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COMPUTATIONAL MODEL OF THE MECHANO-ELECTROPHYSIOLOGICAL COUPLING IN AXONS WITH APPLICATION TO NEUROMODULATION

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For more than half a century, the action potential (AP) has been considered as a purely electrical phenomenon. However, experimental observations of membrane deformations occurring during APs reveal that this process also involves mechanical features [1]. In particular, mechanical waves have been observed to travel conjointly with APs [2]. In order to examine some of the modern hypotheses regarding APs, we propose a coupled mechano-electrophysiological membrane finite element model for neuronal axons. The axon is modelled as 1D axisymmetric thin-wall cylindrical tube. APs are modelled using the classic Hodgkin-Huxley (H-H) equations for the Nodes of Ranvier combined with the cable theory for the internodal regions, whereas mechanical waves are modelled using the dynamic beam equation for a viscoelastic material. Membrane potential changes induce a strain gradient field via the reverse flexoelectric effect, whereas mechanical pulses result in an electrical self-polarisation field according to the direct flexoelectric effect, in turn influencing the membrane potential. Moreover, membrane deformation also alters the values of membrane capacitance and resistance in the H-H equation. These three effects serve as the foundamental coupling mechanisms between the APs and mechanical pulses in the model. A series of numerical studies were conducted systematically to investigate the consequences of interaction between the AP and mechanical wave on both myelinated and unmyelinated axons. Simulation results illustrate that the AP is always accompanied by an in-phase propagating membrane deformation; whereas mechanical pulses with enough magnitude can also trigger APs. The result of interference between two electrical and mechanical pulses depends on their directionalities. These studies provide a potential explanation to these experimentally observed mechano-electrophysiological phenomena in axons, and shed light onto the mechanisms behind ultrasound neuromodulation.

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