Simulated Temperature Increase in a Head/Eye model containing an Intraocular Retinal Prosthesis

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Introduction

In this paper, we study electromagnetic power deposition and temperature elevation in the human head due to an implantable intraocular retinal prosthesis designed to restore limited vision to individuals suffering blindness from outer retinal degeneration such as Retinitis Pigmentosa (RP) and Age-related Macula Degeneration (AMD). Retinal photoreceptors are almost completely absent in the retina of end-stage PR and AMD patients, while the bipolar cell and ganglion cells, through which the photoreceptors normally synapse, may survive at higher rates. The ganglion and bipolar cells remain intact, and due to the anatomy of the retina, they are in a position where they may respond to artificially induced electrical stimulation via an implant. The demonstration that direct electrical stimulation of retinal ganglion cells can create visual sensation in patients has been shown clinically [1]. Patients have been able to recognize English characters and other simple forms when stimulated by a small array of retinal electrodes.

The current implanted retinal stimulator is a 4.7mm X 4.6mm silicon microchip fabricated in AMI-1.2μm CMOS [2]. Power and communication with the implant is performed wirelessly via extraocular and intraocular coils coupled inductively at the frequency of 2 MHz. Associated electromagnetic power deposition in the tissues and power dissipation in the microchip collectively account for tissue heating. We have developed a high-resolution 2D human head and eye model at 0.25mm spatial resolution in order to numerically simulate temperature elevation in the eye and surrounding tissues. A 2D Finite Difference Time domain method (FDTD) with material independent absorbing boundary conditions is used to predict with high detail the specific absorption rate (SAR) induced via inductive powering and telemetry with the implant. A highly detailed heating pattern in the eye tissues due to SAR and power dissipation in the implanted stimulator is computed using a 2D time-domain numerical implementation of the bioheat equation. Results indicate that SAR levels are within ANSI/IEEE published safety limits. A peak temperature increase of 0.75°C associated with a worse case IC power-dissipation of 46.5mW (corresponding to the rare event of all the channels simultaneously active) is predicted.

Methods

The estimation of SAR is computed using the FDTD method [3]. The field distribution from the extraocular coil which occurs in the plane of the 2D head model can be approximated from two current sources of opposite polarity perpendicular to the model plane. Field values are scaled to be consistent with the theoretical magnetic field magnitude along the axis of the 3D coil. A D-H formulation facilitates inclusion of the Perfectly Matched Layer (PML) [4] absorbing boundary conditions within the 2D FDTD formulation. This permits the head/eye model to be truncated to the anterior region of interest containing the eyes and nose, in order to reduce the memory requirements and simulation time length.

In this study, temperature elevation in the eye and surrounding head tissues due to the prosthesis is of interest, particularly near the retina. Therefore, an eye model is developed here which includes 11 tissue types, including the retina. The model is derived from an accurate anatomical sketch of human eye, which has been discretized to a spatial resolution of 0.25mm. A 0.25 mm resolution head model is derived from anatomical data published from the *Visible Man Project*, and the final model has been generated by overlaying the eye model onto the head model. As it is expected that temperature increases arising from inductive coupling and from the active implant will be confined primarily to the region of the eye, the model is truncated posterior to the eyes (again made possible by the PML electromagnetic absorbing layers) as shown in Figure 1. The resulting model dimensions are 249 cells X 598 cells. The physical properties of the tissues in the head/eye model have been taken from the research literature with dielectric properties reported in [5] and thermal properties reported in number of sources [6-7]. The estimation of temperature increase is computed using a numerical thermal method based on the bioheat equation. The spatially and temporally discretized formulation described therein accounts for thermal conduction within the model and convective heat exchange between the model and the surrounding environment. The method considers such physical properties as mass density, specific heat, and thermal conductivity, and also accounts for basal metabolism in tissues, heating effects from SAR, and the cooling effects in blood perfused tissues. The coded implementation of the derivation reported in [6] has also been adjusted to account for power-dissipation in the implanted microchip and blood flow in the choroid of the outer retina, which is proposed to be influential in the auto-regulation of retinal temperature.

Results

Preliminary experiments with inductive coupling revealed that excitations on the order of 200Vpp at 2A in a 2-inch 10-turn exterior coil could yield reasonable power levels for the implant. Therefore, the model of Figure 1 was simulated at the frequency of 2MHz with 2A coil current using a PML thickness of 20 layers in order to estimate SAR. The coil is positioned anterior to the left eye and is modeled as two point sources of opposite polarity. The steady state SAR distribution is provided in Figure 2 with a peak SAR of 404mW/kg. Although the stimulator microchip is placed in the left eye, the right eye receives greater deposited power due to the electric field distribution, which increases away from the coil axis.

In the absence of any microchip power-dissipation, the SAR distribution of Figure 2 is used in the numerical thermal method on the head/eye model of Figure

1. Computed temperature elevation associated with the SAR is provided in Figure 3, with a maximum temperature increase of 0.0269°C predicted. As expected, the region of greatest temperature increase tracks the peak of the SAR distribution in the right eye. NCSU's Retina-3.5 stimulator IC [2] is considered for thermal simulations of implant power-dissipation. By design, this microchip produces biphasic current pulse waveforms for retinal stimulation on 60 output channels, all of which in the worse case we assume to be simultaneously active for these simulations (a rare event in practice). A worse case expected power-dissipation of 46.5mW corresponding to 600uA current amplitude, 3ms pulse widths, and 60Hz repetition rate is considered, consistent with stimulus experiments reported in [1]. Subsequently, this value of power-dissipation is used in the numerical thermal method on the head/eye model to predict temperature elevation due to the stimulator, but considered separate from the thermal influence of SAR. Associated results are provided in Figure 4, with a maximum predicted increase of 0.75°C in the left eye.

Conclusion

FDTD and thermal numerical methods have been used to predict temperature increase associated with the operation of an intraocular retinal prosthesis. An anatomically detailed head and eye model has been developed at 0.25mm resolution. A peak SAR of 404mW/kg has been computed, with an associated temperature increase of 0.0269°C predicted. An expected worse case power-dissipation in the stimulator microchip of 46.5mW has been projected with an associated temperature increase of 0.75°C predicted. It should be noted that this temperature increase is likely to be overestimated due to the use of a 2D approach that allowed us to consider a very high-resolution eye model. Future work will address temperature variations in a complete 3D model, where temperature gradients in all three dimensions will likely lower the maximum estimated temperature increases.

References

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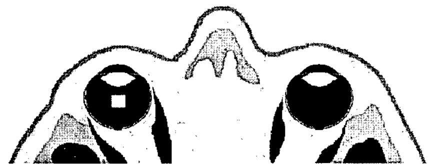

Fig. 1. Truncated human head/eye model (0.25mm resolution) with inclusion of the silicon stimulator IC model in the left eye

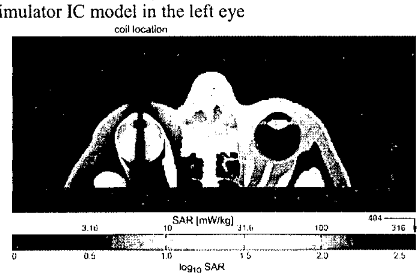

Fig. 2. SAR (log scale) at 2MHz irradiation for 2A primary coil current.

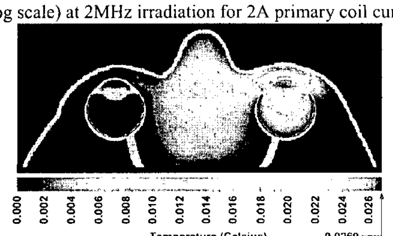

Figure 3: Temperature rise in the human head/eye model due to SAR alone

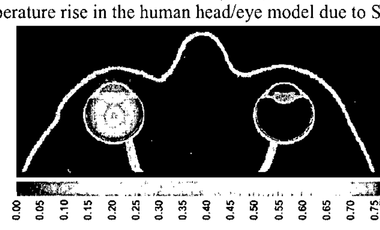

Fig. 4. Temperature rise in the human head/eye model due to power dissipation in the microstimulator (implant) IC alone