Simulations of Microelectrode and Neuron Interfaces Enable Long-Term and High Fidelity Recordings

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Abstract

INTRODUCTION:
Our inability to record single cell activity with high resolution over a long period of time precludes fundamental understanding of nervous system functions, both under normal and pathological conditions. While the fabrication of current micro- and nano-electrodes has advanced our capabilities to perform long-term recordings, this has been at the expense of signal resolution due to low sealing resistance, which is defined as the resistance that restricts current leakage through the gap between a neuron and the electrode. Here we report simulations of a novel microelectrode design fabricated in our lab with nano-edges that permits long-term (≥ 1 month) and high fidelity recordings.

SIMULATION:
To investigate the effect of the sealing resistance, we modeled a neuron-electrode interface using the Electric Currents interface in the COMSOL Multiphysics® software. The goal of this simulation exercise was to improve on previous COMSOL® models of neuron simulation [1-2], and also to determine the effect of the nano-edge on the sealing resistance. The model used is this simulation consists of several domains (Figure 1). The glass substrate acts as an insulating layer and was modeled with an infinite boundary to form the basis of the microelectrode. A 30µm diameter gold microelectrode was then modeled above the glass and a neuron was modeled 50nm above the electrode using a semi-circle. The variability of cell diameters found in vertebrate as well as invertebrate models was reflected by gradually increasing the semi-circle diameter from 5µm to 50µm. A ring of dielectric material ranging from 0nm (no nano-edge) to 50nm (height at which the nano-edge completely fills the gap between the electrode and the neuron) was added around the upper edges of the microelectrode to represent the nano-structure. Values of electrical conductivity and relative permittivity used for the various materials in this simulation are presented in Figure 2. While a standard free tetrahedral mesh was used for the neuron, a free triangular swept mesh was implemented to mesh the smaller portions of the simulation (gold electrode and nano-edge).

RESULTS:
The morphologic changes of the microelectrode structure that were simulated by altering

the height of the nano-edge and the size of the simulated neuron significantly affected the sealing resistance values. Depending on the variations of these variables, the calculated sealing resistances varied between 0.66MΩ to 8.71MΩ (Figures 3 and 4). Compared to traditional microelectrodes with no nano-edge that only create a sealing resistance of 1.0 ± 0.2 MΩ, our newly developed microelectrode permits a significantly higher sealing resistance that in turn allows for a better signal-to-noise ratio. Higher signal-to-noise ratio was experimentally verified with fabricated devices.

CONCLUSION:
The simulation of a new generation of microelectrode with nano-edges that enables long-term (≥ 1 month) and high fidelity recordings with an increased signal-to-noise was presented. These new microelectrodes offer more opportunities than traditional planar electrodes and will enable better understanding of brain function and pathological neural conditions. In addition, the model developed here will help us better assess the development of future bionic hybrids and drug discovery devices.

Reference

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Figures used in the abstract

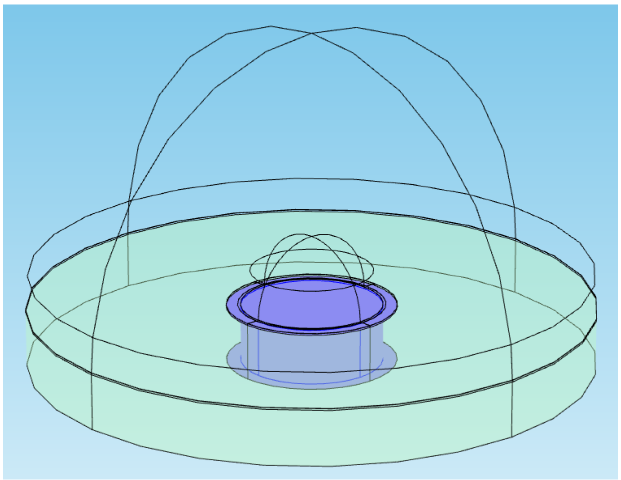

Figure 1: Model used is this simulation consisting of several domains. Here the glass substrate is in green and the electrode with its nano-edge in blue.

Materials	Electrical Conductivity	Relative Permittivity
Gold electrode	45.6e6 [2]	6.9 [2]
Cell Membrane	7.93e-8 [3]	5.6470 [4]
Extracellular Fluid	0.84 [5]	80 [5]
Intracellular Fluid	0.68 [5]	80 [5]
Dielectric nano-edge	3.5e-15 [6]	4.1 [6]

Figure 2: Values of electrical conductivity and relative permittivity used for the simulation.

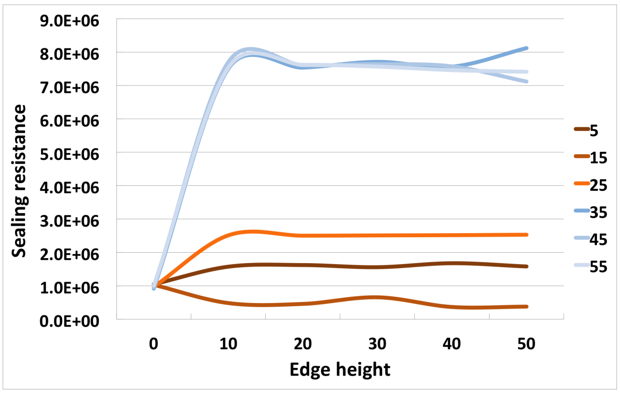

Figure 3: Sealing resistance when edge height increases for each cell diameter (electrode's diameter fixed at 30µm).

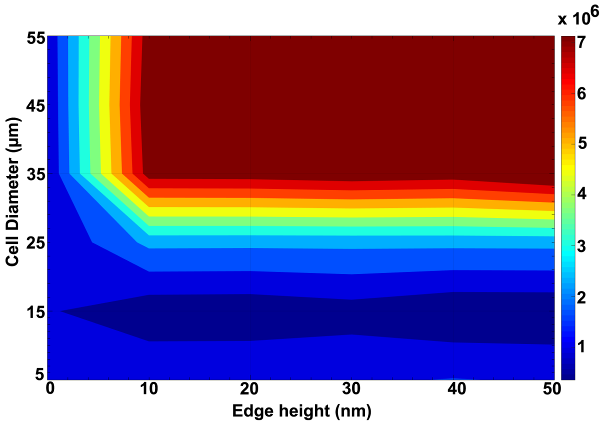

Figure 4: Variation of the sealing resistance depending on the cell diameter and the edge height (electrode’s diameter fixed at 30µm). In this case, this indicates that the presence of the nano-edge is generating an increased sealing resistance as long as the cell diameter is equal or higher than 30µm.