Electroceutical Modeling with Advanced COMSOL® Techniques

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Abstract

Neuromodulation is the use of electromagnetic fields to modulate the human nervous system, typically to treat neurological disorders. Electroceuticals is an ambitious program to modulate any nerve, anywhere, anytime, for any reason — to treat disease, disorders, and enhance or interface with the nervous system. Note that electroceuticals follows medical devices', rather than pharmaceuticals', regulatory process, cutting cost and time from $2.5B and 10 years as much as 80%.

Our lab models neuromodulation of disorders such as deep brain stimulation for Parkinson's disease, spinal cord stimulation for chronic neuropathic back and leg pain, transcranial electric stimulation for age-related cognitive decline, and vagus nerve stimulation for epilepsy.

Toward a general-purpose electroceutical finite element model (FEM), we built the first FEM of multiple nerves calibrated to human parameters in inhomogeneous tissue. The ACDC module models the tissue and an extensive equation-based model simulates the nerves according to the Nobel-Prize-winning Hodgkin-Huxley framework for the squid giant axon, re-calibrated to human parameters.

The talk will walk through the model, explaining its capabilities, as an exposition of various COMSOL techniques including:

• Constructing of rectangular and piecewise stimulation waveforms
• Managing extensive parameters and variables using external files
• Entering anisotropic material properties
• Using COMSOL's units consistency checks
• COMSOL CAD functions such as the helix, Boolean operations and thin layers
• Using Contact impedance to save solve time
• Using Infinite element domains to avoid edge effects
• Mapping an operator onto data with the General Extrusion Component Coupling to calculate running 2nd differences along an edge
• Equation-based modeling: Using the General Form Edge PDE interface to calculate

transmembrane potential over time
• Equation-based modeling: Using the Edge ODEs and DAEs interface to calculate probabilities that ion channel gates are open or closed
• Using formulas in local Variables to calculate, e.g., ion channel open and closing rates
• Solving Laplace's equation with a Stationary solver, then using that solution in the Time-Dependent solver
• Separating the physics solved by each solver so that each can be run independently of the other to save solve time
• Multiplying the electric potential along the axon by the waveform amplitude over time to drastically reduce solve time
• Using Solution Selections Data Sets to isolate the effects of electrical stimulation on various structures within the tissue model

Arle, J. E., Carlson, K. W. (2017). "The use of dynamic computational models of neural circuitry to streamline new drug development." Drug Discovery Today: Disease Models (in press, corrected proof). https://doi.org/10.1016/j.ddmod.2017.01.002
Arle, J. E., Carlson, K. W., Mei, L. (2016). "Investigation of mechanisms of vagus nerve stimulation for seizure using finite element modeling." Epilepsy Res 126: 109-118.
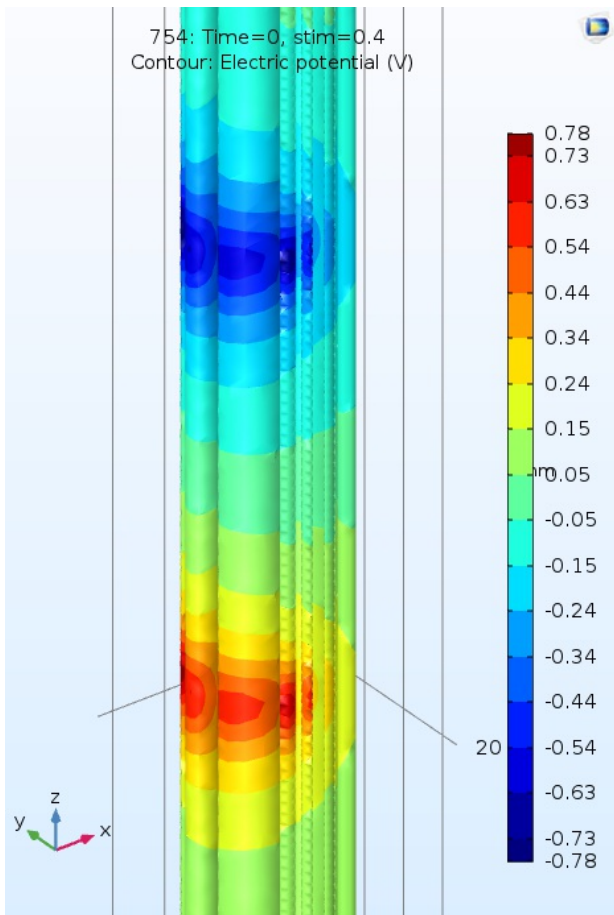
Figures used in the abstract

Figure 1: Figure 1. Contour plot of electric potential along the surface of nerve bundles within the vagus nerve.