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Preliminary Study of the Thermal Impact of a Microelectrode Array Implanted in the Brain

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***Abstract* – One requirement of a chronically implantable, wireless neural interface device is the integration of electronic circuitry with the microelectrode array. Since the electronic IC dissipates a certain amount of power, it will affect the temperature in the tissues surrounding the implant site. In this paper, the thermal influence of an integrated, 3-dimensional Utah Electrode Array, to be implanted in the brain was investigated with simulations using the finite element method (FEM). A temperature increase in the brain tissue was predicted using preliminary simulations with simplified models. The model and method used in the simulations were verified by simple *in vitro* experiments.**

I. Introduction

Recently, efforts have been devoted to develop a fully integrated, wireless neural recording device based on the conventional Utah Electrode Array (UEA). The UEA is a 3-dimensional silicon based structure consisting of a 10 × 10 array of tapered silicon spikes, each with a base width of 80 μm and a length of 1.5 mm (see Figure 1). This device will be implanted in the cortex of the brain to chronically record neural signals. When the UEA operates without wire connections to extracorporeal devices, risk of infection through penetrating wires can be eliminated, and patients can have more freedom of movement and much better aesthetics.

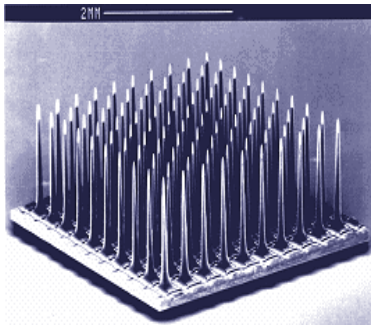

Figure 1: SEM photograph of the Utah Electrode Array.

For this new generation of UEA to operate wirelessly, an electronic VLSI IC must be integrated with the electrode array. The electronic circuitry amplifies detected neural signals, with magnitudes that are generally in the range of a few hundreds of microvolts maximum, processes and transmits them to an extracorporeal receiver and analysis system. An integration scheme of the entire 3-D microelectrode array is shown in Figure 2 [1]. Since the electronic IC dissipates a certain amount of power during operation, it will affect the temperature in the tissues surrounding the implant site.

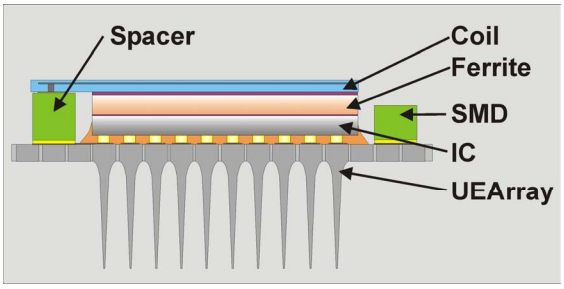

Figure 2: Schematic of the integration and packaging concept of the integrated wireless neural interface.

It is reported that the maximum permissible temperature increase in the cortex is about 1°C or maximum power density is 80 mW/cm^2 of exposed tissue area [2]. Other data [3] states 0.64 W for a 3 mm diameter probe or temperatures greater than 47°C caused spreading depression in rats after 28 seconds of irradiation. In guinea pig olfactory cortical slices, aberrant activity began at 2°C over normal [4]. Thus, predicting the temperature increase in the implanted site of the microelectrode array may require change or modification of the device design and technology in order to guarantee that the device is not harmful to the biological tissues.

To the authors' knowledge, there are no studies addressing thermal effects of an implanted 3-dimensional microelectrode array. In this study, this thermal aspect of the neural interface was investigated using numerical methods as the first step towards *in vivo* thermal evaluation of the recording or stimulating electrode arrays. The temperature increase in the brain due to the array implantation was investigated using the finite element method (FEM). The model and method used in simulations were preliminarily validated through simplified *in vitro* experiments.

II. Methods

Heat transfer in the implanted microelectrode array and its surrounding tissue was simulated through FEM analysis. A finite element tool Femlab (Comsol Inc.) was used. Only heat transfer in conduction was taken into account, since conduction is the most important mechanism of heat transfer within biomaterials [5]. Convection through blood flow, which in effect removes heat from the tissue, was not considered for this preliminary study. Thus, the observations

based on this modelling can be considered as the upper limit of possible temperature increases. Heat transfer was assumed to occur in steady state, thus no thermal diffusion need be considered. The tissues of interest were assumed to be homogeneous and isotropic with no blood flow and tissue metabolism. Under these assumptions, heat transfer is described by

$$\nabla\bullet(-k\nabla T)=Q,$$

where k is the thermal conductivity, T the temperature in Kelvin and Q the heating source. The implanted UEA, integrated with the IC chip was modelled in a 3-D Cartesian coordinate. To reduce the calculation load, the conical shape of electrodes was modelled as rectangular rods having a diameter of 80 µm and a length of 1600 µm. The IC chip was modelled as a cubic volume having dimensions of $6\times6\times0.24$ mm^3. The brain tissue, skull, and scalp were modelled as shown in Figure 3. The thickness of the scalp was assumed as 3 mm, and 5 mm for skull [6]. For the brain tissue, the thickness was selected sufficiently large to be able to assume the temperature at the boundary of the selected region be equal to the ambient temperature, e.g. body temperature of 37°C. The cerebrospinal fluidic (CSF) layer between skull and cortex of the brain was neglected due to its small thickness.

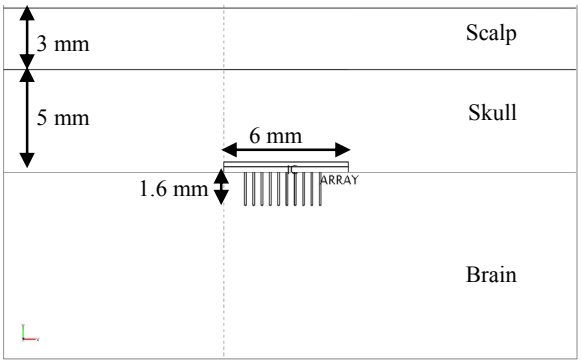

Figure 3: Modeling of the electrode array and surrounding tissues for the FEM simulation.

To solve the differential equation, proper boundary conditions are necessary. All boundaries except the scalp surface can be considered to be at body temperature if the volume to be analyzed is selected to be sufficiently large. Since the heat transfer at the interface of scalp and air was neglected, it was assumed the scalp acts as a thermal insulation barrier.

Unlike many engineering problems, it is not trivial to determine a single representative value of the thermal conductivity for biological materials. Biomaterials such as brain, bone, or skin are usually inhomogeneous and anisotropic, and material properties are widely varying [5], [7]-[12] depending on the measurement methods, measurement sites, and the size of samples taken for measurements. The thermal conductivities of the tissues of interest are listed in Table 1, taken from the literature. It is reported that the presence of blood perfusion increases the thermal responsiveness of the tissue, resulting in a slightly higher "effective" thermal conductivity [13]. This means that the thermal conduction can occur more easily when body fluid transports heat throughout the tissue. In this study, however, the influence of blood perfusion was not considered.

Table 1: Thermal conductivities of the electrode array and its surrounding tissues [5], [7]-[12].

Material	Thermal conductivity (W/mK)
Silicon (electrode and IC)	145.7
Brain	0.528
Skull	0.43
Scalp	0.34

III. Simulation Results and Discussion

The power generation of the IC was modelled to be 13 mW when it is fully operating. Thus, the heat distribution in the tissue due to the implanted UEA was simulated for the chip dissipating 13 mW. The temperature profile around the UEA is shown in Figure 4, in top and cross sectional views. The maximum temperature increase was determined to be 1.2°C on the surface of the IC chip.

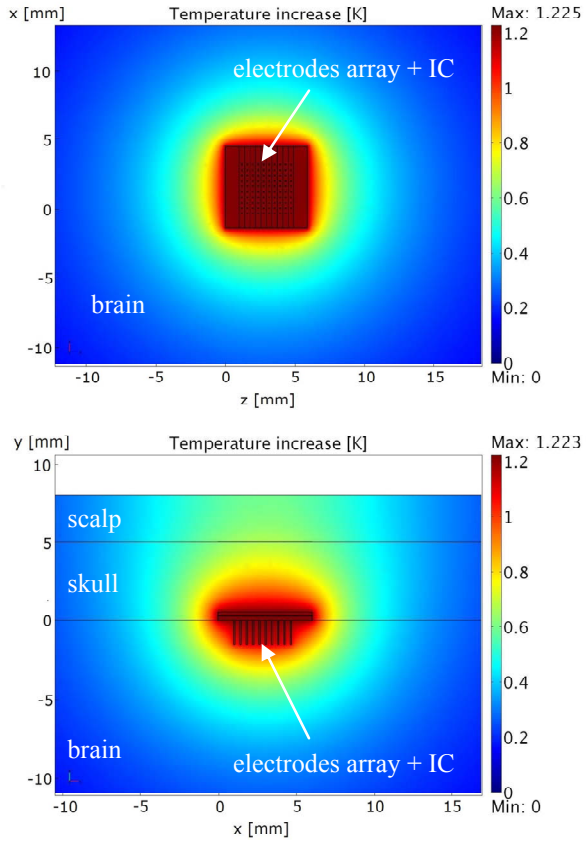

Figure 4: Thermal distribution in the brain tissue surrounding the UEA integrated with the IC. Top view on the surface of the brain (top) and cross sectional view (bottom).

Next, the thermal influence of the electrode tips was simulated. 100 electrodes increase the surface area of the entire array by a factor of about 2. Due to the increase of the surface area contacting with the tissue through the 100 electrode tips, the temperature increase was 0.14°C less than the case where no electrodes included (compare the temperature profiles in Figure 4 and in Figure 5).

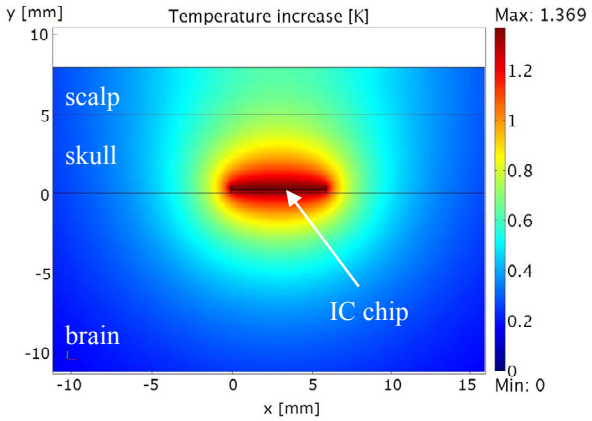

Figure 5: Thermal distribution in the brain tissue surrounding the IC chip without 100 electrode tips.

To validate the modelling and method used in our simulations, a simple *in vitro* measurement was performed using an electrical resistor as a substitute of the IC chip and agar gel as a surrogate brain tissue. The resistor used was a general-purpose carbon film resistor with a diameter of 2 mm and a length of 6 mm. The temperature distribution through a 1 kΩ-resistor dipped slightly into agar was measured using an infrared thermal camera (ThermaCAM PM390 from Inframetrics). The resistor was heated by a controllable power supply through wires. Agar (1.5 %) has a thermal conductivity of 0.6 W/Km [5], [14], which is comparable to that of the brain tissue (see Table 1). The measured temperature distribution is shown in top of Figure 6. This was compared with the simulated result (Figure 6, bottom). It was observed that the temperature increase was 1.3°C from the measurement and 1.27°C from the simulation for the chip dissipating 13 mW.

IV. Conclusion

In this study, thermal impact of a 3-D microelectrode array implanted in the brain was investigated through FEM-simulations. The simulated results showed that the temperature increase due to the array implantation would be around 1.3°C when the IC consumes a power of 13 mW. This value is slightly above the maximum allowable temperature increase stated in previous research. On the other hand, the power density generated by the IC was 17.2 mW/cm^2, which is sufficiently low compared to the maximum permissible power density of 80 mW/cm^2. The influence of the 100

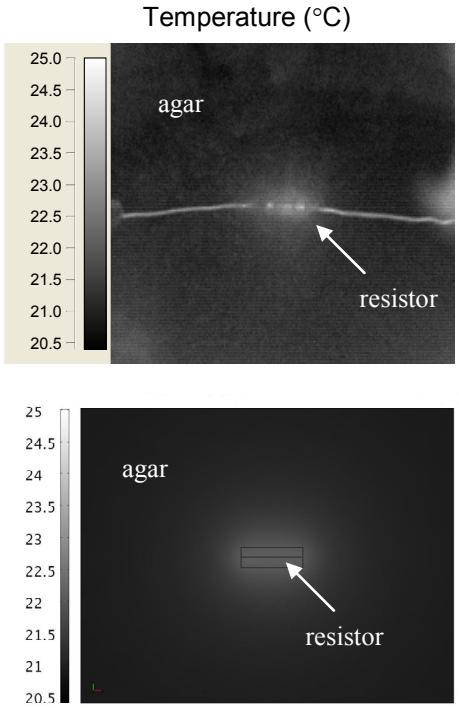

Figure 6: Top view of the measured (top) and simulated (bottom) thermal distribution through a resistor slightly inserted into agar. For comparison, both temperature profiles are displayed in black and white mode.

electrode tips on the temperature increase was also simulated. The surface of the 100 electrodes increases the overall surface area of the array and in effect, lowers the temperature increase.

The simulation was preliminarily verified through simple experiments using a resistor inserted into agar gel. The thermal distribution was detected using a thermal imaging camera. Temperature increases observed from measurement and simulation were in good agreement. In the future, we are planning to monitor the temperature of the neural interface while recording, using an on-chip temperature sensor. This will provide a reliable reference to validate the heat model and simulation method proposed here, and further allow monitoring the temperature of the neural interface during operation.

Acknowledgment

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