Finite Element Model of Neuron-Electrode Sealing Interface

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Abstract —It is desirable to detect any leakage current when microelectrode is used to stimulate a neuron electrically. This digest proposes a new approach to study the neuron-electrode sealing interface problem. As opposite to the traditional bi-domain FEM that needs a two-step process of indirect coupling of two domains with a circuit equation, which involves solving a set of ODE, this paper proposed a more elegant approach to study the neuron-electrode sealing interface problem based on a single domain finite element model. The result shows the stimulation electrical potential distribution and the sealing resistance is similar to the published simulation and experimental results.

I. Introduction

When using a microelectrode to stimulate a neuron electrically, it is desired to maximize the current transfer from the input electrode to the neuron, and typically the neuron will be covered fully by an electrode through a neuron-electrode interface. Typically, there are gaps (d_g of Fig. 1) allow leakage current to get out and reduce the stimulation efficiency between the cell membrane and the substrate. Previous studies were based on equivalent circuit models which do not take into account of the geometries of the neuron and electrode [2]. The proposed method characterizes the neuron membrane by adding a layer in a finite element model of the neuron-electrode interface. This reduces the complexity of the finite element model of the neuron-electrode and allows accurate modeling of the neuron-electrode interface.

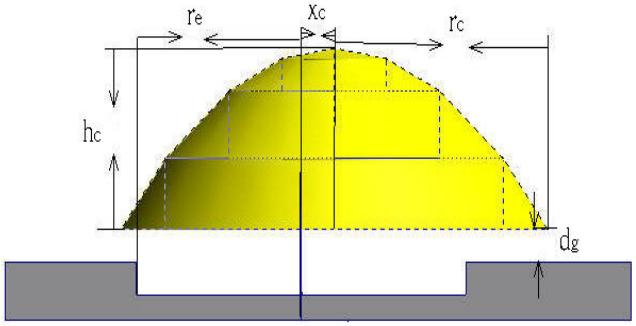

Figure 1 Parameters for geometry of the neuron-electrode interface.

II. METHOD

A neuron-electrode interface model can be represented by Fig. 2. The input current flow from electrode (I_{stim}) is separated into two branches: the leakage current (I_{seal}) and current through the cell (I_{cell}). A coupled circuit and bi- domain finite element model [3] is an improvement over the

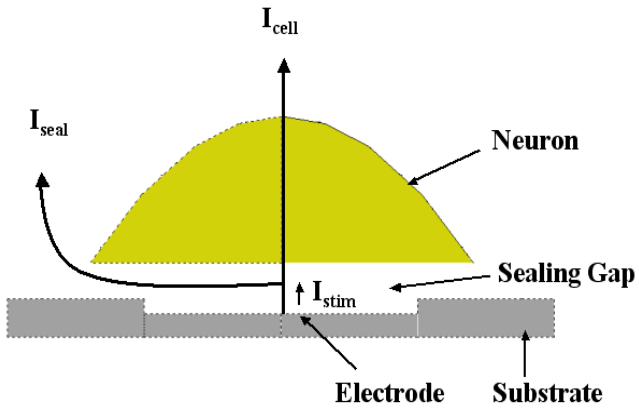

Figure 2 A neuron-electrode sealing interface model.

equivalent circuit model which does not take into account of the geometries of the electrode-neuron interface. In this bi-domain FE model, the Poisson equation was solved in the extracellular domain and the intracellular domain separately in the static problem. The method is complicated because of the difference in finite element and the circuit formulations. Instead of using resistors to represent the real neuron membrane, the proposed method uses an anisotropic layer which allows current to get in or out of the neuron perpendicularly to the membrane is in place to represent the real neuron membrane.

A resistance is used to model the electrical characteristic of the neuron membranes in [3]. This set of differential equations can be represented by a membrane resistance and a shunt membrane capacitance. In this interface model, an interface layer is inserted between extracellular and intracellular domains to represent the neuron membrane. Since passive model of the neuronal membrane is assumed here, only a resistance and a capacitance are incorporated in this layer. The neuron membrane resistance (R_{mem}) can be expressed as:

$$R_{mem} = \frac{\ell}{\sigma A}, \sigma = \sigma_{mem} \cdot \ell \qquad (1)$$

where σ_{mem} the conductivity of the membrane per unit area; σ_{mem}=0.3mS/cm^2 [3], A is the membrane area, and ℓ (=0.3μm) is the distance between extracellular and intracellular domains, consequently, an interface layer conductivity σ=0.9μS/m is obtained. Next, a membrane capacitance C_{mem} is also incorporated in the membrane layer in the current method:

$$C_{mem} = \frac{\varepsilon_{mem} A}{\ell} \qquad (2)$$

where C_{mem} the total capacitance of the membrane and ε_{mem} ($=3\times10^{-9}$ F/m) is the permittivity used to model capacitance for the membrane. The σ and ε_{mem} can be

used to form the anisotropic layer, which represents the membrane.

III. RESULT

Stimulus currents of 1nA are applied into a completely sealed and an incomplete sealed model respectively. In Fig. 3, a complete sealing modeling result was shown. These equipotential lines are concentrated in the sealing gap, equipotential lines in the medium are marked by the boundaries between two adjacent colored regions, demonstrating a obviously potential drop over the sealing gap. Another, an incomplete modeling result was shown. The equipotential lines are spread up more widely, indicating a leakage current into the medium. The changes in membrane potential are reduced to the microvolt range. A sealing resistance of 5.4 MΩ is computed from result as shown in Fig. 3 and a sealing resistance of only 36.6 kΩ is computed in Fig. 4. These results reveal that sealing resistance is strongly related to the stimulus transfer.

The variation of seal resistance by different sealing gap and dimension (radius of neuron) were also simulated. Fig. 5 shows the seal resistance as a function of neuronal radius and electrode radius change, an increasing resistance follows increasing neuron dimension or decreasing sealing gap. By comparing of the proposed FEM method with bi-domain FEM [3], a consistent trend between these two methods was found.

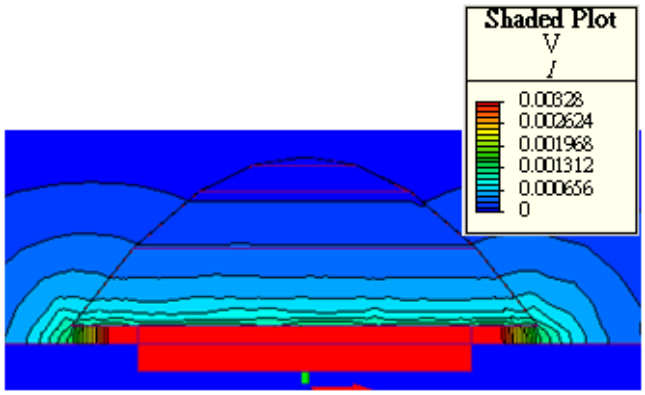

Figure 3 For a completely sealed neuron-electrode interface, an R_{seal} of 5.4MΩ is computed.

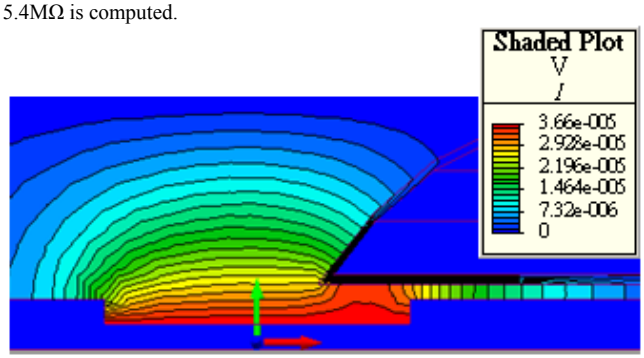

Figure 4 For an incomplete seal between the neuron and the electrode, a 1nA stimulation current generates a R_{seal} of 33.9kΩ, which is consistent with the bi-domain FE modeling result.

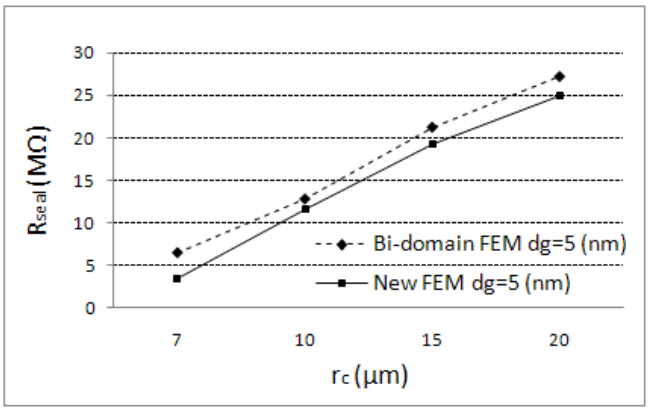

Figure 5 The simulation results from bi-domain finite element model [3] and the proposed modeling method is shown. The sealing resistance, is plotted versus the radius of the neuron while the thickness of the sealing gap is varied (dg=5nm, dg =10nm, dg =20nm).

IV. CONCLUSION

As opposite to the traditional bi-domain FEM that needs a two-step process of indirect coupling of two domains with a circuit equation, which involves solving a set of ODE, this paper proposed a more elegant approach to study the neuron-electrode sealing interface problem based on a single domain finite element model.

V. REFERENCES

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