Pulse propagation at interfaces and their possible relevance for biology

Protons at the speed of sound: Predicting specific biological signaling from physics
Authors: Bernhard Fichtl, Shamit Shrivastava, and Matthias F. Schneider
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Recommended with a Commentary by Julian Kappler and Roland R. Netz, Freie Universität Berlin

The capability to reliably transmit information over macroscopic distances in a split second is crucial for multicellular organisms. For a long time, researchers have theoretically and experimentally investigated how nerve pulse propagation works. In the standard model, introduced by Hodgkin and Huxley (HH) [1], the axon, which is the part of the nerve cell that transmits the nerve pulse, is basically treated as an electrical cable. Nonlinear effects arise in the model from the opening and closing of ion channels that are located in the cell membrane, which create a feedback mechanism that allows the signal to propagate over macroscopic distances. For low-amplitude stimuli nonlinear effects are weak and the nerve signal is not propagated, leading to an all-or-none response of nerve cells.

While the HH model is successful in modeling the observed electrical phenomena, it does not account for several other aspects of nerve pulse propagation. For example, the HH model does not give an explanation for the Meyer-Overton rule, which says that the effectiveness of an anaesthetic is directly proportional to its solubility in a lipid membrane [2, 3]. Furthermore, it is known that a mechanical displacement propagates alongside the electrical pulse [4, 5], and that the net heat release of an axon during a nerve pulse is less than expected from the Ohmic heating of an electrical cable [6].

A more complete picture of nerve pulse propagation should also incorporate these mechanical and thermodynamical aspects, which is why recently both experimental and theoretical interest in pressure waves in membranes has grown. Specifically, the question whether cell-membrane mediated acoustic cell communication and pressure-pulse-induced regulation of membrane protein function plays a role in biological systems has started to attract attention [5, 7, 8, 9, 10]. According to a recent change in perspective, biological interfaces are not only viewed as bounding surfaces, but rather as self-regulated systems that - among other functions - allow for propagation of information [7, 8, 9, 10, 11].

A simple experimental model system for the study of pressure waves in membranes is a lipid monolayer spread at the air-water interface. Indeed it was found that pressure waves

propagate in such a system [9]. They are described by solutions of the Navier-Stokes equation, and small-amplitude (linear) pressure waves obey the dispersion relation [12]

$$(-ik)^2\kappa_{2\mathrm{D}}^{-1} = (-i\omega)^{3/2}\sqrt{\rho\eta}, \tag{1}$$

where $\kappa_{2\mathrm{D}}$ is the lateral compressibility of the monolayer and ρ, η are density and viscosity of the fluid subphase. This relation between wave number k and frequency ω shows that pressure pulses at interfaces do not obey the standard wave equation, where $k^2 \propto \omega^2$, but rather display a fractional behavior $k^2 \propto \omega^{3/2}$, implying that interfacial sound waves have properties fundamentally different from the familiar sound waves in three dimensions.

Pressure pulses at interfaces share many interesting properties with nerve pulses. For example, anaesthetics adsorb preferentially into lipid membranes and thereby alter the compressibility $\kappa_{2\mathrm{D}}$ and thus change the wave propagation properties [8], furthermore, there is little heat exchange between the membrane and the surrounding fluid during a pressure pulse [9]. Pronounced nonlinear effects in the form of an all-or-none behavior for interfacial pressure pulses have been recently observed [10]. While small-amplitude waves have a decay length determined by the complex dispersion relation eq. (1), at large amplitudes the pressure pulse locally modifies the interfacial compressibility $\kappa_{2\mathrm{D}}$ and thereby significantly increases the propagation distance [10]. This all-or-none behavior is reminiscent of nerve pulses, but is realized in the pure lipid systems via the underlying thermodynamic properties of the lipid monolayer. In this context it is also interesting to note that pure lipid membranes exhibit quantized stochastic ion-flux behavior, very similar to the properties of lipid membranes with ion channels [11]. Furthermore, many membrane proteins are pressure sensitive, so that the existence of nonlinear acoustic phenomena in membranes constitutes an exquisite opportunity for smart-membrane-based regulation and information processing applications.

The paper [13] we have chosen for this comment presents further progress towards understanding pressure waves at interfaces. The researchers consider a lipid monolayer on water and find that local addition of gaseous hydrochloric acid, which induces a local perturbation in pH, can excite pressure pulses. Whether or not a pulse is excited depends on the thermodynamic state of the lipid membrane and on the pH of the fluid below, which constitutes a simple mechanism for tuning the pulse formation properties of a membrane. Once a pulse is excited, it is found to be accompanied by both a traveling pH perturbation and an electrical pulse, demonstrating that such waves are not exclusively mechanical. These results once more show that a simple lipid monolayer at the air-water interface exhibits a multitude of complex phenomena, and indeed the authors envision that membrane-bound enzymes might communicate via pH-induced pulses that are excited by locally changing proton concentrations.

Currently, the role of cell-membrane mediated signaling in biology and the relevance of the pressure pulses that accompany action potentials in nerve cells are not fully understood. We believe that acoustic phenomena in living systems constitute an exciting research topic which holds many surprises for the future.

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