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Modeling the electrode-electrolyte interface for recording and stimulating electrodes

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Abstract -- **The design of metal microelectrodes that produce minimal damage to tissue and can successfully record from and stimulate targeted neural structures necessitates a thorough understanding of the electrical phenomena generated in the tissue surrounding the electrodes. Computational modeling has been a primary strategy used to study these phenomena, and the Finite Element Method has proven to be a powerful approach. Much research has been directed toward the development of models for electrode recording and stimulation, but very few models reported in the literature thus far incorporate the effects of the electrode-electrolyte interface, which can be a source of very high impedance, and thus likely a key component of the system.**

To explore the effects that the electrode-electrolyte interface has upon the electric potential and current density surrounding metal microelectrodes, simulations of electrode-saline systems in which the electrodes were driven at AC potentials ranging from 10 mV to 500 mV and frequencies of 100 Hz to 10 kHz have been performed using the Finite Element Method. Solutions obtained using the thin layer approximation for the electrode-electrolyte interface were compared with those generated using a thin uniform layer, a representation that has previously appeared in the literature. Solutions using these two methods were similar in the linear regime of the interface, however, the thin layer approximation has important advantages over its competitor including ease of application and low computational cost.
[1]

I. Introduction

The intelligent design of metal microelectrodes that minimize tissue damage and increase the success for recording and stimulating targeted neural structures requires a thorough understanding of the electrical phenomena generated in the tissues surrounding these electrodes. Computational modeling has been a primary strategy utilized to study these phenomena, and the Finite Element Method has proven to be a powerful modeling approach. Much work has been directed toward the development of models for electrode recording and stimulation, but only recently have researchers begun to consider the effects of the electrode-electrolyte interface [1-5], which can be a source of very high impedance, and thus likely an important component of the system.

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II. Methods

Simulations of electrode-saline systems in which the electrodes were driven at AC potentials ranging from 10 mV to 500 mV and frequencies of 100 Hz to 10 kHz were performed with the Finite Element Method using the FEMLAB software package.

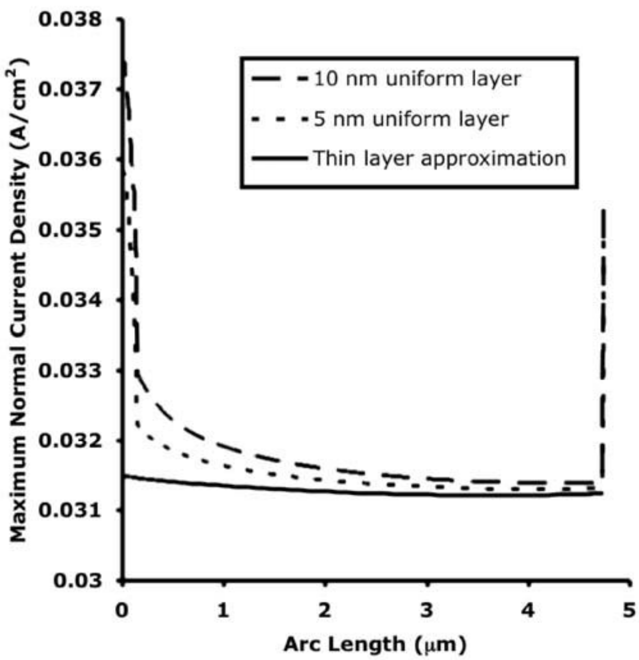

Figure 1: The magnitude of the normal current density is plotted against the arc length measured along the edge of a conical microelectrode immersed in physiological saline and driven at an AC amplitude of 10 mV and a frequency of 10 kHz. The electrode-electrolyte interface was represented by a constant phase angle impedance which was incorporated into the Finite Element Model by means of either the thin layer approximation, a 5 nm uniform layer, or a 10 nm uniform layer.

III. Results

The effects that the electrode-electrolyte interface has upon the electrical potential and current density surrounding metal microelectrodes was explored through quasi-static simulations of electrode-saline systems in which the electrode was driven at AC potentials ranging from 10 mV to 500 mV and frequencies from 100 Hz to 10 kHz. Solutions obtained using the thin layer approximation to incorporate the electrode-electrolyte interface were compared to solutions generated using a thin uniform layer. Figure 1 presents a specific comparison between the solutions obtained with the thin layer approximation and solutions generated with 5 nm and 10 nm uniform layers by plotting the current density passing through the electrode-electrolyte interface along the arc length of a conical microelectrode that is driven at an AC amplitude of 10 mV and a frequency of 10 kHz. Under these conditions, the electrode-electrolyte interface operates in the linear regime, and its electrical properties could be represented by a simple constant phase angle impedance [6-8].

As evident from Figure 1, both methods for incorporation of the electrode-electrolyte interface provide similar solutions in the linear regime of the interface, however, the thin layer approximation has important advantages over its competitor including ease of application and low computational cost. Moreover, because of the low computational cost required by the thin layer approximation, simulations could be carried into the nonlinear regime of the electrode-electrolyte interface using an iterative nonlinear solver. In the nonlinear regime, the electrical properties of the electrode-electrolyte interface become much more complex, and the simulations incorporated the electrical representation of the interface presented by Richardot and McAdams (2002) [9], in which a voltage-dependent constant phase angle impedance is placed in parallel with a voltage-dependent charge transfer resistance. These simulations indicated that the interface acts to increase greatly the uniformity of the current density distribution at lower driving potentials, but that it has a much smaller effect upon the electrical potential and current density distribution when it is driven far into the nonlinear regime. Figure 2 demonstrates this phenomenon by plotting the normalized current density against arc length along a conical microelectrode that was driven at 10 kHz with varying AC amplitudes. The thin layer approximation was applied to incorporate the electrical properties of the interface into models used to generate all of the curves except for the curve labeled "No Layer", which was generated by a model that neglected effects of the interface. When normalized to fit the axes of this plot, the shape of this "No Layer" curve is the same for 100 mV, 300 mV, and 500 mV amplitudes. Thus, it can be observed from Figure 2 that as the system is driven at greater potentials, the solutions generated with models that incorporate an electrode-electrolye interface begin to converge onto solutions derived from models that neglect the interface. At low driving potentials, however, the difference is large.

The low computational cost of the thin layer approximation has also accelerated the creation of models of microelectrode recording by utilizing the Fourier Transform to move from the frequency domain to the time domain. These models have thus far focused on recording from axons of varying sizes and have enabled ongoing research into the effects that the electrode-electrolyte interface, along with electrode shape and size, may have on sampling bias and recorded waveform.

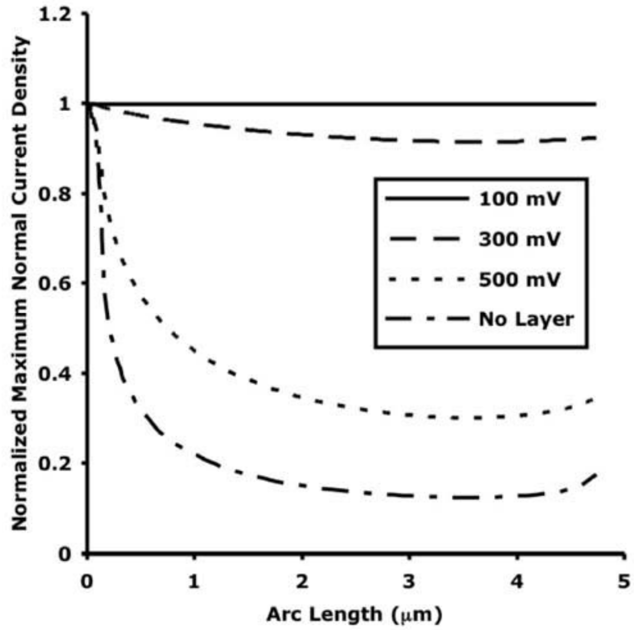

Figure 2: The normalized maximum current density passing through the surface of the electrode is plotted against the arc length measured along the edge of a conical microelectrode immersed in physiological saline and driven at a frequency of 10 kHz and varying AC amplitudes. The electrode-electrolyte interface was represented by a voltage-dependent constant phase angle impedance and a voltage-dependent charge transfer resistance as described by Richardot and McAdams (2002) [9]. The interface was incorporated into the Finite Element Model using a thin layer approximation to generate the curves labeled "100 mV," "300 mV," and "500 mV." The curve labeled "No Layer" was generated from a model that neglected effects of the interface, and its shape is independent of voltage amplitude.

IV. Conclusion

The value of adding the electrode-electrolyte interface to models of electrodes used for recording or stimulation of neurons depends significantly upon the electrical potentials involved. At low potentials the electrode-electrolyte has a substantial effect, but as electrical potential is raised the effect of the interface becomes less important.

References

[1] X. Huang, D. Nguyen, D.W. Greve, and M.M. Domach, "Simulation of Microelectrode Impedance Changes Due to Cell Growth," *IEEE Sensors Journal,* vol. 4, no. 5, pp. 576-583, 2004.

[2] D.R. Cantrell, R.S. Ruoff, and J.B. Troy, "Simulating Stimulation Fields Including the Electrode-Electrolyte Interface," abstract presented at the *Neural Interfaces Workshop*, Bethesda, MD, 2005.

[3] X.F. Wei and W.M. Grill, "Effect of the Electrode-Electrolyte Interface on the Current Density Distribution on Deep Brain Stimulating Electrodes," abstract presented at the *Neural Interfaces Workshop*, Bethesda, MD, 2005.

[4] C.R. Butson and C.C. McIntyre, "Model-Based Analysis of the Effects of Electrode Impedance, Electrode Capacitance, and 3D Tissue Electrical Properties on the Volume of Tissue Activated by Deep Brain Stimulation," abstract presented at the *Neural Interfaces Workshop*, Bethesda, MD, 2005.

[5] C.R. Butson and C.C. McIntyre, "Tissue and electrode capacitance reduce neural activation volumes during deep brain stimulation," *Clinical Neurophysiology*, vol. 116, pp. 2490-2500, 2005.

[6] R.W. de Boer, and A. van Oosterom, "Electrical properties of platinum electrodes: impedance measurements and time-domain analysis," *Medical & Biological Engineering and Computing*, vol. 16, pp. 1-10, 1978.

[7] H.P. Schwan, "Linear and Nonlinear Electrode Polarization and Biological Materials," *Annals of Biomedical Engineering*, vol. 20, pp. 269-288, 1992.

[8] E.T. McAdams and J. Jossinet, "Physical interpretation of Schwan's limit voltage of linearity," *Medical & Biological Engineering & Computing*, vol. 32, pp. 126-130, 1994.

[9] A. Richardot and E.T. McAdams, "Harmonic Analysis of Low-Frequency Bioelectrode Behavior," *IEEE Transactions on Medical Imaging*, vol. 21, no. 6, pp. 604-612, 2002.