

Model of Electrical Stimulation Threshold of Intraretinal Carbon Fiber Electrodes

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Introduction:

Full and partial blindness affect an estimated 43 million people worldwide, significantly impacting quality of life and independence. Assistance by guide dogs and white canes is limited, and there is a growing need for advanced technological solutions. Retinal prostheses provide a possible pathway for visual restoration. However, previous implants suffered from imperfect placement, device detachment, and large electrode size, which led to low quality vision.

Improving electrode design and understanding stimulation dynamics within the retina are critical steps in advancing retinal prostheses. Proper electrode positioning and stimulation parameters are crucial for eliciting desired neural responses, particularly in retinal ganglion cells (RGCs). These cells play a pivotal role in transmitting visual information from the eye to the brain and are ideal targets for retinal prostheses.

In this work, we simulate electrical potentials using COMSOL 6.1 from varying positions around an RGC modeled using the NEURON library in Python. The computational model is adapted to work with a penetrating carbon fiber electrode rather than a disk electrode positioned on the surface of the retina. This model provides valuable insights into optimal electrode positioning and stimulation parameters, guiding subsequent ex-vivo experiments. This approach aims to refine our understanding of the electrode-retina interface, ultimately contributing to the enhancement of retinal neural prostheses.

Materials and Methods:

An existing computational model of a mammalian RGC based on the Python NEURON library was modified to work with electrical potentials obtained from a simulated penetrating carbon fiber electrode. A visual representation was added to show the simulated cell, the external simulated electrical potentials in a gradient at the center of each simulated cell segment, and the carbon fiber electrode tip.

Electric fields were obtained using COMSOL Multiphysics Version 6.1 with the AC/DC electric currents (ec) module. Previous work used a disk electrode placed at the top of the simulated vitreous. We developed a penetrating carbon fiber electrode model that was placed into the retinal layer at varying positions around the simulated RGC. A 1 Amp current was injected at the tip of the electrode with the ground simulated at the pigment epithelium layer. Electric fields were recorded at the center locations of each simulated segment of the RGC. Figure 1 shows the various electrode tip positions about the cell used in experiments.

The electric fields for simulated electrode positions were proportionally scaled per experiment and converted into membrane potentials at every segment of the RGC model. Modeled pulses were biphasic, charge-balanced, cathodic-first current, with no interphase gap. Simulations were run using a bisection algorithm (with convergence of $0.1 \mu\text{A}$) to find the minimum stimulation necessary to invoke an action potential between 1 and 3 milliseconds post-stimulus. Resulting cell behavior was captured at the soma, the sodium channel band, and the axon of the RGC for analysis.

Results, Conclusions, and Discussions:

A total of 21 electrode positions were used to simulate external electric fields around the RGC using COMSOL. Figure 2 shows an example of an observed neuron spiking with a scaled stimulation of $2.246 \mu\text{A}$ placed $10 \mu\text{m}$ above the soma. A general trend emerged where electrodes positioned farther away from the soma of the cell required higher currents to evoke a neural response between 1 and 3 milliseconds post-stimulation. Figure 3 displays the general trend observed with a second degree polynomial with an R^2 value of 0.654.

The choice of such a measurement for neural response was taken due to studies showing neurons spike the most up to 3 milliseconds. Higher stimulations evoked responses happening before 1 ms post-stimulus and were deemed unreliable due to the higher level of artifact present between the start of the stimulus and its end, with an additional time given between 0.45 and 1 ms post-stimulus start to ensure reliable data was taken after each simulation.

The initial batch of experiments shows that penetrating carbon fiber electrodes should be placed as close to the RGC as possible to evoke reliable responses at human-safe stimulations, agreeing with earlier experiments looking at electrode positioning with respect to the cell of interest.

Further work will focus on testing more positions around the cell for a more complete mapping between stimulations and distance, varying the size and properties of the carbon fiber electrode, incorporating a mammalian retinal bipolar cell with synaptic connections to the dendrites of the RGC, and performing ex-vivo patch clamp experiments in mouse retinal tissue.

Future Work:

Next steps involve enhancing the computational model by incorporating synapses between retinal bipolar cells (BPCs) and retinal ganglion cells (RGCs) to evaluate RGC responses to BPC stimulation. Ex-vivo patch clamp experiments in mouse retina will be conducted to collect experimental data, verifying the model's accuracy. Carbon fiber electrode arrays (CFEA) will be used to stimulate BPC somas and record RGC responses. This approach will provide insights into the functional interactions between BPCs and RGCs, with findings supporting further

refinement of the model and experimental protocols for reliable stimulation and response recording.

Poster References:

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