

Optimizing runtime for a multi-compartment cable model of a retinal ganglion cell

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Abstract— Multi-compartment cable models of retinal ganglion cells (RGCs) are important tools used to predict how the retina will respond to extracellular electric stimuli. Even with modern computing, these models are computationally expensive, particularly in simulations that require many neurons [1]. In this work, we used sensitivity analysis to identify the minimum number of compartments (spatial resolution) and maximum integration time step (temporal resolution) for an RGC cable model. Our more efficient model significantly reduces runtime with little impact on predicted activation thresholds.

I. INTRODUCTION

Retinal prostheses are an emerging technology used to treat diseases such as retinitis pigmentosa and age-related macular degeneration. Retinal ganglion cells (RGCs) are the primary neural target for retinal prostheses because they are mostly preserved, can be stimulated electrically to produce visual percepts, and provide a direct connection to the visual cortex via the optic nerve. Multi-compartment cable models of RGCs predict the effects of retinal stimulation in an efficient and cost-effective way, with direct control over many parameters. Here we reduced the complexity of an existing RGC model to reduce runtime while maintaining accuracy.

II. METHODS

An RGC cable model with simplified morphometry was implemented in NEURON V7.7. The initial model had 3060 compartments, each 1 μm long. In addition to passive channels, the RGC model had several nonlinear ion channels including sodium, calcium, A-type potassium, Ca-activated potassium, and delayed-rectifier potassium with governing equations described by Fohlmeister et al [2]. Ion channel density varied by cell region, which included soma (10 μm), axon hillock (40 μm), sodium channel band (40 μm), narrow region (90 μm), and distal axon (2880 μm). The axon contained a 90° bend as it ascended to the nerve fiber layer [3].

We modelled the stimulating electrode as a point source, located 155 μm above the soma. Extracellular voltage (V_e) at each compartment was calculated using Equation (1)

$$V_e = \frac{\rho_e I}{4\pi r} \quad (1)$$

where ρ_e = extracellular resistivity (0.1 S/m), I = pulse amplitude (A), and r = distance between the center of each compartment to the electrode (m).

We scaled V_e by the time-dependent stimulus parameters and calculated the RGC membrane voltage response using a backward Euler method for numerical integration. The

stimulus was a biphasic, cathodic-first pulse (0.45 ms/phase, 20 Hz frequency). We used a bisection algorithm to find the minimum pulse amplitude (I) required to induce an action potential. We systematically modified the number of compartments (N_c) and the time step of integration (dt) and measured the effect on activation threshold and runtime.

III. RESULTS & DISCUSSION

The model with the highest spatial ($n = 3060$) and temporal ($dt = 0.001$ msec) resolution was used to establish the ground truth for activation threshold (26.3 μA). We reduced the number of axon compartments, while maintaining the axon length (Figure 1a). Runtime increased linearly with the number of compartments (1.6 sec/ N_c). Reducing N_c from 2880 to 360 resulted in 0% error and ran 8.7x faster. Using 120 axonal compartments resulted in 0.92% error and ran 18x faster. Figure 1b shows increasing error with increasing dt . A time step of 0.003 msec resulted in 0.51% error and ran 3x faster.

Using a spatial resolution of 24 μm /compartment and temporal resolution of 333 kHz substantially reduces the runtime of an RGC multi-compartment cable model, while changing the predicted activation threshold by less than 2%. We consider these to be optimal model parameters that balance speed and accuracy.

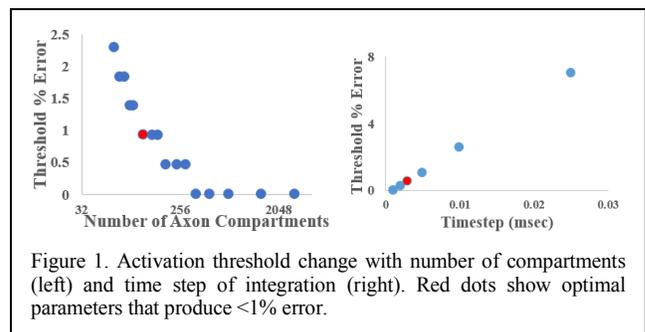


Figure 1. Activation threshold change with number of compartments (left) and time step of integration (right). Red dots show optimal parameters that produce <1% error.

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