COMSOL Thermal Model for a Heated Neural Micro-Probe

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Abstract: This project utilizes the heat transfer module of the COMSOL Multiphysics environment to model the effects that an ohmic heating probe will have on neural tissue. The model quantifies the thermal impact of active components embedded on a neural micro probe by solving the Penne's bioheat equation with an external MATLAB function to determine the heat generation along the length of the probe. The resulting model can be used as design tool for developing novel neural probes that include light and heat sources and active cooling. In order to demonstrate this utility an ohmic heating probe is designed for a particular temperature excursion. The ohmic heating probe will be fabricated and used in subsequent experiments to validate the computational model.

Keywords: finite element modeling, neural probes, nanoscale modeling, electrical heating, bioheat transfer.

1. Introduction

The manner in which the brain functions is still relatively unknown and has therefore been the subject of extensive research in recent years. Neurons function as a result of an electrochemical phenomenon known as the action potential. In essence, an action potential is an electrical signal that travels down the axon of the neuron towards the axon terminal, where the electrical signal is converted to a chemical signal, which then crosses the space known as the synaptic cleft to interact with other neurons. This action potential is initiated via a disturbance in a neuron's resting membrane potential [1]. This is the basic process used by neurons to integrate and disseminate information to other neurons in the brain through the neural networks. Emotion, muscle movement, and consciousness are all controlled in essence by these electrical action potentials. Neurons are typically 10-30 µm across at the body and 1 µm across at the axon [2].

Neuroscientists use neural probes, generally needles with microscale metal electrodes patterned on the surface, to study these neural networks. Figure 1 illustrates a typical neural probe. Probes are typically between 60 and 200 µm wide and 15 to 30 µm thick [2]. These probes are generally comprised of multiple electrodes along the shank with contact patches at the base for recording. The electrodes are used to either electrically stimulate the neurons or monitor their electrical activity.

While depolarizations can be caused by coupling current through an electrode into neural tissue, this method lacks spatial specificity by causing other neurons to fire in response to the stimulus. Additionally, the large current transient interferes with recording the response signals causing a lack of temporal resolution. This can confuse the results of the research and make accurate neural mapping difficult [3, 4].

Another issue with electrical neural probes is that they may cause both Joule heating and metabolically-based temperature increases in neural tissue. Temperature increases as low as 0.5 °C can cause changes in cell function [5].

The incorporation of optical sources for stimulating neurons into neural probes enhances their temporal resolution and target specificity [3,4], but the inclusion of a light source onto the probe may also result in more heating than the electrical probes alone, requiring the addition of some sort of thermal management system. In addition, other groups are investigating probes that intentionally introduce a thermal change for either scientific or therapeutic use [6].

A model for the thermal effects of such probes would provide a powerful tool in the design of such systems. In order to develop such a tool, we are designing a neural probe containing an ohmic heater that could be used for thermal studies. COMSOL was used to model the ohmic heater's thermal effect on neural tissue as a function of applied voltage and heater geometry, in order to optimize the design.

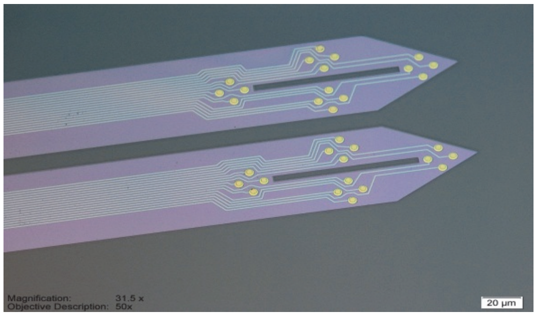

Figure (1): Neural probes containing sensing electrodes. Figure provided by SB Microsystems and reproduced with permission.

2. Theory

The model requires a number of separate, but related mathematical and physical disciplines. The breakdown of this particular model is as follows:

(1) The geometric and electrical properties of the probe must be correlated to its localized heat output.
(2) The heat diffusion into the surrounding tissue needs to be modeled with the Penne's Bioheat equation.

2.1 The Pennes' Bioheat Equation

The Pennes' Bioheat equation, shown as equation (1) below, and featured in the COMSOL heat transfer module can be used to calculate heat transfer in biological systems.

$$\rho C_p \frac{\partial T}{\partial t} = \nabla(k\nabla T) + \rho_b C_b \omega_b [T - T_{blood}] + \dot{q} \quad (1)$$

The first term on the right describes energy transport due to thermal diffusion within the tissue. The second term describes the energy added or removed due to the convective blood flow into and out of the tissue. The third term captures the metabolic heat generation. In equation (1), ρ is the density of the tissue under study, C_p is the specific heat of the tissue, k is the thermal conductivity of the tissue, and T is the temperature of the tissue. ρ_b is the density of the blood, C_b is the specific heat of the blood, and ω_b is the blood perfusion rate. T_{blood} is the temperature of the blood. Heat was added to the system as a volumetric quantity in W/m^3.

2.2 Electrical Calculations

Resistance of a material is dependent mostly upon the geometry of the material and increases linearly with resistivity, ρ; equation (2) below illustrates this relationship.

$$R = \rho \frac{L}{A} \quad (2)$$

Where L is equal to the length of the material and A is equal to the cross-sectional area of the heater. Resistive heating derives from the equation:

$$\dot{q} = \rho J^2 \quad (3)$$

Where J is the current density and $\dot{q}$ is the resulting volumetric heat generation.

3. Modeling Details

3.1 Bioheat Physics Model

A 2D Axisymmetric model was constructed in the Bioheat Transfer subset of the Heat Transfer Module of COMSOL. The model and its boundary conditions is illustrated in Figure 2. The model is "upside down" so that the probe base could be at z = 0 and that positive z would correspond to the distance along the shank in the probe region. The material properties for the different regions were as given in Table 1 below. The scalp surface had a convective boundary condition with a convection coefficient of 3.6 W/(m^{2}K) [7]. The model also included the metabolic heat generation of the different associated tissues provided in table 2.

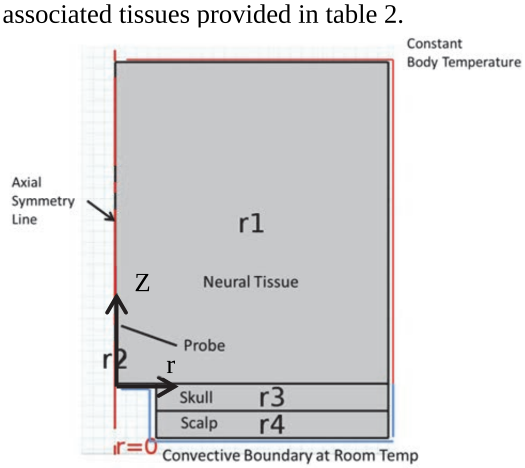

Figure 2: The radial cross-section of the model with active blood perfusion illustrating the boundary conditions. This is a 2D axisymmetric model, with revolution occurring around the axial symmetry line marked on the left.

The actual probe is not cylindrical in shape, but instead is a slab 15 µm thick and 180 µm wide. Here it is modeled as a cylinder with an effective radius, R_{probe}, of 29 µm so that it has the same cross-sectional area as the probe. The probe is also set as a heat source with a user-defined volumetric heat input which depends on the distance along the probe shank, z, and is calculated separately using a MATLAB function. It is assumed that the volumetric heat generation term is uniform across the width of the probe.

Table 2 includes the blood perfusion rate and heat generated due to metabolism for each separate tissue. The values for perfusion rate were given in the medical standard units of ml/(min*100g tissue). In order to use this information in COMSOL, these values needed to have units of 1/sec. To accomplish the conversion, the values had to be multiplied by the density of the tissue to which they apply. The metabolism values are merely representative values, as metabolism of individual regions of the brain can vary greatly depending on the stimulation of the neurons located in that area.

Table 1: Material Properties

Material	Thermal Conductivity k: (W/m*K)	Heat Capacity Cp: J/(Kg*K)	Density : ρ (kg/m^3)
Silicon (Probe)*	130	700	2329
Brain [6]	0.5	3700	1050
Bone (Skull) [6]	1.16	2300	1500
Scalp [6]	0.34	4000	1000

* Properties obtained from COMSOL materials library

Table 2: Perfusion Model Additional Properties

Material	Converted Perfusion Rate (1/sec)	Heat Generation Due to Metabolism (W/m^3)
Brain [6]	0.014	16700
Bone (Skull) [6]	0.00033	368.4
Scalp [6]	0.00045	363.4

3.2 MATLAB Model of Ohmic Heat Source

For the probe illustrate in Figure 3, the metal layer consists of 150 nm Platinum and 10 nm of Titanium. Most of this resistance is in the serpentine portion of the electrode near the tip, but the resistance in the leads is non-negligible. The optimal length of the serpentine portion was investigated through a parametric study in COMSOL.

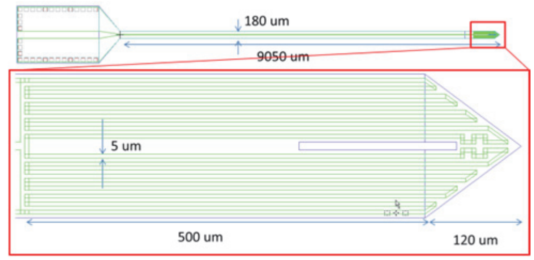

Figure 3: Mask layout for a neural probe containing an ohmic heater being investigated and designed by this work.

Using equation (3), the volumetric heat generation for the lead portion and tip portion of the tip was calculated in a piecewise linear fashion using the equation:

$$\dot{q} = \rho \left(\frac{I}{wt}\right)^2 \frac{N(wt)}{A_x} \qquad (4)$$

This equation describes the heat production per unit volume along the probe shank and is a function of position. N refers to the number of elements of identical geometry along a given range of z values. ρ is the bulk resistivity of Platinum, whose thickness is given by the variable t. The variable w represents the width of the material as viewed from above. While the heat is actually generated within the Platinum strips, the volumetric heat generation calculated is applied to the entire probe volume. This is taken into account in equation (4) by multiplying by the heater cross section and dividing by the probe cross section. I is the electrical current which is calculated from the applied voltage and total resistance using Ohm's Law.

The boundaries for the different portions of the heater (the lead portion and the serpentine portion) were included as variables and could be directly altered by the COMSOL function engine. Other variables were defined such as the applied voltage to the electrodes. This allowed for more rapid design parameter variations to be tested, all from within the COMSOL environment and coupled to the MATLAB computation program. A parametric study was run to determine the optimal heater length of the probe. Figure 4 shows the output of this MATLAB function for the probe dimensions illustrated in Figure 3.

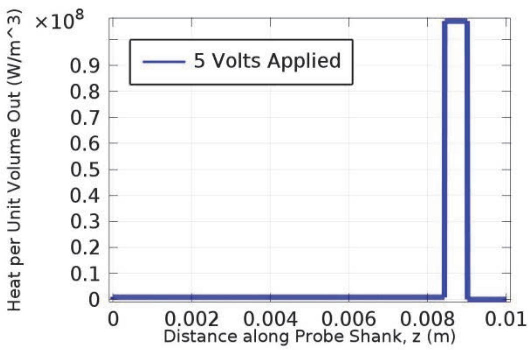

Figure 4: Heat output from Matlab-coupled code showing the variation in applied heat along the length of the probe.

4. Results

Figure 5 below shows the result of the model in the case with 5 V applied to the probe illustrated in Figure 3. In this case, blood perfusion and metabolism is not included as this better mimics how the ohmic probe will be initially tested (using a simulant gel rather than biological tissue). The model indicates a peak temperature deviation from body temperature of more than 17°C.

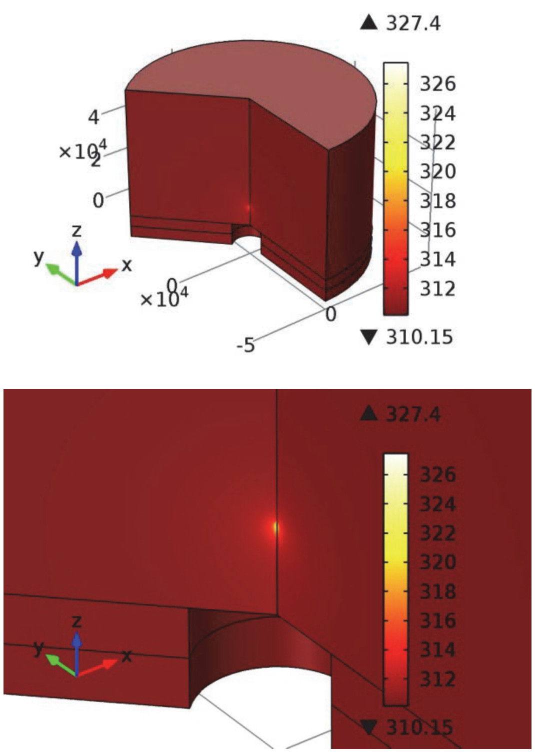

Figure 5: The result with 5V applied to the probe and zero blood perfusion.

This increase in temperature is enough to cause a significant change in cellular physiology and cellular death in the area immediately surrounding the probe. This indicates that the probe should be effective as a design tool capable of inducing a measurable temperature deviation in the material.

This model was run again including blood perfusion and metabolic terms, and the two models are compared in Figures 6a and 6b below. The peak temperature is roughly one degree lower with blood perfusion and metabolic terms included, which is expected given that these processes increase heat transfer away from the probe.

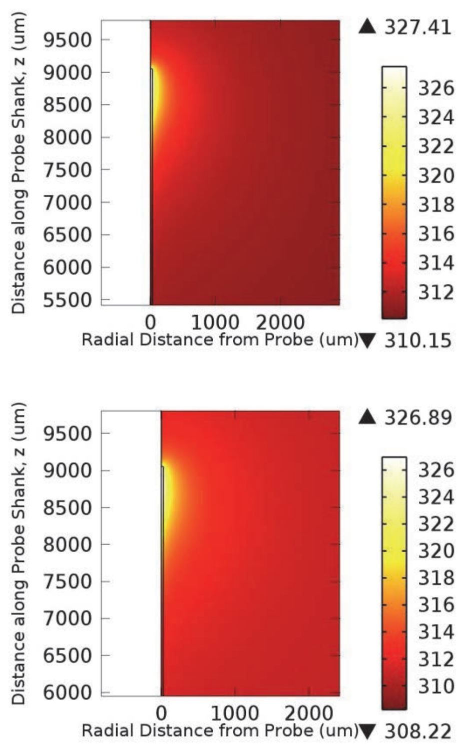

Figure 6a and 6b: 6a: Temperature distribution surrounding the heating probe without modeling the effects of blood perfusion. **6b:** Temperature distribution including the effects of blood perfusion.

This model was then used for a parametric study of the dependence of maximum temperature output on the length of the serpentine portion of the ohmic heater. The results are illustrated in Figure 7 below. The optimal heater length was found to be slightly less than 500 μm.

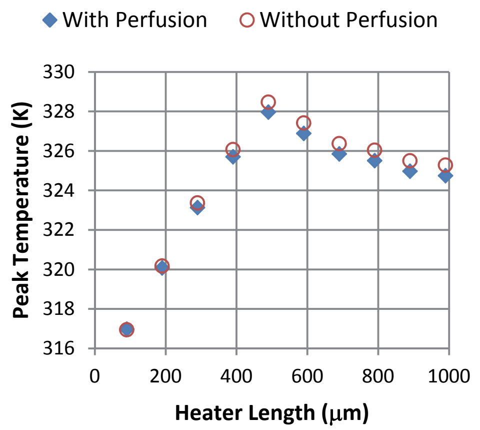

Figure 7: Peak temperature output of the model as a function of heated probe length as determined by a COMSOL parametric study.

5. Summary

COMSOL and MATLAB were used to design an ohmic heater to be used in an investigation of the thermal effects of neural probes. The model allowed for parametric testing of voltage, electrode geometry and thermal boundary conditions. The resulting ohmic heating probe design should be capable of inducing sufficient temperature excursions so as to be measurable in a laboratory for correlating modeling results against experiment. This is a piece in a larger model that could be used in the development of novel neural probe technology.

6. References

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7. Acknowledgements

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