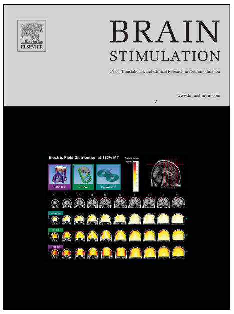

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PII: S1935-861X(22)00083-3

DOI: https://doi.org/10.1016/j.brs.2022.05.004

Reference: BRS 2181

To appear in: *Brain Stimulation*

Received Date: 11 October 2021

Revised Date: 27 April 2022

Accepted Date: 3 May 2022

Please cite this article as: Weinreb E, Moses E, Mechanistic insights into ultrasonic neurostimulation of disconnected neurons using single short pulses, *Brain Stimulation* (2022), doi: https://doi.org/10.1016/j.brs.2022.05.004.

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Elisha Moses - Administration, Supervision, Funding, Resources

Mechanistic insights into ultrasonic neurostimulation of disconnected neurons using single short pulses

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Part of this work was previously presented at the 3rd International Brain Stimulation Conference.

Abstract

Ultrasonic neurostimulation is a potentially potent noninvasive therapy, whose mechanism has yet to be elucidated. We designed a system capable of applying ultrasound with minimal reflections to neuronal cultures. Synaptic transmission was pharmacologically controlled, eliminating network effects, enabling examination of single-cell processes. Short single pulses of low-intensity ultrasound were applied, and time-locked responses were examined using calcium imaging.

Low-pressure (0.35MPa) ultrasound directly stimulated ~20% of pharmacologically disconnected neurons, regardless of membrane poration. Stimulation was resistant to the blockade of several purinergic receptor and mechanosensitive ion channel types. Stimulation was blocked, however, by suppression of action potentials. Surprisingly, even extremely short (4μs) pulses were effective, stimulating ~8% of the neurons. Lower-pressure pulses (0.35MPa) were less effective than higher-pressure ones (0.65MPa). Attrition effects dominated, with no indication of compromised viability.

Our results detract from theories implicating cavitation, heating, non-transient membrane pores >1.5nm, pre-synaptic release, or gradual effects. They implicate a post-synaptic mechanism upstream of the action potential, and narrow down the list of possible targets involved.

Keywords

ultrasonic neuromodulation (UNMOD), focused ultrasound neuromodulation (FUN), transcranial ultrasound stimulation (TUS), transcranial focused ultrasound (tFUS), transcranial pulsed ultrasound (tPUS), low-intensity focused ultrasound (LIFUS).

Abbreviations

AP	Action Potential
APV	2-Amino 5-Phosphonopentanoic Acid
CNQX	Cyanquixaline
CNS	Central Nervous System
FOV	Field of View
GABA	Gamma-Aminobutyric Acid
IACUC	Institutional Animal Care and Use Committee
IC_{50}	Half Maximal Inhibitory Concentration
IQR	Interquartile Range
MS	Mechanosensitive
NBLS	Neuronal Bilayer Sonophore
NMDA	N-Methyl-D-Aspartic Acid
Na_V	Voltage Gated Sodium
PCD	Passive Cavitation Detection
PI	Propidium Iodide
ROI	Region of Interest
RR	Ruthenium Red
SEM	Standard Error of the Mean
TLC	Thermochromic Liquid Crystal
TTX	Tetrodotoxin
UB	Unstimulated Baseline Activity
US	Ultrasound

Introduction

A major issue hindering the advancement of US neurostimulation is the lack of a concrete understanding of the underlying mechanism through which acoustic pressure stimulates neuronal activity. Several possible mechanisms have been proposed, but as yet, none are widely accepted in the field. Mechanisms discussed[1–4] include sonoporation[5], membrane distortion[6] and temperature increases[7–16], as well as synaptic vesicle fusion[17,18] and direct effects on ion channels[5,19–24].

Several experimental issues can confound mechanistic study of US neurostimulation. First, acoustic reflections can distort the spatial and temporal characteristics of the applied US pressure[25–28]. While these reflections can be modeled and accounted for using computational methods that will be critical for the translational applications of US[26,29–33], these reflections make quantitative studies more complex, and demand higher accuracy in the experimental system. Second, when stimulating highly connected neuronal networks, recurrent activity can obscure single-cell level mechanisms, and observed responses may reflect downstream effects of processes occurring outside the examined area. Third, US pulse trains can contain confounding envelope frequencies that emerge from the initiation and termination of individual pulses[34].

We present an experimental system that addresses these issues, enabling the examination of processes governing US stimulation at the single-neuron level. We applied single US pulses to neuronal cultures with minimal acoustic reflections. Synaptic transmission was pharmacologically blocked, eliminating network effects. Optical methods were used to measure neuronal activity and integrity under the application of US, while pharmacological interventions disrupted specific cellular processes, allowing the examination of each process’ role in the mechanism of US neurostimulation.

We used this system to examine and rule out many of the proposed mechanisms, as well as eliminate the candidacy of several ion channels and receptors as the main players in US stimulation. We report a surprising observation of effective stimulation using single extremely short pulses. We also observed significant attrition effects, who’s source has yet to be identified.

Methods

Neuronal cultures

This study was approved by the Weizmann IACUC.

We used dissociated rat hippocampal neural cultures grown on circular glass coverslips[35,36]. These cultures develop into flat, interconnected networks containing 70%-80% excitatory and 30%-20% inhibitory neurons[37]. Neuronal activity was monitored via calcium imaging. This allowed measurement of hundreds of neurons simultaneously while affording easy pharmacological intervention.

Neuronal connectivity was disconnected using a cocktail of synaptic transmission blockers consisting of bicuculline ($GABA_A$ inhibitory receptor antagonist) with CNQX and APV (non-NMDA and NMDA excitatory glutamate receptor antagonists respectively).

In the disconnected cultures, we used TTX to block Na_V channels, eliminating neuronal APs; PI to image membrane poration; RR and GsMTx-4 to block MS ion channels; and suramin to block P2 purinergic receptors.

These methods are detailed in the supplementary.

Experimental system

The system consisted of a US transducer in a water chamber mounted onto an inverted fluorescence microscope. Cultures were positioned at the convergence of the acoustic and optic focus, enabling imaging of the cultures while simultaneously exposing them to US (Figure 1A).

US reflections were minimized by optimizing acoustic impedance matching, having minimal obstructions in the acoustic path, and absorbing the residual acoustic energy.

A 2D large-scale simulation of the basic chamber architecture (Figure 1B) shows that the interaction of US with the air chamber that houses the objective doesn’t disrupt the homogeneity or location of the US focus. A 3D high-resolution simulation near the culture glass (Figure 1C) shows that the US pressure is mostly constant over the entire FOV, and reflections from the thin coverslip glass are minimal.

The low level of reflections in the system was verified using a hydrophone in the experimental chamber (see supplementary text and Figure S4). The location and size of the US focus were examined using a TLC sheet (Supplementary Figure S5).

We used single pulses, a fundamental frequency of 500kHz, peak pressures of 0.35-1.32MPa, and durations of 4μs-40ms. The parameters for each experiment are detailed in the supplementary.

The pressure output of the transducer, as well as the duration of the extremely short pulses were verified using a hydrophone in a large water tank.

The design, simulation, and verifications of the system are detailed in the supplementary.

Experimental procedure

Cultures were placed into the experimental chamber, and their spontaneous activity was first imaged to verify vitality and identify active cells. Pharmacological agents were then introduced and allowed 10 minutes to take effect.

For each stimulation, cultures were exposed to a single US pulse, and time-locked images were acquired for 5 seconds before and 10 seconds after.

Calcium imaging was done using Fluo-4. Such chemical calcium indicators can compromise the culture's vitality over time, so cultures were imaged for a few hours and then disposed of. Alternatively, where stated, the genetically encoded indicator GCaMP was used, and measurements were conducted over a longer period, and over multiple experimental sessions.

The experimental procedure is detailed in the supplementary.

Analysis

In experiments involving intact networks, the mean fluorescent intensity for the entire FOV was taken.

In experiments involving disconnected networks, ROIs were automatically defined over active cell bodies. Automated response detection was then performed for each ROI by examining changes in its intensity following the stimulation. The unstimulated baseline activity was characterized by examining changes in the intensity *before* the stimulation. Comparison of the evoked activity to this unstimulated baseline aided in the differentiation of the evoked activity from any spontaneous activity that remained after network disconnection and from noise-related false detections.

These methods are detailed in the supplementary, along with the calculation of a response's amplitude, duration, and latency. Statistical tests and figure methods are also detailed in the supplementary.

Spontaneous network activity was evaluated before disconnection and the number of neurons that participated in a burst were counted. The number of these "generally active" neurons was used to normalize the number of neurons that respond after disconnection. There were typically ~200 generally active cells within the FOV (191.4±10.2, mean±SEM, n^c=78).

Throughout this paper n^c refers to the number of cultures included in the analyses, n^s to the number of stimulations, and n^n to the number of cells.

Results and discussion

Single US pulses stimulated fully connected neuronal cultures

US reproducibly generated robust group calcium responses immediately following stimulation. Figure 2A shows example stimulations of a fully connected culture.

These cultures naturally display spontaneous bursts of all-or-none synchronous activity, stemming from their extensive connectivity[38]. The evoked responses were consistent in amplitude and shape over time and similar to spontaneous bursts. Spontaneous activity continued even after multiple stimulations, and stimulations given during a previously occurring spontaneous burst didn't initiate additional bursts, as is demonstrated by the fifth burst in the example in Figure 2A. This all hints at a non-destructive stimulation mechanism involving physiological neuronal activation processes.

The pressure levels (0.67MPa) at the frequency used are too low to cause cavitation[39] or significant thermal effects, detracting from these mechanisms, which is encouraging for safe use in humans. To further rule out the possibility of cavitation, we present Supplementary Figure S7, in which passive cavitation detection (PCD)[40] indicates that cavitation is not a factor at the pressures and durations of the pulses we use.

This is in line with several other studies that have reported successful stimulation of in-vitro CNS neurons[14,17,20,23,41–50].

Single US pulses stimulated pharmacologically disconnected neurons

We disconnected the neurons by pharmacologically blocking synaptic transmission, enabling examination of mechanisms at the single-cell level without population effects, and separating postsynaptic processes from those upstream. When disconnected, spontaneous activity shifts from all-or-none bursts to sporadic, uncorrelated single-neuron events[51].

Single US pulses successfully generated calcium responses in disconnected cultures. As shown in Figure 2B (blue), ~20% of the generally active cells were stimulated by US after disconnection.

This shows that US can generate supra-threshold neuronal excitation without requiring network amplification. Stimulation of neurons with blocked synaptic inputs indicates that US has a direct effect downstream of the synaptic transmission, and is not just causing pre-synaptic neurotransmitter release.

This is in line with Tyler et al. (2008)[17], who showed that US stimulation, measured as vesicle exocytosis, was resistant to blockade of excitatory input. They also showed that disruption of the neuronal machinery for vesicle release eliminated this effect, indicating that US didn’t directly cause vesicle membrane fusion.

Recent in-vitro studies paint a more complex picture of the necessity of a pre-synaptic mechanism. Some showed, in line with our observations, that blockade of excitatory connectivity didn’t completely eliminate US stimulation, while others reported that it did[20,50,52]. Interestingly, those experiments that agreed with ours both used calcium imaging, as we did, while those that disagreed both used multielectrode arrays.

One hypothesis as to why only a subset of neurons are responsive to stimulation is that the neurons differ in their excitation thresholds. This could be similar to what we have previously reported with electrical stimulation[53], where the orientation of the neuronal processes with regard to the vector of the applied electric field affects the neuron’s sensitivity. Another possibility is the differential expression of certain MS channels in distinct neuronal cell types[54]. Neuronal cell types also differ in their morphology which can affect the overall mechanical properties of their membrane[55].

External activation of bursts in connected cultures requires the initial stimulation of only a small fraction of neurons (3-5%)[51], so these 20% are more than enough to generate the stimulation we observed in connected networks. Nevertheless, it is still possible that additional neurons were directly activated in the connected culture and that some part of that response *was* eliminated by blocking the synapses.

Figure 2D,E shows the evoked response after disconnection (blue) and the spontaneous burst prior to disconnection (magenta), in the same responsive cells. Although the overall response dynamics were similar, the evoked response had a lower amplitude (0.19±0.02 vs. 0.61±0.06 $\Delta F/F$) and a shorter duration

(1.01±0.05 vs. 1.91±0.08 s) (mean±SEM, $p<0.001$, $n^n=179$). 28±7.8% of the US responsive cells were not considered responsive during the spontaneous burst. The shorter duration and lower amplitude make sense, as the neurons in the disconnected network are expected to have fewer APs than in the connected network, due to lack of feedback excitation loops.

To get a sense of scale for the response amplitude, electrical stimulation of a disconnected culture generated an amplitude of 0.04±0.002ΔF/F (mean±SEM, $n^n=131$), although this is reported to strongly depend on the stimulation and imaging parameters[53].

The observed spatial distribution was not significantly different between the responsive cells after network disconnection and the generally active cells prior to disconnection. This was measured by the mean distance of the cells (within the 0.9mm^2 FOV) from their centroid: (312±26µm for responsive cells vs. 337±11µm for generally active cells, mean±SEM, $p=0.20$, $n^{s,c}=9$). This confirms that the focal area of effective stimulation covered the entire FOV.

AP blockade abolished the response to US

We used TTX to block Na_V channels, eliminating neuronal APs, separating postsynaptic processes from those downstream.

Figure 2B (orange) shows the efficacy of US, after network disconnection and additional AP blockade. AP disruption eliminated the response to US. This indicates that the mechanism being affected by US is upstream of the AP or is the AP process itself. It’s not a lasting poration of the plasma membrane, nor is it a large calcium influx or intracellular calcium release directly generated by US, as these processes would not depend on functioning APs.

This is in line with Tyler et al. (2008)[17], showing AP disruption eliminates the response to US in hippocampal slices. This was also shown in connected networks[41,43,50].

US stimulation was not associated with membrane poration

A membrane integrity assay using PI showed that only a small percentage (4.6±1%, mean±SEM, $n^{s,c}=5$) of successfully stimulated disconnected cells became permeable during stimulation. An example is shown in Figure 3.

This confirms that long-term poration is not part of the stimulation process. Pores that are very transient, or smaller than the 1.5nm detection level of PI[56], may still be relevant[57].

Extremely short US pulses stimulated disconnected neurons

Several proposed mechanisms of US neurostimulation rely at low intensities on a gradual accumulation of effects. To exclude such mechanisms, we used extremely short pulses of only a 2-cycle duration, corresponding to 4μs at 500kHz, 10,000 times shorter than the 40ms pulses common in the literature.

Figure 4A shows the efficacy of 40ms and 4μs duration pulses, after network disconnection. A clear response even to the extremely short pulses is evident.

This is a surprising result. It points at molecular scale processes, which could occur at these time scales. It precludes mechanisms such as stable cavitation, which can generate strong forces through energy accumulation[58], but would necessitate longer pulses. We calculate heating with our pulse parameters at $\sim 5\times 10^{-5}$ ºC/ms which would also require longer pulses to matter.

This is encouraging from a translational standpoint, as extremely short pulses are much safer than longer ones[59], with intensities far below many regulatory limits[60]. They also allow more intricate spatiotemporal patterning and are less prone to form standing waves. While previous studies have used shorter pulses as part of long pulse trains, the shortest single pulses shown to stimulate unmodified neurons were 100μs long[46], an order of magnitude longer than ours. This remarkable result warrants extensive further investigation.

Standard duration pulses activated more cells than the extremely short ones. This is in line with a recent in-vitro study showing lower stimulation thresholds for longer pulses[25].

Longer pulses may simply recruit additional cells as the pulse goes on. To test this, we imaged the initial response dynamics at a high sampling rate (~1kHz). At this rate technical camera limitations constrain imaging to the averaged response over the entire FOV, including many cells. Figure 4C,D shows an observable difference in the initial dynamics of the responses, with a longer latency in response to the longer pulse than to the shorter one (27.5±3.1ms, n^s=6 vs. 16.8±1.5ms, n^s=7; n^c=4; mean±SEM; $p<0.05$), indicating that the longer pulse doesn't simply accumulate responsive cells, rather that the two durations have different effects. There may be an ongoing interaction of the pulse with the neuronal physiology, disrupting the initiation of the response. Alternatively, different pulse durations may be exciting different types of neurons with distinct inherent dynamics.

The NBLS model[6] suggests that during the pulse there is an accumulation of charge, due to changes in the membrane's capacitance, which gradually depolarizes the neuron with each cycle. This mechanism is therefore strongly dependent on pulse duration. We implemented the model using Matlab, and it projected generation of APs only for pulses longer than 5ms (for a pressure peak of 0.5MPa). Thus, it is at odds with our observation. Figure 4F shows the model's projected membrane potential during stimulation both with an extremely short pulse and with a standard duration one.

P2 receptor blockade did not eliminate the response to US, efficacy increased with pressure

P2 purinergic receptors play a crucial role in MS processes[61], and may be relevant for US stimulation. Figure 5A shows the efficacy of pulses at peak pressures of 0.35MPa and of 0.67MPa, after disconnection and additional blockade of P2 receptors using suramin.

Blocking P2 receptors did not prevent stimulation. Thus, purinergic signaling is not a necessary part of the mechanism. It should be noted that suramin (in reference to $P2Y_2$ receptors) was used at a moderate concentration of twice the IC_{50}. Suramin is neurotoxic above this concentration[62].

The higher pressure activated more cells than the lower pressure. It also generated a higher response amplitude (0.55±0.05ΔF/F, n^n=532 vs. 0.32±0.04ΔF/F, n^n=88; mean±SEM; $p<0.001$). The response is shown in Figure 5B. A possible cause for the increased amplitude is that longer bursts of multiple APs are generated in the responsive neurons, but this has not been verified. These results align with previous in-vitro[25,43,45,48] and in-vivo studies[20,63–65] showing stimulation efficacy increases with pressure.

MS ion channel blockade did not affect the efficacy of US

Several MS ion channel types have been implicated in the literature, notably TRPA, TRPC, TRPV, K2P, and Piezo channels[20–24,66,67].

Of these, RR blocks the TRPA, TRPV, TREK-2, and Piezo channels[68–70]. Figure 5C shows the efficacy after network disconnection, with and without additional MS channel blockade using RR. RR didn’t significantly affect the efficacy of US. This considerably narrows down the list of candidate channels.

This result conflicts with a recent study reporting that TRPA1 disruption *did* eliminate the response in hippocampal neurons[20]. However, as the authors suggest, they probably actually blocked the response in astrocytes, and measured the downstream effect on the neurons. This is an example of the complexity in interpreting observations from connected networks.

GsMTx-4, a blocker of Piezo1 and TRPC(1,5,6) channels[71–73], was applied to a single culture (Figure 5E). As with RR, GsMTx-4 didn’t significantly reduce the efficacy of US.

This conflicts with a recent study showing GsMTx-4 *did* eliminate the response in cortical cultures[23]. One possible cause of this discrepancy may be that certain MS channels, that are not blocked by GsMTx-4, and are much more highly expressed in the hippocampus than in the cortex (such as TRPM3[74]), may be able to support a response in the hippocampal cultures, even when the other GsMTx-4 sensitive channels are blocked, but are not able to support a response in the cortex, due to their low level of expression there. Additionally, we used GsMTx-4 at a moderate concentration of twice the IC_{50} (in reference to TRPC channels), while they used a much higher concentration (1µM vs 40µM), which may have increased blocking efficacy or may block a broader array of channels.

The response is shown in Figure 5D,F. The responses from cultures with RR had a higher amplitude (0.5±0.06ΔF/F, n^n=146 vs. 0.2±0.02ΔF/F, n^n=188; $p<0.001$) and a longer duration (1.12±0.08 vs. 0.85±0.04 s, $p<0.01$) than from cultures without RR (mean±SEM). The responses from the culture with GsMTx-4 also had a higher amplitude (0.42±0.05ΔF/F, n^n=278 vs. 0.23±0.01ΔF/F, n^n=220; $p<0.001$), and a longer duration (1.1±0.05 vs. 0.76±0.03 s, $p<0.001$) than the responses from the culture without GsMTx-4 (mean±SEM). A possible cause for this is the inhibitory effect these compounds can have on large-conductance calcium-activated potassium channels[75,76], which contribute to post-AP repolarization[77].

These results do not rule out the possible relevance of other MS channels or receptors. On the contrary, we believe this remains the most probable mechanism generating the effects we observe.

Attrition effects were dominant and occurred at the single-cell level

In disconnected cultures, after an initial successful stimulation at a given pressure, the following stimulations were not effective until the pressure was increased, at which point another successful stimulation would occur. This could be repeated for several stimulations (example in Supplementary Figure S8). In order to avoid these attrition related confounds, in most of the experiments described only the first stimulation was used.

Figure 6A compares the first stimulation and the following three at the same pressure (with a 25-minute recovery period between stimulations). While the first stimulation was effective, the following three were much less effective. These three following stimulations didn’t differ in their efficacy (Supplementary Figure S9).

To check if an even longer recovery time made repeated stimulations more effective, we increased the time between consecutive stimulations to 3 days. In order to do this, we used GCaMP, a genetically encoded calcium indicator that doesn’t significantly reduce the viability of the cultures, and thus the cultures can be imaged over an extended period. Connected cultures were stimulated several times, and then returned to the incubator. After three days, the cultures were first checked for spontaneous activity to ensure their viability, then pharmacologically disconnected, and stimulated again. Figure 6C shows the response (after the 3-day recovery period) in these previously stimulated cultures, and for reference the response in fresh disconnected cultures that were not previously stimulated. We can see that even after this 3-day recovery period, attrition effects remained, and there was no observable response in the previously stimulated cultures.

Increases in pressure did generate additional successful stimulations, with no need for an extended recovery time. We examined if this resulted from new cells being recruited at higher intensities, or if the same cells that were responsive to the first stimulation but didn't respond to additional stimulations at the same pressure, became responsive again at higher pressures.

Indeed, most of the cells that were responsive to a first, lower-pressure (0.35MPa) stimulation, were also responsive to a following, higher-pressure (0.67MPa) stimulation (78.8±4.6%, mean±SEM, $n^{s,c}$=8). However, most of the cells that were responsive to a following higher pressure stimulation were new cells that didn't previously respond to a lower pressure stimulation (74.3±6.7%, mean±SEM, $n^{s,c}$=8). Figure 6D shows an example. This indicates that the attrition effects occur, at least partially, at the single-cell level.

Figure 6E compares the response to the lower-pressure stimulation in cells that responded only to the lower-pressure stimulation, and in cells that also responded to a later higher-pressure stimulation. There was no difference, and thus no indication of different processes taking place during the first stimulation.

These observations align with several studies showing that repeated or continued US stimulation coincides with a degradation in the response[44,78–80]. They may also be related to reports of US having long-term effects in-vivo, at timescales ranging from minutes[16,80–84] to weeks[85,86]. The mechanism responsible for attrition is unclear. One possibility is that MS channels undergo inactivation after being affected by US, and that other MS channels with higher stimulation thresholds are activated by the following higher-pressure pulse. MS channels may also undergo adaptation, requiring higher pressures to reactivate[87]. Another possibility is that the adherence of the cells to the glass is partially disrupted, reducing associated US shear forces, requiring an increase in US pressure for subsequent stimulation.

The ability of cells to respond multiple times to stimulation indicates that their viability is not dramatically disrupted by stimulation. This is also supported by the calcium levels in the responsive cells returning to baseline fairly quickly after stimulation.

Experimental limitations

One potential issue is our use of a glass substrate. Its rigidity may affect the mechanical sensitivities of the neurons grown on it[88]. Neurons in flat cultures also grow and connect differently than neurons in the complex 3D environment of the brain. Additionally, the glass-neuron interface may subject neurons to unphysiological shear forces under US[89].

A second potential issue is that our experiments were conducted at room temperature, which may alter the dynamics of cellular processes in comparison to physiological temperatures[90,91]. Additionally, our calcium concentration was modified from that of other in-vitro studies, to better represent the concentration in-vivo[92]. This may complicate comparing results, as calcium concentrations can substantially affect excitability in these cultures[93].

Third, mechanisms which we found to be negligible in our experimental conditions, may still be relevant at different stimulation parameters, or when targeting different neuronal populations. Additionally, our pharmacologically disconnected cultured neurons are not fully representative of neurons in vivo, and thus our conclusions may not completely translate to that domain.

A very recent publication by Yoo et al. (2022)[94] examined US stimulation of cortical neurons cultured on a flexible substrate. Their results complement and support our conclusions that poration, heating, and NBLS effects are not involved. Furthermore, their results using pharmacological interventions with RR and suramin align with ours, despite methodological differences. Their study provides substantial evidence implicating MS channels in the mechanism.

Conclusion

In conclusion, our results detract from mechanistic theories that implicate cavitation, heating, non-transient membrane pores >1.5nm, pre-synaptic release, or gradual effects. They implicate a post-synaptic mechanism upstream of the AP process and narrow down the list of relevant receptors and ion channels.

We hope this work will advance US neurostimulation and help realize its potential as an effective tool for research and the treatment of human distress.

Acknowledgments

We would like to thank Victor Steinberg and Daniella Goldfarb for advice and equipment, Menachem Segal for fruitful discussions, Rony Paz for guidance, Dominik Freche for assistance with model implementation, and Inbar Zohar for assistance with experiments.

Funding

This work was supported by the Israel Science Foundation [grant #2767/20] and the Minerva Stiftung.

Funding sources had no involvement in the study itself.

Data availability

Data will be made available upon reasonable request.

Declarations of interest

Declarations of interest: none.

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Figure captions

Fig. 1. Experimental chamber

A: The US transducer was mounted in a water chamber on an inverted microscope. The culture was positioned at both the acoustic and optic focus within an inner chamber filled with imaging medium. US passed from the transducer, through a mylar sheet into the inner chamber, through the culture, through a second mylar sheet back out into the water chamber, and into an acoustic absorber. US was applied to the culture from the side, at a 90° angle to the optic axis, keeping the objective out of the acoustic path, preventing reflections.

Axis cross scale: 10mm.

B: 2D large-scale simulation of the basic chamber architecture. Culture glass is shown as a guide, and is not part of the 2D large-scale simulation. Spatial resolution of simulation grid: 500μm. Scale bar: 10mm.

C: 3D high-resolution simulation of the acoustic pressure being applied to the culture glass. Image slices of the 3D volume are located at the center of the culture glass. Spatial resolution of simulation grid: 50μm.

Fig. 2. Stimulation of connected and disconnected cultures

A: Example stimulation of a connected culture. Mean calcium traces from the entire FOV. Shown is an unstimulated spontaneous burst, three successful stimulations, and an unsuccessful stimulation applied during a previous spontaneous burst.

B: Percentage of generally active cells responsive to stimulation in disconnected cultures. ~20% (19.4±4.4%, UB=1.3±0.4%, $n^{s,c}$=9, blue) of the cells responded to US. With additional TTX the efficacy was much smaller and similar to the unstimulated baseline activity (3±0.3%, UB=2.5±0.4%, $n^{s,c}$=13, orange). (mean±SEM, UB - unstimulated baseline activity)

C: Median calcium traces from the responsive cells, corresponding to **B**. n^{n}(blue)=179, n^{n}(orange)=65.

D: Median calcium traces of an evoked response after disconnection (blue) and of a spontaneous burst prior to disconnection (magenta), in the same responsive cells. n^{n}=179.

E: Same as **D**, each trace normalized by its peak intensity (before averaging).

In this, and in all following figures unless indicated otherwise - Boxplot lines mark the median, boxes extend 25th-75th percentiles, whiskers extend to the most extreme data that are within 1.5 × IQR from the box. In traces, 25th-75th percentiles are shown shaded, vertical grey line marks the time of stimulation. $*p<0.05$; $**p<0.01$; $***p<0.001$; $p>0.05$, not significant (n.s.).

Fig. 3. Example of membrane integrity assay using PI

A single stimulation in a disconnected culture. 68 of the generally active cells responded (blue), only 2 of them had become permeable during stimulation (red).

Left: Calcium imaging baseline before stimulation.

Right: PI fluorescence imaging. Intensity increase from before stimulation to 10min after.

Scale bar: 100um.

Fig. 4. Stimulation with extremely short pulses

A: Percentage of generally active cells responsive to short 4µs (8.3±3.3%, UB=2.2±0.3%, $n^{s,c}$=14, red), and to standard 40ms (19.4±4.4%, UB=1.3±0.4%, $n^{s,c}$=9, blue) pulses, in disconnected cultures (mean±SEM). Removal of the outlier in the short pulse group did not change this outcome. UB - unstimulated baseline activity.

B: Median calcium traces from responsive cells, corresponding to **A**. n^n(red)=164, n^n(blue)=179.

C: Mean, full FOV, calcium traces of the initial response dynamics, in responsive disconnected cultures, at a high sampling rate. SEM shown shaded. Blue bar along the x-axis shows the standard pulse duration, the bar for the short pulse is too short to be visible. n^s(red)=7, n^s(blue)=6.

D: Same as **C**, each trace normalized by its peak intensity (before averaging).

E: Hydrophone measurement of the 4µs pulse. The hydrophone was positioned ~1mm above the center of the face of the culture glass within the experimental chamber.

F: Simulation of the response in the NBLS model. Membrane voltage calculated with a standard 40ms pulse (left, blue bar) and a short 10µs pulse (right, red bar) using a peak pressure of 0.5MPa. Multiple APs occur with the standard duration pulse, but none with the short one.

Fig. 5. Pharmacological blockade of MS ion channels and receptors

A, C, E: Percentage of generally active cells responsive to stimulation. UB - unstimulated baseline activity.

B, D, F: Median calcium traces from responsive cells, corresponding to **A,C,E**.

A: Suramin did not block the response in disconnected cultures. The higher pressure of 0.67MPa was more effective (36.4±6.1%, UB=1.7±0.5%, $n^{s,c}$=7, red) than 0.35MPa (11.5±6.6%, UB=2.7±1.2%, $n^{s,c}$=4, green) (mean±SEM).

B: n^{n}(green)=88, n^{n}(red)=532.

C: The efficacy in disconnected cultures with additional RR (12.3±4.6%, UB=2.6±0.3%, $n^{s,c}$=7, magenta), was similar to without RR (9.5±2.5%, UB=3.9±0.9%, $n^{s,c}$=9, blue) (mean±SEM, p=0.31). Removal of the outlier in the RR group did not change this outcome.

D: n^{n}(magenta)=146, n^{n}(blue)=188.

E: The efficacy in a single disconnected culture with additional GsMTx-4 (10.1±2.9%, UB=2.1±0.3%, n^{s}=5, orange), was similar to without GsMTx-4 (11.4±6.1%, UB=2.7±0.4%, n^{s}=5, blue) (mean±SEM, p=0.43).

F: n^{n}(orange)=278, n^{n}(blue)=220.

Fig. 6. Response attrition

A: Percentage of generally active cells responsive to stimulations at a constant pressure with a 25-minute recovery time between pulses, in disconnected cultures. After an initial successful stimulation at the given pressure (9.5±2.5%, UB=3.9±0.9%, $n^{s,c}$=9, blue), the following 3 stimulations at the same pressure had a low efficacy, close to their unstimulated baseline activity (3.4±0.5%, UB=2.3±0.3%, n^{s}=27, gray) (mean±SEM). UB - unstimulated baseline activity.

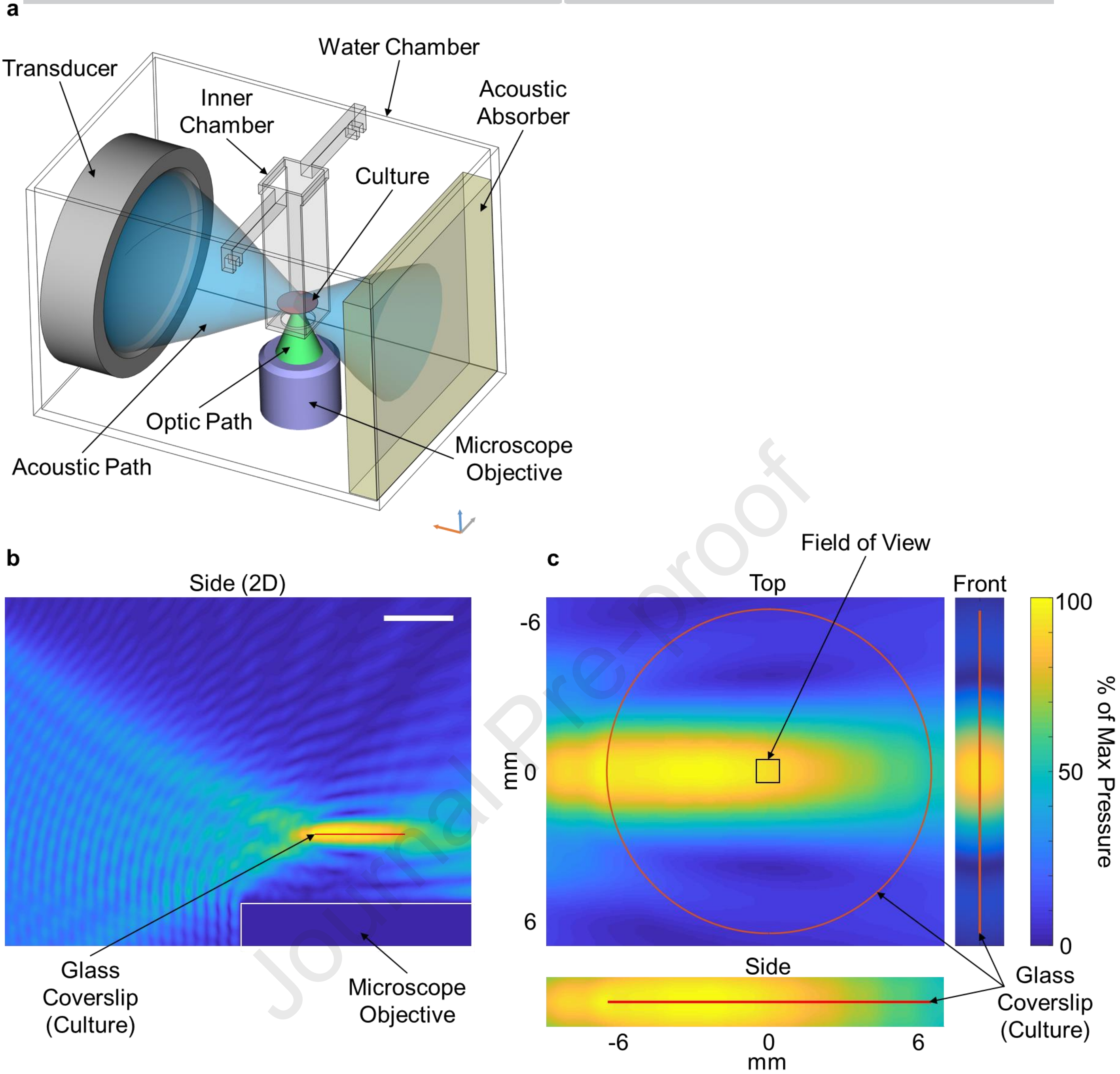
B: Median calcium traces from responsive cells, corresponding to **A**. n^{n}(blue)=188, n^{n}(gray)=225.

C: Response to stimulation in disconnected cultures that were previously stimulated at the same pressure 3 days before (gray, $n^{s,c}$=3), and in fresh disconnected cultures that were not previously stimulated (magenta, $n^{s,c}$=6). Shown is the mean calcium trace from the full FOV. SEM shown shaded. Calcium imaging was done using GCaMP.

D, E: Successful stimulation with a lower-pressure pulse, followed by a second successful stimulation with a higher-pressure pulse, in disconnected cultures.

D: An example culture. Shown are cells responsive only to the first stimulation at the lower pressure (green squares), those responsive only to the following stimulation at the higher pressure, (red circles), and those responsive to both stimulations (orange triangles). 90% (26 of 29) of the cells responsive to the first stimulation were also responsive to the second stimulation in this example. Scale bar: 100μm.

E: Median calcium traces of the response to the lower-pressure stimulation, in the cells that responded only to the lower-pressure stimulation (green, n^n=30), and in those that responded to both pressures (orange, n^n=124)(n^c=8).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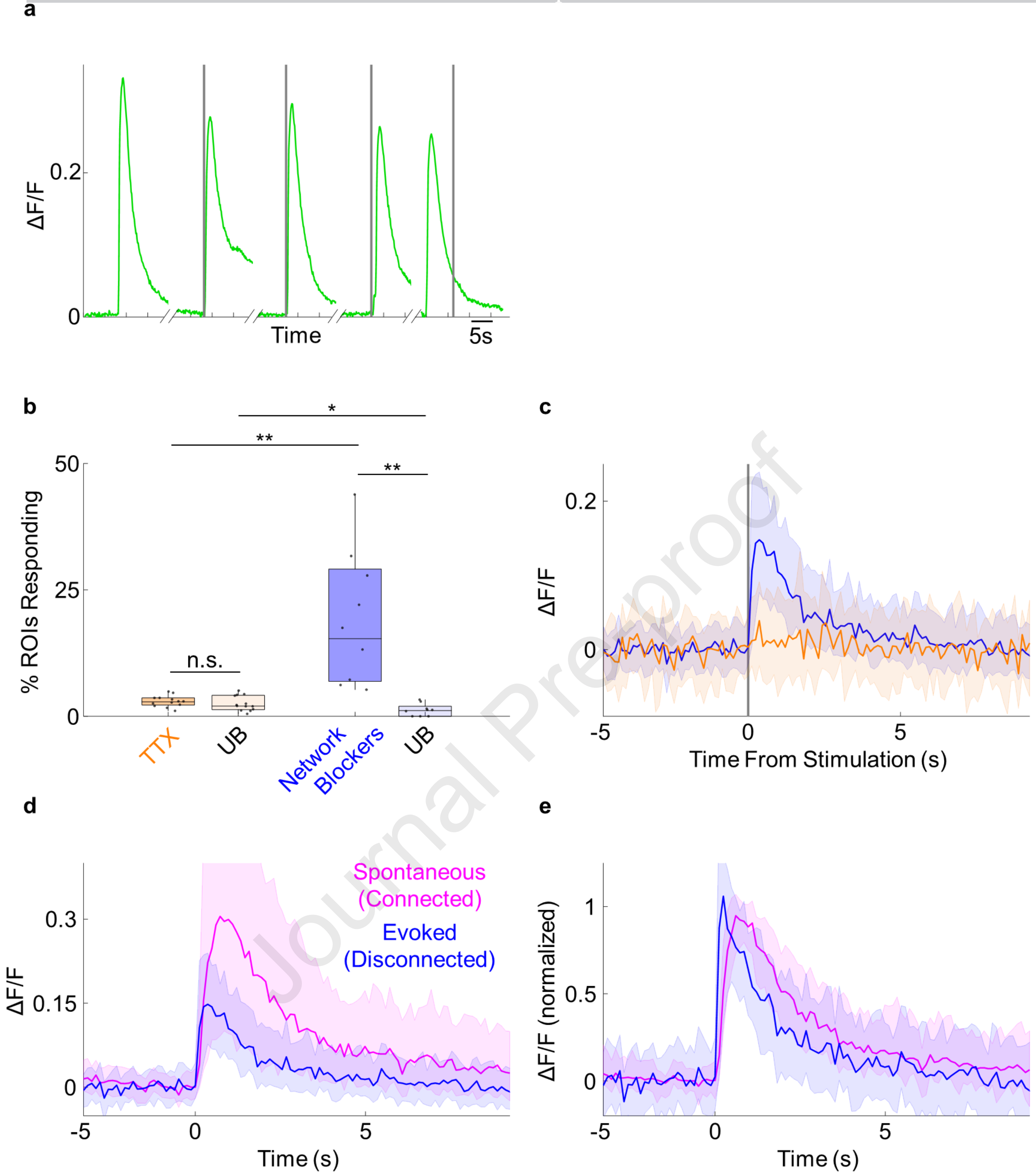
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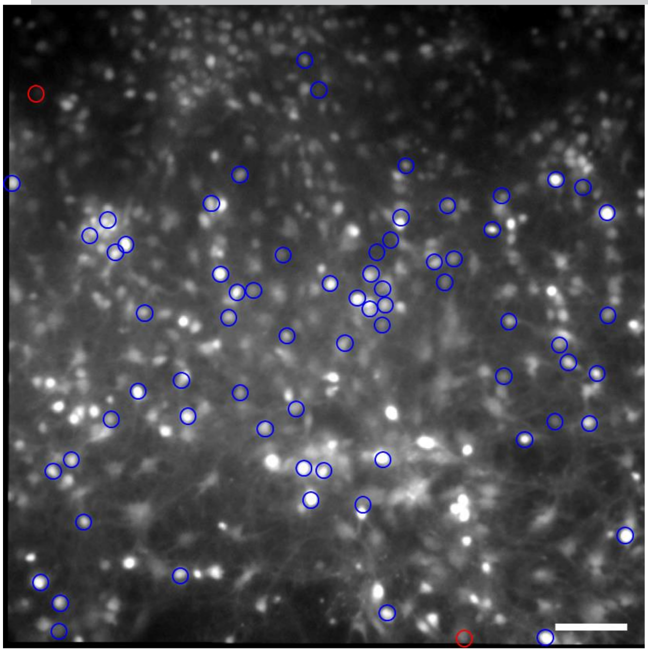
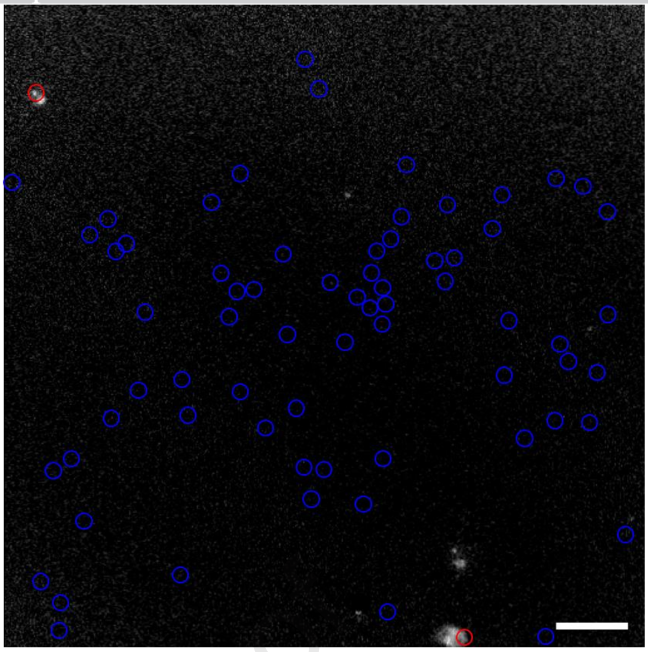
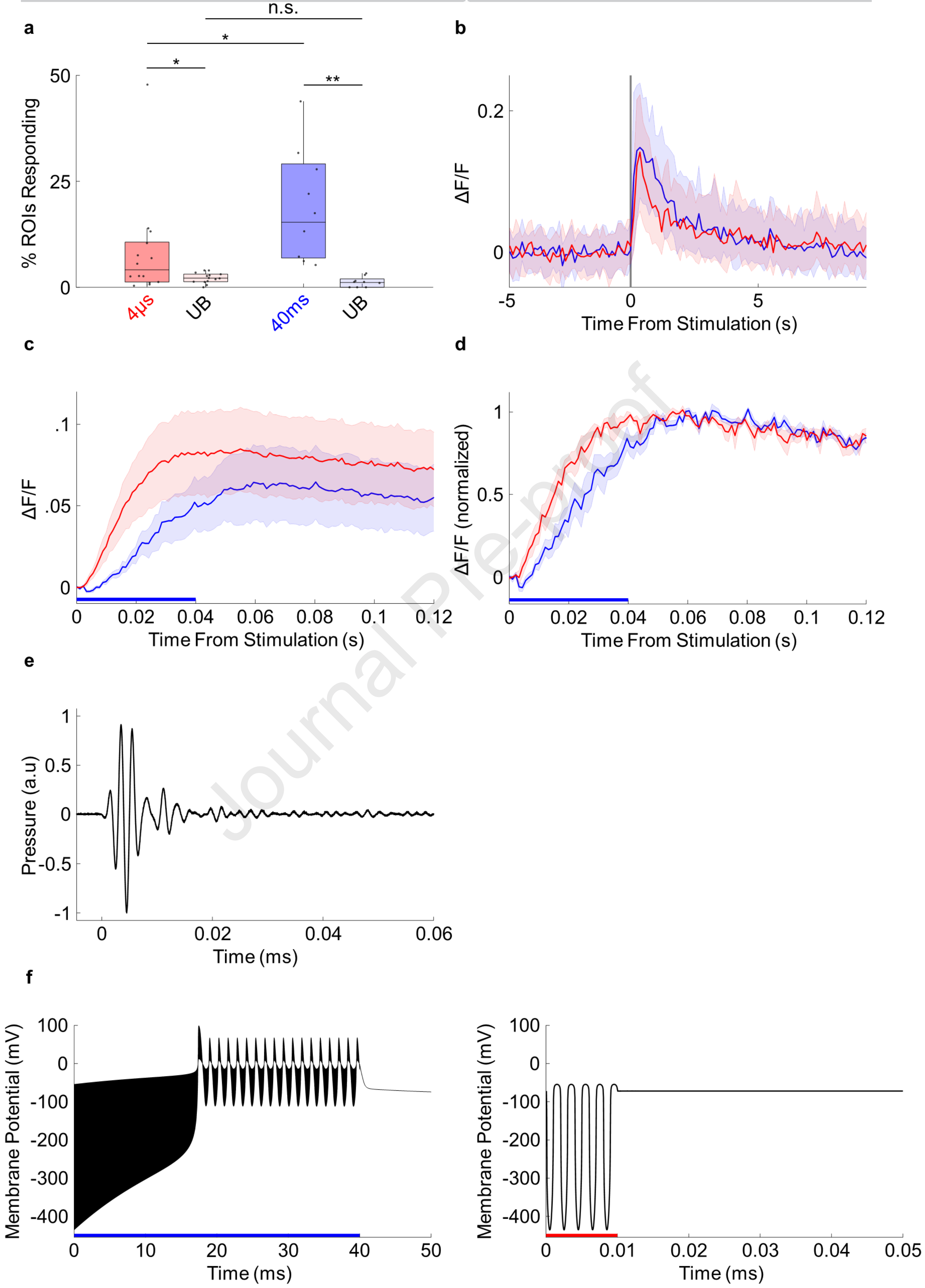
0
n.s.
**
*
**
TTX
UB
Network Blockers
UB
c
ΔF/F
0.2
0
-5
0
5
Time From Stimulation (s)
d
ΔF/F
0.3
0.15
0
-5
0
5
Time (s)
Spontaneous (Connected)
Evoked (Disconnected)
e
ΔF/F (normalized)
1
0.5
0
-5
0
5
Time (s)

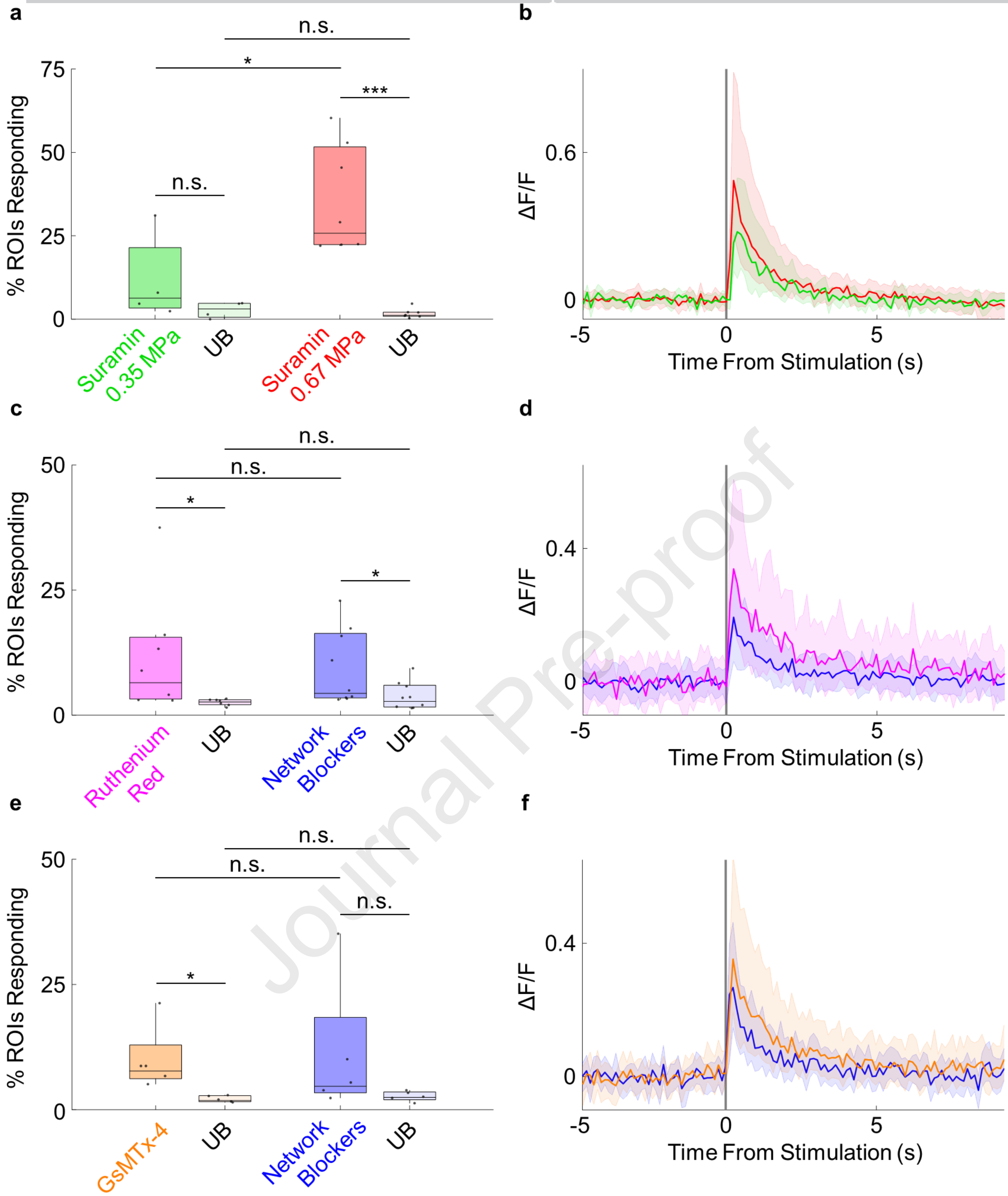


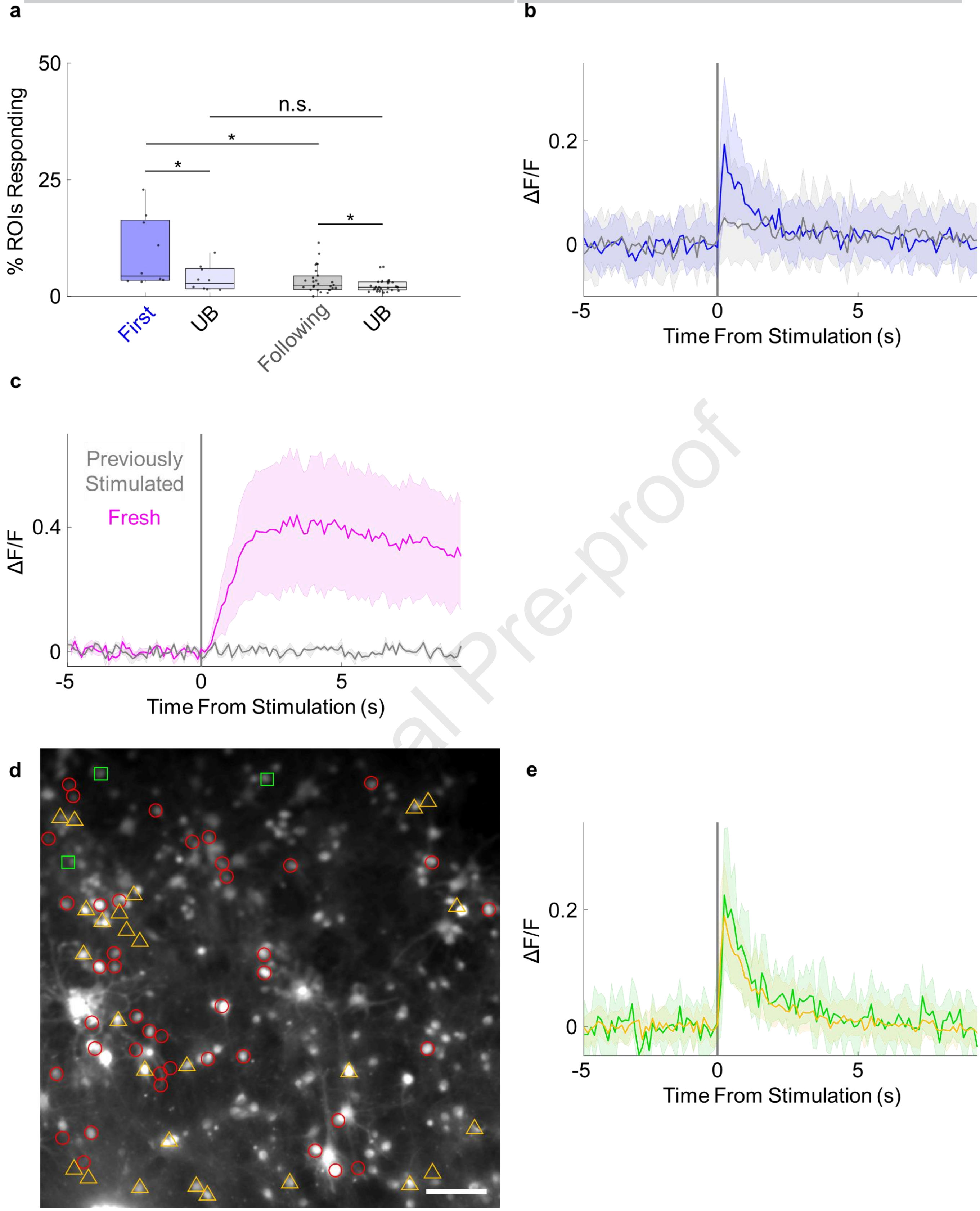
Baseline Calcium



Permeation


n.s.
a
*
*
**
50
25
0
% ROIs Responding
4μs
UB
40ms
UB
b
0.2
0
ΔF/F
-5
0
5
Time From Stimulation (s)
c
.1
.05
0
ΔF/F
0
0.02
0.04
0.06
0.08
0.1
0.12
Time From Stimulation (s)
d
1
0.5
0
ΔF/F (normalized)
0
0.02
0.04
0.06
0.08
0.1
0.12
Time From Stimulation (s)
e
1
0.5
0
-0.5
-1
Pressure (a.u)
0
0.02
0.04
0.06
Time (ms)
f
100
0
-100
-200
-300
-400
Membrane Potential (mV)
0
10
20
30
40
50
Time (ms)
100
0
-100
-200
-300
-400
Membrane Potential (mV)
0
0.01
0.02
0.03
0.04
0.05
Time (ms)


a
n.s.
*
***
n.s.
75
50
25
0
% ROIs Responding
Suramin 0.35 MPa
UB
Suramin 0.67 MPa
UB
b
0.6
0
ΔF/F
-5
0
5
Time From Stimulation (s)
c
n.s.
n.s.
*
*
50
25
0
% ROIs Responding
Ruthenium Red
UB
Network Blockers
UB
d
0.4
0
ΔF/F
-5
0
5
Time From Stimulation (s)
e
n.s.
n.s.
n.s.
*
50
25
0
% ROIs Responding
GsMTx-4
UB
Network Blockers
UB
f
0.4
0
ΔF/F
-5
0
5
Time From Stimulation (s)


a
b
50
25
0
% ROIs Responding
n.s.
*
*
*
First
UB
Following
UB
0.2
0
ΔF/F
-5
0
5
Time From Stimulation (s)
c
Previously Stimulated
Fresh
0.4
0
ΔF/F
-5
0
5
Time From Stimulation (s)
d
e
0.2
0
ΔF/F
-5
0
5
Time From Stimulation (s)

Highlights

- Single, extremely short (4μs) ultrasound pulses stimulate neuronal cultures
- Stimulation is resistant to synaptic blockade and independent from membrane poration
- Action potentials are necessary, implicating an upstream post-synaptic mechanism
- Results detract from cavitation, heating, pre-synaptic release, or gradual mechanisms
- TRPA, TRPV, TREK-2, and Piezo channels as well as P2 receptors are precluded

AUTHOR DECLARATION

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

We further confirm that any aspect of the work covered in this manuscript that has involved either experimental animals or human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.

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Elisha Moses 10/10/21