂.^{75,76}

The whole-cell intracellular Ca^{2+} transient seems to correspond to the temporal and spatial summation of Ca^{2+} "sparks"⁷⁷ triggered locally by the Ca^{2+} influx flowing through a single L-type Ca^{2+} channel.^{78,79} Ca^{2+} sparks were first described as spontaneous events due to single RyR openings.^{78,80} However, they are more likely due to the activation of a cluster of RyR release channels working as a single functional unit. Parker in 1996 has shown that a Ca^{2+} spark can activate a lateral neighbor located along a z-line.⁸¹ This means that gradation of CICR is due to the activation of different numbers of RyR clusters rather than increasing ionic fluxes through each RyR cluster and that CICR is characterized by an intrinsic positive feedback.

CICR seems to be the main mode of excitation-contraction coupling in cardiac myocytes as demonstrated by several studies based on the close correlation between $I_{Ca,L}$ and Ca^{2+} transients as a function of voltage.^{55,82-84}

Regulation of L-Type Channel Activity

β -Adrenergic Regulation

The amplitude and kinetics of $I_{Ca,L}$ depend on the channel properties as well as on voltage and ionic conditions. In addition, $I_{Ca,L}$ is tightly regulated by both physiological and pharmacological agents. To this respect, the β -adrenergic stimulation is a major pathway of regulation of the cardiac function and thereby Ca²⁺ channels. During exercise, release of catecholamines increases cardiac output by increasing the heart rate, by enhancing contractility and accelerating relaxation. β -adrenergic agonists increase cardiac $I_{Ca,L}^2$ by activating the cAMP-dependent channel phosphorylation pathway⁸⁵ of cardiac L-type Ca²⁺ channels.⁸⁶ Three types of β -adrenoreceptors have been identified on cardiac cells. β_1 and β_2 -subtypes are colocalized on cardiac myocytes, but β_1 -receptors are more abundant in the normal adult mammalian heart.⁸⁷⁻⁸⁹ The recently identified β_3 -receptors, are localized on atrial cells and seem to be involved in pathological processes.^{90,91}

 β_1 and β_2 receptors differ in their effect on Ca²⁺ currents, cytosolic Ca²⁺ and contraction.⁹² The more specific β_1 -adrenoreceptors stimulation corresponds to the classical notion of β -adrenoreceptors signaling leading to substantial phosphorylation of proteins such as L-type Ca²⁺ channels, phospholamban, I-troponin and C-protein, and responsible for the multiple effects on contraction and relaxation of the cardiac muscle. β_2 -AR stimulation seems to act only on Ca_v1.2a channels. Contrary to β_1 -adrenergic receptors that couple exclusively to the G_s protein,⁹³ β_2 -adrenergic receptors are coupled to both G_s and G_i. This latter unexpected pathway is responsible for the spatial restriction of β_2 -AR signaling.⁹⁴ The β_3 -receptor is coupled only to G_i protein and is responsible for a negative inotropic effect.⁹¹

Regulation by the Protein Kinase A

Stimulation of $I_{Ca,L}$ by β -adrenoreceptors in cardiac cells leads to enhanced single-channel activity by increasing the channel mean open time.^{8,95} Stimulation by protein kinase A (PKA) leads to a two to seven fold increase of $I_{Ca,L}$ amplitude and to a negative shift of the current

voltage-dependence of activation and inactivation.^{11,96,97} PKA phosphorylates only the 250 kDa form of the α_1 -subunit but not the truncated 200 kDa form.^{98,99} Serine 1928, located in the COOH-terminal tail of the α_1 -subunit, is essential for the PKA-induced channel phosphorylation.⁹⁹ Other studies have shown that the β -subunit is also phosphorylated in vitro²⁹ and in vivo in cardiac tissue after stimulation of the adenylyl cyclase/PKA pathway.¹⁰⁰

The Missing Link

Although numerous studies have reported PKA-induced phosphorylation of L-type Ca^{2+} channels in native cardiac cells, it has been a challenge to the reconstitute the PKA-regulation of $Ca_v 1.2 Ca^{2+}$ currents in heterologous systems. Recombinant $Ca_v 1.2$ currents are increased by only 20 to 30% by PKA-stimulation when native currents are amplified two to seven fold.¹⁰¹ There would be a missing link in the channel complex as suggested by the study of Charnet et al which showed that the coinjection of cardiac mRNA with recombinant $Ca_v 1.2$ channels in oocytes allows to recover the regulation properties.¹⁰² More recently, several studies report the need for PKA targeting to the chance of AKAPs (A-Kinase Anchoring Proteins), but it is not sufficient since the coexpression of AKAP79 with the cardiac α_1 -subunit and β_{2a} in HEK293 failed to reproduce the phosphorylation.¹⁰³

In summary, there is clear evidence that PKA can stimulate cardiac $Ca_v 1.2a$ channels via serine 1928 on the α_1 -subunit but probably other regulatory proteins contribute to this process.

Acetylcholine and Cardiac Ca²⁺ Currents

There is a strong interaction between the β -adrenergic signaling cascade and other pathways, particularly with that of the muscarinic receptor stimulation. Different studies have reported cGMP/PKG-mediated inhibition of Ca_v1.2 currents.¹⁰⁴⁻¹⁰⁸ Acetylcholine (ACh) has little effect on the basal current but strongly antagonizes the β -adrenergic- or forskolin-stimulated I_{Ca,L}.^{109,110} Part of this effect is mediated by muscarinic receptors coupled to G_i which inhibits adenylyl cyclase (AC) as confirmed recently in G_{i2} alpha gene knockout mice lacking muscarinic regulation of Ca²⁺ channels in the heart.¹¹¹

Another pathway activated by ACh is the stimulation of guanylate cyclase and the production of cGMP. Ca_v1.2 Ca²⁺ currents can be either stimulated or inhibited by the cGMP-pathway. One mechanism accounts for the stimulation of Ca²⁺ currents and reflects the cGMP-dependent inhibition of phosphodiesterase 3 (PDE3) which leads to augmentation of cAMP levels and, consequently, Ca²⁺ current potentiation.^{112,113} On the other hand, three mechanisms can explain cGMP-induced inhibition of $I_{Ca,L}$: (1) phosphorylation of the channel by PKG (cGMP-dependent protein kinase);¹¹⁴ (2) PKG-mediated activation of a phosphatase which dephosphorylates the channel; this mechanism occurs after previous PKA-stimulation;^{115,116} (3) cGMP activation of phosphodiesterase 2 (PDE2) leading to decreased cAMP levels.^{117,118}

In cardiac cells nitric oxide (NO) stimulates cGMP production by directly activating a cytoplasmic guanylate cyclase and thereby regulates $Ca_v 1.2$ currents.¹¹³ ANF, the atrial natriuretic factor, has a membrane located binding site on cardiac cells, which is a guanylate cyclase. ANF also regulates $I_{Ca,L}$ in both positive and negative ways as reported for the cGMP/PKG pathway in cardiac myocytes.¹¹⁹

Thus, the final outcome of the regulation of $I_{Ca,L}$ by phosphorylations is the result of the relative balance of protein kinase and phosphatase activity and depends on the cardiac cell type considered.

Regulation by Protein Kinase C

There is no agreement in the current literature concerning the effects of protein kinase C (PKC)-regulation on Ca_v1.2 channels.

While several studies in native cardiac cells have reported PKC-induced potentiation of $I_{Ca,L}^{120-122}$ others have shown an inhibition.¹²³ In heterologous systems, the same controversy exists concerning the stimulation¹²⁴ or inhibition of recombinant Ca²⁺ currents.¹²⁵ In vitro, both α_1 -subunit and β_2 -subunit are phosphorylated by PKC.¹²⁶ Recently, recordings of Ca_v1.2 currents in tsA-201 cells have shown that PKC produces an inhibition of $I_{Ca,L}$ through phosphorylation of threonine-27 and threonine-31 at the NH₂-terminal region of the α_1 -subunit.¹²⁷ However, these data are inconsistent with the model of the tonic inhibition exerted by the NH₂-terminal end (first 46 amino acids) in basal condition and relieved by PKC-phosphorylation.¹²⁵ Further studies will probably elucidate these discrepancies.

Regulation by Ca²⁺ Antagonists

 C_{a_v1} channels are highly sensitive to DHPs. Indeed, DHPs inhibit $I_{Ca,L}$ by preferentially binding to the inactivated state of the channel.^{128,129} DHP binding to C_{a_v1} channels is voltage dependent.¹²⁸ Also, some DHPs stimulating $I_{Ca,L}$ activity are used in academic research. These agonists, BayK8644 (-) and a novel benzoyl pyrrole FPL-64176 dramatically increase $I_{Ca,L}$ by prolonging the channel open time and slightly increasing the single-channel conductance.¹³⁰⁻¹³³ There are two other classes of Ca^{2+} antagonists, phenylalkylamines (PAA, e.g., verapamil) and benzothiazepines (BTZs e.g., diltiazem), that are also widely used as therapeutic agents. Charged compounds (i.e.verapamil) preferentially bind to the open-state of Ca^{2+} channels and are use-dependent. Neutral DHPs molecules (i.e., nitrendipine) may bind and block the channel either in the open or inactivated state and have pronounced voltage-dependent effects. These antagonists are used as vasodilatators since they preferentially act on vascular $Ca_v1 Ca^{2+}$ channels and because of the more depolarized voltage of resting smooth muscle myocytes.¹³⁴

Ca²⁺-Dependent Facilitation of I_{Ca.L}

 $Ca_v I Ca^{2+}$ channels can be positively and negatively regulated by the Ca^{2+} entering the cell and acting as a positive or negative feedback respectively. In addition to membrane depolarization and Ca^{2+} channel phosphorylation, modulation of $I_{Ca,L}$ by frequency of Ca^{2+} channel activation is probably of major importance for heart physiology. Early studies suggested that repetitive stimulations of frog atrial fibers can up-regulate Ca^{2+} channel activity.¹³⁵ Similar observations were reported in dissociated mammalian cardiac cells ¹³⁶⁻¹³⁸ and this has been confirmed later at the single channel level.¹³⁹ An increase in the rate of stimulation can produce a potentiation of I_{CaL} only when cells are stimulated from negative holding potentials.¹³⁵⁻¹⁴¹ In mammalian cardiomyocytes, the high frequency-induced potentiation of I_{CaL} consists of both a moderate increase of peak current amplitude and a marked slowing of the inactivation kinetics. This "positive staircase", not apparent with Ba²⁺ as the charge carrier, is mediated by CAMKII-dependent phosphorylation and is Ca²⁺ dependent.¹⁴²⁻¹⁴⁴

This frequency-dependent facilitation of $I_{Ca,L}$ occurs in human cardiomyocytes and is modulated by β -adrenergic stimulation. This mechanism could be responsible in part for the "Bowditch staircase" since it disappears in failing myocardium.¹⁴⁵

Ca²⁺-Dependent Inactivation of I_{Ca,L}

Decrease of I_{CaL} occurs when cells are stimulated from depolarized membrane holding potentials, reflecting a reduction of Ca^{2*} channel availability for opening because of incomplete voltage-dependent reactivation.^{136,140,146,147} Indeed, full recovery from inactivation requires more negative membrane potentials.

It should be noted that another type of voltage-dependent facilitation can occur, independently of the rate of stimulation.^{148,149} Such mechanism was evidenced in human cardiac myocytes. This facilitation by the diastolic membrane potential is favored by intracellular cAMP and reflects removal of $I_{Ca,L}$ inactivation induced by release of Ca²⁺ from the SR.¹⁵⁰

T-Type Ca²⁺ Channels in Myocardial Cells

T-Type Cardiac Channels

Two distinct families of Ca²⁺ channels have been identified in cardiac tissue. L-type Ca²⁺ channels which are essential in triggering Ca2+ release from internal stores and Low-Voltage-Activated (LVA) T-type Ca2+ channels (ICAT), whose role remains obscure either in physiological or pathophysiological conditions. Functional features of T-type Ca²⁺ channel activity include: low threshold of activation, small unitary conductance, rather slow activation and fast inactivation inducing a typical criss-crossing pattern of current traces for increasing depolarizations, negative steady state inactivation and slow deactivation kinetics. In addition, T-type currents as compared to L-type currents are more sensitive to block by mibefradil and Ni²⁺ ions. An alternative in silico cloning strategy resulted in the identification of full-length cDNAs encoding three distinct Ca_v subunits encoding T-type Ca²⁺ currents: Ca_v3.1 in rat,¹⁵¹ mouse¹⁵² and human,^{153,154} Ca_v3.2 and Ca_v3.3 in rat¹⁵⁵ and human.¹⁵⁶ Because Ca_v3.1 was identified by screening a human heart library, it has been originally considered as the cardiac T-type channel isoform. Northern blot analysis has shown the expression of Ca. 3.2 in the heart but also the presence of the Ca₄3.1 transcript. It has become an interesting question to identify which isoform(s) is coding for $I_{Ca,T}$ in cardiac cells. The molecular basis of the α_1 subunit encoding the T-type Ca2+ channel in AT-1 cells, an immortalized cell line derived from mouse atrial tissue was investigated. A comparison of the biophysical properties between I_{Ca.T} from this cell line and the Ca_y3.1/Ca_y3.2 currents¹⁵⁷ indicated that most of the basic electrophysiological properties are rather similar and not discriminative. However, detailed analysis of the recovery from inactivation as well as PCR experiments from cultured AT-1 cells indicated that $I_{Ca,T}$ in AT1 cells is generated by the Ca_v3.1 isoform.¹⁵⁷ The question was to know if this result could be extended to any cardiac cell. When comparing the properties of ICAT in native cardiovascular cells with those of recombinant currents, difficulties arise from the fact that many early studies have been either conducted in different experimental conditions or in different species. Cardiac T-type currents have also mostly been studied in cultured embryonic or neonatal myocytes because of their low expression or absence in respectively adult atrial and ventricular myocytes except in several species such as guinea pig. Subsequent studies on freshly dissociated rat cardiomyocytes during development have shown the presence of ICa_T in both atrial and ventricular myocytes during the early neonatal period. ICa_T peaks around 8 days postnatally in atrial myocytes and decreases to reach a very low density after three weeks while it completely disappears in ventricular myocytes.¹⁵⁸ I_{Ca.T} in neonatal rat atrial myocytes has low Ni2+ sensitivity (IC50 160 µM), also suggesting a linkage with the Ca.3.1 isoform. A similar result was reported in embryonic mouse and rat ventricular myocytes.^{159,160} The expression of a specific Ca_v3.1 variant (Ca_v3.1-d) was described in embryonic mouse ventricular cells.¹⁵⁹ In some early studies such as in rabbit sino-atrial,¹⁶¹ in adult guinea pig cells,¹⁶² T-currents were reported to be totally blocked by a lower concentration Ni²⁺ ions (about 40 μ M). This may suggest differential expression of Ca₂3.1 and Ca₂3.2 isoforms among cardiac tissue, differences between species or a possible developmental regulation between isoforms as suggested by Ferron et al.¹⁶⁰ One should also mention another study, using an antisense strategy, which suggested that the cardiac T-type current in three weeks post-natal rats is related to the Ca₂.3 subunit.^{163,164} This result remains puzzling since some properties such as the threshold of activation and deactivation properties markedly differ between ICa,T and Ca,2.3 currents. In addition, ICa,T from freshly dissociated neonatal rat atrial tissue was found as insensitive to the Ca $_{\rm v}2.3$ specific toxin SNX 482.¹⁵⁸ It is however worth to note that T-type channel expression in these experiments¹⁶³ was induced by insulin-like growth factor 1 (IGF-1) treatment.

It should also be mentioned that no $I_{Ca,T}$ has yet been described in adult human heart.¹⁶⁵ By contrast, a LVA Ca²⁺ current was first reported in human atria¹⁶⁶ sharing some typical properties with sodium channels such as TTX sensitivity and designated as I_{CaTTX} . Its descripTTX and Ni²⁺ in the absence of external sodium ions. In addition, there are differences between $I_{Ca,T}$ and I_{CaTTX} in terms of biophysical properties. I_{CaTTX} exhibits a run up after the rupture of the patch membrane, a lower voltage for peak current, a more negative steady state inactivation relationship, faster time constants for recovery from inactivation and a faster rate of deactivation. The molecular basis of I_{CaTTX} are unknown. Thus, whether this current is related to modified sodium channels in the absence of external sodium ions¹⁶⁸ or is it related to a new population of channels remains to be determined.

What could be the physiological role of these LVA channels in the heart? T-type channels are assumed to play a role in pacemaking activity because of their presence in sino-atrial node and the negative chronotropic effect induced by their inhibition.¹⁶¹ An interesting feature of T-type Ca²⁺ currents is related to their slow deactivation kinetics and the existence of a window current in the range of the cell membrane resting potential. In spite of their rapid kinetics of inactivation, the existence of a window current would confer a role of T-type channels in maintaining intracellular Ca²⁺ concentration.¹⁷⁰ While T-type currents do not seem to play an important role in cardiac E-C coupling¹⁷¹ they could contribute to excitability during early development,¹⁵⁹ fine tuning of basal Ca²⁺ levels and control physiological processes such as hormone secretion as previously suggested in adrenal cells.¹⁷² Their expression is also cell cycle dependent¹⁷³ and their involvement in cell growth and proliferation was suggested in both cardiac¹⁷⁴ and smooth muscle cells.¹⁷⁵ Future studies will probably look for a role of I_{Ca,T} and I_{CaTTX} in pathological conditions. I_{Ca,T} was shown to be reexpressed during experimental rat cardiac hypertrophy^{176 177} and would be expected to generate cardiac arrhythmias. It would be interesting to know if the reexpression of T-type channels is involved in the genesis or a consequence of heart remodeling.

Pharmacology of T-Type Ca²⁺ Currents

To date, no drugs showing specificity for $I_{Ca,T}$ versus $I_{Ca,L}$ have been described. Some DHPs show moderate block of $I_{Ca,T}$ for micromolar drug concentrations (see for example ref. 178). Recently, mibefradil, a tetralol derivative belonging to a structurally and pharmacologically distinct class of Ca^{2+} antagonists has been proposed for clinical use due to its particular pharmacological and cardiovascular profile. As compared to DHPs, PAAs and BTZs, mibefradil show preferential block for T-type Ca^{2+} channels.¹⁷⁹ In contrast to the other Ca^{2+} channel antagonists, mibefradil decreases heart rate without concomitant negative inotropism.¹⁸⁰ However, mibefradil is not a selective blocker of $I_{Ca,T}$. Indeed, strong voltage- and use-dependent block of $I_{Ca,L}$ in the micromolar range have been reported in cardiac cells.¹⁸¹ To this respect, mibefradil shows common properties to both DHPs and PAAs, its blocking action being enhanced by both positive membrane voltages and high frequency of current activation.¹⁸¹ The lack of specificity of mibefradil thus poses a number of interpretative problems when tackling the differential physiological role of $I_{Ca,T}$ and $I_{Ca,L}$ in cardiac physiology.

Cardiac Ca²⁺ Channels and Pacemaker Activity

Ionic Mechanisms of Pacemaking

Cardiac pacemaker activity is generated in the sino-atrial node (SAN) by a specialized population of cells. Automaticity in SAN cells is due to the presence of the diastolic depolarisation, a slow depolarisation phase which leads the membrane potential from the end of an action potential toward the threshold of the following action potential.^{182,183} Pacemaker activity then spreads to other areas of the heart via the conduction system, and finally triggers the contraction of the cardiac muscle. The myogenic heart consists of many cell types capable of pacemaker activity in the SAN, the His bundle, the atrio-ventricular node (AV node), and the Purkinje fibers. However, the faster intrinsic rate of SAN pacemaker cells determines the heart rate in physiological conditions. Pacemaker cells express a specific set of ionic channels. These channels have been extensively described during the past fifteen years, due to patch clamp studies on isolated rabbit pacemaker cells and more recently in guinea pig.¹⁸⁴ Particularly, five classes of ionic channels are involved in the regulation of pacemaker activity: the hyperpolarization-activated channel (I_f), two distinct potassium channels (I_{Kr} and I_{Ks}), the G protein-gated potassium channel which is activated by muscarinic agonist (I_{KACh}), the sustained inward current (I_{st}) and finally, I_{Ca,T} and I_{Ca,L}. Consistent with what observed in working cardiac myocytes, I_{Ca,L} is activated by stronger depolarisations than I_{Ca,T} and is sensitive to DHPs. I_{Ca,T} is activated at negative voltages and is sensitive to Ni²⁺ ions.

Another fundamental property of pacemaker cells is the opposite regulation of the spontaneous activity by sympathetic and parasympathetic neurotransmitter receptors agonists. To date, two different pathways underlying autonomic regulation of heart rate have been identified; a fast pathway that is linked to activation of the muscarinic receptor and leads to direct opening of IKACh channels by G-proteins, and a slower pathway which depends from intracellular AC activity and cAMP production. The opening of IKACh channels in pacemaker cells is stimulated by both muscarinic and adenosine receptor agonists and leads to slowing of automaticity by causing membrane hyperpolarization.^{185,186} Intracellular cAMP production is stimulated by B-adrenergic receptor agonists and leads to facilitation of If channel opening by direct binding of cAMP to the channel^{187,188} and activation of PKA which, in turn, stimulates $I_{Ca,L}$ and I_{st} by phosphorylation (for review see refs. 187-189). The chronotropic effect of β -adrenergic stimulation is thus supposed to depend from both the direct activation of If by cAMP and channel phosphorylation of ICa,L and Ist. Consistently, the negative chronotropic effect following muscarinic receptor activation will depend from both IKACh activation, If inhibition and Ca²⁺ channel dephosphorylation. We will now closely discuss the available data on the role of Ca²⁺ channels in the generation and regulation of cardiac pacemaking.

Role of I_{Ca,L} in the Generation and Regulation of Pacemaker Activity

Early studies on the effects of the β -adrenergic agonist adrenaline on pacemaking of SAN tissue strips first suggested that Ca²⁺ currents are involved in the generation of automaticity.^{190,191} Action-potential clamp experiments conducted on isolated rabbit pacemaker cells have shown that I_{Ca,L} is present during the diastolic depolarization.¹⁹² Recently, three lines of evidence further support the view that I_{Ca,L} plays an important role in the generation of pacemaker activity. First, pharmacological inhibition of I_{Ca,L} significantly slows pacemaker activity of isolated rabbit SAN cells in vitro.¹⁹³ Second, the dihydropyridine Ca²⁺ channel antagonist nicardipine induces bradycardia in anaesthetized mice.¹⁹⁴ Third, it has recently been shown, in rabbit pacemaker cells, that I_{Ca,L} is activated from a threshold of about -50 mV and that, due to this apparently "low" voltage dependency for activation, I_{Ca,L} supplies sizable inward current during the diastolic depolarization.¹⁹⁵

As it is the case in the working myocardium, $I_{Ca,L}$ in the SAN is sensitive to cAMP-dependent regulation by a mechanism requiring the activity of PKA.¹⁹⁶ Together with that of I_f, the stimulation of I_{Ca} by adrenaline has been proposed to play a fundamental role in the β -adrenergic regulation of pacemaking.¹⁹¹ To this respect, it is interesting to note that $I_{Ca,L}$ and I_f show similar sensitivity to application of Isoproterenol.¹⁹⁷ Also, given that I_f regulation by internal cAMP does not require protein phosphorylation, it has been proposed that fast heart rate regulation by β -adrenergic agonists does not imply $I_{Ca,L}$ rather, it mainly requires I_f.¹⁹⁷ However, this hypothesis would need to be experimentally verified.

The intracellular signalling pathway underlying muscarinic regulation of $I_{Ca,L}$ has been recently described into detail.^{198,199} This pathway is dependent on NO production and subsequent cAMP down regulation by a cAMP-specific phosphodiesterase, a phenomenon that will inhibit cAMP-dependent phosphorylation of $I_{Ca,L}$ channels. The relative contribution of $I_{Ca,L}$,

I_f and I_{KACh} to the muscarinic regulation of pacemaker activity has been investigated in two different studies.^{185,197} Particularly, it has been proposed that, for low concentrations of applied ACh, I_f is the only current involved in rate slowing. For higher doses of ACh, in addition to opening of I_{KACh} channels, I_{Ca,L} inhibition will also be involved. However, this view has been recently challenged in an in vivo study employing a genetically modified mouse strain lacking the cardiac I_{KACh}.²⁰⁰ Indeed, it has been shown that these mice are unable to regulate heart rate in a fast time scale, thus indicating that I_{KACh} plays a fundamental role in the beat-to-beat regulation of cardiac pacemaking.

Role of $I_{Ca,T}$ in the Generation of Pacemaker Activity

Hagiwara, Irisawa & Kameyama provided the first assessment of the role of ICAT in pacemaking in their classical paper on rabbit SAN cells.¹⁶¹ ICaT was activated for a negative voltage interval (about -50 mV) thus overlapping most of the diastolic depolarization range. These authors also reported slowing of automaticity by the T-type Ca²⁺ channel blockers tetrametrine and Ni²⁺ at concentrations that did not affect $I_{Ca,L}$. On the basis of these observations, they concluded that ICa,T plays a significant role in the generation of pacemaker activity. Doerr and coworkers¹⁹² also attempted to measure $I_{Ca,T}$ in action potential clamp experiments by using extracellular 40 µM Ni²⁺. They reported measurable I_{Ca,T} in the diastolic depolarization and suggested that both ICaL and ICAT participated in the diastolic depolarization. However, we can expect that ICa,T would be almost completely inactivated by the positive maximum diastolic potentials observed in most primary pacemaker cells (between -50 and -60 mV),¹⁶¹ thus complicating the interpretation of these experimental observations. One possibility is that ICAT participates to the diastolic depolarization by a "window" current component.¹⁶² However, the existence of "window" $I_{Ca,T}$ in primary pacemaker cells has not yet been demonstrated. In summary, the exact role of ICa,T in primary pacemaking still needs to be elucidated. However, the robust expression of ICa.T in mouse pacemaker cells²⁰¹ suggests that this current may also be involved in pacemaking in physiological situation where the maximum diastolic potential undergoes spontaneous hyperpolarization (e.g., muscarinic receptor activation) or in automaticity of atrial pacemakers. To this respect, Huser and coworkers have recently been able to study the contribution of intracellular Ca²⁺ release to automaticity of cat latent pacemaker cells.²⁰² They described intracellular Ca²⁺ release during the late phase of diastolic depolarization. Ca²⁺release was abolished by extracellular Ni²⁺ ions, thus indicating that I_{Ca,T} was triggering intracellular Ca²⁺ release in the diastolic depolarization. Such a mechanism, may be also operant in primary pacemaker cells in the SAN.

Future Directions

In order to gain new insights into the generation and regulation of pacemaker activity, it would be extremely important to provide genetic evidence linking the activity of a given ionic channel gene to specific alteration of heart rate. The use of genetically modified mouse strains would thus constitute a new and powerful tool to investigate the role of specific genes coding for ionic channels in the regulation of heart rate. To this respect the recent isolation and electrophysiological description of mouse SAN pacemaker cells opens the way to the possibility of studying cardiac automaticity in genetically modified mice²⁰¹ Gene families coding for ionic channels involved in heart rate regulation have been cloned, and expression of some of these genes has been consistently found in cardiac tissue (for review see ref. 203). With respect to Ca^{2+} channels, the Ca_v1.2 gene plays a major role in the determination of the cardiac I_{Ca_xL}. However, the Ca_v1.3 gene is also expressed in atrium²⁰⁴ and in SAN.²⁰⁵ The Ca_v3.1 gene is the major gene expressed in myocardium^{154,158} and in SAN tissue.²⁰⁵ The Ca_v3.2 gene has also been detected in mouse SAN.²⁰⁵ Two different strains of knockout mice lacking Ca_v1.3 channels have been developed.^{204,206} Both strains present striking SAN dysfunction. Indeed, both bradycardia and sino-atrial arrhythmia have been observed in Ca_v1.3^{-/-} mouse strains in vivo.^{204,206} Secondly, slowing of pacemaker activity measured in isolated atria²⁰⁴ and intact SAN^{206} have been reported. Quantification of $I_{Ca,L}$ in pacemaker cells from one of these knockout strains showed that current activation is shifted positive with respect to wild-type pacemaker cells, an observation which is consistent with the existence of a low-voltage-activated $I_{Ca,L}$ component coded by the Cav1.3 gene as reported using recombinant Cav1.3 channels^{207,208} A mouse strain lacking Cav3.1 channels has been recently described.²⁰⁶ The cardiac phenotype of this strain still needs to be described.

In summary, we can expect that the use of genetically modified mouse strains will allow a better understanding of the ionic mechanisms underlying cardiac pacemaker activity. More generally, understanding the basis of automaticity may yield important indications in the development of new drugs that specifically influence heart rate without affecting cardiac inotropism. Indeed, ionic channels showing preferential expression in pacemaker tissue compared to the myocardium may constitute suitable targets for these drugs. This kind of chronotropic selectivity could be particularly important in the treatment of ischemic heart disease.²⁰⁹

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References

- 1. Rougier O, Garnier D. Analysis of the potassium current of cardiac auricular fibers in frogs. J Physiol (Paris) 1969; 61(Suppl 2):391.
- 2. Vassort G, Rougier O, Garnier D et al. Effects of adrenaline on membrane inward currents during the cardiac action potential. Pflugers Arch 1969; 309(1):70-81.
- 3. Bustamante JO, Watanabe T, Murphy DA et al. Isolation of single atrial and ventricular cells from the human heart. Can Med Assoc J 1982; 126(7):91-3.
- 4. Beeler Jr GW, Reuter H. The relation between membrane potential, membrane currents and activation of contraction in ventricular myocardial fibres J Physiol 1970; 207(1):211-29.
- 5. Neher E, Sakmann B. Noise analysis of drug induced voltage clamp currents in denervated frog muscle fibres. J Physiol 1976; 258(3):705-29.
- 6. Hume JR, Giles W. Active and passive electrical properties of single bullfrog atrial cells. J Gen Physiol 1981; 78(1):19-42.
- 7. Neher E, Sakmann B. Single-channel currents recorded from membrane of denervated frog muscle fibres. Nature 1976; 260(5554):799-802.
- Cachelin AB, de Peyer JE, Kokubun S et al. Ca²⁺ channel modulation by 8-bromocyclic AMP in cultured heart cells. Nature 1983; 304(5925):462-4.
- 9. Cachelin AB, De Peyer JE, Kokubun S et al. Sodium channels in cultured cardiac cells. J Physiol 1983; 340:389-401.
- Cavalie A, Ochi R, Pelzer D et al. Elementary currents through Ca²⁺ channels in guinea pig myocytes. Pflugers Arch 1983; 398(4):284-97.
- 11. Tsien RW, Bean BP, Hess P et al. Mechanisms of Ca²⁺ channel modulation by beta-adrenergic agents and dihydropyridine Ca²⁺ agonists. J Mol Cell Cardiol 1986; 18(7):691-710.
- Yatani A, Codina J, Imoto Y et al. A G protein directly regulates mammalian cardiac Ca²⁺ channels. Science 1987; 238(4831):1288-92.
- 13. Horn R, Marty A. Muscarinic activation of ionic currents measured by a new whole-cell recording method. J Gen Physiol 1988; 92(2):145-59.
- Rae J, Cooper K, Gates P et al. Low access resistance perforated patch recordings using amphotericin B. J Neurosci Methods 1991; 37(1):15-26.
- 15. Fleckenstein A. History of Ca²⁺ antagonists. Circ Res1983; 52(2 Pt 2):3-16.
- Striessnig J. Pharmacology, structure and function of cardiac L-type Ca²⁺ channels. Cell Physiol Biochem 1999; 9(4-5):242-69.
- 17. Bean BP. Two kinds of Ca²⁺ channels in canine atrial cells. Differences in kinetics, selectivity, and pharmacology J Gen Physiol 1985; 86(1):1-30.
- Hirano Y, Fozzard HA, January CT. Characteristics of L- and T-type Ca²⁺ currents in canine cardiac Purkinje cells. Am J Physiol 1989; 256(5 Pt 2):1478-92.

- 19. Curtis BM, Catterall WA. Purification of the Ca²⁺ antagonist receptor of the voltage-sensitive Ca²⁺ channel from skeletal muscle transverse tubules. Biochemistry 1984; 23(10):2113-8.
- 20. Mikami A, Imoto K, Tanabe T et al. Primary structure and functional expression of the cardiac dihydropyridine-sensitive Ca2+ channel. Nature 1989; 340(6230):230-3.
- 21. Catterall WA. Structure and function of voltage-gated sodium and Ca2+ channels. Curr Opin Neurobiol 1991; 1(1):5-13.
- 22. Takimoto K, Li D, Nerbonne JM et al. Distribution, splicing and glucocorticoid-induced expression of cardiac alpha 1C and alpha 1D voltage-gated Ca²⁺ channel mRNAs. J Mol Cell Cardiol 1997; 29(11):3035-42.
- 23. Wyatt CN, Campbell V, Brodbeck J et al. Voltage-dependent binding and Ca2+ channel current inhibition by an anti-alpha 1D subunit antibody in rat dorsal root ganglion neurones and guinea-pig myocytes. J Physiol 1997; 502(Pt 2):307-19.
- 24. Yaney GC, Wheeler MB, Wei X et al. Cloning of a novel alpha 1-subunit of the voltage-dependent Ca²⁺ channel from the beta-cell. Mol Endocrinol 1992; 6(12):2143-52.
- 25. Ertel EA, Campbell KP, Harpold MM et al. Nomenclature of voltage-gated Ca2+ channels. Neuron 2000; 25(3):533-5.
- 26. Welling A, Ludwig A, Zimmer S et al. Alternatively spliced IS6 segments of the alpha 1C gene determine the tissue-specific dihydropyridine sensitivity of cardiac and vascular smooth muscle L-type Ca²⁺ channels. Circ Res 1997; 81(4):526-32.
- 27. Ruth P, Rohrkasten A, Biel M et al. Primary structure of the beta subunit of the DHP-sensitive Ca²⁺ channel from skeletal muscle. Science 1989; 245(4922):1115-8.
- 28. Perez-Reyes E, Castellano A, Kim HS et al. Cloning and expression of a cardiac/brain beta subunit of the L-type Ca²⁺ channel. J Biol Chem 1992; 267(3):1792-7.
- 29. Hullin R, Singer-Lahat D, Freichel M et al. Ca2+ channel beta subunit heterogeneity: functional expression of cloned cDNA from heart, aorta and brain. Embo J 1992; 11(3):885-90.
- 30. Castellano A, Wei X, Birnbaumer L et al. Cloning and expression of a neuronal Ca²⁺ channel beta subunit. J Biol Chem 1993; 268(17):12359-66.
- 31. Collin T, Wang JJ, Nargeot J et al. Molecular cloning of three isoforms of the L-type voltage-dependent Ca²⁺ channel beta subunit from normal human heart. Circ Res 1993; 72(6):1337-44.
- 32. Perez-Reyes E, Schneider T. Molecular biology of Ca^{2*} channels. Kidney Int1995; 48(4):1111-24. 33. Pragnell M, De Waard M, Mori Y et al. Ca^{2*} channel beta-subunit binds to a conserved motif in the I-II cytoplasmic linker of the alpha 1-subunit. Nature 1994; 368(6466):67-70.
- 34. De Jongh KS, Warner C, Catterall WA. Subunits of purified Ca2+ channels. Alpha2 and delta are encoded by the same gene. J Biol Chem 1990; 265(25):14738-41.
- 35. Tanabe T, Beam KG, Adams BA et al. Regions of the skeletal muscle dihydropyridine receptor critical for excitation-contraction coupling. Nature 1990; 346(6284):567-9.
- 36. Yang J, Ellinor PT, Sather WA et al. Molecular determinants of Ca2+ selectivity and ion permeation in L-type Ca²⁺ channels. Nature 1993; 366(6451):158-61.
- 37. Yatani A, Bahinski A, Wakamori M et al. Alteration of channel characteristics by exchange of poreforming regions between two structurally related Ca²⁺ channels. Mol Cell Biochem 1994; 140(2):93-102.
- 38. Ellinor PT, Yang J, Sather WA et al. Ca2+ channel selectivity at a single locus for high-affinity Ca²⁺ interactions. Neuron 1995; 15(5):1121-32.
- 39. Babitch J. Channel hands. Nature 1990; 346(6282):321-2.
- 40. Adams B, Tanabe T. Structural regions of the cardiac Ca channel alpha subunit involved in Ca-dependent inactivation. J Gen Physiol 1997; 110(4):379-89.
- 41. Zuhlke RD, Reuter H. Ca²⁺-sensitive inactivation of L-type Ca²⁺ channels depends on multiple cytoplasmic amino acid sequences of the alpha1C subunit. Proc Natl Acad Sci USA 1998; 95(6):3287-94.
- 42. Lory P, Varadi G, Slish DF et al. Characterization of beta subunit modulation of a rabbit cardiac L-type Ca²⁺ channel alpha 1 subunit as expressed in mouse L cells. FEBS Lett1993; 315(2):167-72.
- 43. Costantin J, Noceti F, Qin N et al. Facilitation by the beta2a subunit of pore openings in cardiac Ca²⁺ channels. J Physiol 1998; 507(Pt 1):93-103.
- 44. Gerster U, Neuhuber B, Groschner K et al. Current modulation and membrane targeting of the Ca²⁺ channel alpha1C subunit are independent functions of the beta subunit. J Physiol 1999; 517(Pt 2):353-68.
- 45. Gao T, Chien AJ, Hosey MM. Complexes of the alpha1C and beta subunits generate the necessary signal for membrane targeting of class C L-type Ca²⁺ channels. J Biol Chem 1999; 274(4):2137-44.
- 46. Singer D, Biel M, Lotan I et al. The roles of the subunits in the function of the Ca^{2+} channel. Science 1991; 253(5027):1553-7.

- 47. Shistik E, Ivanina T, Puri T et al. Ca²⁺ current enhancement by alpha 2/delta and beta subunits in Xenopus oocytes: contribution of changes in channel gating and alpha 1 protein level. J Physiol 1995; 489 (Pt 1):55-62.
- 48. Mori Y, Friedrich T, Kim MS et al. Primary structure and functional expression from complementary DNA of a brain Ca²⁺ channel. Nature 1991; 350(6317):398-402.
- 49. Platano D, Qin N, Noceti F et al. Expression of the alpha(2)delta subunit interferes with prepulse facilitation in cardiac L-type Ca2+ channels. Biophys J 2000; 78(6):2959-72.
- 50. Striessnig J, Murphy BJ, Catterall WA. Dihydropyridine receptor of L-type Ca²⁺ channels: identification of binding domains for [3H](+)-PN200-110 and [3H]azidopine within the alpha 1 subunit. Proc Natl Acad Sci USA 1991; 88(23):10769-73.
- 51. Catterall WA, Striessnig J. Receptor sites for Ca²⁺ channel antagonists. Trends Pharmacol Sci 1992; 13(6):256-62.
- 52. Tang S, Yatani A, Bahinski A et al. Molecular localization of regions in the L-type Ca2+ channel critical for dihydropyridine action. Neuron 1993; 11(6):1013-21.
- 53. Striessnig J, Glossmann H, Catterall WA. Identification of a phenylalkylamine binding region within the alpha 1 subunit of skeletal muscle Ca2+ channels. Proc Natl Acad Sci USA 1990; 87(23):9108-12.
- 54. Wei X, Pan S, Lang W et al. Molecular determinants of cardiac Ca²⁺ channel pharmacology. Subunit requirement for the high affinity and allosteric regulation of dihydropyridine binding J Biol Chem 1995; 270(45):27106-11.
- 55. Beuckelmann DJ, Wier WG. Mechanism of release of Ca²⁺ from sarcoplasmic reticulum of guinea-pig cardiac cells. J Physiol 1988; 405:233-55.
- 56. Nabauer M, Callewaert G, Cleemann L et al. Regulation of Ca2+ release is gated by Ca2+ current, not gating charge, in cardiac myocytes. Science 1989; 244(4906):800-3.
- 57. Valdeolmillos M, O'Neill SC, Smith GL et al. Ca²⁺-induced Ca²⁺ release activates contraction in intact cardiac cells. Pflugers Arch 1989; 413(6):676-8.
- 58. Fabiato A, Fabiato F. Activation of skinned cardiac cells. Subcellular effects of cardioactive drugs Eur J Cardiol 1973; 1(2):143-55.
- 59. Fabiato A. Simulated Ca²⁺ current can both cause Ca²⁺ loading in and trigger Ca²⁺ release from the sarcoplasmic reticulum of a skinned canine cardiac Purkinje cell. J Gen Physiol 1985; 85(2):291-320.
- 60. Fabiato A, Fabiato F. Contractions induced by a Ca²⁺-triggered release of Ca²⁺ from the sarcoplasmic reticulum of single skinned cardiac cells. J Physiol 1975; 249(3):469-95.
- Fabiato A, Fabiato F. Effects of magnesium on contractile activation of skinned cardiac cells. J 61. Physiol 1975; 249(3):497-517.
- 62. Fabiato A, Fabiato F. Effects of pH on the myofilaments and the sarcoplasmic reticulum of skinned cells from cardiace and skeletal muscles. J Physiol 1978; 276:233-55.
- 63. Fabiato A, Fabiato F. Ca²⁺-induced release of Ca²⁺ from the sarcoplasmic reticulum of skinned cells from adult human, dog, cat, rabbit, rat, and frog hearts and from fetal and new-born rat ventricles. Ann N Y Acad Sci 1978; 307:491-522.
- 64. Fabiato A, Fabiato F. Use of chlorotetracycline fluorescence to demonstrate Ca²⁺-induced release of Ca²⁺ from the sarcoplasmic reticulum of skinned cardiac cells. Nature 1979; 281(5727):146-8.
- 65. Fabiato A. Myoplasmic free Ca2+ concentration reached during the twitch of an intact isolated cardiac cell and during Ca²⁺-induced release of Ca²⁺ from the sarcoplasmic reticulum of a skinned cardiac cell from the adult rat or rabbit ventricle. J Gen Physiol 1981; 78(5):457-97.
- 66. Fabiato A. Ca²⁺-induced release of Ca²⁺ from the cardiac sarcoplasmic reticulum. Am J Physiol 1983; 245(1):C1-14.
- 67. Fabiato A. Rapid ionic modifications during the aequorin-detected Ca2+ transient in a skinned canine cardiac Purkinje cell. J Gen Physiol 1985; 85(2):189-246.
- 68. Fabiato A. Time and Ca²⁺ dependence of activation and inactivation of Ca²⁺-induced release of Ca2+ from the sarcoplasmic reticulum of a skinned canine cardiac Purkinje cell. J Gen Physiol 1985; 85(2):247-89.
- 69. Niggli E, Lederer WJ. Voltage-independent Ca²⁺ release in heart muscle. Science 1990; 250(4980):565-8.
- 70. Sham JS, Song LS, Chen Y et al. Termination of Ca^{2+} release by a local inactivation of ryanodine receptors in cardiac myocytes. Proc Natl Acad Sci USA 1998; 95(25):15096-101.
- 71. Sipido KR, Callewaert G, Carmeliet E. Inhibition and rapid recovery of Ca²⁺ current during Ca²⁺ release from sarcoplasmic reticulum in guinea pig ventricular myocytes. Circ Res 1995; 76(1):102-9. 72. Sham JS, Cleemann L, Morad M. Functional coupling of Ca²⁺ channels and ryanodine receptors
- in cardiac myocytes. Proc Natl Acad Sci USA 1995; 92(1):121-5.
- 73. Lederer WJ, Niggli E, Hadley RW. Sodium-Ca2+ exchange in excitable cells: fuzzy space. Science 1990; 248(4953):283.

- Stern MD. Theory of excitation-contraction coupling in cardiac muscle. Biophys J 1992; 63(2):497-517.
- 75. Protasi F, Sun XH, Franzini-Armstrong C. Formation and maturation of the Ca²⁺ release apparatus in developing and adult avian myocardium. Dev Biol 1996; 173(1):265-78.
- Bers DM, Stiffel VM. Ratio of ryanodine to dihydropyridine receptors in cardiac and skeletal muscle and implications for E-C coupling. Am J Physiol 1993; 264(6 Pt 1):C1587-93.
- Cannell MB, Cheng H, Lederer WJ. Spatial nonuniformities in [Ca²⁺]i during excitation-contraction coupling in cardiac myocytes. Biophys J 1994; 67(5):1942-56.
 Cheng H, Lederer WJ, Cannell MB. Ca²⁺ sparks: elementary events underlying excitation-contraction
- Cheng H, Lederer WJ, Cannell MB. Ca²⁺ sparks: elementary events underlying excitation-contraction coupling in heart muscle. Science 1993; 262(5134):740-4.
- 79. Lopez-Lopez JR, Shacklock PS, Balke CW et al. Local Ca²⁺ transients triggered by single L-type Ca²⁺ channel currents in cardiac cells. Science 1995; 268(5213):1042-5.
- Song LS, Stern MD, Lakatta EG et al. Partial depletion of sarcoplasmic reticulum Ca²⁺ does not prevent Ca²⁺ sparks in rat ventricular myocytes. J Physiol 1997; 505 (Pt 3):665-75.
- Parker I, Zang WJ, Wier WG. Ca²⁺ sparks involving multiple Ca²⁺ release sites along Z-lines in rat heart cells. J Physiol 1996; 497 (Pt 1):31-8.
- Cannell MB, Berlin JR, Lederer WJ. Effect of membrane potential changes on the Ca²⁺ transient in single rat cardiac muscle cells. Science 1987; 238(4832):1419-23.
- Callewaert G, Cleemann L, Morad M. Epinephrine enhances Ca²⁺ current-regulated Ca²⁺ release and Ca²⁺ reuptake in rat ventricular myocytes. Proc Natl Acad Sci USA 1988; 85(6):2009-13.
- London B, Krueger JW. Contraction in voltage-clamped, internally perfused single heart cells. J Gen Physiol 1986; 88(4):475-505.
- Tsien RW, Giles W, Greengard P. Cyclic AMP mediates the effects of adrenaline on cardiac purkinje fibres. Nat New Biol 1972; 240(101):181-3.
- Reuter H, Scholz H. The regulation of the Ca²⁺ conductance of cardiac muscle by adrenaline. J Physiol 1977; 264(1):49-62.
- Stiles GL, Taylor S, Lefkowitz RJ. Human cardiac beta-adrenergic receptors: subtype heterogeneity delineated by direct radioligand binding. Life Sci 1983; 33(5):467-73.
- Stiles GL, Strasser RH, Lavin TN et al. The cardiac beta-adrenergic receptor. Structural similarities of beta1 and beta 2 receptor subtypes demonstrated by photoaffinity labeling. J Biol Chem 1983; 258(13):8443-9.
- 89. Bristow MR, Ginsburg R. Beta 2 receptors on myocardial cells in human ventricular myocardium. Am J Cardiol 1986; 57(12):3F-6F.
- 90. Krief S, Lonnqvist F, Raimbault S et al. Tissue distribution of beta 3-adrenergic receptor mRNA in man. J Clin Invest 1993; 91(1):344-9.
- Gauthier C, Tavernier G, Charpentier F et al. Functional beta3-adrenoceptor in the human heart. J Clin Invest 1996; 98(2):556-62.
- 92. Xiao RP, Lakatta EG. Beta 1-adrenoceptor stimulation and beta 2-adrenoceptor stimulation differ in their effects on contraction, cytosolic Ca²⁺, and Ca²⁺ current in single rat ventricular cells. Circ Res 1993; 73(2):286-300.
- Chen-Izu Y, Xiao RP, Izu LT et al. G(i)-dependent localization of beta(2)-adrenergic receptor signaling to L-type Ca(²⁺) channels. Biophys J 2000; 79(5):2547-56.
- 94. Xiao RP, Avdonin P, Zhou YY et al. Coupling of beta2-adrenoceptor to Gi proteins and its physiological relevance in murine cardiac myocytes. Circ Res 1999; 84(1):43-52.
- Yue DT, Herzig S, Marban E. Beta-adrenergic stimulation of Ca²⁺ channels occurs by potentiation of high-activity gating modes. Proc Natl Acad Sci USA 1990; 87(2):753-7.
- 96. Trautwein W, Cavalie A, Allen TJ et al. Direct and indirect regulation of cardiac L-type Ca²⁺ channels by beta-adrenoreceptor agonists. Adv Second Messenger Phosphoprotein Res 1990; 24:45-50.
- 97. Sculptoreanu A, Rotman E, Takahashi M et al. Voltage-dependent potentiation of the activity of cardiac L-type Ca²⁺ channel alpha 1 subunits due to phosphorylation by cAMP- dependent protein kinase. Proc Natl Acad Sci USA 1993; 90(21):10135-9.
- 98. Yoshida A, Takahashi M, Nishimura S et al. Cyclic AMP-dependent phosphorylation and regulation of the cardiac dihydropyridine-sensitive Ca channel. FEBS Lett 1992; 309(3):343-9.
- 99. De Jongh KS, Murphy BJ, Colvin AA et al. Specific phosphorylation of a site in the full-length form of the alpha 1 subunit of the cardiac L-type Ca²⁺ channel by adenosine 3',5'- cyclic monophosphate-dependent protein kinase. Biochemistry 1996; 35(32):10392-402.
- 100. Haase H, Karczewski P, Beckert R et al. Phosphorylation of the L-type Ca²⁺ channel beta subunit is involved in beta-adrenergic signal transduction in canine myocardium. FEBS Lett 1993; 335(2):217-22.

- 101. Gao T, Yatani A, Dell'Acqua ML et al. cAMP-dependent regulation of cardiac L-type Ca²⁺ channels requires membrane targeting of PKA and phosphorylation of channel subunits. Neuron 1997; 19(1):185-96.
- 102. Charnet P, Lory P, Bourinet E et al. cAMP-dependent phosphorylation of the cardiac L-type Ca channel: a missing link? Biochimie 1995;77(12):957-62.
- 103. Dai S, Klugbauer N, Zong X et al. The role of subunit composition on prepulse facilitation of the cardiac L-type Ca²⁺ channel. FEBS Lett 1999; 442(1):70-4.
- 104. Bkaily G, Sperelakis N. Injection of guanosine 5'-cyclic monophosphate into heart cells blocks Ca²⁺ slow channels. Am J Physiol 1985; 248(5Pt 2):H745-9.
- 105. Haddad GE, Sperelakis N, Bkaily G. Regulation of the Ca²⁺ slow channel by cyclic GMP dependent protein kinase in chick heart cells. Mol Cell Biochem 1995; 148(1):89-94.
- 106. Hartzell HC, Fischmeister R. Opposite effects of cyclic GMP and cyclic AMP on Ca²⁺ current in single heart cells. Nature 1986; 323(6085):273-5.
- 107. Levi RC, Alloatti G, Penna C et al. Guanylate-cyclase-mediated inhibition of cardiac ICa by carbachol and sodium nitroprusside. Pflugers Arch 1994; 426(5):419-26.
- 108. Mery PF, Lohmann SM, Walter U et al. Ca²⁺ current is regulated by cyclic GMP-dependent protein kinase in mammalian cardiac myocytes. Proc Natl Acad Sci USA 1991; 88(4):1197-201.
- 109. Hescheler J, Kameyama M, Trautwein W. On the mechanism of muscarinic inhibition of the cardiac Ca current. Pflugers Arch 1986; 407(2):182-9.
- 110. Fischmeister R, Hartzell HC. Mechanism of action of acetylcholine on Ca²⁺ current in single cells from frog ventricle. J Physiol 1986; 376:183-202.
- 111. Chen F, Spicher K, Jiang M et al. Lack of muscarinic regulation of Ca²⁺ channels in G(i2)alpha gene knockout mouse hearts. Am J Physiol Heart Circ Physiol 2001; 280(5):H1989-95.
- 112. Ono K, Trautwein W. Potentiation by cyclic GMP of beta-adrenergic effect on Ca²⁺ current in guinea-pig ventricular cells. J Physiol 1991; 443:387-404.
- 113. Kirstein M, Rivet-Bastide M, Hatem S et al. Nitric oxide regulates the Ca²⁺ current in isolated human atrial myocytes. J Clin Invest 1995; 95(2):794-802.
- 114. Jiang LH, Gawler DJ, Hodson N et al. Regulation of cloned cardiac L-type Ca²⁺ channels by cGMP-dependent protein kinase. J Biol Chem 2000; 275(9):6135-43.
- 115. White RE, Lee AB, Shcherbatko AD et al. Potassium channel stimulation by natriuretic peptides through cGMP-dependent dephosphorylation. Nature 1993; 361(6409):263-6.
- 116. Hescheler J, Kameyama M, Trautwein W et al. Regulation of the cardiac Ca²⁺ channel by protein phosphatases. Eur J Biochem 1987; 165(2):261-6.
- 117. Fischmeister R, Hartzell HC. Cyclic guanosine 3',5'-monophosphate regulates the Ca²⁺ current in single cells from frog ventricle. J Physiol 1987; 387:453-72.
- 118. Mery PF, Pavoine C, Pecker F et al. Erythro-9-(2-hydroxy-3-nonyl)adenine inhibits cyclic GMP-stimulated phosphodiesterase in isolated cardiac myocytes. Mol Pharmacol 1995; 48(1):121-30.
- 119. Le Grand B, Deroubaix E, Couetil JP et al. Effects of atrionatriuretic factor on Ca²⁺ current and Cai-independent transient outward K+ current in human atrial cells. Pflugers Arch 1992; 421(5):486-91.
- 120. Dosemeci A, Dhallan RS, Cohen NM et al. Phorbol ester increases Ca²⁺ current and simulates the effects of angiotensin II on cultured neonatal rat heart myocytes. Circ Res 1988; 62(2):347-57.
- 121. He JQ, Pi Y, Walker JW et al. Endothelin-1 and photoreleased diacylglycerol increase L-type Ca²⁺ current by activation of protein kinase C in rat ventricular myocytes. J Physiol 2000; 524 Pt 3:807-20.
- 122. Liu QY, Karpinski E, Pang PK. Comparison of the action of two protein kinase C activators on dihydropyridine-sensitive Ca²⁺ channels in neonatal rat ventricular myocytes. Biochem Biophys Res Commun 1993; 191(3):796-801.
- 123. Zhang ZH, Johnson JA, Chen L et al. C2 region-derived peptides of beta-protein kinase C regulate cardiac Ca²⁺ channels. Circ Res 1997; 80(5):720-9.
- 124. Bourinet E, Fournier F, Lory P et al. Protein kinase C regulation of cardiac Ca²⁺ channels expressed in Xenopus oocytes. Pflugers Arch 1992; 421(2-3):247-55.
- 125. Shistik E, Ivanina T, Blumenstein Y et al. Crucial role of N terminus in function of cardiac L-type Ca²⁺ channel and its modulation by protein kinase C. J Biol Chem 1998; 273(28):17901-9.
- 126. Puri TS, Gerhardstein BL, Zhao XL et al. Differential effects of subunit interactions on protein kinase A- and C- mediated phosphorylation of L-type Ca²⁺ channels. Biochemistry 1997; 36(31):9605-15.
- 127. McHugh D, Sharp EM, Scheuer T et al. Inhibition of cardiac L-type Ca²⁺ channels by protein kinase C phosphorylation of two sites in the N-terminal domain. Proc Natl Acad Sci USA 2000; 97(22):12334-8.

- 128. Bean BP. Nitrendipine block of cardiac Ca²⁺ channels: high-affinity binding to the inactivated state. Proc Natl Acad Sci USA 1984; 81(20):6388-92.
- 129. Sanguinetti MC, Kass RS. Voltage-dependent block of Ca²⁺ channel current in the calf cardiac Purkinje fiber by dihydropyridine Ca²⁺ channel antagonists. Circ Res 1984; 55(3):336-48.
- Brown AM, Kunze DL, Yatani A. The agonist effect of dihydropyridines on Ca channels. Nature 1984; 311(5986):570-2.
- 131. Hess P, Lansman JB, Tsien RW. Different modes of Ca channel gating behaviour favoured by dihydropyridine Ca agonists and antagonists. Nature 1984; 311(5986):538-44.
- 132. Kokubun S, Reuter H. Dihydropyridine derivatives prolong the open state of Ca channels in cultured cardiac cells. Proc Natl Acad Sci USA 1984; 81(15):4824-7.
- 133. Lacerda AE, Brown AM. Nonmodal gating of cardiac Ca²⁺ channels as revealed by dihydropyridines. J Gen Physiol 1989; 93(6):1243-73.
- 134. McDonald TF, Pelzer S, Trautwein W et al. Regulation and modulation of Ca²⁺ channels in cardiac, skeletal, and smooth muscle cells. Physiol Rev 1994; 74(2):365-507.
- 135. Noble S, Shimoni Y. The Ca²⁺ and frequency dependence of the slow inward current 'staircase' in frog atrium. J Physiol 1981; 310:57-75.
- 136. Fedida D, Noble D, Spindler AJ. Use-dependent reduction and facilitation of Ca²⁺ current in guinea-pig myocytes. J Physiol 1988; 405:439-60.
- 137. Lee KS. Potentiation of the Ca²⁺-channel currents of internally perfused mammalian heart cells by repetitive depolarization. Proc Natl Acad Sci USA 1987; 84(11):3941-5.
- 138. Richard S, Tiaho F, Charnet P et al. Two pathways for Ca²⁺ channel gating differentially modulated by physiological stimuli. Am J Physiol 1990; 258(6 Pt 2):1872-81.
- 139. Schouten VJ, Morad M. Regulation of Ca²⁺ current in frog ventricular myocytes by the holding potential, c-AMP and frequency. Pflugers Arch 1989; 415(1):1-11.
- 140. Richard S, Charnet P, Nerbonne JM. Interconversion between distinct gating pathways of the high threshold Ca²⁺ channel in rat ventricular myocytes. J Physiol 1993; 462:197-228.
- 141. Tiaho F, Piot C, Nargeot J et al. Regulation of the frequency-dependent facilitation of L-type Ca²⁺ currents in rat ventricular myocytes. J Physiol 1994; 477(Pt 2):237-51.
- 142. Yuan W, Bers DM. Ca-dependent facilitation of cardiac Ca current is due to Ca-calmodulin-dependent protein kinase. Am J Physiol 1994; 267(3 Pt 2):H982-93.
- 143. Anderson ME, Braun AP, Schulman H et al. Multifunctional Ca²⁺/calmodulin-dependent protein kinase mediates Ca²⁺-induced enhancement of the L-type Ca²⁺ current in rabbit ventricular myocytes. Circ Res 1994; 75(5):854-61.
- 144. Xiao RP, Cheng H, Lederer WJ et al. Dual regulation of Ca²⁺/calmodulin-dependent kinase II activity by membrane voltage and by Ca²⁺ influx. Proc Natl Acad Sci USA 1994; 91(20):9659-63.
- 145. Piot C, Lemaire S, Albat B et al. High frequency-induced upregulation of human cardiac Ca²⁺ currents. Circulation 1996; 93(1):120-8.
- 146. Hryshko LV, Bers DM. Ca current facilitation during postrest recovery depends on Ca entry. Am J Physiol 1990; 259(3 Pt 2):951-61.
- 147. Peineau N, Garnier D, Argibay JA. Rate dependence of action potential duration and Ca²⁺ current in isolated guinea-pig cardiocytes. Exp Physiol 1992; 77(4):615-25.
- Pietrobon D, Hess P. Novel mechanism of voltage-dependent gating in L-type Ca²⁺ channels. Nature 1990; 346(6285):651-5.
- 149. Tiaho F, Nargeot J, Richard S. Voltage-dependent regulation of L-type cardiac Ca channels by isoproterenol. Pflugers Arch 1991; 419(6):596-602.
- 150. Barrere-Lemaire S, Piot C, Leclercq F et al. Facilitation of L-type Ca²⁺ currents by diastolic depolarization in cardiac cells: impairment in heart failure. Cardiovasc Res 2000; 47(2):336-49.
- Perez-Reyes E, Cribbs LL, Daud A et al. Molecular characterization of a neuronal low-voltage-activated T-type Ca²⁺ channel. Nature 1998; 391(6670):896-900.
- 152. Klugbauer N, Marais E, Lacinova L et al. A T-type Ca²⁺ channel from mouse brain. Pflugers Arch 1999; 437(5):710-5.
- 153. Monteil A, Chemin J, Bourinet E et al. Molecular and functional properties of the human alpha(1G) subunit that forms T-type Ca²⁺ channels. J Biol Chem 2000; 275(9):6090-100.
- 154. Cribbs LL, Gomora JC, Daud AN et al. Molecular cloning and functional expression of Ca(v)3.1c, a T-type Ca²⁺ channel from human brain [published erratum appears in FEBS Lett 2000 Mar 31;470(3):378]. FEBS Lett 2000; 466(1):54-8.
- 155. Lee JH, Daud AN, Cribbs LL et al. Cloning and expression of a novel member of the low voltage-activated T- type Ca²⁺ channel family. J Neurosci 1999; 19(6):1912-21.
- 156. Monteil A, Chemin J, Leuranguer V et al. Specific properties of T-type Ca²⁺ channels generated by the human alpha 11 subunit. J Biol Chem 2000; 275(22):16530-5.

- 157. Satin J, Cribbs LL. Identification of a T-type Ca²⁺ channel isoform in murine atrial myocytes (AT-1 cells). Circ Res 2000; 86(6):636-42.
- 158. Leuranguer V, Monteil A, Bourinet E et al. T-type Ca²⁺ currents in rat cardiomyocytes during postnatal development: Contribution in hormone secretion. Am J Physiol 2000; 279:H2540-2548.
- 159. Cribbs LL, Martin BL, Schroder EA et al. Identification of the t-type Ca²⁺ channel (Ca(v)3.1. d) in developing mouse heart Circ Res 2001; 88(4):403-7.
- 160. Ferron L, Capuano V, Deroubaix E et al. Functional and molecular characterization of a T-type Ca(^{2*}) channel during fetal and postnatal rat heart development. J Mol Cell Cardiol 2002; 34(5):533-46.
- 161. Hagiwara N, Irisawa H, Kameyama M. Contribution of two types of Ca²⁺ currents to the pacemaker potentials of rabbit sino-atrial node cells. J Physiol (Lond) 1988; 395:233-53.
- 162. Zhou Z, Lipsius SL. T-type Ca²⁺ current in latent pacemaker cells isolated from cat right atrium. J Mol Cell Cardiol 1994; 26(9):1211-9.
- 163. Piedras-Renteria ES, Chen CC, Best PM. Antisense oligonucleotides against rat brain alpha1E DNA and its atrial homologue decrease T-type Ca²⁺ current in atrial myocytes. Proc Natl Acad Sci USA 1997; 94(26):14936-41.
- 164. Mitchell JW, Larsen JK, Best PM. Identification of the Ca²⁺ channel alpha 1E (Ca(v)2.3.) isoform expressed in atrial myocytes Biochim Biophys Acta 2002; 1577(1):17-26.
- 165. Richard S, Leclercq F, Lemaire S et al. Ca²⁺ currents in compensated hypertrophy and heart failure. Cardiovasc Res 1998; 37(2):300-11.
- 166. Lemaire S, Piot C, Seguin J et al. Tetrodotoxin-sensitive Ca²⁺ and Ba²⁺ currents in human atrial cells. Receptors Channels 1995; 3(2):71-81.
- 167. Aggarwal R, Shorofsky SR, Goldman L et al. Tetrodotoxin-blockable Ca²⁺ currents in rat ventricular myocytes; a third type of cardiac cell sodium current. J Physiol (Lond) 1997; 505(Pt 2):353-69.
- 168. Cole WC, Chartier D, Martin M et al. Ca²⁺ permeation through Na+ channels in guinea pig ventricular myocytes. Am J Physiol 1997; 273(1 Pt 2):H128-37.
 169. Heubach JF, Kohler A, Wettwer E et al. T-Type and tetrodotoxin-sensitive Ca²⁺ currents coexist
- 169. Heubach JF, Kohler A, Wettwer E et al. T-Type and tetrodotoxin-sensitive Ca²⁺ currents coexist in guinea pig ventricular myocytes and are both blocked by mibefradil. Circ Res 2000; 86(6):628-35.
 170. Chemin J, Monteil A, Briquaire C et al. Overexpression of T-type Ca²⁺ channels in HEK-293 cells
- 170. Chemin J, Monteil A, Briquaire C et al. Overexpression of T-type Ca²⁺ channels in HEK-293 cells increases intracellular Ca²⁺ without affecting cellular proliferation. FEBS Lett 2000; 478(1-2):166-72.
- 171. Sipido KR, Carmeliet E, Van de Werf F. T-type Ca²⁺ current as a trigger for Ca²⁺ release from the sarcoplasmic reticulum in guinea-pig ventricular myocytes [see comments]. J Physiol (Lond) 1998; 508(Pt 2):439-51.
- 172. Enyeart JJ, Mlinar B, Enyeart JA. T-type Ca²⁺ channels are required for adrenocorticotropin-stimulated cortisol production by bovine adrenal zona fasciculata cells. Mol Endocrinol 1993; 7(8):1031-40.
- 173. Kuga T, Kobayashi S, Hirakawa Y et al. Cell cycle---dependent expression of L- and T-type Ca²⁺ currents in rat aortic smooth muscle cells in primary culture. Circ Res 1996; 79(1):14-9.
- 174. Xu XP, Best PM. Increase in T-type Ca²⁺ current in atrial myocytes from adult rats with growth hormone-secreting tumors. Proc Natl Acad Sci USA 1990; 87(12):4655-9.
- 175. Richard S, Neveu D, Carnac G et al. Differential expression of voltage-gated Ca⁽²⁺⁾-currents in cultivated aortic myocytes. Biochim Biophys Acta 1992; 1160(1):95-104.
- 176. Nuss HB, Houser SR. T-type Ca²⁺ current is expressed in hypertrophied adult feline left ventricular myocytes. Circ Res 1993; 73(4):777-82.
- 177. Martinez ML, Heredia MP, Delgado C. Expression of T-type Ca^(2*) channels in ventricular cells from hypertrophied rat hearts. J Mol Cell Cardiol 1999; 31(9):1617-25.
- 178. Romanin C, Seydl K, Glossmann H et al. The dihydropyridine niguldipine inhibits T-type Ca²⁺ currents in atrial myocytes. Pflugers Arch 1992; 420(3-4):410-2.
- 179. Mishra SK, Hermsmeyer K. Selective inhibition of T-type Ca²⁺ channels by Ro 40-5967. Circ Res 1994; 75(1):144-8.
- 180. Veniant M, Clozel JP, Hess P et al. Ro 40-5967, in contrast to diltiazem, does not reduce left ventricular contractility in rats with chronic myocardial infarction. J Cardiovasc Pharmacol 1991; 17(2):277-84.
- 181. Leuranguer V, Mangoni ME, Nargeot J et al. Inhibition of T-type and L-type Ca²⁺ channels by mibefradil: physiologic and pharmacologic bases of cardiovascular effects. J Cardiovasc Pharmacol 2001; 37(6):649-61.
- Bouman LN, Jongsma HJ. Structure and function of the sino-atrial node: a review. European Heart Journal 1986; 7(2):94-104.
- 183. Weidmann S. Historical perspective. In: Zipes DP, Bayley SC, Elharrar V, eds. The Slow Imward Current and Cardiac Arrhythmias. The Hague: Nijoff, 1980.

- 184. Boyett MR, Honjo H, Kodama I. The sinoatrial node, a heterogeneous pacemaker structure. Cardiovasc Res 2000; 47(4):658-87.
- DiFrancesco D, Ducouret P, Robinson RB. Muscarinic modulation of cardiac rate at low acetylcholine concentrations. Science 1989; 243(4891):669-71.
- Belardinelli L, Giles WR, West A. Ionic mechanisms of adenosine actions in pacemaker cells from rabbit heart. J Physiol (Lond) 1988; 405:615-33.
- DiFrancesco D, Tortora P. Direct activation of cardiac pacemaker channels by intracellular cyclic AMP. Nature 1991; 351(6322):145-7.
- 188. DiFrancesco D, Mangoni M. Modulation of single hyperpolarization-activated channels (i(f)) by cAMP in the rabbit sino-atrial node. J Physiol (Lond) 1994; 474(3):473-82.
- 189. Noma A. Ionic mechanisms of the cardiac pacemaker potential. Jpn Heart J 1996; 37(5):673-82.
- 190. Noma A, Morad M, Irisawa H. Does the "pacemaker current" generate the diastolic depolarization in the rabbit SA node cells? Pflugers Arch 1983; 397(3):190-194.
- 191. Brown HF, DiFrancesco D, Noble SJ. How does adrenaline accelerate the heart? Nature 1979;280(5719):235-236.
- 192. Doerr T, Denger R, Trautwein W. Ca²⁺ currents in single SA nodal cells of the rabbit heart studied with action potential clamp. Pflugers Arch 1989; 413(6):5599-603.
- 193. Kodama I, Nikmaram MR, Boyett MR et al. Regional differences in the role of the Ca²⁺ and Na+ currents in pacemaker activity in the sinoatrial node. Am J Physiol 1997; 272(6Pt 2):2793-806.
- 194. Lande G, Demolombe S, Bammert A et al. Transgenic mice overexpressing human KvLQT1 dominant negative isoform. Part II: Pharmacological profile Cardiovasc Res 2001; 50(2):328-34.
- 195. Verheijck EE, van Ginneken AC, Wilders R et al. Contribution of L-type Ca²⁺ current to electrical activity in sinoatrial nodal myocytes of rabbits. American Journal of Physiology 1999; 276(3Pt 2):1064-77.
- 196. Petit-Jacques J, Bois P, Bescond J et al. Mechanism of muscarinic control of the high-threshold Ca²⁺ current in rabbit sino-atrial node myocytes. Pflugers Archiv 1993; 423(1-2):21-27.
- 197. Zaza A, Robinson RB, DiFrancesco D. Basal responses of the L-type Ca²⁺ and hyperpolarization-activated currents to autonomic agonists in the rabbit sino-atrial node. Journal of Physiology 1996; 491(Pt 2):347-55.
- 198. Han X, Shimoni Y, Giles WR. An obligatory role for nitric oxide in autonomic control of mammalian heart rate. J Physiol (Lond) 1994; 476(2):309-14.
- 199. Han X, Kobzik L, Severson D et al. Characteristics of nitric oxide-mediated cholinergic modulation of Ca²⁺ current in rabbit sino-atrial node. J Physiol (Lond) 1998; 509(Pt 3):741-54.
- Wickman K, Nemec J, Gendler SJ et al. Abnormal heart rate regulation in GIRK4 knockout mice. Neuron 1998; 20(1):103-14.
- 201. Mangoni ME, Nargeot, J. Properties of the hyperpolarization-activated current (If) in isolated mouse sino-atrial cells. Cardiovasc Res 2001; 52:51-64.
- 202. Huser J, Blatter LA, Lipsius SL. Intracellular Ca²⁺ release contributes to automaticity in cat atrial pacemaker cells. J Physiol (Lond) 2000; 524 Pt 2:415-22.
- 203. Roden DM, Balser JR, George AL et al. Anderson ME. Cardiac ion channels Annu Rev Physiol 2002; 64:431-75.
- 204. Platzer J, Engel J, Schrott-Fischer A et al. Congenital deafness and sinoatrial node dysfunction in mice lacking class D L-type Ca²⁺ channels. Cell 2000; 102(1):89-97.
- 205. Bohn G, Moosmang S, Conrad H et al. Expression of T- and L-type Ca²⁺ channel mRNA in murine sinoatrial node. FEBS Lett 2000; 481(1):73-6.
- 206. Zhang Z, Xu Y, Song H et al. Functional Roles of Ca(v)1.3. (alpha(1D)) Ca²⁺ channel in sinoatrial nodes: insight gained using gene-targeted null mutant mice. Circ Res 2002; 90(9):981-7.
- 207. Xu W, Lipscombe D. Neuronal Ca(V)1.3. alpha(1) L-type channels activate at relatively hyperpolarized membrane potentials and are incompletely inhibited by dihydropyridines. J Neurosci 2001; 21(16):5944-51.
- 208. Koschak A, Reimer D, Huber I et al. alpha 1D (cav1.3.) subunits can form l-type ca²⁺ channels activating at negative voltages. J Biol Chem 2001; 276(25):22100-6.
- 209. Striessnig J. Targeting voltage-gated Ca2+ channels. Lancet 2001; 357(9264):1294.

Post-Genomic Insights into T-Type Calcium Channel Functions in Neurons

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Abstract

renomic mining, the process of sifting through billions of genomic and EST sequences of several different species has led to the molecular identification of a family of low voltage activating channels, more commonly referred to as T-type channels. Historically, these channels were initially identified through the use of the patch-clamp technique on various neuronal preparations. They were characterized by their small conductance, rapid voltage-dependent inactivation, a small window current and slow deactivation kinetics and their remarkable property of being able to open at membrane potentials just above the resting membrane potential of neurons. This property would allow for the entry of Ca^{2+} without the initiation of an action potential triggered by the opening of sodium channels. Thus the activity of these channels would contribute to modifying membrane excitability, allowing Ca²⁺ signaling events to occur at subthreshold potentials, and potentially modulate waveform patterns. Now, with the clones in hand, we have entered an exciting time where the molecular machinery can be dissected, modified and manipulated not only to investigate their biophysical properties, but to appreciate their role in a diverse range of cellular processes, find novel and useful therapeutic and pharmacological reagents, hunt down subunits and modifying proteins, study their localization and trafficking and incorporate these findings into the emerging field of systems biology where their roles can be placed in the context from a single neuron, to the organ, to the organism.

Introduction

Calcium influx via Low Threshold Spikes (LTS) into neurons near their membrane resting potential has been implicated more than 20 years ago in the rhythmic pacing of inferior olivary neurons.^{1,2} These studies established that hyperpolarizing current injection evoked at negative voltages results in a rebound excitation depolarization of a small amplitude, slow kinetics and relatively long duration that is crowned at more positive potentials by fast and large sodium spikes. These particular action potentials or Low Threshold Spikes, where shown to be insensitive to sodium and potassium channel blockers but completely eliminated upon removal of extracellular calcium or in the presence of inorganic calcium channel blockers. Barium ions can substitute to calcium suggesting that the calcium channel underlying this LTS is equally permeable to both ions with similar current kinetics. This LTS and the low voltage gated calcium entry associated with it have been recognized as a widely distributed mechanism of neuronal excitability of the central and peripheral nervous system.

The development of the patch clamp technique in the mid to late 70s helped to isolate and characterize the functional properties of the particular calcium channels gated at these negative

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voltages. Accordingly they have been named Low Voltage Activated (LVA) or T-types in reference to their (T)ransient kinetics and (T)iny conductances. In agreement with the description of LTS, the biophysical characterization of T-type channels showed that their hallmark is a steady state activation and inactivation at negative potentials resulting in a strong channel inactivation at the membrane resting potential, peculiar kinetics (i.e., slow activation kinetics near the membrane resting potential, fast activation and inactivating kinetics at more positive potentials, slow deactivation), and overlapping activation and inactivation curves for a range of potential between -70 and -50 mV generating a steady window current at resting membrane potentials of most excitable cell types. Therefore these biophysical characteristics define two types of calcium influx important to take into consideration to understand T-type channel function. One is transient during action potentials and the other is a small but sustained current at resting potentials. The specific properties of T-type channels suggested their implication in a number of physiological or pathological conditions such as absence seizure epilepsy for example, but two major obstacles to a deeper understanding of their role remained. The first one was the lack of pharmacological tools selective to these channels, and for a long time the lack of molecular substrate for these channels. With all the classical approaches of molecular cloning having proved futile in finding T-type channels, efforts turned to blast and word searching the sequences being deposited at the National Center of Biotechnology Information (NCBI, http://www.ncbi.nlm.nih.gov/) databanks, using what is now termed 'in silico' cloning. Thus, in combination of with the near completion of several genomes sequences and millions of ESTs (expressed tag sequences) that exploration of sequence data bases led to the identification of three genes encoding for pore forming alpha1 subunits of T-type channels namely Ca_v3.1, Ca_v3.2, and Ca_v3.3 (or α_{1G} , α_{1H} , and α_{1I} in the former nomenclature).³⁻¹⁰ This approach pioneered by Ed Perez Reyes's group paved the way for investigating the function and properties of T-type channels in recombinant and native tissues.

Contributions of Recombinant Channel Studies

One of the first achievements of the T-type channel cloning is an explanation of T-type channel heterogeneity observed in native systems. In the absence of selective pharmacology, functional studies in different models suggested an apparent diversity. These observations were based on differential sensitivity to nickel or amiloride block, diverse inactivation kinetics, and different permeation profiles to divalent ions.¹¹ Thus, functional expression of recombinant T-type channels has been clearly instrumental to a more clear-cut definition of the characteristics of pure population of channels that can not be distinguished in native cells. For example, high affinity block by Nickel ions is only present in Ca_v3.2 channels, while Ca_v3.1 and Ca_v3.3 are both at least 20 fold less sensitive.¹² Also, Ca_v3.3 differs dramatically from Ca_v3.1 and Ca_v3.2 by slower activation and inactivation kinetics. Isolation and analysis of transcripts by conventional screening of libraries and PCR of specific regions revealed the presence of alterna-tive splicing within each family member.^{6,7,14,15} Expression studies of these isoforms revealed important differences in their electrophysiological properties. For example, modulation of steady state inactivation of some Cav3.1 variants was shown to reduce strongly their potential window current and their availability to be activated during an action potential.¹⁶ In the same line of observations, functional properties of Ca_v3.3 were shown to be modulated by exon splicing.¹⁷⁻¹⁹ Transcripts with premature stops or deletion of several exons leading to truncated channels have been reported²⁰ (Monteil, unpublished observations). Although the effect of these truncated channels remains to be studied, it can be hypothesised that they can function as dominant negatives as reported for some High Voltage Activated (HVA) calcium channels.^{21,22}

An other step toward understanding of T-type calcium channel contribution to neuronal excitability has been to stimulate recombinant channels with a variety of neuronal action potential waveforms. These studies highlighted how the three T-type channel forms can induce distinct calcium entry. In terms of kinetics the current generated by the Ca₂3.3 channels differs from those associated to Ca₂3.1 and Ca₂3.2 expression. Using isolated or trains of action po-

tentials, fast or slow EPSPs as stimuli, a number of similar approaches showed that Ca_v3.3 can undergo steady and facilitating calcium influx during intense electrical activity. By contrast, Ca_v3.1 and Ca_v3.2 are more rapidly inactivated but respond better to isolated membrane activities.²³⁻²⁵ In the absence of specific pharmacology efforts to understand the specific role of a T-type current from of given neuronal type have relied on computer models.²⁶⁻²⁸ Properties of recombinant T-type channels have therefore been used to see how they interplay with other conductances to promote rhythmic activity in such neuronal cell models. These studies showed that Ca_v3.1 and Ca_v3.3 respective properties are compatible with discharge patterns of relay and reticular neurons of the thalamus.^{6,25}

Unlike many sodium channels and HVA calcium channels, poor pharmacology has hampered efforts to biochemically characterize the LVA complexes and electrophysiologically tease out the contribution of members of this family to membrane excitability. Here again the use of expressed T-type channels has provided powerful screening assays to identify selective antagonists or agonists for these channels. Conventionally, cone snail, spider and scorpion toxins which contain an array of proteinacious material are isolated, separated by HPLC and then each extract applied onto cells expressing either a single cDNA, as in a stably or transiently transfected cell line or onto a cell expressing several different channel subtypes. Once the interesting fraction has been identified, the isolated peptide fraction is sequenced and resynthesized. The application of extracts purified from the scorpion Parabuthus transvaalicus led to the identification of Kurtoxin which was shown to block cloned Ca_v3.1 and Ca_v3.2 channels at sub-micromolar concentrations.²⁹ A recent study of two related toxins (KLI and KLII) purified from an other scorpion venom (Parabuthus granulatus) showed that Ca. 3.3 is much less sensitive suggesting that this toxin can discriminate between members of the Ca_v3 subfamily.³⁰ However Kurtoxin and KLII appeared to also block sodium channel and HVA calcium channels²⁹⁻³¹ rendering them almost useless to dissect selectively the contribution of T-channels to a given physiological function. Efforts in toxin identification using such screens are underway in different laboratories, and in the long term, we can hope to isolate selective toxins for each T-channel isotypes. Although specific toxins have a great interest in fundamental research, therapeutic perspective resulting from functional modification of T-type channels mainly concerns organic chemical compounds. For this aspect, recombinant T-type channels can be instrumental of high throughput screening. These screens mainly based on cytosolic calcium monitoring can certainly exploit the window current of expressed channels at resting membrane potentials that was shown to constitutively increase basal intracellular calcium.³² Non selective blockade of native T-type channels by a range of neuroactive molecules ranking from anti-epileptics, neuroleptics, anesthetics, or anti-hypertensive molecules have been reported.^{11,33} For the moment, recombinant channels have only been used to test the blocking affinities of some of these compounds.³⁴⁻³⁶ Two noteworthy clinically relevant molecules are Mibefradil and Ethosuximide. The first one has been developed as an anti-hypertensive therapeutic agent. The mechanism of action proposed was an inhibition of T-type channels.³⁷ The use of recombinant calcium channels clearly showed the lack of selectivity for T-type channels compared to HVA channels,³⁸⁻⁴² although the preferential affinity for the inactivated state promotes a stronger block of T-type channels.⁴³ Ethosuximide is an anticonvulsant used in the treatment of absence seizure. Its anti epileptic activity has been proposed to result from T-type channels inhibition in the thalamus, 44,45 although it remains controversial. 46 The use of recombinant T-type channels showed that Ethosuximide and its metabolites are able to block all Ca_v3 members at clinically relevant concentrations.⁴⁷ In the absence of more selective blockers, these two drugs are still used as tools to explore the role T-type channel in physiologic functions. For example they have been administered in rodents intraperitoneally or intrathecally in studies on the involvement of T-channels in nociception.⁴⁸⁻⁵⁰ All the results argue for a role of T-type channel in nociception as initially proposed following their identification in isolated dorsal root ganglion neurons. 51-53 More recent studies have reinforced and elaborated on the role of T-type channels in nociception. It as been shown first that antisense transfection in primary

culture of nodose ganglion neuron reduces strongly their T-type currents and their excitability.⁵⁴ Northern blots, RT-PCR, and in situ hybridization showed that sensory neurons as well as neurons from the superficial laminae of the dorsal horn express Ca_x3.2 almost exclusively.^{3,54,55} Therefore recombinant Ca_x3.2 was useful to identify new regulatory mechanisms of DRG T-type channels possibly implicated in pain sensing. That was the case for the characterization of their redox modulation,⁵⁶ or their modulation by nitric oxide.⁵⁷ Other forms of modulation of DRG T-type channels, such as their potential inhibition by the opioid like receptor ligand (ORL) nociceptine,⁵⁸ were however impossible to reproduce on expressed Ca_x3.2.⁵⁹

Finally, cloned T-type channels have been used to try to identify their possible modulation by intracellular cascades or endogenous circulating biomolecules. Besides redox and nitric oxide modulation, Ca_v3 channels where shown to be sensitive to arachidonic acid (AA), an important second messenger.⁶⁰ As anandamide, a precursor of AA, has been shown to be a natural ligand of several ion channels including potassium channels and vanilloid receptors, Chemin and coworkers studied its effects on expressed Ca_v3 channels.⁶¹ Their results show that Ca_v3 channels have a high affinity biding site for anandamide, and that the mechanism of current block by this endocanabinoid is state dependent. The binding of this molecule significantly effects the kinetic properties of the T-type channels, and would alter the contribution of the current to neuronal excitability. Future works will undoubted address issues in recombinant systems on the role of specific residues and regions of T-type channels important in these types of modulation. Other modulators of T-type channels described in isolated neurons will certainly benefit from the availability of T-type channel cDNAs to elucidate the underlying mechanisms.

T-Type Channels and Neurophysiology

Understanding the role of T-type channels in the global context of physiology is the step forward the cloning of their constitutive genes. Although no selective pharmacology is available yet, identification of the Ca_x3 gene family opened the door to their functional elimination using genetic manipulations. This was firstly achieved with Ca_x3.1 whose gene (cacna1g) was inactivated in the mouse.⁶² The Ca_x3.1 (-/-) mice have been used to address the issue of the role of T-type calcium channels in the genesis of spike-and-wave discharges (SWDs), a sign of absence seizures in the thalamocortical network. According to the predominant expression of Ca_x3.1 in thalamocortical relay neurons⁵⁵ and its increased expression in animal strains genetically predisposed to absence seizures,^{63,64} the other T-type channels have been postulated to only play a minor role in this phenomenom.

The results show that thalamic relay neurons are deficient in T-type channels and consequently have profound modifications of their excitability. It was notably demonstrated that low threshold spikes (LTS) are absent in these neurons as well as their burst-mode of firing action potentials. The major consequence of these modifications is a resistance of Cav3.1 (-/-) mice to the generation of SWDs induced by GABA_B receptor stimulation, a hallmark of absence seizures. Therefore, this study unambiguously demonstrated the epileptogenic role of T-type channels in the genesis of absence seizure, and further validates T-type channels as an antiepileptic drug target. Moreover, in murine models of absence seizure such as the tottering, lethargic, or stargazer strains carrying mutations in various high-voltage-activated calcium channels subunits genes, an increase of T-type channel current in thalamic relay neurons was recently reported.⁶⁵ Other forms of epilepsy may be also concerned by plasticity of T-type channel expression. For example after induction of chronic status epilepticus (SE) in the pilocarpine model, hippocampal or subicular pyramidal neurons changes their intrinsic firing properties with an augmented proportion of bursting-mode and after depolarization potentials. This change has been associated with an increase of nickel sensitive T-type currents, 66,67 attributable to a transcriptional regulation of Cav 3.2.68 Therefore bursting-mode may be controlled by different T-type channel isotypes in different brain regions. Conversely, in other neurons, selective coupling of T-type channels with calcium sensitive potassium channels can hamper bursting by generating after-hyperpolarization potentials.^{69,70}

Generation of genetically modified mice has just started with Ca_v3.1 and more recently Ca_v3.2.⁷¹ We can hope from these models and certainly from the future ones (conditional knock outs, transgenic animals, etc.) to further understand the pertinence of T-type channel expression. These aspects concern an array of neurophysiological functions ranging from neuronal development and differentiation,^{72,73} excitability as described for their epileptogenic role but also in long lasting synaptic plasticity,⁷⁴⁻⁷⁷ neurotransmitter release,^{78,79} or multiple intracellular calcium dependant cascades.

In summary, understanding of T-type channel cellular functions tremendously benefited from the identification of their molecular structure, and the exciting challenge is now to unravel their role in the context of integrated physiology.

References

- Llinas R, Yarom Y. Properties and distribution of ionic conductances generating electroresponsiveness of mammalian inferior olivary neurones in vitro. J Physiol 1981; 315:569-84.
- 2. Llinas R, Yarom Y. Electrophysiology of mammalian inferior olivary neurones in vitro. Different types of voltage-dependent ionic conductances. J Physiol 1981; 315:549-67.
- Cribbs LL, Lee JH, Yang J et al. Cloning and characterization of alpha1H from human heart, a member of the T-type Ca²⁺ channel gene family. Circ Res 1998; 83(1):103-9.
- Klugbauer N, Marais E, Lacinova L et al. A T-type calcium channel from mouse brain. Pflugers Arch 1999; 437(5):710-5.
- 5. Lee JH, Daud AN, Cribbs LL et al. Cloning and expression of a novel member of the low voltage-activated T- type calcium channel family. J Neurosci 1999; 19(6):1912-21.
- 6. McRory JE, Santi CM, Hamming KS et al. Molecular and Functional Characterization of a Family of Rat Brain T- type Calcium Channels. J Biol Chem 2001; 276(6):3999-4011.
- 7. Monteil A, Chemin J, Bourinet E et al. Molecular and functional properties of the human alpha(1G) subunit that forms T-type calcium channels. J Biol Chem 2000; 275(9):6090-100.
- 8. Monteil A, Chemin J, Leuranguer V et al. Specific properties of T-type calcium channels generated by the human alpha 11 subunit. J Biol Chem 2000; 275(22):16530-5.
- 9. Perez-Reyes E. Molecular characterization of a novel family of low voltage-activated, T-type, calcium channels. J Bioenerg Biomembr 1998; 30(4):313-8.
- 10. Williams ME, Washburn MS, Hans M et al. Structure and functional characterization of a novel human low-voltage activated calcium channel. J Neurochem 1999; 72(2):791-9.
- Huguenard JR. Low-threshold calcium currents in central nervous system neurons. Annu Rev Physiol 1996; 58:329-48.
- 12. Lee JH, Gomora JC, Cribbs LL et al. Nickel block of three cloned T-type calcium channels: Low concentrations selectively block alpha1H. Biophys J 1999; 77(6):3034-42.
- Frazier CJ, Serrano JR, George EG et al. Gating kinetics of the alpha11 T-type calcium channel. J Gen Physiol 2001; 118(5):457-70.
- 14. Mittman S, Guo J, Emerick MC et al. Structure and alternative splicing of the gene encoding alpha11, a human brain T calcium channel alpha1 subunit. Neurosci Lett 1999; 269(3):121-4.
- Mittman S, Guo J, Agnew WS. Structure and alternative splicing of the gene encoding alpha1G, a human brain T calcium channel alpha1 subunit. Neurosci Lett 1999; 274(3):143-6.
- Chemin J, Monteil A, Bourinet E et al. Alternatively spliced alpha(1G) (Ca²⁺(V)3.1) intracellular loops promote specific T-type Ca(2+) channel gating properties. Biophys J 2001; 80(3):1238-50.
- 17. Murbartian J, Arias JM, Lee JH et al. Alternative splicing of the rat Ca²⁺(v)3.3 T-type calcium channel gene produces variants with distinct functional properties(1). FEBS Lett 2002; 528(1-3):272-8.
- Gomora JC, Murbartian J, Arias JM et al. Cloning and expression of the human T-type channel Ca²⁺(v)3.3: Insights into prepulse facilitation. Biophys J 2002; 83(1):229-41.
- 19. Chemin J, Monteil A, Dubel S et al. The alpha11 T-type calcium channel exhibits faster gating properties when overexpressed in neuroblastoma/glioma NG 108-15 cells. Eur J Neurosci 2001; 14(10):1678-86.
- 20. Beedle AM, Hamid J, Zamponi GW. Novel human a1G calcium channel splice variants. Biophysical J 2001; 80(1):120a.
- 21. Raghib A, Bertaso F, Davies A et al. Dominant-negative synthesis suppression of voltage-gated calcium channel Cav2.2 induced by truncated constructs. J Neurosci 2001; 21(21):8495-504.
- 22. Ebihara T, Komiya Y, Izumi-Nakaseko H et al. Coexpression of a Ca²⁺(v)1.2 protein lacking an N-terminus and the first domain specifically suppresses L-type calcium channel activity. FEBS Lett 2002; 529(2-3):203-7.

- 23. Warre RC, McNaughton NC, Randall AD. Differential discrimination of fast and slow synaptic waveforms by two low-voltage-activated calcium channels. Neuroscience 2002; 110(2):375-88.
- 24. Kozlov AS, McKenna F, Lee JH et al. Distinct kinetics of cloned T-type Ca(2+) channels lead to differential Ca2 + entry and frequency-dependence during mock action potentials. Eur J Neurosci 1999; 11(12):4149-58.
- Chemin J, Monteil A, Perez-Reyes E et al. Specific contribution of human T-type calcium channel isotypes (alpha(1G), alpha(1H) and alpha(1I)) to neuronal excitability. J Physiol 2002; 540(Pt 1):3-14.
- Destexhe A, Contreras D, Steriade M et al. In vivo, in vitro, and computational analysis of dendritic calcium currents in thalamic reticular neurons. J Neurosci 1996; 16(1):169-85.
- Destexhe A, Neubig M, Ulrich D et al. Dendritic low-threshold calcium currents in thalamic relay cells. J Neurosci 1998; 18(10):3574-88.
- Huguenard JR, McCormick DA. Simulation of the currents involved in rhythmic oscillations in thalamic relay neurons. J Neurophysiol 1992; 68(4):1373-83.
- Chuang RS, Jaffe H, Cribbs L et al. Inhibition of T-type voltage-gated calcium channels by a new scorpion toxin. Nat Neurosci 1998; 1(8):668-74.
- 30. Olamendi-Portugal T, Ines Garcia B, Lopez-Gonzalez I et al. Two new scorpion toxins that target voltage-gated Ca(2+) and Na(+) channels. Biochem Biophys Res Commun 2002; 299(4):562-8.
- 31. Sidach SS, Mintz IM. Kurtoxin, a gating modifier of neuronal high- and low-threshold ca channels. J Neurosci 2002; 22(6):2023-34.
- 32. Chemin J, Monteil A, Briquaire C et al. Overexpression of T-type calcium channels in HEK-293 cells increases intracellular calcium without affecting cellular proliferation. FEBS Lett 2000; 478(1-2):166-72.
- Todorovic SM, Lingle CJ. Pharmacological properties of T-type Ca(2+) current in adult rat sensory neurons: effects of anticonvulsant and anesthetic agents. J Neurophysiol 1998; 79(1):240-52.
- Todorovic SM, Perez-Reyes E, Lingle CJ. Anticonvulsants but not general anesthetics have differential blocking effects on different T-type current variants. Mol Pharmacol 2000; 58(1):98-108.
- McNaughton NC, Hainsworth AH, Green PJ et al. Inhibition of recombinant low-voltage-activated Ca(2+) channels by the neuroprotective agent BW619C89 (Sipatrigine). Neuropharmacology 2000; 39(7):1247-53.
- Santi CM, Cayabyab FS, Sutton KG et al. Differential inhibition of T-type calcium channels by neuroleptics. J Neurosci 2002; 22(2):396-403.
- Mishra SK, Hermsmeyer K. Selective inhibition of T-type Ca(2+) channels by Ro 40-5967. Circ Res 1994; 75(1):144-8.
- Jimenez C, Bourinet E, Leuranguer V et al. Determinants of voltage-dependent inactivation affect Mibefradil block of calcium channels. Neuropharmacology 2000; 39(1):1-10.
- 39. Martin RL, Lee JH, Cribbs LL et al. Mibefradil block of cloned T-type calcium channels. J Pharmacol Exp Ther 2000; 295(1):302-8.
- 40. Benardeau A, Weissenburger J, Hondeghem L et al. Effects of the T-type Ca(2+) channel blocker mibefradil on repolarization of guinea pig, rabbit, dog, monkey, and human cardiac tissue. J Pharmacol Exp Ther 2000; 292(2):561-75.
- Bezprozvanny I, Tsien RW. Voltage-dependent blockade of diverse types of voltage-gated Ca(2+) channels expressed in Xenopus oocytes by the Ca(2+) channel antagonist mibefradil (Ro 40-5967). Mol Pharmacol 1995; 48(3):540-9.
- Michels G, Matthes J, Handrock R et al. Single-channel pharmacology of mibefradil in human native T-type and recombinant Ca²⁺(v)3.2 calcium channels. Mol Pharmacol 2002; 61(3):682-94.
- McDonough SI, Bean BP. Mibefradil inhibition of T-type calcium channels in cerebellar purkinje neurons. Mol Pharmacol 1998; 54(6):1080-7.
- Coulter DA, Huguenard JR, Prince DA. Differential effects of petit mal anticonvulsants and convulsants on thalamic neurones: Calcium current reduction. Br J Pharmacol 1990; 100(4):800-6.
- Coulter DA, Huguenard JR, Prince DA. Specific petit mal anticonvulsants reduce calcium currents in thalamic neurons. Neurosci Lett 1989; 98(1):74-8.
- 46. Leresche N, Parri HR, Erdemli G et al. On the action of the anti-absence drug ethosuximide in the rat and cat thalamus. J Neurosci 1998; 18(13):4842-53.
- 47. Gomora JC, Daud AN, Weiergraber M et al. Block of cloned human T-type calcium channels by succinimide antiepileptic drugs. Mol Pharmacol 2001; 60(5):1121-32.
- Todorovic S, Meyenburg A, Jevtovic-Todorovic V. Mechanical and thermal antinociception in rats following systemic administration of mibefradil, a T-type calcium channel blocker. Brain Res 2002; 951(2):336.

- Dogrul A, Zagli U, Tulunay FC. The role of T-type calcium channels in morphine analgesia, development of antinociceptive tolerance and dependence to morphine, and morphine abstinence syndrome. Life Sci 2002; 71(6):725-34.
- 50. Matthews EA, Dickenson AH. Effects of ethosuximide, a T-type Ca(2+) channel blocker, on dorsal horn neuronal responses in rats. Eur J Pharmacol 2001; 415(2-3):141-9.
- Carbone E, Lux HD. A low voltage-activated, fully inactivating Ca²⁺ channel in vertebrate sensory neurones. Nature 1984; 310(5977):501-2.
- Bossu JL, Feltz A, Thomann JM. Depolarization elicits two distinct calcium currents in vertebrate sensory neurones. Pflugers Arch 1985; 403(4):360-8.
- Kostyuk PG, Shuba Ya M, Savchenko AN. Three types of calcium channels in the membrane of mouse sensory neurons. Pflugers Arch 1988; 411(6):661-9.
- 54. Lambert RC, McKenna F, Maulet Y et al. Low-voltage-activated Ca(2+) currents are generated by members of the CavT subunit family (alpha1G/H) in rat primary sensory neurons. J Neurosci 1998; 18(21):8605-13.
- 55. Talley EM, Cribbs LL, Lee JH et al. Differential distribution of three members of a gene family encoding low voltage-activated (T-type) calcium channels. J Neurosci 1999; 19(6):1895-911.
- 56. Todorovic SM, Jevtovic-Todorovic V, Meyenburg A et al. Redox modulation of T-type calcium channels in rat peripheral nociceptors. Neuron 2001; 31(1):75-85.
- Todorovic SM, Jevtovic-Todorovic V, Mennerick S et al. Ca²⁺(v)3.2 channel is a molecular substrate for inhibition of T-type calcium currents in rat sensory neurons by nitrous oxide. Mol Pharmacol 2001; 60(3):603-10.
- Abdulla FA, Smith PA. Nociceptin inhibits T-type Ca(2+) channel current in rat sensory neurons by a G-protein-independent mechanism. J Neurosci 1997; 17(22):8721-8.
- Beedle AM, Poirot O, Barrere C et al. Inhibition of voltage gated calcium channels by nociceptine. In: 32nd Annual Meeting of the Society for Neuroscience; 2002. Orlando: 2002: 341.5.
- 60. Zhang Y, Cribbs LL, Satin J. Arachidonic acid modulation of alpha1H, a cloned human T-type calcium channel. Am J Physiol Heart Circ Physiol 2000; 278(1):H184-93.
- Chemin J, Monteil A, Perez-Reyes E et al. Direct inhibition of T-type calcium channels by the endogenous cannabinoid anandamide. EMBO J 2001; 20(24):7033-40.
- 62. Kim D, Song I, Keum S et al. Lack of the burst firing of thalamocortical relay neurons and resistance to absence seizures in mice lacking alpha(1G) T-type Ca(2+) channels. Neuron 2001; 31(1):35-45.
- 63. Talley EM, Solorzano G, Depaulis A et al. Low-voltage-activated calcium channel subunit expression in a genetic model of absence epilepsy in the rat. Brain Res Mol Brain Res 2000; 75(1):159-65.
- 64. Tsakiridou E, Bertollini L, de Curtis M et al. Selective increase in T-type calcium conductance of reticular thalamic neurons in a rat model of absence epilepsy. J Neurosci 1995; 15(4):3110-7.
- 65. Zhang Y, Mori M, Burgess DL et al. Mutations in high-voltage-activated calcium channel genes stimulate low-voltage-activated currents in mouse thalamic relay neurons. J Neurosci 2002; 22(15):6362-71.
- 66. Wellmer J, Su H, Beck H et al. Long-lasting modification of intrinsic discharge properties in subicular neurons following status epilepticus. Eur J Neurosci 2002; 16(2):259-66.
- 67. Su H, Sochivko D, Becker A et al. Upregulation of a T-type Ca²⁺ channel causes a long-lasting modification of neuronal firing mode after status epilepticus. J Neurosci 2002; 22(9):3645-55.
- 68. Becker AJ, Su H, Sochivko D et al. Experience-dependent modification of neuronal firing mode by transcriptional regulation of a T-type Ca²⁺ channel. In: 31st Annual Meeting of the Society for Neuroscience; 2001. San Diego: 2001: 707.10.
- 69. Williams S, Serafin M, Muhlethaler M et al. Distinct contributions of high- and low-voltage-activated calcium currents to after hyperpolarizations in cholinergic nucleus basalis neurons of the guinea pig. J Neurosci 1997; 17(19):7307-15.
- Wolfart J, Roeper J. Selective coupling of T-type calcium channels to SK potassium channels prevents intrinsic bursting in dopaminergic midbrain neurons. J Neurosci 2002; 22(9):3404-13.
- 71. Chen C-C, Wang Z, Barresi R et al. Functional studies of Ca.3.2 calcium channels using a gene-targeted strategy. Biophysical J 2002; 82(1):572a.
- Chemin J, Nargeot J, Lory P. Neuronal T-type alpha 1H calcium channels induce neuritogenesis and expression of high-voltage-activated calcium channels in the NG108-15 cell line. J Neurosci 2002; 22(16):6856-62.
- Frischknecht F, Randall AD. Voltage- and ligand-gated ion channels in floor plate neuroepithelia of the rat. Neuroscience 1998; 85(4):1135-49.

- 74. Oliet SH, Malenka RC, Nicoll RA. Two distinct forms of long-term depression coexist in CA1 hippocampal pyramidal cells. Neuron 1997; 18(6):969-82.
- Nicoll RA, Oliet SH, Malenka RC. NMDA receptor-dependent and metabotropic glutamate receptor-dependent forms of long-term depression coexist in CA1 hippocampal pyramidal cells. Neurobiol Learn Mem 1998; 70(1-2):62-72.
- 76. Wang Y, Rowan MJ, Anwyl R. Induction of LTD in the dentate gyrus in vitro is NMDA receptor independent, but dependent on Ca(2+) influx via low-voltage-activated Ca²⁺ channels and release of Ca²⁺ from intracellular stores. J Neurophysiol 1997; 77(2):812-25.
- 77. Wasling P, Hanse E, Gustafsson B. Long-term depression in the developing hippocampus: low induction threshold and synapse nonspecificity. J Neurosci 2002; 22(5):1823-30.
- 78. Bao J, Li JJ, Perl ER. Differences in Ca²⁺ channels governing generation of miniature and evoked excitatory synaptic currents in spinal laminae I and II. J Neurosci 1998; 18(21):8740-50.
- 79. Pan ZH, Hu HJ, Perring P et al. T-type Ca(2+) channels mediate neurotransmitter release in retinal bipolar cells. Neuron 2001; 32(1):89-98.

CHAPTER 22

Voltage-Gated Ca²⁺ Channels of the Vertebrate Retina: From the Genetics of Blindness to Encoding the Visual World

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Abstract

🛚 a²⁺ channel-mediated synaptic transmission and calcium signaling in the retina reveals neurobiological solutions to a diversity of signal processing challenges. In rod and cone photoreceptors, graded and sustained transduction signals, generated over a narrow range of membrane potentials, are synaptically transmitted to second order horizontal and bipolar cells. In rods, novel Ca²⁺ channels (α_{1F} ; Ca_v1.4) have been implicated at this synapse through genetic studies of people with night blindness, while in cones, biophysically similar α_{1D} (Ca_v1.3) channels appear to be utilized for this purpose. Although the synaptic output of horizontal cells appears to be Ca2+ - independent, these cells express L-type Ca2+ channels. Bipolar cells, which are also graded potential neurons, utilize both L- and T-type Ca²⁺ channels at their output synapse where the transience of the neural signals is enhanced. At the ganglion cell level, network integration of excitatory and inhibitory signals generates the throughput of the optic nerve. T-type Ca²⁺ channels together with several sub-types of high-voltage-activated Ca^{2+} channel subtypes play roles in signal integration and are modulated by neurotransmitters and signaling molecules such as nitric oxide (NO). Pervasive in developing retinal cells and in retinal precursor cells, T-type Ca²⁺ channels (α_{1G} and α_{1H} ; Ca_v3.1 and 3.2) undergo down-regulation as the cells mature into differentiated neurons and glia. Since all neuronal Ca²⁺ channel subtypes appear to be represented in the retina, this accessible and well-understood tissue offers many advantages to aid in our understanding of the physiological role of Ca²⁺ channels in the brain.

Introduction

The retina, the thin, transparent film of neural tissue at the back of the eye, is composed of a highly organized structure of neurons and glia that express a diversity of voltage-gated calcium channels (Ca^{2+} channels). Ca^{2+} channels provide the principle pathway for Ca^{2+} influx into retinal neurons and play fundamental roles in visual signal processing in the retina. Recent molecular biological and genetic discoveries, together with knowledge garnered from electrophysiological and behavioral experiments, has now provided us with a more complete picture of the Ca^{2+} channel subtypes and their function in specific retinal neurons and glia.

There are at least six major classes of neurons and three types of glia in the retina (Fig.1). Light hyperpolarizes rod and cone photoreceptors by causing the closure of CNG channels located in the outer segments of both cell types. Rods, which mediate vision under low light

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Figure 1. Organization of the retina. This schematic view of a retinal cross section shows the five principle retinal neurons and glia. ONL, outer nuclear layer: Rod photoreceptors (R) are shown with subcellular compartments (*ros*, rod outer segment, the site of visual transduction; *e*, ellipsoid, a mitochondrial rich region; *m*, myoid, a portion of the rod that undergoes circadian extension and retraction). Single cones (C) and double cones (DC) are indicated (cos specifies cone outer segment). Rods and cones synapse with second order cells in the outer plexiform layer (OPL). Within the inner nuclear layer (INL) lie the somata of horizontal cells (H), bipolar cells (B), amacrine cells (A), and Müller glial cells (M; shown with Landolt club -l). In the inner plexiform layer (IPL), synapses are made between the neurites of amacrine, bipolar, and ganglion cells (G). Ganglion cell bodies reside in the ganglion cell layer (GCL). The Müller cells span the entire depth of the retinal layers. The shading in this figure reflects the localization of nitric oxide synthase, the nitric oxide producing enzyme, as shown originally in Kurennyi et al, 1995. Nitric oxide was shown to modulate some Ca²⁺ channels in the retina (Reproduced with permission from John Wiley & Sons).

conditions, and cones, used for color vision in medium to brightly-lit conditions, reduce their glutamate release as they hyperpolarize in response to light. Second order horizontal cells, which are involved in the enhancement of contrast in the visual scene by providing lateral and chromatic inhibition, respond to the glutamate released by photoreceptors at sign-conserving synapses. The horizontal cells send signals back to cone photoreceptors and modulate the activity of the synapse. Second order bipolar cells, upon which inputs from many photoreceptors converge, further tune and then transmit the integrated signals to the spiking amacrine and ganglion cells of the inner retina. Müller cells, the radial glia that span the retina, actively maintain the chemical milieu of the retina.

 Ca^{2+} channels found in the retina include all known mammalian brain Ca^{2+} channel subtypes.¹ The nine identified pore-forming α_1 subunits are usually accompanied by auxiliary or regulatory subunits. Ca^{2+} channel types identified in retina include: the high voltage activated (HVA), dihydropyridine (DHP)-sensitive L-type Ca^{2+} channels formed from α_{1C} ($Ca_v1.2$), α_{1D} ($Ca_v1.3$) and α_{1F} ($Ca_v1.4$) subunits; HVA P/Q-type α_{1A} ($Ca_v2.1$) and HVA N-type α_{1B} ($Ca_v2.2$) subunits; as well as the intermediate voltage-activated R-type α_{1E} ($Ca_v2.3$) and low voltage-activated (LVA) T-type α_{1G} ($Ca_v3.1$), α_{1H} ($Ca_v3.2$), and α_{11} ($Ca_v3.3$) subunits. This chapter describes the expression of Ca^{2+} channels in retinal neurons, with emphasis on the properties of the channels in photoreceptors and bipolar cells, the graded potential neurons of the outer retina, as well as ganglion cells, the cells responsible for the neuronal output of the retina. An overview of evidence that describes differential expression of Ca^{2+} channel subtypes during retinal development is included.

Ca²⁺ Channels in the Graded Potential Neurons of the Outer Retina

The neurons of the outer retina, including rods, cones, and horizontal and bipolar cells, do not generate action potentials and, as in other non-spiking neural networks, signal via graded changes in their membrane potential.² Other prominent features of this synaptic regimen include sustained signals, exhibiting little inactivation, and a relatively narrow range of membrane potentials over which rods and cones signal. Photoreceptors and bipolar cells utilize a special type of synapse to support the continuous release of neurotransmitter that accompanies their non-spiking signals. It contains a specialized structure called a ribbon that orchestrates the flow of transmitter filled vesicles to the release site. Here, Ca²⁺ channels mediate the Ca²⁺ influx required for vesicle fusion. In photoreceptors, L-type Ca²⁺ channels (and possibly CNG channels^{3,4}) appear to mediate synaptic release, while both T- and L-type Ca²⁺ channels have been shown to contribute to exocytosis from bipolar cell presynaptic terminals. Horizontal cells, on the other hand, do not exhibit presynaptic membrane specializations and release neurotransmitters in a Ca²⁺-independent manner.⁵ They express non-classical L-type Ca²⁺ channels,⁶ presumably to serve some other calcium signaling roles.

A New L-Type Ca²⁺ Channel at the Photoreceptor Synapse

Neurotransmitter release from vertebrate photoreceptors is mediated by non-inactivating, HVA calcium channels that are considered to be of the L-type due to their dihydropyridine (DHP) sensitivity.⁷⁻¹² In both rods and cones, the L-type Ca²⁺ channels have a distinct pharmacological profile comprised of relatively weak sensitivity to DHPs and reversible block by the N-type Ca²⁺ channel blocker, ω -conotoxin GVIA (Fig. 2).^{11,12} This profile most closely resembles that of a_{1D} subunit-containing Ca²⁺ channels (Ca_v1.3).¹³ Antibodies directed against a_{1D} subunits in mammalian retina, however, label only in cones and not in rods, ^{14,15} although antibody specificity must be considered in non-mammalian studies.¹⁶ In auditory hair cells, the L-type channels have been identified to be formed from splice variants of a_{1D} primary subunits.^{17,18} It is not surprising, then, that the phenotype of the α_{1D} knockout mouse includes deafness.¹⁹ Visual defects were not noted in this knockout mouse, although if α_{1D} is the cone Ca²⁺ channel, this would be consistent with the rod-dominated vision present in rodents.

In support of a different L-type Ca²⁺ channel expressed in rods, genetic analysis of people with incomplete X-linked congenital stationary night blindness (CSNB2) has revealed the mutation responsible for the condition: the CACNA1F gene codes for a new L-type Ca2+ channel forming subunit, the α_{1F} .^{20,21} CSNB is a recessive non-progressive retinal disorder characterized by loss of night vision and reduced day vision. Patients with the incomplete version of this disease, CSNB2, have decreased dark adaptation and their electroretinograms show no rod b-waves, indicating a decreased efficacy of synaptic transmission from rod photoreceptors.²² Genetic analyses revealed that the locus for CSNB2 segregates with markers from Xp11.23, identified as a retina-specific Ca²⁺ channel a₁ subunit gene (CACNA1F), the protein product of which showed high homology to L-type Ca²⁺ channel α_1 subunits. Analysis of CACNA1F among families with CSNB2 revealed that the loss of function mutations cause premature protein truncation (Fig. 3). Since the defining feature of CSNB2 is night blindness, which is a rod disease, this would suggest that in humans, the gene product of CACNA1F is the previously undefined and novel rod Ca²⁺ channel. In support of $\alpha 1_F$ as the rod photoreceptor Ca^{2+} channel, immunhistochemical staining using antibodies against the human and rat α_{1F} peptide was obtained in the cell bodies and synaptic terminals of photoreceptors in the rat



Figure 2. Cone L-type Ca²⁺ channels show reversible block by ω -conotoxin GVIA. Panels A and B show current traces from isolated cone photoreceptors, recorded under voltage clamp during steps from -60 to 0 mV. Block of Ca²⁺ channel current by ω -conotoxin GVIA (1 μ M) is occluded by nifedipine. Panel Cshows the time course of the entire experiment, with additions of nifedipine, nifedipine plus conotoxin, cadmium and conotoxin alone indicated by the black bars. From Wilkinson & Barnes, 1996 (reproduced with permission from Journal of General Physiology).

retina.²³ In the rat retina, differential staining using both antibodies may have revealed an additional α_{1F} isoform localized to the photoreceptor synaptic terminals.²³

T-Type Ca²⁺ Channels Can Mediate Release of Transmitter from Bipolar Cells

Bipolar cells, second order retinal neurons that are responsible for transmitting the visual signal from photoreceptors in the outer retina to third order amacrine and ganglion cell neurons of the inner retina, express both L- and T-type Ca²⁺ channels in distinct cellular compartments.²⁴⁻²⁷ Bipolar cells have been classified as rod or cone types based on the source of their synaptic input and as ON or OFF types based on the polarity of their response to light.²⁸



Figure 3. Mutations of the α 1F Ca²⁺ channel are responsible for the failed synaptic transmission of rod mediated vision. The four repeating motifs, each with six transmembrane spanning helices, of the predicted membrane topology of the channel subunit encoded by the CACNA1F gene as originally described.²⁰ Truncated, non-functional channels occur as a result of the deletion, insertion and mutation sites shown. The locations of all 20 mutations identified to date in patients with incomplete CSNB are indicated. Figure is from Boycott et al, 2001 (ref. 85; reproduced with permission of Human Genetics).

While it remains the rule in most neurons, including photoreceptors, that neurotransmitter release appears to be mediated by HVA channels, in bipolar cells, T-type Ca²⁺ channels are also capable of mediating transmitter release.²⁹ In addition to previous reported L-type Ca²⁺ channels,^{30,31} expression of all three T-channel α 1 subunits (α_{1G} , α_{1H} , and α_{1l}) has been detected in bipolar cells using single-cell PCR techniques. The presence of T-channels, which activate at hyperpolarized potentials close to rest and undergo fast inactivation, endow these cells with specialized properties. Since the range of membrane potentials over which activation and inactivation occur overlaps, these channels can undergo rapid cycling between open, inactivated, and closed states, giving rise to continuous calcium influx, referred to as window current, in a range of negative membrane potentials where HVA channels do not normally activate.

Pan et al²⁹ showed that \tilde{T} -type Ca²⁺ channel currents are present in mammalian retinal bipolar cell synaptic terminals and that activation of these channels in isolated axon terminals of rod and cone bipolar cells could trigger transmitter release. Membrane potentials in bipolar cells vary between -70 and -20 mV, well within the normal activation range of T-type Ca²⁺ channels. Neurotransmitter release in response to depolarizations around -40 mV would therefore be expected to be mediated predominantly by T-type Ca²⁺ channel currents, with stronger depolarizations giving rise to the additional activation of L-type Ca²⁺ channels. In some OFF cone bipolar cells, which have dark membrane potentials near -40 and -50 mV, and hyperpolarize in response to light,³² it is possible that T-channels may be predominantly responsible for presynaptic Ca²⁺ influx and transmitter release. Heterogeneous expression of LVA and HVA Ca²⁺ channels in the terminals of different subtypes of bipolar cells may contribute to the diversity of synaptic transmission observed between bipolar cells and third order amacrine cells and ganglion cells, in which both transient and sustained responses are recorded in response to sustained bipolar cell activity.^{33,34}

Ca²⁺ Channel Subtypes in Spiking Cells of the Inner Retina

Visual information encoded by graded potentials in neurons of the outer retina is distributed to ganglion cells of the inner nuclear layer, which in turn transmit this signal to the various visual centers of the brain. Thus, ganglion cells are the final recipients of visual information in the retina and the receptive field organization of these neurons provides for both contrast enhancement and color opponency in retinal signal processing. Light responses in ganglion cells are shaped principally by glutamatergic synaptic input from bipolar cells,^{33,35} the kinetics of which may be further modulated by glutamate receptor-mediated desensitization in ganglion cell dendritic arbors³⁶ and voltage-gated ion channels.^{37,38} The inner retina appears responsible for spatial and temporal processing of the visual signal, and this task places additional requirements on the synaptic interactions, and thus on synaptic (and post-synaptic) Ca^{2+} channels. Spike producing amacrine cells, which carry signals of temporal and spatial change laterally inhibit ganglion cells and feedback negatively onto bipolar cell synaptic terminals, and express L-type Ca^{2+} channels.³⁹ Amacrine-amacrine synapses have been studied in detail and this model provides an important and insightful tool into the function of L-type Ca^{2+} channels at a spiking synapse.⁴⁰

Signal Processing by Multiple Ca²⁺ Channel Subtypes in Ganglion Cells

Action potential producing ganglion cells in vertebrate retina have been reported to express multiple Ca^{2+} channel subtypes.⁴¹ In salamander ganglion cells, ω -conotoxin GVIA and dihydropyridines act on separate types of Ca^{2+} channels, consistent with expression of both N-type and L-type, respectively.^{42,43} This is in contrast to cone photoreceptors of this same species in which a single type of Ca^{2+} channel appears sensitive to both ω -conotoxin GVIA and dihydropyridines.¹¹ Results obtained in other studies of ganglion cells are also consistent with the notion that L-type Ca^{2+} channels co-express with other types of Ca^{2+} channels in these cells. For example, DHP-sensitive Ca^{2+} channel current coexists with ω -conotoxin GVIA-insensitive current in turtle ganglion cells,⁴⁴ but coexists with ω -conotoxin GVIA-sensitive current in rat ganglion cells.^{41,45}

Aside from the N- and L-type Ca^{2+} channels, the identities of other Ca^{2+} channel subtypes underlying the whole-cell Ca^{2+} channel current in ganglion cells has not been clarified. However, a study using polyclonal antibodies against α_{1E} (which may mediate some R-type currents) in the tiger salamander retina revealed immunoreactivity for α_{1E} in the ganglion-cell containing inner plexiform layer of the retina.⁴⁶ However, this immunoreactivity was not specifically in ganglion cell bodies nor localized to ganglion cells processes and could have been confined to the processes of amacrine, bipolar or Müller cells.⁴⁷ In contrast, α_{1D} immunoreactivity was located in both synaptic layers (outer and inner plexiform layers) as well as ganglion cell bodies and optic nerve fibers. These findings are consistent with an in situ hybridization study showing α_{1D} expression in all nuclear layers of the rat retina.⁴⁶ The pattern of α_{1D} staining in the inner retina may be consistent with ganglion cell localization, although owing to the close association between Müller cell processes and ganglion cells structures, glial-localization of α_{1D} channels cannot be ruled out. L-type Ca^{2+} currents and α_{1D} expression have been reported in cultured human Müller cells⁴⁹

Regulation of Ca²⁺ Channels in Ganglion Cells: Glutamate, Adenosine and Nitric Oxide in Neuronal Integration and Pathophysiology

A variety of retinal transmitters and neuromodulators, including glutamate acting via ionotropic and metabotropic receptors,^{42,50-52} adenosine acting at A1 receptors,^{52,53} as well as NO,⁴³ have been shown to regulate Ca^{2+} channels in ganglion cells. Alterations in Ca^{2+} channel activation, linked to changes in Ca^{2+} signaling by ganglion cells, can result in changes in retinal output since the integrative activities of ganglion cells depend on a number of Ca^{2+} mediated responses.



Figure 4. In retinal ganglion cells, the activation of N-type Ca^{2+} channels is facilitated by NO. In panel A, the nitric oxide donor SNAP produces an increase and leftward shift in the current-voltage relation of the cell, an effect mediated by enhancement (facilitation) of approximately 30% of the total HVA current (corresponding to the N-type Ca^{2+} channel population of ganglion cells). Panel C shows activation curves derived from the tail currents shown in panel B. These tail currents were recorded at -60 mV following voltage clamp steps to more positive voltages. The traces illustrated with dots were recorded at -10 mV in control and in the presence of SNAP. The activation curve recorded in the presence of SNAP was steepened and shifted relative to control. In a model where 30% of the channels underwent facilitation of activation with a 16 mV negative shift, such an effect produced by NO reflects an increase in open probability of N-type Ca^{2+} channels. From Hirooka et al, 2000 (reproduced with permission from the American Physiological Society).

There remains considerable interest in the potential roles of Ca^{2+} -stimulated production of nitric oxide (NO) as an anterograde and retrograde messenger in retinal signal processing. Neuronal NO synthase (nNOS), the Ca^{2+} /calmodulin sensitive enzyme responsible for synthesizing NO from L-arginine, has been localized in specific retinal cells by the histochemical marker NADPH-diaphorase (Fig. 1) and by anti-NOS immunoreactivity.⁵⁴⁻⁵⁸ Staining for NOS in the inner retina includes a small population of amacrine cells, ^{59,60} as well as the distal processes of Muller cells that lie in juxtaposition to ganglion cells. Independent of effects on cyclic nucleotide gated (CNG) channels, NO is now known to modulate ganglion cell N-type

 Ca^{2*} channels by facilitating their voltage-dependent activation via a soluble-guanylyl cyclase and PKG-dependent phosphorylation.⁴³ Previous work has detected transcripts for guanylate cyclase in the ganglion cell layer of the rat retina.⁶¹ Thus, it would appear that NO produced in the vicinity of ganglion cells would have the potential to modulate Ca^{2*} signaling via changes to the voltage-dependent gating of Ca^{2*} channels.

Increases in NO that would facilitate the activation of Ca^{2+} channels during depolarizations would in turn be expected to affect all Ca^{2+} - mediated pathways, including the activation of Ca^{2+} -dependent ion channels, altering the integration of synaptic signals impinging on ganglion cells. It is possible that plasticity of the synapses made onto ganglion cells could be dependent on post-synaptic Ca^{2+} signaling, which appears to be itself NO dependent in these cells.

In addition to the obvious roles in retinal synaptic transmission, NO together with glutamate receptor activation, have also been implicated in retinal diseases such as glaucomatous optic nerve neuropathy and retinal ischemia, in which loss of ganglion cells can lead to blindness.⁶²⁻⁶⁵ It is thought that part of the pathology associated with these diseases may result from chronic increased $[Ca^{2+}]_i$ in ganglion cells. Support for a contribution of Ca^{2+} channels in retinal pathophysiology, has come from both in vitro and in vivo evidence, using ganglion cell culture models⁶⁶ and animal models of glaucoma and retinal ischemia, as well as clinical studies of a cohort of patients with open-angle glaucoma.⁶⁷ These studies show that Ca^{2+} channel blockers decreased ganglion cell loss and appear to improve long-term outcome.

Differential Expression of Ca²⁺ Channel Subtypes during Retinal Development

Alterations in Ca^{2+} channel currents and $[Ca^{2+}]_i$ have been demonstrated to occur in the cell cycle and during the embryonic development of a variety of organisms.⁶⁸⁻⁷⁰ In some cell types, increases in $[Ca^{2+}]_i$ due in part to activation of Ca^{2+} channels are important for the progression of the cell cycle,⁷¹⁻⁷³ and may thus contribute to the regulation of cell proliferation, migration and neurite outgrowth.⁷⁴⁻⁷⁶

Ca²⁺ Channels in the Developing Retina

Alterations in Ca²⁺ channel currents has been reported in developing retina. During embryogenesis, multiple retinal cell types arise from the optic cup, an outcrop of the neural tube composed of what appears to be a homogenous cell population. Ganglion cells, one of the first cell types to differentiate in the vertebrate retina,⁷⁷ have been demonstrated to generate spontaneous action potentials at prenatal stages that are associated with the expression of voltage-activated cation channels.⁷⁸ Whole-cell patch-clamp analysis of mouse ganglion cells in retinal whole-mounts at embryonic day 15 (E15) revealed that Ca^{2+} channel current from these immature neurons was predominantly due to T-type channels with a small contribution from HVA channels.⁷⁹ By E18, the current-voltage relationships of Ca^{2+} currents in embryonic ganglion cells appeared similar to those observed in freshly dissociated postnatal ganglion cells, in which HVA currents were more pronounced. Similar findings were also reported for rat ganglion cells in which the Ca²⁺ channels expressed at E17 to E19 were found to be exclusively of the T-type, with HVA current appearing at E20 and consisting of a conotoxin GVIA-sensitive current, a DHP-sensitive current and a toxin-resistant current type.^{80,81} In contrast to the increased density of HVA Ca²⁺ channels observed in ganglion cells during postnatal development, T-type Ca²⁺ channel expression appeared to be down-regulated. These findings are also in keeping with other studies in which developing neurons preferentially express T-type Ca²⁺ channel currents, and suggests that T-type Ca^{2+} channels may be important during neuronal development, possibly by contributing to the generation of spontaneous firing behavior and rhythmic oscillatory activity.75

Bringmann et al⁸² studied the developmental regulation of Ca²⁺ channel-mediated currents in mammalian retinal Müller cells. They demonstrated differential expression of T-type and HVA Ca²⁺ channel currents during development of immature retinal precursor cells into mature Müller cells. T-type Ca²⁺ channel currents were expressed at high densities in the developing cells and the current density fell off during differentiation into the mature Müller cell phenotype. HVA currents in contrast were only expressed at later developmental stages. It was suggested that the activity of T-type Ca^{2+} channels may be necessary for: 1) precursor cell proliferation occurring during development, and 2) Ca^{2+} entry in developing Müller cells that leads to differentiation events, including the growth of glial side branches.

Retinal Progenitor Cells Express T-Type Ca²⁺ Channels

A recent examination of the electrophysiological properties and expression of T-type Ca²⁺ channels in retinoblastoma cells, tumor cells derived from retinal precursor cells, reported that these cells expressed mRNA for all three T-channel subtypes (α_{1G} , α_{1H} and α_{1I}). Expression of α_{1G} and α_{1H} T-type Ca²⁺ channel current was prominent in the undifferentiated mitogenic cells and diminished when retinoblastoma cells differentiated to a neuronal phenotype.⁸³ Although a small HVA current was present in undifferentiated cells, this became more pronounced in the differentiated neuronal phenotype. These results are consistent with a prominent role for T-type Ca²⁺ channels in proliferating retinal precursor cells, and further suggests that differential expression of Ca²⁺ channel gene transcripts occurs in the developing retina and has a regulatory role in Ca²⁺ channel expression during differentiation.⁸⁴

Conclusions

A diversity of Ca^{2+} channel subtypes take part in the processing and synaptic transfer of visual information as signals pass from neuron to neuron in the retina. From the graded potential neurons in the outer retina that utilize L-type Ca^{2+} channels to transmit over a narrow range of potentials, to change enhancement and temporal integration mediated by L-, Nand T-type Ca^{2+} channels in spiking neurons that form the output of the retina, Ca^{2+} channels of every type are employed in this neural network. Developmental studies of this tissue reveal changing requirements for the expression of Ca^{2+} channels, with T-type being predominant in the cycling neuronal precursor cells. In this respect, the retina offers useful insights into the neural requirements and types of roles for which the various Ca^{2+} channel subtypes may be best suited.

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References

- 1. Miller RJ. Rocking and rolling with Ca²⁺ channels. Trends Neurosci 2001; 24:445-449.
- 2. Dowling JE. The Retina: An approachable part of the brain. Cambridge: Belknapp Press, 1987.
- 3. Rieke F, Schwartz EA. A cGMP-gated current can control exocytosis at cone synapses. Neuron 1994; 13:863-873.
- 4. Savchenko A, Barnes S, Kramer RH. Cyclic nucleotide-gated channels in synaptic terminals mediate feedback modulation by nitric oxide. Nature 1997; 390:694-698.
- Schwarz EA. Calcium-independent release of GABA from isolated horizontal cells of the toad retina. J Physiol 1982; 323:211-227.
- 6. Pfeiffer-Linn CL, Lasater EM. Whole cell and single-channel properties of a unique voltage-activated sustained calcium current identified in teleost retinal horizontal cells. J Neurophysiol 1996; 75:609-619.
- 7. Bader CR, Bertrand D, Schwartz EA. Voltage-activated and calcium-activated currents studied in solitary rod inner segments from the salamander retina. J Physiol 1982; 331:253-284.
- Corey DP, Dubinsky JM, Schwartz EA The calcium current in inner segments of rods from the salamander (Ambystoma tigrinum) retina. J Physiol 1984; 354:557-575.
- 9. Barnes S, Hille B. Ionic channels of the inner segment of tiger salamander cone photoreceptors. J Gen Physiol 1989; 94:719-743.
- Lasater EM, Witkovsky P. The calcium current of turtle cone photoreceptor axon terminals. Neurosci Res Supp 1991; 15:S165-S173.

- Wilkinson MF, Barnes S. The dihydropyridine-sensitive Ca²⁺ channel subtype in cone photoreceptors. J Gen Physiol 1996; 107:621-630.
- 12. Kourennyi DK, Barnes S. Depolarization-induced calcium channel facilitation in rod photoreceptors is independent of G-proteins and phosphorylation. J Neurophysiol 2000; 84:133-138.
- 13. Williams ME, Feldman, DH, McCue AF, et al. Structure and functional expression of alpha1, alpha2, and beta subunits of a novel human neuronal calcium channel. Neuron 1992; 8:71-84.
- Taylor WR, Morgans C. Localization and properties of voltage-gated calcium channels in cone photoreceptors of Tupaia belangeri. Vis Neurosci 1998; 15:541-52.
- Morgans CW. Calcium channel heterogeneity among cone photoreceptors in the tree shrew retina. Eur J Neurosci 2000; 11:2989-2993.
- 16. Nachman-Clewner M, St. Jules R, Townes-Anderson E. L-type calcium channels in the photoreceptor ribbon synapse: Localization and role in plasticity. J Comp Neurol 1999; 415:1-16.
- Kollmar R, Fak J, Montgomery LG et al. Hair cell-specific splicing of mRNA for the alpha1D subunit of voltage-gated Ca²⁺ channels in the chicken's cochlea. Proc Natl Acad Sci USA 1997; 23:14889-14893.
- Kollmar R, Montgomery LG, Fak J et al. Predominance of the alpha1D subunit in L-type voltage-gated Ca²⁺ channels of hair cells in the chicken's cochlea. Proc Natl Acad Sci USA 1997; 23:14883-14888.
- Platzer J, Engel J, Schrott-Fischer A et al. Congenital deafness and sinoatrial node dysfunction in mice lacking class D L-type Ca²⁺ channels. Cell 2000; 102:89-97.
- 20. Bech-Hansen NT, Naylor MJ, Maybaum TA, et al. Loss-of-function mutations in a calcium-channel alpha1-subunit gene in Xp11.23 cause incomplete X-linked congenital stationary night blindness. Nature Genet 1998; 19:264-267.
- 21. Strom TM, Nyakatura G, Apfelstedt-Sylla E, et al. An L-type calcium-channel gene mutated in incomplete X-linked congenital stationary night blindness. Nature Genet 1998; 19:260-263.
- 22. Miyake Y, Yakasaki K, Horiguchi M et al. Congential stationary night blindness with negative electroretinogram. Arch Ophthalmol 1986;104: 1013-1020.
- 23. Morgans CW. Localization of the alpha(1F) Calcium channel subunit in the rat retina. Invest Ophth Vis Sci 2001; 42, 2414-2418.
- 24. Maguire G, Maple B, Lukasiewicz P et al. g-aminobutyrate type B modulation of L-type calcium channel current at bipolar cell terminals in the retina of the tiger salamander. Proc Natl Acad Sci USA 1989; 86:10144-10147.
- 25. Kaneko A, Suzuki S, Pinto LH et al. Membrane currents and pharmacology of retinal bipolar cells: a comparative study on goldfish and mouse. Comp Biochem Physiol C 1991; 98:115-127.
- 26. Pan Z-H. Differential expression of high- and two types of low-voltage-activated calcium currents in rod and cone bipolar cells of the rat retina. J Neurophysiol 2000; 83:513-527.
- Pan Z-H. Voltage-gated Ca²⁺ channels and ionotropic GABA receptors localized at axon terminals in of mammalian retinal bipolar cells. Vis Neurosci 2001; 18:279-288.
- Werblin FS, Dowling JE. Organization of the retina of the mudpuppy, Necturus maculosus. II. Intracellular recording. J. Neurophysiol 1969; 32:339-355.
- Pan Z-H, Hu H, Perring P et al. T-type Ca²⁺ channels mediate neurotransmitter release in retina bipolar cells. Neuron 2001; 32:89-98.
- 30. de la Villa P, Vaquero CF, Kaneko A. Two types of calcium currents of the mouse bipolar cells recorded in the retinal slice preparation. Eur J Neurosci 1998; 10:317-23.
- 31. Tachibana M, Okada T, Arimura T et al. Dihydropyridine-sensitive calcium current mediates neurotransmitter release from bipolar cells of the goldfish retina. J Neurosci 1993; 13:2898-909.
- 32. Euler T, Masland RH. Light-evoked responses of bipolar cells in a mammalian retina. J Neurophysiol 2000; 79:1384-1395.
- Awatramani GB, Slaughter MM. Origin of transient and sustained responses in ganglion cells of the retina. J Neurosci 2000; 20:7087-7095.
- 34. Bieda MC, Copenhagen DR. Inhibition is not required for the production of transient spiking responses from retinal ganglion cells. Vis Neurosci 2000; 17:243-254.
- 35. Lukasiewicz P, Lawrence JE, Valentino TL. Desensitizing glutamate receptors shape excitatory synaptic inputs to tiger salamander retinal ganglion cells. J Neurosci 1995; 15:6189-6199.
- 36. Lukasiewicz PD, Wilson JA, Lawrence JE. AMPA-preferring receptors mediate excitatory synaptic inputs to retinal ganglion cells. J Neurophysiol 1997; 77:57-64.
- 37. Diamond JS, Copenhagen DR. The relationship between light-evoked synaptic activity and spiking behavior of salamander retinal ganglion cells. J Physiol 1995; 487:711-725.

- Tabata T, Olivera BM, Ishida AT. Omega-conotoxin-MVIID blocks an omega-conotoxin-GVIA-sensitive, high-threshol Ca²⁺ current in fish retinal ganglion cells. Neuropharmacol 1996; 35:633-636.
- Gleason E, Borges S, Wilson M. Control of transmitter release from retinal amarine cells by Ca²⁺ influx and efflux. Neuron 1994; 13:1109-1117.
- 40. Gleason E, Borges S, Wilson M. Synaptic transmission between pairs of retinal amacrine cells in culture. J Neurosci 1993; 13:2359-2370.
- 41. Guenther E, Rothe T, Taschnberger H et al. Separation of calcium currents in retinal ganglion cells from postnatal rat. Brain Res 1994; 633:223-235.
- 42. Shen W, Slaughter M. Metabotropic and ionotropic glutamate receptors regulate calcium channel currents in salamander retinal ganglion cells. J Physiol 1998; 510:815-828. 1998.
- Hirooka K, Kourennyi DK, Barnes S. Calcium channel activation facilitated by nitric oxide in retinal ganglion cells. J Neurophys 2000; 83:198-207.
- Liu Y, Lasater E. Calcium currents in turtle retinal ganglion cells. I. The properties of T- and L-type currents. J Neurophysiol 1994; 71:733-742.
- 45. Karschin A, Lipton SA. Calcium currents in solitary retinal ganglion cells from postnatal rat. J Physiol 1989; 418:379-396.
- 46. Henderson D, Doerr TA, Gottesman J et al. Calcium channel immunoreactivity in the salamander retina. Neuroreport 2001; 12:1493-1499.
- 47. Kamphuis W, Hendrikson, H. Expression patterns of voltage-dependent calcium channel alpha 1 subunits (alpha 1A-alpha 1E) mRNA in rat retina. Brain Res Mol Brain Res 1998; 55:209-220
- 48. Puro DG, Hwang J-J, Kwon O-J et al. Characterization of an L-type calcium channel expressed by human retinal (Müller) glial cells. Mol Brain Res 1996;37:41-48.
- Newman EA. Voltage-dependent calcium and potassium channels in retinal glial cells. Nature 1985; 317:809-811.
- Akopian A. and Witkovsky, P. Activation of metabotropic glutamate receptors decreases a high threshold calcium current in spiking neurons of the Xenopus retina. Vis Neurosci 1996; 13:549-557.
- 51. Zhang J, Shen W, Slaughter MM. Two metabotropic gamma-aminobutyric acid receptors differentially modulate calcium currents in retinal ganglion cells. J Gen Physiol 110:45-58, 1997.
- 52. Zhang C, Schmidt JT. Adenosine A1 and class II metabotropic glutamate receptors mediate shared presynaptic inhibition of retinotectal transmission. J Neurophysiol 1999; 82:2947-2955.
- 53. Sun X, Barnes S, Baldridge WH. Adenosine inhibits calcium channel currents via A₁ receptors on tiger salamander retinal ganglion cells in a mini-slice preparation. J Neurochem 2002; In press.
- 54. Dawson TM., Bredt DS, Fotuhi M et al. Nitric oxide synthase and neuronal NADPH diaphorase are identical in brain and peripheral tissues. Proc Natl Acad Sci USA 1991; 88:7797-7801.
- 55. Hope BT, Michael GJ, Knigge KM et al. Neuronal NADPH diaphorase is a nitric oxide synthase. Proc Natl Acad Sci USA 1991; 88:2811-2814.
- Kurennyi DE, Thurlow G, Turner RW et al. Nitric oxide synthase in tiger salamander retina. J Comp Neurol 1995; 361:525-536.
- 57. Liepe BA, Stone C, Koistanaho J et al. Nitric oxide synthase in Muller cells and neurons of salamander and fish retina. J Neurosci 1994; 14:7641-7654.
- 58. Blute TA, Mayer B, Eldred WD. Immunocytochemical and histochemical localization f nitric oxide synthase in the turtle retina. Vis Neurosci 1997; 14:717-729.
- 59. Sagar S. NADPH-diaphorase histochemistry in the rabbit retina. Brain Res. 373:153-158, 1986.
- Sandell JH. NADPH-diaphorase cells in the mammalian inner retina. J Comp Neurol 1985; 238:466-472.
- 61. Ahmad I, Barnstable CJ. Differential laminar expression of particulate and soluble guanylate cyclase genes in rat retina. Exp Eye Res 1993; 56:41-62.
- Kelly MEM, Barnes S. Physiology and pathophysiology of nitric oxide in the retina. The Neuroscientist 1997; 3:357-360.
- 63. Hartwick AT. Beyond intraocular pressure: Neuroprotective strategies for future glaucoma therapy. Optom Vis Sci 2001; 78:85-94.
- 64. Melena J, Osborne NN. Voltage-dependent calcium channels in the rat retina: involvement in NMDA-stimulated influx of calcium. Exp Eye Res 2001; 72:393-401.
- 65. Melena J, Stanton D, Osborne NN. Comaprative effects of antiglaucoma drugs on voltage-dependent calcium channels. Graefe's Arch Clin Exp Ophthalmol 2001; 239:522-530.
- 66. Sucher NJ, Lei SZ, Lipton SA. Calcium channel antagonists attenuate NMDA receptor-mediated neurotoxicity of ganglion cells in culture. Brain Res 1991; 551:297-302.
- 67. Netland PA, Chaturvedi N, Dreyer EB. Calcium channel blockers in the management of low-tension and open-angle glaucoma. Am J Ophthalmol 1993; 115:608-613.

- 68. Berridge MJ. Calcium signaling and cell proliferation. Bioessays 1995; 17:491-500.
- 69. Kono T, Jones KT, Bos-Mikich A, Carroll J. A cell cycle-associated change in Ca²⁺ releasing activity leads to the generation of Ca²⁺ transients in mouse embryos during the first mitoric division. J Cell Biol 1996; 132:915-23.
- 70. Kuga T, Kobayashi S, Hirakawa Y et al. Cell cycle-dependent expression of L- and T-type Ca²⁺ currents in rat aortic smooth muscle cells in primary culture. Circ Res 1996; 79:14-19.
- 71. Day ML, Johnson MH, Cook DI. Cell cycle regulation of a T-type calcium current in early mouse embryos. Pflugers Arch 1998; 436:834-842.
- 72. Winston N, McGuiness O, Johnson MH et al. The exit of mouse oocytes from meiotic M-phase requires an intact spindle during intracellular calcium release. J Cell Sci 1995; 108:143-51.
- 73. Ciapa B, Pesando D, Wilding M et al. Cell-cycle calcium transients driven by cyclic changes in inositol trisphosphate levels. Nature 1994; 368:875-878.
- 74. Doherty P, Walsh FS. Signal transduction events underlying neurite outgrowth stimulated by cell adhesion molecules. Curr Opin Neurobiol 1994; 4:49-55.
- 75. Gu X, Spitzer NS. Low threshold Ca²⁺ current and its role in spontaneous elevations of intracellular Ca²⁺ in developing Xenopus neurons. J Neurosci 1993; 13:4936-4948.
- Rakic P, Cameron RS, Komura H. Recognition, adhesion, transmembrane signaling and cell motility in guided neuronal migration. Curr Opin Neurobiol 1994; 4:63-69.
- Waid DK, McLoon SC. Immediate differentiation of ganglion cells following mitosis in the developing retina. Neuron 1995; 14:117-124.
- 78. Rothe T, Juttner R, Bahring R et al. Ion conductances related to development of repetitive firing in mouse retinal ganglion neurons in situ. J Neurobiol 1999; 38:191-206.
- Rorig B, Grantyn R. Ligand and voltage-gated ion channels are expressed by embryonic mouse retinal neurons. Neuroreport 1994; 5:1197-1200.
- 80. Schmid S, Geunther E. Developmental regulation of voltage-activated Na^{*} and Ca²⁺ currents in retinal ganglion cells in rat retinal ganglion cells. Neuroreport 1996; 7:677-681.
- Schmid S, Geunther E. Voltage-activated calcium currents in rat retinal ganglion cells in situ: Changes during prenatal and postnatal development. J Neurosci 1999; 19:3486-3494.
- 82. Bringmann A, Schopf S, Reichenbach A. Developmental regulation of calcium channel-mediated currents in retinal glial (Müller) cells. J Neurophysiol 2000; 84:2975-2983.
- Hirooka K, Bertolesi GE, Kelly ME et al. S. T-type calcium channel α1G and α1H subunits in human retinoblastoma cells, and their loss after differentiation. J Neurophysiol 2002; 88(1):196-205.
- 84. Okagaki R, Izumi H, Okada T et al. The maternal trnascript for truncated voltage-dependent Ca²⁺ channels in the ascidian embryo: A potential suppressive role in Ca²⁺ channel expression. Dev Biol 2001; 230:258-277.
- 85. Boycott KM, Maybaum TA, Naylor MJ et al. A summary of 20 CACNA1F mutations identified in 36 families with incomplete X-Inked congenital stationary night blindness and characterization of splice variants. Human Genetics 2001; 108:91-97.
CHAPTER 23

Exploring the Function and Pharmacotherapeutic of Potential Voltage-Gated Ca²⁺ Channels with Gene-Knockout Models

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Introduction

 \neg he importance of the intracellular free Ca²⁺ concentration as a key cellular signal transduction mechanism requires a tight control of Ca2+ homeostasis thus enabling the independent regulation of free cytosolic Ca²⁺ levels even within different cellular signaling compartments. In electrically excitable cells voltage-gated Ca²⁺ channels (VGCCs) convert membrane potential changes into an intracellular Ca2+ signal by mediating Ca2+ ion entry along its electrochemical gradient during depolarization.¹ The resulting intracellular Ca²⁺ transient controls essential Ca2+-dependent physiological processes. These include neurotransmitter release from fast chemical synapses in nerve terminals and from sensory cells, hormone release from endocrine cells, excitation-contraction coupling in heart, skeletal and smooth muscle and control of pacemaker activity in heart and neurons.² Each of these specific tasks requires adjustment of Ca²⁺ channel function to its specific needs by targeting the channels to specific sites of the plasma membrane and by fine-tuning their opening and closing behaviour (gating). This explains why evolution generated a large number of different voltage-gated Ca^{2+} channel types which can be distinguished based on their biophysical properties and the way they are regulated by second messenger pathways.^{2,3} Until now drugs and toxins specifically blocking the activity of individual channel types represented the most important tool to dissect their individual role for specific cellular functions and facilitated their biochemical isolation and cloning.3,4

The different Ca^{2+} channel types known to date, their specific modulators and proposed physiological roles are summarized in Table 1. Voltage-gated Ca^{2+} channels form hetero-oligomeric complexes of several subunits (Fig. 1). This subunit structure is reviewed in detail in other articles in this body and therefore is not discussed in much detail here. Figure 1 illustrates that α_1 subunits comprise the Ca^{2+} -selective ion pore itself. They determine most of the biophysical parameters (i.e. single channel conductance, activation and inactivation) and carry the drug and toxin interaction sites. So far ten different α_1 subunit isoforms, each of them undergoing further fine-tuning by extensive alternative splicing, were identified in the human genome. Based on their different biophysical and pharmacological characteristics they give rise to 5 different Ca^{2+} channel types (Table 1). Both β and α_2 - δ subunits (and to some extent also γ -subunits, see below) are also required for proper channel targeting to the plasma membrane and fine-tuning of the gating properties of most $\alpha 1$ subunits.³ At least

Type	α1 Subunit	Tissue Expression	Function	Deficiency Model	Drugs/Toxins
	Cav1.1α1 (α1S)	skeletal muscle	excitation-contraction coupling	muscular dysgenic mouse (<i>mdg/mdg</i>)	Organic L-type channel blockers Dihydropyridines (<i>Nifedipine</i>), Phenylalkylamines (<i>Verapamil</i>), Bonzothiczonines (<i>Dihi-zowi</i>
	Ca _v 1.2α1 (α1C)	cardiac/smooth muscle; neurons;	excitation-contraction coupling excitation-transcription coupling	Ca _v 1.2α1 ^{-/-} (2)	Derizoniazephies (L'hiuazeni)
	Cav1.3α1 (α1D)	endocrine cells heart atria; neurons;	stimulus-secretion coupling sinoatrial heart rate control excitation transcription coupling;	Cav1.2α1 ⁴⁻ (2)	
		endocrine cells; censory rells	modulation of firing pattern stimulus-secretion coupling stimulus-secretion coupling		
	Cav1.4α1 (α1F)	retina	stimulus-secretion coupling	CSNB2 (human)	
D/Q	Cav2.1α1 (α1A)	neurons; endocrine cells	stimulus-secretion coupling	Cav2.1α1 ⁴⁻ (2)	w-Aga-IVA
Z	Ca _v 2.2α1 (α1B)	neurons; endocrine cells	stimulus-secretion coupling	$Ca_{2.2\alpha1}^{-1}$ (3)	w-CgTX-GVIA
~	Cav2.3α1 (α1E) + Ca 2α1	neurons; endocrine cells	stimulus-secretion coupling	Cav2.3α1 ⁻⁷⁻ (4)	SNX-482
		cardiac/smooth muscle	2		
Ŧ	Cav3.1α1 (α1G)	neurons;	burst-firing; automaticity	Cav3.1α1 ⁴⁻ (1)	(Kurtoxin, Mibefradil)
	Cav3.2α1 (α1H)	cargiac muscle smooth muscle.	s vasodilation	Cav3.2α1 ⁴⁻ (1)	
		cardiac muscle, kidney, liver	~		
	Cav3.3α1 (α11)	neurons	automaticity	not yet available	

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mouse strains.



Figure 1. Subunit structure of voltage-gated Ca²⁺ channels. Accessory $\alpha 2$ - δ and β subunits are associated with Ca_v1 and Ca_v2 α 1 subunits but their contribution to T-type Ca²⁺ channel complexes (Ca_v3 α 1 family) is less clear. Biophysical and pharmacological properties are largely defined by the α 1 subunits (see Table 1).

four different β -subunits, four $\alpha 2$ - δ subunits and 8 γ -subunits exist. More than one isoform of each of these subunits may be expressed in a single cell.

As $\alpha 1$ subunits are required for channel formation, disruption of a particular $\alpha 1$ subunit gene must lead to a complete loss of the corresponding Ca^{2+} currents. To compensate for this defect a cell may upregulate a Ca^{2+} channel type formed by a different α_1 -subunit isoform. In contrast, disruption of a β or α_2 - δ gene must not necessarily lead to a complete loss of function of a particular channel type normally associated with this subunit because compensation by other isoforms of these accessory subunits may occur. In this article all so far published Ca^{2+} channel subunit deficient animal models will be discussed. Most of them were generated by gene-targeting in mice. However, researchers also benefit from spontaneous mouse mutants and human diseases with known monogenic genetic defects of Ca^{2+} channel subunits.

Abbreviations

- DHP diyhdropyridine
- EPSP excitatory postsynaptic potential
- LTCC L-type Ca²⁺ channels
- LTS low threshold spikes
- TCR thalamocortical relay neuron

The Cav1 (L-Type) Ca²⁺ Channel Family

L-type Ca²⁺ channels (LTCCs) could be purified from different tissues (skeletal muscle, heart), and their currents isolated in different cells by means of their high affinity for the classical organic Ca²⁺ channel blockers³ (Table 1). Among those dihydropyridines (DHPs) proved especially helpful due to their very high binding affinity and high selectivity for LTCCs and the availability of both Ca²⁺ channel blockers (e.g., nifedipine, isradipine) and Ca²⁺ channel activators (e.g., BAYK 8644, FPL 64176^{3,5,6}). All four subunits capable of forming LTCCs ($Ca_v 1.1\alpha_1 - Ca_v 1.4$) possess a high affinity DHP interaction domain whose amino acids have been identified.^{5,6} Despite their pharmacological relationship these channels are functionally diverse (Table 1) and should therefore be unable to completely compensate for each other in knockout models.

$Ca_v 1.1\alpha_1$ -Deficiency

 $Ca_{*}1.1\alpha_{1}$ is exclusively expressed in the transverse tubules of skeletal muscle where it undergoes a rapid conformational change upon membrane-depolarization. It thereby initiates SR Ca^{2+} release by allosterically activating SR ryanodine receptors.⁷ A slower voltage-dependent conformational change also activates the channel's Ca^{2+} conductance, which is not important for immediate signaling but may be involved in the regulation of musle Ca^{2+} homeostasis.⁸ Mice with muscular dysgenesis, caused by an autosomal recessive lethal mutation in the $Ca_{*}1.1\alpha_{1}$ subunit served as the first $Ca_{*}1.1\alpha_{1}$ deficient mouse model (*mdg/mdg* mice^{9,10}). *Mdg/mdg* mice enabled the pioneering work revealing the above-mentioned role of $Ca_{*}1.1\alpha_{1}$ for skeletal muscle EC-coupling.¹¹ These mice die at birth from asphyxia due to the expected failure of their skeletal muscle to contract. Differences between $Ca_{*}1.1\alpha_{1}$ -mediated skeletal muscle – type ECC (independent of Ca^{2+}_{*} entry) and $Ca_{*}1.2\alpha_{1}$ -mediated cardiac muscle – type ECC (dependent on Ca^{2+}_{*} entry) and the underlying molecular mechanisms were successfully studied by expressing cloned $Ca_{*}1.1\alpha_{1}$, $Ca_{*}1.2\alpha_{1}$ as well as chimeric constructs and mutants thereof in *mdg/mdg* myotubes ^{7,8} and immortalized *mdg/mdg* cells.^{12,13}

$Ca_v 1.2\alpha_1$ -Deficiency

In contrast to $Ca_v 1.1\alpha_1$, $Ca_v 1.2\alpha_1$ expression is not restricted to a single tissue. It is widely and densely expressed in the cardiovascular system (heart atria and ventricles, sinoatrial node cells, vascular smooth muscle),^{14,15} uterine, tracheal and intestinal smooth muscle^{16,17} but also in endocrine and neuroendocrine cells (e.g., pancreatic β -cells, pituitary gland) and neurons.^{14,18-20} Vasodilation and cardiac depression, the therapeutically exploited pharmacological effects of Ca²⁺ channel blockers, are believed to be almost exclusively mediated by block of Ca, 1.2 channels in the cardiovascular system. Unfortunately, these drugs have only provided limited insight into the role of these channels for neuronal function. Brain LTCCs (80% of which consist of $Ca_v 1.2\alpha_1$ and 20% of Cav1.30(1;20) are not believed to directly control presynaptic Ca2+ entry and neurotransmission at fast chemical synapses.²¹ Instead, they are located on dendrites and neuronal cell bodies²⁰ and Ca²⁺ entry through these channels modulates neuronal function by altering gene transcription.^{22,23} CNS effects of LTCC modulators are subtle. DHPs alter the sensitivity to cocain reward^{24,25} and modulate alcohol withdrawal symptoms.²⁶ DHP channel activators also produce a (toxic) neurobehavioural syndrome in rodents with severe dystonia and behavioural abnormalities (including self-biting²⁷). Upregulation of LTCC activity in aged rats (which may, however, be mainly due to upregulation of $Ca_v 1.3\alpha_1$, see reference 28) may contribute to the age-related decrease in cognitive function. Obviously, $Ca_v 1.2\alpha_1$ -deficient mice are urgently needed to reveal the physiological role of this most abundant LTCC in the mammalian brain.

 $Ca_v 1.2\alpha_1$ -deficient mice have successfully been generated.²⁹ These animals died at embryonic day 12.5 suggesting that the embronic heart requires $Ca_v 1.2$ for normal rhythmic activity after day 13 p.c. Until day 12.5 p.c. contractions were sustained by an L-type current which could not be attributed to any of the other known L-type α_1 subunits. It may therefore comprise a yet unknown α_1 isoform or an embryonic, yet unidentified splice-variant of one of the known L-type α_1 subunits. These findings emphasize the important role of this subunit for cardiac development but prevented the analysis of $Ca_v 1.2\alpha_1$ deficiency after birth and in adult animals. However, by generating a targeting vector exploiting the Cre-loxP recombination technique, mice were constructed in which $Ca_v 1.2\alpha_1$ deficiency can be induced after birth by tissue-selective activation of cre recombinase. Selective deletion of $Ca_v 1.2a_1$ in smooth muscle revealed their important role for blood pressure control. $Ca_v 1.2$ not only mediates the depolarization-induced (i.e., voltage-activated) contraction but also contributes to noradrenaline and angiotensin II-induced



Figure 2. Properties of heterologously expressed Cav1.3 Ca²⁺ channels. Cav1.301 and Cav1.201 subunits were heterologously expressed in human embryonic kidney tsA-201 cells together with CavB3 and $\alpha 2-\delta 1$ subunits. Note that under identical experimental conditions Cav1.301-mediated currents activated at about 15 mV more negative voltages than Cav1.201. Inward currents were recorded using 15 mM Ba²⁺ as charge carrier. A) I-V curves were constructed by depolarizations from a holding potential of -80 mV to the indicated test potentials. Peak current amplitude is plotted against voltage. B) Inactivation time course of Ba²⁺ inward currents during 5-s depolarizing pulses from a holding potential of -80 mV to the peak voltage of the I-V curve. A Ca²⁺ channel current recorded in cochlear inner hair cells (IHC) is shown as a comparison. Using Cav1.3^{-f-} mice it was shown³³ that more than 90% of this IHC Ca²⁺ current are Cav1.3 mediated. Note the even slower inactivation of Cav1.301 currents in the IHCs. Taken from reference 37 with permission.

(i.e., receptor-mediated) contraction.^{29a} Selective knockout of Ca_v1.2a1 in pancreatic β -cells revealed that only Ca_v1.2 channels contribute to glucose-induced insulin secretion in mice.^{29b}

$Ca_v 1.3\alpha_1$ -Deficiency

Until the availability of $Ca_v 1.3\alpha_1$ deficient mice the role of this LTCC subtype remained enigmatic. This was in part due to the fact that its unique biophysical properties that can provide important hints about its physiological role were not discovered in early expression studies.^{30,31} Based on the high relative abundance of $Ca_v 1.3\alpha_1$ mRNA in pancreatic islets it was proposed that this LTCC plays a key role for stimulus-secretion coupling in pancreatic β -cells.³² $Ca_v 1.3\alpha_1$ was found to coexist with $Ca_v 1.2\alpha_1$ in many tissues. Due to the lack of Ca^{2+} channel blockers distinguishing between these two isoforms their relative contribution to L-type channel mediated functions could not be assessed.

 $Ca_v 1.3\alpha_1$ -deficient mice reproduce normally, have no gross anatomical defects and lack deficits in motor function.^{33,34} However, these mice show two important phenotypes. They are deaf and suffer from sinoatrial node dysfunction.^{33,34} The deafness is due to the complete absence of L-type Ca^{2+} currents in the inner hair cells of the cochlea.³³ $Ca_v 1.3\alpha_1$ -mediated L-type currents comprise about 90% of the total $I_{Ca,L}$ in these cells. As $I_{Ca,L}$ is closely coupled to tonic neurotransmitter release in IHCs,³⁵ the absence of Ca_v1.3 currents should largely abolish sound-evoked neurotransmitter release. As previously reported for hair cells in the chick cochlea,³⁶ the activation threshold of Ca_v1.3 currents in mouse IHCs was considerably lower (around -60 mV at physiological Ca²⁺ concentrations) than for Ca_v1.2 (around -40 mV) and inactivated with a much slower time course.³³ These two biophysical features, negative activation threshold and slow inactivation, distinguish Ca_v1.3 from Ca_v1.2 channels. The difference is inherent to the α_1 subunits as confirmed by heterologous expression studies³⁷⁻³⁹ (Fig. 2). Despite normal cochlear



Figure 3. Telemetric electrocardiographic recordings in Cav3.1-deficient mice. Cav1.3 α 1-deficiency is associated with severe sinoatrial node arrhythmia and bradycardia. The phenotype disappears under conditions of high heart rates. Heart rates are given as intervals between the R-spikes of ECG-waveforms (RR-intervals) for 30-s episodes under resting conditions, during physical activity and after injection of isoprenaline or atropine (1 mg/kg i.p.) to increase heart rate. 150-ms intervals correspond to a heart rate of 400 beats per minute. Note that the RR variability is a measure for arrhythmia.

development in utero and immediately after birth, a degeneration of the cochlear sensory cells was observed about 2 weeks after birth, starting with degeneration of outer hair cells in apical turns.³³ More recent studies confirmed the role of Ca_v1.3-signaling for normal development.^{33a} Cav1.3^{-/-} deficiency abolishes postnatal Ca²⁺-spiking and impairs IHC development. Cav1.3^{-/-} IHCs keep their efferent cholinergic innervation and lack high conductance Ca²⁺-activated K⁺-channels (BK_{Ca}).^{33b}

 $Ca_v 1.3\alpha_1$ -deficient mice also exhibit an arrhythmic and bradycardic heart beat (Fig. 3). Telemetric ECG recordings and experiments with spontaneously beating isolated mouse atria clearly demonstrated that this is due to an intrinsic defect in the sinoatrial node.³³ Sinoatrial bradyarrhythmia was present at low heart rates but this pathological phenotype completely dissappeared when heart rate increased (ref. 33, Fig. 3). This finding is in excellent agreement with recent patch-clamp studies of the biophysical properties of L-type currents in mouse and rabbit sinoatrial node cells.⁴⁰⁻⁴² In these cells L-type Ca²⁺ channels contribute to an inward current throughout the diastolic depolarization phase (DD). DD is the spontaneous depolarization between action potentials responsible for the automaticity of the sinoatrial node. It starts after an action potential at the maximum diastolic potential of about -60 mV. By reaching a threshold voltage at about -45 mV DD triggers the following action potential. It was predicted that two properties of the sinoatrial $I_{C_4,L}$ were important for its contribution to DD: a negative activation threshold^{41,42} and a slowly inactivating current component.⁴¹ As expected, $I_{Ca,L}$ with these properties was found in sinoatrial cells isolated from wildtype mice but was absent in cells from knockout mice^{43,44} and must therefore be Ca₂1.3 α_1 mediated. As Ca₂1.2 α_1 subunits do not possess these special biophysical properties these channels is unlikely to contribute to DD. This explains why Cav1.2 currents are unable to compensate for regular sinoatrial node function in Cav1.3^{-/-} mice.⁴³

Conflicting data with respect to the role of Cav1.3 L-type channels for pancreatic β-cell function have been obtained from the two independently generated Ca_v1.3 α_1 -deficient mouse models. Whereas one group reported no effect on glucose tolerance, glucose-induced insulin-secretion and β -cell L-type currents^{18,33} a decreased glucose-tolerance was reported for the other mouse strain.³⁴ Although whole cell I_{Ca,L} in β -cells was not decreased in Ca,1.3 α_1^{-1} mice, the voltage-dependence of activation was shifted by about 10 mV towards more positive voltages.³⁴ This was interpreted as evidence for the absence of a negatively activating Cav1.3 L-type current component compensated by enhanced Ca, 1.2. Homozygous knockouts also showed a decrease of size and number of pancreatic islets, a reduced β-cell number per islet and evidence for reduced β -cell generation.³⁴ This suggested that Ca_v1.3 α_1 sustains a trophic effect on pancreatic β -cells. More recently, a completely different approach has been taken to assess the role of $Ca_{x}1.3$ channels in vivo and in vitro. By mutation of a single amino acid residue in Ca_v1.2 α 1 subunits (threonine-1066 to tyrosine, see chapter on Ca²⁺ channel drug binding domains in this body) in mice, animals were created with Ca, 1.2 channels lacking high affinity for DHP Ca²⁺ channel blockers and activators^{34a} but without affecting function and expression of Ca_v1.2 (Ca_v1.2DHP^{-/-} mice). This allowed separation of the DHP effects of Ca_v1.2 from those of Cav1.3 and other LTCCs. Using this model, it could be unequivocally demonstrated that $Ca_v 1.3$ does not contribute significantly to pancreatic β -cell L-type currents which therefore must be formed by Ca, 1.2. These results nicely confirmed the above-mentioned findings with β-cell-specific Ca_v1.2 knockout.^{29b} Ca_v1.2DHP^{-/-} mice further revealed that Ca_v1.3 does not contribute to cardiac inotropy, and arterial smooth muscle contractility. With this model DHPs could also be established as mood-modifying agents: L-type channel blockers revealed antidepressant-like effects in wildtype mice that were abolished in $Ca_{1.2}DHP^{-1}$ mice. The known neurotoxicity of the DHP channel activator BayK 8644 was abolished in these mice (and must therefore be mediated by Cav1.2) and allowed to disclose a depression-like behavioral effect. BayK 8644 activated only a specific set of brain areas. In the ventral striatum, BayK-induced release of glutamate and 5-HT, but not of dopamine and of noradrenaline was abolished. This animal model should therefore provide a useful tool to elucidate whether Ca, 1.3-selective channel modulation represents a novel pharmacological approach to modify CNS function without major peripheral effects.

$Ca_v 1.4\alpha_1$ -Deficiency

Despite the attractiveness of mouse models, genetic defects in defined human genes provide direct insight into the function of the affected protein for human physiology and pathophysiology. This is the case for Ca_v1.4 α 1 which was discovered as a retina-specific protein mutated in patients suffering from X-linked incomplete congenital stationary night blindness. Congenital stationary night blindness (CSNB) is a heterogeneous, non-progressive retinal disorder characterized by life-long impairment of night vision and variably reduced day vision without identifiable structural abnormality of the retina.^{45,46} Due to the X-linked, recessive inheritance pattern of this disease only males and heterozygous females are affected.⁴⁷ Clinical heterogeneity between families has led to the classification into complete CSNB (designated CSNB1) and incomplete CSNB (designated CSNB2) based on abnormalities in the electroretinogram and psychophysical testing.⁴⁸ In patients with complete CSNB rod function is completely absent compared to patients with incomplete CSNB where rod function is recordable but decreased. Incomplete CSNB is thought to result from defect neurotransmission mainly from photoreceptors to second-order retinal neurons.⁴⁹

Neurotransmitter release from retinal photoreceptors is mediated by Ca^{2+} entry through DHP-sensitive VGCCs and subsequent glutamate release.⁵⁰⁻⁵³ These VGCCs possess properties resembling Ca_v1.3 currents (see above) with activation at negative voltages, slow inactivation and modest DHP sensitivity. Heterologous expression in mammalian cells revealed that Ca_v1.4 channels possess similar biophysical properties.^{53a-c} From immunohistochemical studies it appears as if Ca_v1.4 α_1 represented the major synaptically localized Ca²⁺ channel and is therefore crucial for neurotransmitter release from photoreceptors in different species.^{52,54}

The discovery of mutations in $Ca_v 1.4\alpha_1$ subunits of VGCCs in patients with CSNB2 lead to the conclusion that abnormal $Ca_v 1.4\alpha_1$ function results in impairment of Ca^{2+} influx that is required for normal photoreceptor-to-bipolar cell synaptic transmission.^{47,55} The majority of mutations reported so far lead to truncations within the transmembrane repeats, their connecting linkers or other severe aberrations in highly conserved regions and are therefore likely to lead to non-functional channels. It is unknown if other ionic currents (e.g., L-type $Ca_v 1.3$ channels) undergo compensatory upregulation in retinal cells of CSNB2 patients. Obviously $Ca_v 1.4\alpha_1$ -deficient mouse models must be produced to answer such questions. However, it must be emphasized that vision predominantly depends on rod function in mice and $Ca_v 1.4$ mutations may therefore lead to more ppronounced vision disturbances than in humans.

The Ca_v2 (P/Q-, N- and R-Type) Ca²⁺ Channel Family

The Cav2 family of VGCCs is predominantly expressed in neurons, although expression has also been demonstrated in (neuro-)endocrine cells (e.g., in pancreatic β - and adrenal chromaffin cells (Ca₂2.1 α_1 , Ca₂2.2 α_1 , and Ca₂2.3⁵⁶⁻⁵⁹), heart muscle (Ca₂2.3 α_1^{60}) and testis $(Ca_v 2.3\alpha_1^{61})$. Unlike LTCCs, Ca_v2 channels are not sensitive to DHPs and also much less sensitive to verapamil and diltiazem⁶² (Table 1). They are therefore also classified as "non-L-type" Ca²⁺ channels. Also in contrast to LTCCs, Ca₂.1 and Ca₂.2 (and to some extent also Ca₂.3⁶³) mediate fast neurotransmitter release from nerve terminals in central synapses and from motor neurons in the neuromuscular junction.^{21,64} All three channel types are expressed not only on the presynaptic membrane but also on dendrites and cell bodies. 65,66 The contribution of these different channel types for neuronal non-L-type Ca²⁺ current components and for transmitter release could be quantified by employing specific blockers (Table 1). Given their widespread expression in the mammalian brain and their crucial role for neurotransmitter release one would predict severe disturbances of brain function in knockout mice. From previous pharmacological analysis it was expected that the absence of $Ca_v 2.1\alpha_1$ and $Ca_v 2.2\alpha_1$ would exclusively and completely eliminate N-type (ω -CgTx IVA-sensitive) and P/Q-type (ω -AgaIVA- and ω -CgTx MVIIC-sensitive) current components, respectively. In contrast, the role of $Ca_{x}2.3\alpha_{1}$ subunits for the so-called R-type current (defined as the Ca^{2+} current component resistant to saturating concentrations of any of the specific inhibitors of the other known Ca²⁺ channel types) was much less clear. This was especially due to the observation that SNX-482, a peptide toxin which selectively blocks recombinant Ca.2.3 α_1 -mediated currents did not⁶⁷ or only partially block R-type currents in different neurons.^{67,68} Obviously, Ca₂.3 α_1 -deficient mice were eagerly awaited to quantify its role for R-type currents in different neurons.

$Ca_v 2.1\alpha_l$ -Deficiency

At many synapses excitatory neurotransmitter release is more dependent on P/Q-type than N-type Ca²⁺ channels, whereas GABA release is more dependent on N-type than P/Q-type channels⁶⁹⁻⁷³ but control of inhibitory neurotransmitter release by P/Q-type channels has also been reported.^{74,75} The preferential contribution of Ca_v2.1 to the total I_{Ca} in cerebellar Purkinje cells (about 90%²¹) and acetylcholine release from motor nerve terminals ⁷⁶ would predict that Ca_v2.1 α_1 deficiency results in severe myasthenia and cerebellar symptoms. Ca_v2.1 α_1^{-1} mice were independently generated in two laboratories.^{21,77} Although embryonic and postnatal development appeared normal they time-dependently developed a severe neurologic syndrome after P10 consisting in ataxia, dystonia, spasms and weakness. Homozygous mice did usually not survive past weaning. They exhibited abnormal and delayed neuronal development evident e.g., as failure of migration and persistence of an external granule cell layer at P21, focal axonal swelling of Purkinje cell axons and increased abundance of TH-positive neurons in deeper cortical layers at P21.²¹ In homozygous animals surviving for 15 weeks a decrease in the volume of the cerebellum was associated with loss of Purkinje and granule cells.⁷⁷ In heterozygous mice I_{Ca} density was decreased by about 50% only in one of the two models.⁷⁷ This decrease did not result in any histological or functional abnormalities, indicating that P/Q-type current must be lowered to more than 50% to cause neurodegeneration in mice.



Figure 4. Effect of Ca_{*}2.1-deficiency on neurotransmission in hippocampal synapses. Effects on synaptic transmission of altering Ca²⁺ influx in wildtype (\bullet) and mutant (O) animals. A) Blockade of N-type Ca²⁺ channels with ω -CgTx-GVIA (1 μ M) reduced the strength of synaptic transmission by half in wildtype but eliminated the EPSP in mutants. B) Enhancement of Ca²⁺ influx by broadening action potentials with 4-AP (100 μ M) increased the strength of synaptic transmission 2-fold in wildtype and 3-fold in mutants. C) After application of 4-AP, blockade of N-type Ca²⁺ channels considerably reduced synaptic strength in Ca_{*}2.1 α 1^{-/-} 'slices, with a much smaller effect in wildtype. D) After application of 4-AP and ω -CgTx-GVIA, blockade of P/Q-type Ca²⁺ channels with ω -Aga-IVB (1 μ M) decreased the strength of synaptic transmission in wildtype by more than 75% but had no effect in mutants. E and F) Representative responses to sequential application of Ca²⁺ channel blockers in the presence of 4-AP in wt (E) and Ca_{*}2.1 α 1^{-/-} (F) animals. Taken from reference 21 with permission.

In contrast to $Ca_v 2.2\alpha_1^{-1}$ and $Ca_v 2.3\alpha_1^{-1}$ mice, the absence of $Ca_v 2.1\alpha_1$ and P/Q-type currents caused alterations in other Ca^{2+} current components. R-type currents (which are unlikely to be carried by $Ca_v 2.1\alpha_1$ (see below⁷⁸) decreased in cerebellar granule cells whereas Nand L-type currents were upregulated in cerebellar Purkinje cells.^{21,77} Interestingly, an upregulation of L-type currents has also been reported in *tottering* mice, a spontaneous mouse mutant suffering from ataxia, dystonia and absence seizures⁷⁹ Upregulated L-type currents seem to enhance the dystonia in these mice.⁷⁹ Therefore it is possible that LTCC upregulation also contributes to the dystonic phenotype in $Ca_v 2.1\alpha_1^{-1-}$ -deficient mice.

The consequences of Ca₂2.1 α_1 -deficiency on synaptic transmission were studied by measuring field excitatory postsynaptic potentials (EPSPs) in the CA1 area of the hippocampus after stimulation of Schaffer collaterals and the commissural pathways²¹ (Fig. 4). Blockade of N-type channels with the selective N-type blocker 1 μ M ω -CgTx-GVIA halved the EPSP slope in wildtype mice but nearly eliminated synaptic transmission in Ca₂2.1 α_1 -^{*t*} (Fig. 4A). This indicated enhanced reliance of neurotransmission on N-type channels in Ca₂2.1 α_1 -^{*t*} mice. If the total number of Ca²⁺ channels available for neurotransmission at individual release sites was reduced in the Ca₂2.1 α_1 -^{*t*} neurons then they should exhibit a stronger relative increase of EPSP slope by stimulation of presynaptic Ca²⁺ influx after broadening of the presynaptic action potential with the K⁺-channel blocker 4-aminopyridine.⁸⁰ Figure 5B showed that this was indeed the case. Compensation by N-type channels was also evident in the presence of 4-AP. Blockade of synaptic strength in wildtype slices depended mainly on P/Q-type current (78% inhibition by the P/Q-type selective blocker ω -Aga-IVB, Fig. 4D) but only marginally on N-type channels (13% inhibition by ω -CgTx-GVIA, Fig. 4C). In contrast, in Ca₂2.1 α_1 -^{*t*} mice



Figure 5. Antinociceptive effects of Ca₂2.201-deficiency in neuropathic pain. Mechanical allodynia and thermal hyperalgesia induced by spinal nerve ligation. Fifty percent hindpaw withdrawal thresholds to stimulation with von Frey hairs (A) and hindpaw withdrawal latencies to thermal stimuli (B) are plotted against the days after the operation. Circles, uninjured side; triangles, operated side. +/+, wild-type; +/-, heterozygote; -/-, homozygous mutant. Homozygous mutants developed an attenuated post-operative decrease in the threshold and the latency, which are clearly observed in wild-type and heterozygous mutant mice as neuropathic pain symptoms. +/+, n = 9-13; +/-, n = 11-14; -/-, n = 5-8. Taken from reference 87 with permission.

neurotransmission mainly relied on N-type channels evident as a 74% inhibition of synaptic strength by the P/Q-type selective blocker ω -Aga-IVB (Fig. 4D). These data show that N-type channels can, at least in part, compensate for P/Q-type channel presynaptic function. This is also true for the neuromuscular junction where compensation by N- and R-type channels occurs.^{21-80a} The lower efficiency of these channels in supporting excitation-secretion coupling is compensated in Ca_x2.1^{-/-} mice by additional presynaptic mechanisms such as enhanced Ca²⁺-sensitivity of the neurotransmitter release machinery.^{80b}

Unfortunately, the severity of the Ca_v2.1 α_1 ^{-/-} phenotype did not allow a systematic analysis of the role of P/Q-type channels for various brain functions such as cognition, behaviour and pain sensation. Pharmacological block of P/Q-type channels in the brain suggested that they, together with N- and R-type (see below) type channels, are involved in transmission of certain forms of pain.^{81,82} Obviously, these questions need to be addressed by brain region specific knockouts preserving P/Q-type channel function in the cerebellum.

The neurological syndrome of Ca_v2.1^{-/-} mice and the pattern of neuronal degeneration resembles the phenotype of spontaneous mouse mutants reported earlier. Spontaneous mutations (missense and/or C-terminal truncations) in the Ca_v2.1 α_1 gene (CACNA1A, mouse chr. p19q13) underly the autosomal recessive mutants *tottering, leaner, rocker*, and *rolling* (for review see ref. 83). Homozygous mutants exhibit cerebellar signs (ataxia, dystonia), absence epilepsy-like seizures and cerebellar degeneration to various extents.⁸³ These mutations result in a partial loss of P/Q-type channel function.⁸³ The presence of Ca_v2.1 α_1 protein and/or of residual P/Q-type currents may explain why these mutants can survive to adulthood unlike Ca_v2.1 α_1^{-t-} mice. Interestingly, a 70-80% reduction of P/Q-type current was found in homozygous *leaner* mice. They also show profound cerebellar degeneration unlike the heterozygous Ca_v2.1 α_1^{+t-} mice in which current density decreases by about 50% in Purkinje cells (ref. 77, see above). These data suggest that cerebellar degeneration requires reduction of P/Q-type current density below a critical threshold of 50-70%.

Rare inherited human diseases are also caused by $Ca_v 2.1\alpha_1$. Episodic Ataxia type 2 (EA-2) is a human disease in which $Ca_v 2.1\alpha_1$ mutations cause a complete or almost complete loss of channel function.^{84,85} EA-2 is inherited in an autosomal dominant manner allowing synthesis of normal $Ca_v 2.1\alpha_1$ subunits from the unaffected allele. In contrast to apparently healthy heterozygous $Ca_v 2.1\alpha_1^{+/-}$ mice, disease signs (including cerebellar atrophy) are present despite the existence of an unaffected allele in these patients. This could merely reflect a species difference. An alternative explanation is the presence of dominant negative effects of the human EA-2 mutants, antagonizing the activity of $Ca_v 2.1\alpha_1$ derived from the unaffected allele. At present the results about the presence of such dominant negative effects are controversial.^{84,85} Moreover, even if dominant-negative effects by truncated constructs could be demonstrated by heterologous expression experiments, their pathophysiological significance is likely to be limited because most of these mutants are likely to undergo Nonsense-Mediated mRNA Decay.^{85a}

$Ca_{r}2.2\alpha_{l}$ -Deficiency

Based on the large contribution of N-type channels to presynaptic Ca^{2+} influx in many synapses, including sympathetic neurons,⁸⁶ it was surprising that $Ca_v 2.2\alpha_1$ -deficiency caused no obvious pathological syndrome. Three independent $Ca_v 2.2^{-1-}$ lines have been characterized⁸⁷⁻⁸⁹ (Table 2). As expected all three lacked ω -CgTx GVIA-sensitive currents. Unlike for $Ca_v 2.1\alpha_1$ -deficiency, no compensatory upregulation of other VGCCs was found.

The selective block of N-type Ca²⁺ channels is currently developed as a promising pharmacotherapeutic concept to treat severe and opioid-resistant pain syndromes, including neuropathic pain.⁸² Intrathecally injected ziconotide (SNX-111), a W-CgTx GVIA-related peptide, showed considerable efficacy against neuropathic pain in clinical trials. Unfortunately, side effects resulting from N-type block were described. These include increased dizziness, blurred vision, nystagmus, sedation, anxiety, halluzinations and hypotension and limit the clinical use of this peptide.⁹⁰⁻⁹² Whereas the pathophysiological significance of N-type channels for nociception could be nicely confirmed in Ca. 2.2-1- mice (see below) no other functional disturbances were yet reported that correspond to these side effects of intrathecal ziconotide in humans. Motor function and spontaneous locomotor activity were normal in knockout mice, although a recent study found evidence for higher spontaneous activity during the dark phase and during exposure to a novel environment.^{92a} Evidence for a decreased rather than increased level of anxiety was detected in different behavioural paradigms (open field, acoustic startle response, elevated plus-maze⁸⁷). Hypotension was also absent (see below). Cav2.2^{-/-} mice had unchanged thresholds for normal and noxious mechanical stimuli^{87,88}(but see ref. 89). However, antinociceptive effects were evident as delayed responses to thermal noxious stimuli, which involve spinal reflexes (tail and paw flick tests refs. 87,89). $Ca_{2}2\alpha_{1}$ deficiency consistently delayed inflammatory pain development in the formalin test. In this test a brief period of acute pain (phase 1, lasting about 5 min) is followed by a persistent inflammatory pain response which starts about 15 min after paw injection (phase 2). In Ca_v2.2⁻¹⁻ mice the first half of phase 2 (phase 2A, sensitive to COX-inhibitors⁸⁷), but not phases 2B (insensitive to COX-inhibitors) and 1, was completely

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Subunit Defciency	References	Anatomical Abnormalities	Effect on Ca ²⁺ -Current	Body Functions	Blood Heart Pressure Rate	Motor Function	Anxiety	Locomotor Activity	Learning and Memory
Cav2.2α1	87	none	N-type absent, no compensatory upregulation (DRG, SCG)	normal body temperature	normal	normal	decreased	normal	n.e.
	88,93	лопе		л.е.	both elevated; markedly reduced baroreceptor response	normal	n.e.	n.e.	л.е.
	89	none		n.e.	n.e.	normal	n.e.	n.e.	п.е.
Cav2.3α1	66	none	R-type reduced by 81% in CeA	n.e.	n.e.	normal	increased	normal	n.e.
	98	none	SNX-482 sensitive component of R-type eliminated in CGC	ið. L	j. L	n.e.	n.e.	n.e.	n.e.
	96,97, 140,141	none	·	altered sperm motility; decreasec insulin response ar glucose tolerance, increased weight	n.e.	ы. С	increased	reduced	decreased spatial (Morris water maze), unchanged fear memory
	59	none		decreased glucose tolerance and insulin secretion	n.e.	n.e.	n.e.	n.e.	n.e.
								Continued	I on next page

Table 2.	Continued							
Subunit Defciency	References	Threshold for Mechanical Stimuli	Threshold for Mechanical Noxious Stimuli	Latency to Noxious Thermal Stimuli (Spinal)	Latency to Noxious Thermal Stimuli (Spinal + Supraspinal)	Acute and Inflammatory Somatic Pain (Formalin Writhing)	Visceral Pain (Acetic Acid Writhing Response)	Neuropathic Pain
Cav2.2α1	87	normal	normal	increased (tail flick, not paw flick)	normal	phase 1 normal phase 2 delayed	normal	allodynia and thermal hyperalgesia decreased
	88,93	n.e.	normal		increased	phase 1 normal phase 2 delayed	n.e.	n.e.
	89	ъе	increased	increased (tail flick and paw flick)	normal	phase 1 normal phase 2 delayed	decreased	n.e.
Cav2.3α1	66	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
	86	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
	96,97, 140,141	normal	i. L	normal	normal	phase 1 normal phase 2 decreased	decreased (but only for heterozygous mutants)	ы Ц
	59	n.e.	n.e.	n.e.	п.е.	n.e.	n.e.	n.e.
Data obtair cervical ga	ned with the sa	tme mouse line v CC= cerebellar e	were combined (se	veral references); Ce - no evnerimental di	eA= central amygdala ata available at present	neurons; DRG= dorsal	root ganglion cell	s; SCG= superior
LEIVILAI BA	inglion cells; C	CC= CELEDEIIAL ?	granule cells; n.e. :	= по ехрептелка и	ata avaliatie at presen	Ľ		

suppressed.⁸⁷⁻⁸⁹ These mice also showed a marked reduction of neuropathic pain symptoms,⁸⁷ measured as decreased thresholds to mechanical (allodynia) and thermal (thermal hyperalgesia) stimuli after nerve ligation. This confirms the important pharmacotherapeutical potential of N-type channels for this pain syndrome.

N-type channels play a major role for noradrenaline release from sympathetic nerve terminals.⁸⁶ This explains bradycardic and hypotensive actions of N-type channel blockers in vivo. However, the data on the effect of Cav2.2 deficiency on the cardiovascular system are conflicting. One study reported normal resting heart rates and blood pressure,⁸⁷ whereas another group, surprisingly, found both parameters increased. They could show an abnormal baroreflex response in Ca₂2.2^{-/-} mice resulting in a defect in neurotransmitter release from cardiac sympathetic (but not parasympathetic) nerve endings.⁹³ It remains to be clarified why this leads to the development of hypertension. Obviously, this is of great interest, because it may shed light on the counterregulatory mechanisms occurring under conditions of long term inhibition of sympathetic tone. Taken together the existing data obtained with Ca₂.2.⁴⁻ mice re-emphasize the attractivity of selective N-type channel blockers as analgesics. They show that the complete and permanent block of N-type channel function, at least in mice, does not lead to the side effects observed in humans but mediates potent antinociceptive actions. One could speculate that peptide bockers like ziconotide do not reach all N-type channels in the brain at equally high concentrations due to their low penetration into lipophilic compartments.⁹⁴ This could lead to a heterogeneous block of N-type channels which may be the cause for toxicity. This hypothesis can only be tested once more hydrophobic Cav2.2-selective blockers with high brain penetration become available.

$Ca_v 2.3\alpha_1$ -Deficiency

Three groups have independently generated Ca_v2.3^{-/-} mice ⁵⁹ (Table 2). Again no severe pathology has so far been described in these mice. Altered sperm motility, decreased glucose tolerance and insulin secretion were reported indicating that these channels also control physiological processes outside the nervous system.^{59,95} Enhanced anxiety⁹⁶ and altered spatial (but not fear) memory has also been reported.⁹⁷

Analysis of Ca^{2+} current components in $Ca_v 2.3^{-1-}$ mice revealed that $Ca_v 2.3\alpha_1$ only partially contributes to the formation of R-type current. Its contribution varied from 30% in cerebellar granule cells⁹⁸ to >79% in central amygdala⁹⁹ hippocampal CA1 and neocortical neurons.^{99a} The molecular entities underlying the residual R-type current in $Ca_v 2.3^{-1-}$ neurons remain unidentified.

Ca_v2.3^{-/-} mice have normal mechanosensitivity but altered nociception in the formalin-test with a reduced phase 2 response. Interestingly, by exposing the mice to an episode of visceral inflammatory pain 2-3 weeks before, the phase 2 pain response in the formalin test was reduced in wildtype but increased in Ca_v2.3^{-/-} mice. This suggests activation of a long-lasting descending antinociceptive pathway by the visceral conditional stimulus. Ca_v2.2 α_1 -deficient mice also showed this response. This was interpreted as evidence that Ca_v2.3 α_1 -mediated R-type as well as N-type channels participate in this descending antinociceptive pathway. Expression of these channels in brain regions known to mediate antinociception (Ca_v2.2 α_1 in the rostral medial medulla including the Nucleus raphe magnus and both α_1 subunits in the periaqueductal grey) could be demonstrated.^{66,87,96} Effects on neuropathic pain have not yet been assessed in Ca_v2.3^{-/-} mice.

The Cav3 (T-Type) Ca²⁺ Channel Family

T-type channels are characterized by their low activation threshold and fast inactivation. This group is therefore also termed "low-voltage activated" Ca^{2+} channels. However, this term may not longer be useful as $Ca_v 1.3\alpha_1$ can also give rise to Ca^{2+} currents with activation thresholds close to those of T-type channels (see above). Their low activation thresholds allows T-type channels to mediate Ca^{2+} currents and membrane depolarization even before cells reach their

thresholds for firing action potentials. They can therefore serve pacemaker functions in heart and neurons and underly the Ca²⁺-dependent generator potential triggering burst-firing in thalamic and inferior olive neurons¹⁰⁰ (see below). A specific feature of thalamocortical relay neurons (TCR) is to fire action potentials in response to hyperpolarizing stimuli, such as GABA_B-receptor activation. The hyperpolarizing stimulus then triggers a low-threshold Ca²⁺-dependent potential ("low-threshold spikes", LTS) which depolarizes the neurons and triggers brief bursts of Na⁺-dependent action potentials.^{100,101} Hyperpolarization can trigger the LTS because it removes inactivation from the ionic conductance generating this response, presumably T-type Ca²⁺ channels. The resulting burst-firing behaviour contributes to the formation of sustained synchronous network discharges in the thalamus which underlies so-called absence seizures and the typical spike-and-wave discharges in electroencephalograms recorded simultaeously.^{101,102} Spike-and-wave discharges are generated when a physiological tonic mode of neuronal firing shifts to a burst-firing mode. LTS is likely to be mediated by T-type channels because succinimide antiepileptics block T-type currents and show efficacy in the treatment of absence epilepsy.¹⁰²

Like L-type channels, T-type channels also possess a broad expression profile not restricted to neurons. They are e.g., expressed in various muscle and endocrine cells as well.¹⁰³

The absence of selective high affinity T-type channel probes has slowed the analysis of their subunit structure, function and pharmacotherapeutic potential. For this reason their further characterization is crucially dependent on the availability of knockout mouse models.

 $Ca_v 3.1\alpha_1$ -deficient mice¹⁰¹ show no gross anatomical, histological and physiological abnormalities in peripheral tissues and the CNS. As this T-type Ca²⁺ channel isoform is the only one expressed in thalamocortical relay (TCR) neurons it was interesting to look for changes in their neuronal activity and their role for LTS. Low-voltage activated Ca²⁺ currents were completely absent in TCR neurons isolated from Ca_v3.1^{-/-} mice but high-voltage activated channels were expressed at normal densities. Burst firing of TCR neurons was absent but neurons were still able to fire trains of action potentials upon depolarization (Fig. 6). GABA_B-receptor activation produced absence seizures evident as spike-and-wave discharges only in wildtype mice but not in homozygous mutants.¹⁰¹ Thus Ca_v3.1 channels could be unequivocally identified as the generators of LTS and important targets for antiepileptic drugs.

The ventroposterolateral (VPL) thalamocortical neurons have also been implicated in central pain pathways (see ref. 101a). Injection of T-type channel blockers into this brain region induce hyperalgesia to visceral pain.^{101a} Similarly, such a hyperalgesia is also present in Ca_v3.1^{-/} mice.^{101a} In the knockout animals this could be nicely correlated with characteristic changes in the firing pattern of a subset of single units in the VPL region of the thalamus under basal conditions and after induction of visceral pain. In these "visceral pain-responsive" neurons single spikes as well as burst spikes were observed in wildtype mice but burst spikes were completely absent in homozygous knockouts. An intraperitoneal injection of acetic acid evoked an early-onset surge of mainly unitary single spikes followed by a gradual increase of burst spikes which reflect the activation of T-type channels. This increase in burst activity was associated with a decrease of the firing rate of single spikes. In the $Ca_v 3.1\alpha 1$ deficient mice VPL neurons showed the early-onset increase of single spikes like in wildtype but, due to the lack of T-type channels, the burst activity did not increase and single spike frequency did not decay with time. This was taken as evidence that T-type Ca²⁺ channels in VPL thalamocortical neurons are activated after a surge of pain signal influx from the viscera and then play an inhibitory role in the processing of those signals, thereby suppressing pain responses.

Cav3.2 channel knockout mice are viable and fertile but are somewhat smaller than wiltype mice. They exhibit limited but progressive cardiac fibrosis.^{101b} The mice did not confirm the long-standing hypothesis that T-type channels control diastolic depolarization in the heart. However, homozygous knockouts revealed constricted coronary arteries with irregular shapes. This vasoconstriction could be explained by a decreased NO-mediated vasodilatory response although $Ca_v 3.2^{-1}$ arteries responded normally to vasodilation by L-type channel blockers.



Figure 6. Effect of Ca_v3.1 α 1-deficiency on thalamocortical relay (TCR) neuron firing. Intrinsic firing properties of TCR neurons at the ventrobasal complex. A) Burst firing patterns elicited by hyperpolarization: 100 ms of **negative** step-current inputs at -70 mV elicited a rebound LTS and burst firing. Holding membrane potentials were maintained by DC current input. The amount of current injected is indicated below each trace. Scale bars: horizontal, 100 ms; vertical, 50 ms. B) LTS Burst firing patterns elicited by **positive** step-current inputs at -80 mV. Note the increasing number of lower frequency spikes firing frequency in wild type TCR neurons more than 700 pA of positive current input. These seem to reflect a tonic firing of action potentials. Only the high-frequency, burst-mode firing supported by T-type currents are missing in Ca_v3.1 α 1^{-/-} neurons. C) Tonic firing patterns elicited by positive step-current inputs at -60 mV. T-type and Ca_v3.1 α 1^{-/-} neurons. D) Relation between the number of spikes and the amount of current injected. The number of spikes during 100 ms positive step-current inputs either wehn membrane potentials are held at -60 mV (left) or at -80 mV) (right). Taken from reference 101 with permission.

Interestingly, Ca₄3.2 channels were found to biochemically associate with large conductance BK_{Ca} channels after heterologous expression in HEK-293 cells and in mouse brain microsomes.^{101b} Taken together these findings suggest that Ca₄3.2 T-type channels mediate a Ca²⁺ current in coronary arteries which activates BK_{Ca} channels and allows them to clamp the membrane voltage to hyperpolarized potentials. The impaired activity of this mechanism in Ca₄3.2^{-/-} mice can explain increased vascular tone and the defective response to NO- (cGMP-) mediated vasodilation which requires, at least in part, BKCa channel activation by Ca²⁺. It is likely that the cardiac fibrosis results from reduced myocardial blood flow and myocardial ischemia.

Ca²⁺ Channel β-Subunits

 β -subunits are important for plasma membrane targeting and help fine-tuning α_1 function. Deficiency of a particular β -subunit must result in the dysfunction of α_1 subunits with which they normally associate. However, compensation by other β -subunit isoforms may occur due to their similar affinity for the β -subunit binding site of α_1 subunits and the expression of more than one subunit isoform in neurons or muscle cells.^{16,57,104,105}

$Ca_{v}\beta_{1}$ -Deficiency

 $Ca_{\nu}\beta_{1}$ gives rise to two different splice variants. $Ca_{\nu}\beta_{1}$ b represents a neuronal isoform which can associate with different Ca^{2*} channel α_{1} subunits in mammalian brain.¹⁰⁶⁻¹⁰⁸ In contrast, $Ca_{\nu}\beta_{1}a$ is almost exclusively expressed in skeletal muscle and therefore essential for normal $Ca_{\nu}1.1$ function. Unlike in neurons, no other β subunit is abundantly expressed in skeletal muscle which could compensate for $Ca_{\nu}\beta_{1}$. $Ca_{\nu}\beta_{1}$ subunit deficiency results in a dramatic decrease of $Ca_{\nu}1.1\alpha_{1}$ expression.¹⁰⁹ Therefore the phenotype is dominated by skeletal muscle dysfunction indistinguishable from the *mdg/mdg* phenotype (see above).¹⁰⁹ The lethal phenotype has been successfully rescued in $Ca_{\nu}\beta_{1}^{-1-}$ mice carrying a $Ca_{\nu}\beta_{1}a$ transgene under the control of a human skeletal muscle actin-promotor.¹¹⁰ These mice (produced for studies of β -subunit effects on retinal function) do not express $Ca_{\nu}\beta_{1}a$ in the retina, suggesting that they also lack $Ca_{\nu}\beta_{1}b$ subunits in neurons. They appeared completely normal. Neurophysiological and behavioural tests have not yet been performed with these mice to reveal distinct changes of behaviour or neurophysiological parameters.

$Ca_{\nu}\beta_2$ -Deficiency

 $Ca_v\beta_2$ is the predominant β -subunit isoform expressed in the heart. Only minor amounts of $Ca_v\beta_3$ subunits are present.¹⁶ Like $Ca_v1.2\alpha_1$ -deficiency, the absence of $Ca_v\beta_2$ prevents normal embryonic development ¹¹⁰ presumably due to a defect in cardiac function. The lethal phenotype could be rescued in $Ca_v\beta_2$.¹⁻ knockout mice expressing a rat $Ca_v\beta_2$ under a cardiac-specific α -myosin heavy chain promotor.¹¹⁰ The absence of $Ca_v\beta_2$ in the retina caused visual disturbances similar to those observed in CSNB2 patients with $Ca_v1.4$ mutations (see above). In contrast to wildtype littermates, $Ca_v1.4\alpha_1$ subunits were not present in the outer plexiform layer where they are believed to mediate neurotransmitter release from photoreceptors to bipolar cells. This provides first (albeit very indirect) evidence that $Ca_v\beta_2$ subunits are the major β subunit isoform in photoreceptors and they form complexes with $Ca_v1.4\alpha_1$. Mice deficient in $Ca_v\beta_1$ (see above), $Ca_v\beta_3$ and $Ca_v\beta_4$.¹¹⁰ (see below) showed no structural and functional abnormalities in the retina.

$Ca_{v}\beta_{3}$ -Deficiency

 $Ca_{\nu}\beta3$ and $Ca_{\nu}\beta4$ are the most abundant β -subunits expressed in the mammalian brain. 42% of L-type channels (rabbit cerebral cortex¹⁰⁸), 56% of N-type channels¹⁰⁶ and 36% of P/ Q-type channels (rabbit brain¹⁰⁷) are associated with Ca_{\nu}\beta3. Similarly large fractions of channels are associated with Ca_νβ4 (42, 31, and 48%¹⁰⁶⁻¹⁰⁸). Ca_νβ3^{-/-} mice did not exhibit a specific pathology, except for an increased blood pressure in response to high-salt diet. Depolarization-induced vascular smooth muscle contractility was unaffected suggesting a salt-sensitive defect caused by $Ca_v\beta 3$ -deficiency in the kidney.¹¹¹

Detailed analysis of sympathetic neurons (superior cervical ganglion cells), which express several Ca²⁺ channel types, revealed a decrease in the density of N-type and L-type Ca²⁺ currents in Ca_{*} β 3^{-/-} mice.¹¹² P/Q-type current density was not affected but the absence of Ca_{*} β 3 subunits caused a change in the activation kinetics of P/Q-currents. In wildtype cells 61% of the channels activated at negative voltages (V_{0.5}' = -21 mV) whereas 39% required stronger depolarizations (V_{0.5} = 20 mV). In Ca_{*} β 3^{-/-} cells V_{0.5} was shifted to more negative voltages (-1 mV) which resulted in more P/Q-type current activating by depolarizations positive to -10 mV. These kinetic changes are most likely due to a compensatory association of other β -subunits that are unable to stabilize the more depolarized activation component.

Due to this reduction in N-type currents in $Ca_v\beta_3^{-1}$ mice it was not surprising that nociception was also found to be altered. Similar to $Ca_v2.2\alpha_1^{-1}$ mice the phase 2 inflammatory pain (formalin) response was reduced and homozygous mutants showed increased thresholds for acute thermal but not mechanical pain.¹¹³ The density of N-type channels (determined by [¹²⁵I]- ω -CgTx-GVIA binding) was reduced in DRG neuron membranes which seemed to be due to an increase of the proportion of neurons with small N-type current components.¹¹³ In addition, biophysical changes of DRG Ca²⁺ currents were observed which make them less responsive to membrane depolarization and may contribute to the altered pain perception at the spinal level.

At present it is unclear if biophysical changes occur also in other brain neurons and if $Ca_v 2.2\alpha_1^{-1}$ deficiency has any functional consequences on other brain function.

Transient changes in the development of subcortical neuronal pathways were discovered in $Ca_v\beta^{3-t}$ mice. In anterograde tracer studies a delay in the refinement of visual pathway neurons projecting from the retina to the dorsal lateral geniculate nucleus and superior colliculus was detected. ¹¹⁴ During early postnatal development these neurons project to both appropriate and inappropriate sites. The correct retinotopic representation is then produced by retraction and/or elimination of inappropriately targetet fibers. This process is mediated in part by nitric oxide¹¹⁵ presumably by affecting long term depression (LTD). The observed delay of the retraction of fibers in the ipsilateral retinocollicular and contralateral retinogeniculate pathways in $Ca_v\beta^{3-t}$ mice supports the view that LTCCs participate in the generation of a signal inducing fiber retraction. LTCCs also mediate LTD (and long term potentiation) in the developing superior colliculus in a developmentally regulated manner.¹¹⁵ A likely explanation is therefore that $Ca_v\beta_3$ -deficiency decreases L-type currents (like in sympathetic neurons) leading to a decrease of LTD and fiber refinement. However, an alteration of L-type currents in visual pathway neurons has not been shown and no direct correlation between refinement and LTD (or LTD) could yet be established.

$Ca_{v}\beta_{4}$ -Deficiency

Biochemical studies revelaed that $Ca_{\nu}\beta4$ is the major β -subunit associated with P/Q-type channels in the cerebellum.^{104,107,108} Spontaneous mouse mutants lacking functional β_4 subunits (lethargic mice) suffer from ataxia, focal motor seizures and absence epilepsy. It was therefore surprising that P-type Ca^{2+} currents in cerebellar Purkinje cells were not altered in homozygous lethargic mice.¹⁰⁴ This suggested that other β -subunits compensate for $Ca_{\nu}\beta_4$ -deficiency and was confirmed by coimmunoprecipitation experiments in which enhanced complex formation of N-type $(Ca_{\nu}2.2\alpha_1)$ and P/Q-type $(Ca_{\nu}2.1\alpha_1)$ channel mainly with with $Ca_{\nu}\beta_1$ b and $Ca_{\nu}\beta_3$ subunits was detected in lethargic solubilized brain membranes.^{104,116} The consequences of $Ca_{\nu}\beta_4$ -deficiency vary for different neurons. Successful compensation of β_4 function can explain why the Ca^{2+} dependence and relative contribution of P/Q- and N-type channels to neurotransmitter release at hippocampus Schaffer collateral synapses is unchanged.¹¹⁷ In contrast, excitatory but not inhibitory neurotransmitter release was reduced in thalamic neurons.⁷¹ This was also observed for *tottering* mouse mutants carrying a $Ca_{\nu}2.1\alpha_1$ mutation

disturbing P/Q-type Ca²⁺ channel function and reducing expression density.^{72,118} This suggests that P/Q-type channels are mainly affected by the Ca_v β_4 -deficiency and supports the observation that excitatory neurotransmitter release is more dependent on P/Q-type than N-type Ca²⁺ channels (see above). As these thalamic neurons play a role in the generation of absence epilepsy, the imbalance of thalamic neurotransmitter release provides an explanation for the epilepsy phenotype of these mutants.⁷¹

Mutations in the Ca₄ β_4 subunit have also been found in patients with hereditary forms of episodic ataxia or idiopathic generalized epilepsy.¹¹⁹ Like in mouse mutants the clinical phenotype resembles another rare human disease with a defect in the Ca₄2.1 α_1 subunit gene, Episodic Ataxia Type-2. In contrast to the mouse lethargic mutation, the two reported human Ca₄ β_4 mutants lead to a missense mutation in the N-terminal region of Ca₄ β_4 (C104F) or to a C-terminal 38-amino acid truncation (R482X). Both should still bind to α_1 subunits and, accordingly, support robust P/Q-type currents after heterologous coexpression because the mutations do not affect the high affinity interaction with α_1 subunits. In coexpression experiments only the R482X mutant changed channel function by slightly increasing channel inactivation.¹¹⁹ It is at present unclear if these slight changes in channel function observed in heterologous expression systems explain the pathology or if other biochemical roles of Ca₄ β_4 are affected, such as channel targeting. It is at present unknown which clinical phenotype would result from a complete absence of Ca₄ β_4 in humans.

Other Subunits

α_2 - δ -Subunit Deficiency

Like β -subunits, α_2 - δ increases α_1 -subunit expression at the plasma membrane and can also affect gating when co-expressed in mammalian cells or Xenopus laevis oocytes. In heterologous expression systems effects on gating are usually less pronounced than for β -subunits. At present 4 different α_2 - δ subunit isoforms are known. α_2 - δ_1 was the first to be characterized and was cloned from skeletal muscle.¹²⁰ It is not only expressed in skeletal muscle but in many tissues including the brain, heart, lung, spleen, kidney, liver, testis. In the mouse α_2 - δ_2 is strongly expressed in the brain but also peripheral tissues and α_2 - δ_3 is brain-specific.¹²⁰⁻¹²³ α_2 - δ_4 was cloned recently.¹²⁴ It is expressed in the pituitary and adrenal gland, the intestine, fetal liver and at low densities in brain. The anticonvulsant drug gabapentin binds with high affinity to α_2 - δ_1 , intermediate affinity to α_2 - δ_2 but not to α_2 - δ_3 and α_2 - δ_4 .^{122,124} As the mechanism and extent of Ca²⁺ channel modulation by gabapentin are still controversial,¹²⁵⁻¹²⁷ this drug did not prove helpful to assess the (patho)physiological and pharmacotherapeutic role of α_2 - δ subunits in vivo.

Two allelic strains of the spontaneous mouse mutant *ducky* (du/du and du^{2J}/du^{2J}) exist which lack functional α_2 - δ_2 subunits.¹²¹ α_2 - δ_2 is expressed at high densities in Purkinje cells and the molecular layer of the cerebellum consistent with expression on Purkinje cell bodies and its dendritic tree.¹²¹ Homozygous mice suffer from cerebellar ataxia, paroxysmal dyskinesia and absence epilepsy. In the *du/du* strain a genomic rearrangement (including duplications of exons 2 and 3) results in 2 aberrant transcripts, a prematurely truncated N-terminal transcript and a larger aberrant form encoded by exons 2-39.¹²¹ Only the N-terminal transcript yields a low abundance protein product (10 kDa) which is detected in *du/du* cerebellar Purkinje cell bodies.¹²⁸ In *du2J/du2J* mice a 2 basepair deletion results in protein truncation (exon 9).¹²¹

As the absence of full-length α_2 - δ_2 results in a pathological phenotype which resembles those of spontaneous mutants affecting Ca_v2.1 α_1 subunits (*tottering, leaner*, see above) it was speculated that α_2 - δ_2 -deficiency could primarily affect P/Q-type Ca²⁺ channel function in the cerebellum. α_2 - δ_2 enhances Ca_v2.1 Ca²⁺ current density upon coexpression in heterologous systems. Accordingly, cerebellar Purkinje cell P-type Ca²⁺ currents were reduced in *du/du* mice due to a decreased density of functional channels in the plasma membrane.¹²⁸ These results suggested that α_2 - δ_2 associates with Ca_v2.1 α_1 to form P-type currents in cerebellar Purkinje cells. The 10 kDa *du/du* protein reduced Ca_v2.1 α_1 -mediated Ca²⁺ currents upon heterologous coexpression.¹²⁸ Whether this also contributes to P-type current reduction and the *du/du* phenotype remains unclear.

In *duldu* mice the number of cerebellar Purkinje cells was not decreased but they exhibited an abnormal cytoarchitecture. This included atypical initial lateral extensions of the primary dendrite and delayed targeting of the pial surface. The dendritic tree was significantly less complex, reduced in size and frequently did not reach the border of the molecular layer.¹²⁸ It must be noted that both allelic *ducky* mutants do not represent true α_2 - δ_2 null mutations because truncated forms of the protein are synthesized.

γ-Subunit Deficiency

At present at least 8 different γ -subunit genes are known.^{129,130} The role of γ -subunits for Ca²⁺ channel function is still enigmatic. In skeletal muscle Ca₄ γ_1 -subunits were shown to be stoichiometrically associated with Ca₄1.1 α_1 in the channel complex. Unlike in the case of Ca₄ β_1 , Ca₄ γ_1 deficient mice show no pathology. Detailed analysis revealed a 30% increase in isolated skeletal muscle myocyte Ca²⁺ current density (in mice below 4 weeks of age), a modest slowing of current inactivation kinetics and a shift of the steady-state inactivation curve to more negative potentials (age-independent^{131,132}). Intracellular Ca²⁺ release, which is triggered by Ca₄1.1 α_1 channels independent of Ca²⁺ influx in skeletal muscle myocytes, was also increased.¹³³ However, Ca₄ γ_1 -subunit deficiency had no effect on electrically evoked contraction parameters.¹³³ Ca₄ γ_1 can therefore not be considered essential for normal excitation-contraction coupling and spontaneous null mutants are likely to remain undetected.

In contrast to γ_1 , an important role for normal brain function could be established for Ca_y γ_2 -subunits but their association with different neuronal VGCCs is controversial. Ca_y γ_2 was discovered as the protein absent in the spontaneous mouse mutant stargazer and therefore termed stargazin.¹³⁴ Stargazer mice suffer from head-tossing, ataxia and severe absence epilepsy. Waggler mutants were identified as an allelic disorder with a very similar phenotype.¹³⁴ The stargazer allele is associated with the insertion of an early retrotransposon into intron 2 in the same transcriptional direction resulting in a premature transcriptional termination.¹³⁴ An association of $Ca_v \gamma_2$ subunits with P/Q- and N-type Ca^{2+} channels has been demonstrated biochemically.¹³⁵ Coexpression of $Ca_v \gamma_2$ with $Ca_v 2.1$ shifted the steady-state inactivation curve to more negative voltages in some studies^{134,136} (but see ref. 135) and decelerated Ca₂2.2 current activation kinetics.¹³⁵ Ca_v2.1 and Ca_v2.2-mediated currents were decreased by Ca_v γ_2 when coexpressed with α_2 - δ subunit.^{135,136} Reduction of Ca²⁺ channel currents seems to be a common feature of many γ -subunits because it was also observed for Ca, γ_1 (see above) and Ca, γ_7 .¹³⁰ Both, functional effects and biochemical association, suggest that ${\rm Ca}_v\gamma_2$ is a neuronal ${\rm Ca}^{2+}$ channel subunit. However, the interpretation of the stargazer phenotype as a Ca²⁺ channel channelopathy is complicated by the finding that stargazer mice lack functional AMPA receptors on cerebellar granule cells.¹³⁷ Surprisingly, stargazin serves not only as a Ca²⁺ channel subunit but also as an anchoring protein and interacts with both AMPA receptor subunits and synaptic PDZ proteins (e.g.PSD-95). This interaction was found to be essential for delivering functional receptors to the surface membrane and synapses of granule cells.¹³⁷ If Ca_vy₂ affects Ca²⁺ channel gating and expression then its absence should also affect Ca²⁺ channel gating in intact neurons. However, in cerebellar granule cells Ca²⁺ currents were indistinguishable from wildtype.¹³⁷ It is possible that compensation by other γ -subunits can mask Ca_v γ_2 -deficiency. We have learned from the *lethargic* mice (see above) that Ca²⁺ currents (i.e. P-type currents in cerebellar Purkinje cells; ref. 104) must not necessarily be affected in one type of neuron, yet Ca²⁺ channel dysfunction can occur in another (i.e. thalamic neurons; ref. 71). At present it is unclear if AMPA-receptor targeting or altered Ca2+ channel function or both are responsible for the stargazer and waggler phenoptyes.

Summary

For nine of the ten voltage-gated Ca^{2*} channel α_1 -subunit genes knockout models are already available. Although many of the associated phenotypes were expected, some of them provided exciting new insight into Ca^{2*} channel physiology and pathophysiology. How can our insight into Ca^{2*} channel function be extended beyond this basic characterization using gene-targeting? Future studies will certainly exploit already available, more sophisticated possibilities of gene-knockout strategies allowing the time-dependent and/or tissue-specific deletion of subunit genes. As evident from the existing data this will be especially useful to study the role of specific Ca^{2*} channel subunits for brain function. In addition targeted mutations within Ca^{2+} channel subunits removing consensus sites for phosphorylation, subunit interaction or drug binding will represent valuable tools to study the impact of altered channel regulation. Such mutations will also help to generate valuable animal models for human diseases. An example is the introduction of single mutations into the gene encoding $Ca_2.1 \alpha_1$, ¹⁴² known to cause rare forms of migraine in humans (Familial Hemiplegic Migraine^{138,139}).

The described knockout models clearly revealed that voltage-gated Ca^{2+} channel remain an exciting and promising target for drug development. New generations of Ca^{2+} channel modulators may turn out to be useful for the treatment of migraine ($Ca_v 2.1\alpha_1$), pain ($Ca_v 2.2\alpha_1$, $Ca_v 2.3\alpha_1$), hearing disorders ($Ca_v 1.3\alpha_1$), cardiovascular diseases ($Ca_v 1.3\alpha_1$), cognitive dysfunction ($Ca_v 1.3\alpha_1$) and epilepsy ($Ca_v 2.2\alpha_1$, $Ca_v 3.1\alpha_1$).

Note Added in Proof

This chapter was submitted based on published evidence as of August 2002. Some, but not all, of the more recent literature was included in proof stage (July 2004).

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References

- 1. Hille B. Ionic channels of excitable membranes. 3 ed. Sunderland: Sinauer, 2001.
- 2. Catterall WA. Structure and regulation of voltage-gated calcium channels. Annu Rev Cell Dev Biol 2000; 16:521-555.
- 3. Striessnig J. Pharmacology, structure and function of cardiac L-type Ca²⁺ channels. Cell Physiol Biochem 1999; 9:242-269.
- Glossmann H, Striessnig J. Molecular properties of calcium channels. Rev Physiol Biochem Pharmacol 1990; 114:1-105.
- 5. Hockerman GH, Peterson BZ, Johnson BD et al. Molecular determinants of drug binding and action on L-type calcium channels. Annu Rev Pharmacol Toxicol 1997; 37:361-396.
- 6. Striessnig J, Grabner M, Mitterdorfer J et al. Structural basis of drug binding to L calcium channels. Trends Pharmacol Sci 1998; 19:108-115.
- 7. Tanabe T, Beam KG, Adams BA et al. Regions of the skeletal muscle dihydropyridine receptor critical for excitation-contraction coupling. Nature 1990; 346:567-569.
- Tanabe T, Adams BA, Numa S et al. Repeat I of the dihydropyridine receptor is critical in determining calcium channel activation kinetics. Nature 1991; 352:800-803.
- 9. Powell JA. Muscular dysgenesis: A model system for studying skeletal muscle development. FASEB J 1990; 4:2798-808.
- Chaudhari N. A single nucleotide deletion in the skeletal muscle-specific calcium channel transcript of muscular dysgenesis (mdg) mice. J Biol Chem 1992; 267:25636-25639.
- 11. Beam KG, Adams BA, Niidome T et al. Function of a truncated dihydropyridine receptor as both voltage sensor and calcium channel. Nature 1992; 360:169-171.
- 12. Flucher BE, Kasielke N, Grabner M. The triad targeting signal of the skeletal muscle calcium channel is localized in the COOH terminus of the α_{1S} subunit. J Cell Biol 2000; 151:467-78.
- 13. Flucher BE, Kasielke N, Gerster U et al. Insertion of the full-length calcium channel α_{15} subunit into triads of skeletal muscle in vitro. FEBS Lett 2000; 474:93-8.

- 14. Takimoto K, Li D, Nerbonne JM, Levitan ES. Distribution, splicing and glucocorticoid-induced expression of cardiac α_{1C} and α_{1D} voltage-gated Ca²⁺ channel mRNAs. J Mol Cell Cardiol 1997; 29:3035-3042.
- 15. Bohn G, Moosmang S, Conrad H et al. Expression of T- and L-type calcium channel mRNA in murine sinoatrial node. FEBS Lett 2000; 481:73-6.
- Reimer D, Huber IG, Garcia ML et al. β subunit heterogeneity of L-type Ca²⁺ channels in smooth muscle tissues. FEBS Lett 2000; 467:65-69.
- Liu X, Rusch NJ, Striessnig J et al. Down-regulation of L-type calcium channels in inflamed circular smooth muscle cells of the canine colon. Gastroenterology 2001; 120:480-9.
 Barg S, Ma X, Eliasson L et al. Fast exocytosis with few Ca²⁺ channels in insulin-secreting mouse
- Barg S, Ma X, Eliasson L et al. Fast exocytosis with few Ca²⁺ channels in insulin-secreting mouse pancreatic B cells. Biophys J 2001; 81:3308-23.
- Fass DM, Takimoto K, Mains RE et al. Tonic dopamine inhibition of L-type Ca²⁺ channel activity reduces alpha1D Ca²⁺ channel gene expression. J Neurosci 1999; 19:3345-3352.
- Hell JW, Westenbroek RW, Warner C et al. Identification and differential subcellular localization of the neuronal class C and Class D L-type calcium channel α₁ subunits. J Cell Biol 1993; 123:949-962.
- 21. Jun K, Piedras-Renteria ES, Smith SM et al. Ablation of P/Q-type Ca²⁺ channel currents, altered synaptic transmission, and progressive ataxia in mice lacking the α_{1A} -subunit. Proc Natl Acad Sci USA 1999; 96:15245-15250.
- 22. Graef IA, Mermelstein PG, Stankunas K et al. L-type calcium channels and GSK-3 regulate the activity of NF-ATc4 in hippocampal neurons. Nature 1999; 401:703-708.
- 23. Dolmetsch RE, Pajvani U, Fife K et al. Signaling to the nucleus by an L-type calcium channel-calmodulin complex through the MAP kinase pathway. Science 2001; 294:333-9.
- 24. Kuzmin A, Semenova S, Ramsey NF et al. Modulation of cocaine intravenous self-administration in drug-naive animals by dihydropyridine Ca²⁺ channel modulators. Eur J Pharmacol 1996; 295:19-25.
- 25. Licata SC, Freeman AY, Pierce-Bancroft AF et al. Repeated stimulation of L-type calcium channels in the rat ventral tegmental area mimics the initiation of behavioral sensitization to cocaine. Psychopharmacology (Berl) 2000; 152:110-8.
- 26. Watson WP, Misra A, Cross AJ et al. The differential effects of felodipine and nitrendipine on cerebral dihydropyridine binding ex vivo and the ethanol withdrawal syndrome in mice. Br J Pharmacol 1994; 112:1017-1024.
- Jinnah HA, Yitta S, Drew T et al. Calcium channel activation and self-biting in mice. Proc Natl Acad Sci USA 1999; 96:15228-32.
- Thibault O, Landfield PW. Increase in single L-type calcium channels in hippocampal neurons during aging. Science 1996; 272:1017-1020.
- 29. Seisenberger C, Specht V, Welling A et al. Functional embryonic cardiomyocytes after disruption of the L-type α_{1C} (Ca_v1.2) calcium channel gene in the mouse. J Biol Chem 2000; 275:39193-9.
- 29a. Moosmang S, Schulla V, Welling A et al. EMBO J 2003; 22:6027-6034.
- 29b. Schulla V, Renstrom E, Feil R et al. Impaired insulin secretion and glucose tolerance in beta cell-selective Cav1.2 Ca²⁺ channel null mice. EMBO J 2003; 22:3844-3854
- Williams ME, Feldman DH, McCue AF et al. Structure and functional expression of alpha1, alpha2, and beta subunits of a novel human neuronal calcium channel subtype. Neuron 1992; 8:71-84.
- 31. Bell DC, Butcher AJ, Berrow NS et al. Biophysical properties, pharmacology, and modulation of human, neuronal L-type α_{1D} (Ca_v1.3) voltage-dependent calcium currents. J Neurophysiol 2001; 85:816-827.
- 32. Iwashima Y, Pugh W, Depaoli AM et al. Expression of calcium channel mRNAs in rat pancreatic islets and downregulation after glucose infusion. Diabetes 1993; 42:948-955.
- Platzer J, Engel J, Schrott-Fischer A et al. Congenital deafness and sinoatrial node dysfunction in mice lacking class D L-type calcium channels. Cell 2000; 102:89-97.
- 33a. Brandt A, Striessnig J, Moser T. Cav1.3 Channels are essential for development and presynaptic activity of cochlear inner hair cells. J Neurosci 2003; 23:10832-10840.
- 33b. Glueckert R, Wietzorrek G, Kammen-Jolly K et al. Role of class D L-type Ca²⁺ channels for cochlear morphology. Hear Res 2003; 178:95-105.
- 34. Namkung Y, Skrypnyk N, Jeong MJ et al. Requirement for the L-type Ca²⁺ channel alpha1D subunit in postnatal pancreatic beta cell generation. J Clin Invest 2001; 108:1015-22.
- 34a. Sinnegger-Brauns MJ, Herzenauer A, Huber IG et al. Isoform-specific regulation of mood behavior and pancreatic beta cell and cardiovascular function by L-type Ca²⁺ channels. J Clin Invest 2004; 113:1430-1439.
- 35. Spassova M, Eisen MD, Saunders JC et al. Chick cochlear hair cell exocytosis mediated by dihydropyridine- sensitive calcium channels. J Physiol 2001; 535:689-96.

- 36. Zidanic M, Fuchs PA. Kinetic analysis of barium currents in chick cochlear hair cells. Biophys J 1995; 68:1323-1336.
- 37. Koschak A, Reimer D, Huber I et al. α_{1D} (Cav1.3) subunits can form 1-type Ca²⁺ channels activating at negative voltages. J Biol Chem 2001; 276:22100-6.
- 38. Xu W, Lipscombe D. Neuronal Ca,1.3α₁ L-type channels activate at relatively hyperpolarized membrane potentials and are incompletely inhibited by dihydropyridines. J Neurosci 2001; 21:5944-51.
- 39. Safa P, Boulter J, Hales TG. Functional properties of Cav1.3 α_{1D} L-type Ca²⁺ channel splice variants expressed by rat brain and neuroendocrine GH3 cells. J Biol Chem 2001; 276:38727-37.
- 40. Mangoni ME, Nargeot J. Properties of the hyperpolarization-activated current (I(f)) in isolated mouse sino-atrial cells. Cardiovasc Res 2001; 52:51-64.
- Mangoni ME, Fontanaud P, Noble PJ et al. Facilitation of the L-type calcium current in rabbit sino-atrial cells: effect on cardiac automaticity. Cardiovasc Res 2000; 48:375-92.
- 42. Verheijck EE, van Ginneken AC, Wilders R et al. Contribution of L-type Ca²⁺ current to electrical activity in sinoatrial nodal myocytes of rabbits. Am J Physiol 1999; 276:H1064-H1077
- 43. Zhang Z, Xu Y, Song H et al. Functional Roles of $Ca_v 1.3 \alpha_{1D}$ calcium channel in sinoatrial nodes: insight gained using gene-targeted null mutant mice. Circ Res 2002; 90:981-7.
- 44. Mangoni ME, Couette B, Bourinet E et al. Functional role of L-type Ca₂1.3 Ca²⁺ channels in cardiac pacemaker activity. Proc Natl Acad Sci USA 2003; 100:5543-5548.
- 45. Boycott KM, Pearce WG, Bech-Hansen NT. Clinical variability among patients with incomplete X-linked congenital stationary night blindness and a founder mutation in CACNA1F. Can J Ophthalmol 2000; 35:204-13.
- 46. Pearce SF, Hawrot E. Intrinsic fluorescence of binding-site fragments of the nicotinic acetylcholine. Biochem J 1990; 29:10649-10659.
- Bech-Hansen NT, Naylor MJ, Maybaum TA et al. Loss-of-function mutations in a calcium-channel alpha1-subunit gene in Xp11.23 cause incomplete X-linked congenital stationary night blindness. Nat Genet 1998; 19:264-267.
- 48. Miyake Y, Yagasaki K, Horiguchi M et al. Congenital stationary night blindness with negative electroretinogram. A new classification. Arch Ophthalmol 1986; 104:1013-20.
- 49. Hood DC, Greenstein V. Models of the normal and abnormal rod system. Vision Res 1990; 30:51-68.
- Wilkinson MF, Barnes S. The dihydropyridine-sensitive calcium channel subtype in cone photoreceptors. J Gen Physiol 1996; 107:621-30.
- 51. Schmitz Y, Witkovsky P. Dependence of photoreceptor glutamate release on a dihydropyridinesensitive calcium channel. Neuroscience 1997; 78:1209-16.
- 52. Taylor WR, Morgans C. Localization and properties of voltage-gated calcium channels in cone photoreceptors of Tupaia belangeri. Vis Neurosci 1998; 15:541-52.
- 53. Nachman-Clewner M, St Jules R, Townes-Anderson E. L-type calcium channels in the photoreceptor ribbon synapse: localization and role in plasticity. J Comp Neurol 1999; 415:1-16.
- 53a. Koschak A, Reimer D, Walter D et al. Cav1.4α₁ subunits can form slowly inactivating dihydropyridine-sensitive L-type Ca²⁺ channels lacking Ca²⁺-dependent inactivation. J Neurosci 2003; 23:6041-6049.
- 53b. Baumann L, Gerstner A, Zong X et al. Functional characterization of the L-type Ca²⁺ channel Ca₂1.4α₁ from mouse retina. Invest Ophthalmol Vis Sci 2003; 45:708-713.
- 53c. McRory JE, Hamid J, Doering CJ et al. The CACNA1F gene encodes an L-type calcium channel with unique biophysical properties and tissue distribution. J Neurosci 2004; 24:1707-1718.
- 54. Morgans CW, Gaughwin P, Maleszka R. Expression of the α_{1F} calcium channel subunit by photoreceptors in the rat retina. Mol Vis 2001; 7:202-9.
- 55. Strom TM, Nyakatura G, Apfelstedt-Sylla E et al. An L-type calcium-channel gene mutated in incomplete X-linked congenital stationary night blindness. Nat Genet 1998; 19:260-263.
- 56. Garcia-Palomero E, Renart J, Andres-Mateos E et al. Differential expression of calcium channel subtypes in the bovine adrenal medulla. Neuroendocrinology 2001; 74:251-61.
- 57. Garcia-Palomero E, Cuchillo-Ibanez I, Garcia AG et al. Greater diversity than previously thought of chromaffin cell Ca²⁺ channels, derived from mRNA identification studies. FEBS Lett 2000; 481:235-239.
- 58. Ligon B, Boyd AE 3rd, Dunlap K. Class A calcium channel variants in pancreatic islets and their role in insulin secretion. J Biol Chem 1998; 273:13905-11.
- 59. Pereverzev A, Mikhna M, Vajna R et al. Disturbances in glucose-tolerance, insulin-release, and stress-induced hyperglycemia upon disruption of the Ca₂2.3 α_{1E} subunit of voltage-gated Ca²⁺ channels. Mol Endocrinol 2002; 16:884-95.

- 60. Weiergraber M, Pereverzev A, Vajna R et al. Immunodetection of α_{1E} voltage-gated Ca²⁺ channel in chromogranin-positive muscle cells of rat heart, and in distal tubules of human kidney. J Histochem Cytochem 2000; 48:807-19.
- 61. Lievano A, Santi CM, Serrano CJ et al. T-type Ca^{2*} channels and α_{1E} expression in spermatogenic cells, and their possible relevance to the sperm acrosome reaction. FEBS Lett 1996; 388:150-4.
- 62. Johnson BD, Hockerman GH, Scheuer T et al. Distinct effects of mutations in transmembrane segment IVS6 on block of L-type calcium channels by structurally similar phenylalkylamines. Mol Pharmacol 1996; 50:1388-1400.
- 63. Gasparini S, Kasyanov AM, Pietrobon D et al. Presynaptic R-type calcium channels contribute to fast excitatory synaptic transmission in the rat hippocampus. J Neurosci 2001; 21:8715-21.
- 64. Qian J, Noebels JL. Presynaptic Ca²⁺ channels and neurotransmitter release at the terminal of a mouse cortical neuron. J Neurosci 2001; 21:3721-8.
- 65. Westenbroek RE, Sakurai T, Elliott EM et al. Immunochemical identification and subcellular distribution of the α_{1A} subunits of brain calcium channels. J Neurosci 1995; 15:6403-6418.
- 66. Yokoyama CT, Westenbroek RE, Hell JW et al. Biochemical properties and subcellular distribution of the neuronal class E calcium channel α_1 subunit. J Neurosci 1995; 15:6419-32.
- 67. Newcomb R, Szoke B, Palma A et al. Selective peptide antagonist of the class E calcium channel from the venom of the tarantula Hysterocrates gigas. Biochemistry 1998; 37:15353-62.
- 68. Tottene A, Volsen S, Pietrobon D. α_{1E} subunits form the pore of three cerebellar R-type calcium channels with different pharmacological and permeation properties. J Neurosci 2000; 20:171-8.
- Doroshenko PA, Woppmann A, Miljanich G et al. Pharmacologically distinct presynaptic calcium channels in cerebellar excitatory and inhibitory synapses. Neuropharmacology 1997; 36:865-72.
- Potier B, Dutar P, Lamour Y. Different effects of omega-conotoxin GVIA at excitatory and inhibitory synapses in rat CA1 hippocampal neurons. Brain Res 1993; 616:236-41.
- Caddick SJ, Wang C, Fletcher CF et al. Excitatory but not inhibitory synaptic transmission is reduced in lethargic (Cacnb4(lh)) and tottering (Cacna1atg) mouse thalami. J Neurophysiol 1999; 81:2066-74.
- 72. Leenders AG, van den Maagdenberg AM, Lopes da Silva FH et al. Neurotransmitter release from tottering mice nerve terminals with reduced expression of mutated P- and Q-type Ca²⁺-channels. Eur J Neurosci 2002; 15:13-8.
- Burke SP, Adams ME, Taylor CP. Inhibition of endogenous glutamate release from hippocampal tissue by Ca²⁺ channel toxins. Eur J Pharmacol 1993; 238:383-6.
- 74. Stephens GJ, Morris NP, Fyffe RE et al. The Cav2.1/ α_{1A} (P/Q-type) voltage-dependent calcium channel mediates inhibitory neurotransmission onto mouse cerebellar Purkinje cells. Eur J Neurosci 2001; 13:1902-12.
- Poncer JC, McKinney RA, Gähwiller BH et al. Either N-or P-type calcium channels mediate GABA release at distinct hippocampal inhibitory synapses. Neuron 1997; 18:463-472.
- 76. Rosato Siri MD, Uchitel OD. Calcium channels coupled to neurotransmitter release at neonatal rat neuromuscular junctions. J Physiol 1999; 514(Pt 2):533-40.
- 77. Fletcher CF, Tottene A, Lennon VA et al. Dystonia and cerebellar atrophy in Cacna1a null mice lacking P/Q calcium channel activity. FASEB J 2001; 15:1288-90.
- 78. Piedras-Renteria ES, Tsien RW. Antisense oligonucleotides against alpha1E reduce R-type calcium currents in cerebellar granule cells. Proc Natl Acad Sci USA 1998; 95:7760-5.
- 79. Campbell DB, Hess EJ. L-type calcium channels contribute to the tottering mouse dystonic episodes. Mol Pharmacol 1999; 55:23-31.
- 80. Wheeler DB, Randall A, Tsien RW. Roles of N-type and Q-type Ca²⁺ channels in supporting hippocampal synaptic transmission [see comments]. Science 1994; 264:107-111.
- 80a. Urbano FJ, Piedras-Renteria ES, Jun K et al. Altered properties of quantal neurotransmitter release at endplates of mice lacking P/Q-type Ca²⁺ channels. Proc Natl Acad Sci USA 2003; 100:3491-3496.
- 80b. Piedras-Renteria ES, Pyle JL, Diehn M et al. Presynaptic homeostasis at CNS nerve terminals compensates for lack of a key Ca²⁺ entry pathway. Proc Natl Acad Sci USA 2004; 101:3609-3614.
- Sluka KA. Blockade of N- and P/Q-type calcium channels reduces the secondary heat hyperalgesia induced by acute inflammation. J Pharmacol Exp Ther 1998; 287:232-7.
- Jain KK. An evaluation of intrathecal ziconotide for the treatment of chronic pain. Expert Opin Investig Drugs 2000; 9:2403-10.
- Pietrobon D. Calcium channels and channelopathies of the central nervous system. Mol Neurobiol 2002; 25:31-50.
- Jouvenceau A, Eunson LH, Spauschus A et al. Human epilepsy associated with dysfunction of the brain P/Q-type calcium channel. Lancet 2001; 358:801-7.

- 85. Wappl E, Koschak A, Poteser M et al. Functional consequences of P/Q-type Ca²⁺ channel Ca_{*}2.1 missense mutations associated with episodic ataxia type 2 and progressive ataxia. J Biol Chem 2002; 277:6960-6.
- 85a. Maquat LE. Nonsense-mediated mRNA decay: splicing, translation and mRNP dynamics. Nat Rev Mol Cell Biol 2004; 5:89-99.
- 86. Hirning LD, Fox AP, McCleskey EW et al. Dominant role of N-type Ca²⁺ channels in evoked release of norepinephrine from sympathetic neurons. Science 1988; 239:57-60.
- Saegusa H, Kurihara T, Zong S et al. Suppression of inflammatory and neuropathic pain symptoms in mice lacking the N-type Ca²⁺ channel. EMBO J 2001; 20:2349-56.
- Hatakeyama S, Wakamori M, Ino M et al. Differential nociceptive responses in mice lacking the alpha(1B) subunit of N-type Ca²⁺ channels. Neuroreport 2001; 12:2423-7.
- 89. Kim C, Jun K, Lee T et al. Altered nociceptive response in mice deficient in the α_{1B} subunit of the voltage-dependent calcium channel. Mol Cell Neurosci 2001; 18:235-45.
- Atanassoff PG, Hartmannsgruber MW, Thrasher J et al. Ziconotide, a new N-type calcium channel blocker, administered intrathecally for acute postoperative pain. Reg Anesth Pain Med 2000; 25:274-8.
- Penn RD, Paice JA. Adverse effects associated with the intrathecal administration of ziconotide. Pain 2000; 85:291-6.
- McGuire D, Bowersox S, Fellmann JD et al. Sympatholysis after neuron-specific, N-type, voltage-sensitive calcium channel blockade: first demonstration of N-channel function in humans. J Cardiovasc Pharmacol 1997; 30:400-3.
- 92a. Beuckmann CT, Sinton CM, Miyamoto N et al. N-type calcium channel α_{1B} subunit (Ca₄2.2) knock-out mice display hyperactivity and vigilance state differences. J Neurosci 2003; 23:6793-6797.
- 93. Ino M, Yoshinaga T, Wakamori M et al. Functional disorders of the sympathetic nervous system in mice lacking the α_{1B} subunit (Cav 2.2) of N-type calcium channels. Proc Natl Acad Sci USA 2001; 98:5323-8.
- 94. Newcomb R, Abbruscato TJ, Singh T et al. Bioavailability of Ziconotide in brain: influx from blood, stability, and diffusion. Peptides 2000; 21:491-501.
- Matsuda Y, Saegusa H, Zong S et al. Mice lacking Ca_v2.3 α_{1E} calcium channel exhibit hyperglycemia. Biochem Biophys Res Commun 2001; 289:791-5.
- 96. Saegusa H, Kurihara T, Zong S et al. Altered pain responses in mice lacking α_{1E} subunit of the voltage- dependent Ca²⁺ channel. Proc Natl Acad Sci USA 2000; 97:6132-7.
- 97. Kubota M, Murakoshi T, Saegusa H et al. Intact LTP and fear memory but impaired spatial memory in mice lacking Ca,2.3 α_{1E} channel. Biochem Biophys Res Commun 2001; 282:242-8.
- 98. Wilson SM, Toth PT, Oh SB et al. The status of voltage-dependent calcium channels in α_{1E} knock-out mice. J Neurosci 2000; 20:8566-71.
- 99. Lee SC, Choi S, Lee T et al. Molecular basis of R-type calcium channels in central amygdala neurons of the mouse. Proc Natl Acad Sci USA 2002; 99:3276-81.
- 99a. Sochivko D, Pereverzev A, Smyth N et al. The Ca₂.3 Ca²⁺ channel subunit contributes to R-type Ca²⁺ currents in murine hippocampal and neocortical neurones. J Physiol 2002; 542:699-710.
- 100. Jahnsen H, Llinas R. Electrophysiological properties of guinea-pig thalamic neurones: an in vitro study. J Physiol 1984; 349:205-26.
- 101. Kim D, Song I, Keum S et al. Lack of the burst firing of thalamocortical relay neurons and resistance to absence seizures in mice lacking α_{IG} T-type Ca²⁺ channels. Neuron 2001; 31:35-45.
- 101a. Kim D, Park D, Choi S et al. Thalamic control of visceral nociception mediated by T-type Ca²⁺ channels. Science 2003; 302:117-119.
- 101b.Chen CC, Lamping KG, Nuno DW et al. Abnormal coronary function in mice deficient in α1H T-type Ca²⁺ channels. Science 2003; 302:1416-1418.
- 102. Huguenard JR. Heterogeneity of LVA calcium currents in thalamic neurons and their functional role in burst firing. In: Tsien RW, Clofel J-P, Nargeot J, eds. Low-voltage-activated T-type calcium channels. Adis International, 1998.
- 103. Perez-Reyes E. Three for T: Molecular analysis of the low voltage-activated calcium channel family. Cell Mol Life Sci 1999; 56:660-9.
- 104. Burgess DL, Biddlecome GH, McDonough SI et al. β-subunit reshuffling modifies N- and P/Q-type Ca²⁺ channel subunit compositions in lethargic mouse brain. Mol Cell Neurosci 1999; 13:293-311.
- 105. Safayhi H, Haase H, Kramer U et al. L-type calcium channels in insulin-secreting cells: Biochemical characterization and phosphorylation in RINm5F cells. Mol.Endocrinol. 1997; 11:619-629.
- 106. Scott VES, De Waard M, Liu H et al. β-subunit heterogeneity in N-type calcium channels. J.Biol.Chem. 1996; 271:3207-3212.
- 107. Liu H, De Waard M, Scott VES et al. Identification of three subunits of the high affinity omega-Conotoxin MVIIC-sensitive calcium channel. J Biol Chem 1996; 271:13804-13810.

- Pichler M, Cassidy TN, Reimer D et al. β-subunit heterogeneity in neuronal L-type calcium channels. J Biol Chem 1997; 272:13877-13882.
- 109. Gregg RG, Messing A, Strube C et al. Absence of the beta subunit (cchb1) of the skeletal muscle dihydropyridine receptor alters expression of the α1 subunit and eliminates excitation-contraction coupling. Proc Natl Acad Sci USA 1996; 93:13961-6.
- 110. Ball SL, Powers PA, Shin HS et al. Role of the β_2 subunit of voltage-dependent calcium channels in the retinal outer plexiform layer. Invest Ophthalmol Vis Sci 2002; 43:1595-603.
- 111. Murakami M, Yamamura H, Murakami A et al. Conserved smooth muscle contractility and blood pressure increase in response to high-salt diet in mice lacking the β_3 subunit of the voltage-dependent calcium channel. J Cardiovasc Pharmacol 2000; 36(Suppl 2):S69-73.
- 112. Namkung Y, Smith SM, Lee SB et al. Targeted disruption of the Ca²⁺ channel β₃ subunit reduces N- and L- type Ca²⁺ channel activity and alters the voltage-dependent activation of P/Q-type Ca²⁺ channels in neurons. Proc Natl Acad Sci USA 1998; 95:12010-5.
- 113. Murakami M, Fleischmann B, De Felipe C et al. Pain perception in mice lacking the β_3 subunit of voltage-activated calcium channels. J Biol Chem 2002; 277:40342-40351.
- 114. Cork RJ, Namkung Y, Shin HS et al. Development of the visual pathway is disrupted in mice with a targeted disruption of the calcium channel β₃-subunit gene. J Comp Neurol 2001; 440:177-91.
- 115. Lo FS, Mize RR. Properties of LTD and LTP of retinocollicular synaptic transmission in the developing rat superior colliculus. Eur J Neurosci 2002; 15:1421-32.
- 116. McEnery MW, Copeland TD, Vance CL. Altered expression and assembly of N-type calcium channel α_{1B} and β subunits in epileptic lethargic (lh/lh) mouse. J Biol Chem 1998; 273:21435-8.
- 117. Qian J, Noebels JL. Presynaptic Ca²⁺ influx at a mouse central synapse with Ca²⁺ channel subunit mutations. J Neurosci 2000; 20:163-70.
- 118. Wakamori M, Yamazaki K, Matsunodaira H et al. Single tottering mutations responsible for the neuropathic phenotype of the P-type calcium channel. J Biol Chem 1998; 273:34857-34867.
- 119. Escayg A, De Waard M, Lee DD et al. Coding and noncoding variation of the human calcium-channel β₄-subunit gene CACNB4 in patients with idiopathic generalized epilepsy and episodic ataxia. Am J Hum Genet 2000; 66:1531-9.
- 120. Ellis SB, Williams ME, Ways NR et al. Sequence and expression of mRNAs encoding the alpha1 and α_2 subunits of a DHP-sensitive calcium channel. Science 1988; 241:1661-1664.
- 121. Barclay J, Balaguero N, Mione M et al. Ducky mouse phenotype of epilepsy and ataxia is associated with mutations in the Cacna2d2 gene and decreased calcium channel current in cerebellar Purkinje cells. J Neurosci 2001; 21:6095-104.
- 122. Marais E, Klugbauer N, Hofmann F. Calcium channel $\alpha_2\delta$ subunits-structure and Gabapentin binding. Mol Pharmacol 2001; 59:1243-8.
- 123. Gong HC, Hang J, Kohler W et al. Tissue-specific expression and gabapentin-binding properties of calcium channel $\alpha_2\delta$ subunit subtypes. J Membr Biol 2001; 184:35-43.
- 124. Qin N, Yagel S, Momplaisir ML et al. Molecular cloning and characterization of the human voltage-gated calcium channel $\alpha_2 \delta_4$ subunit. Mol Pharmacol 2002; 62:485-96.
- 125. Martin DJ, McClelland D, Herd MB et al. Gabapentin-mediated inhibition of voltage-activated Ca²⁺ channel currents in cultured sensory neurones is dependent on culture conditions and channel subunit expression. Neuropharmacology 2002; 42:353-66.
- 126. Schumacher TB, Beck H, Steinhauser C et al. Effects of phenytoin, carbamazepine, and gabapentin on calcium channels in hippocampal granule cells from patients with temporal lobe epilepsy. Epilepsia 1998; 39:355-63.
- 127. Field MJ, Hughes J, Singh L. Further evidence for the role of the $\alpha_2\delta$ subunit of voltage dependent calcium channels in models of neuropathic pain. Br J Pharmacol 2000; 131:282-6.
- 128. Brodbeck J, Davies A, Courtney JM et al. The ducky mutation in Cacna2d2 results in altered Purkinje cell morphology and is associated with the expression of a truncated $\alpha_2\delta_2$ protein with abnormal function. J Biol Chem 2002; 277:7684-93.
- 129. Burgess DL, Gefrides LA, Foreman PJ. A cluster of three novel Ca²⁺ channel gamma subunit genes on chromosome 19q13.4: evolution and expression profile of the gamma subunit gene family. Genomics 2001; 71:339-50.
- 130. Moss FJ, Viard P, Davies A et al. The novel product of a five-exon stargazin-related gene abolishes Ca₂2.2 calcium channel expression. EMBO J 2002; 21:1514-23.
- 131. Freise D, Held B, Wissenbach U et al. Absence of the γ subunit of the skeletal muscle dihydropyridine receptor increases L-type Ca²⁺ currents and alters channel inactivation properties. J Biol Chem 2000; 275:14476-81.
- 132. Held B, Freise D, Freichel M et al. Skeletal muscle L-type Ca²⁺ current modulation in γ_1 -deficient and wildtype murine myotubes by the γ_1 subunit and cAMP. J Physiol 2002; 539:459-68.

- 133. Ursu D, Sebille S, Dietze B et al. Excitation-contraction coupling in skeletal muscle of a mouse lacking the dihydropyridine receptor subunit γ_1 . J Physiol 2001; 533:367-77.
- 134. Letts VA, Felix R, Biddlecome GH et al. The mouse stargazer gene encodes a neuronal Ca²⁺-channel γ subunit. Nat Genet 1998; 19:340-347.
- 135. Kang MG, Chen CC, Felix R et al. Biochemical and biophysical evidence for γ_2 subunit association with neuronal voltage-activated Ca²⁺ channels. J Biol Chem 2001; 276:32917-24.
- 136. Klugbauer N, Dai S, Specht V et al. A family of γ-like calcium channel subunits. FEBS Lett 2000; 470:189-97.
- 137. Chen L, Chetkovich DM, Petralia RS et al. Stargazing regulates synaptic targeting of AMPA receptors by two distinct mechanisms. Nature 2000; 408:936-43.
- 138. Ophoff RA, Terwindt GM, Vergouwe MN et al. Familial hemiplegic migraine and episodic ataxia type-2 are caused by mutations in the calcium channels gene CACNL1A4. Cell 1996; 87:543-552.
- 139. Kraus RL, Sinnegger MJ, Glossmann H et al. Familial hemiplegic migraine mutations change α_{1A} calcium channel kinetics. J Biol Chem 1998; 273:5586-5590.
- 140. Sakata Y, Saegusa H, Zong S et al. Ca_v2.3 α_{1E} Ca²⁺ channel participates in the control of sperm function. FEBS Lett 2002; 516:229-33.
- 141. Matsuda Y, Saegusa H, Zong S et al. Mice lacking Ca(v)2.3 α_{1E} calcium channel exhibit hyperglycemia. Biochem Biophys Res Commun 2001; 289:791-5.
- 142. Van Den Maagdenberg AM, Pietrobon D, Pizzorusso T et al. A cacnala knockin migraine mouse model with increased susceptibility to cortical spreading depression. Neuron 2004; 41:701-710.

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