Computational Electromagnetics for a Retinal Prosthesis to Restore Partial Vision in the Blind

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Abstract

This paper addresses the latest advancements in the application of computational electromagnetics and smart telemetry systems to the development of a retinal prosthesis to restore the sight in the blind. Numerical methods and models have been developed to a) accurately characterize the thermal increase in the human head and eye associated with the operation of the retinal prosthesis, b) determine the current spread in the retinal tissue associated with the implanted microstimulator array, and c) design a high data rate smart telemetry system with extended capabilities with respect to traditional telemetry systems.

1. Introduction

Retinitis Pigmentosa (RP) and Age-related Macular Degeneration (AMD) lead to blindness through progressive loss of retinal photoreceptors. Attempts are underway to construct a visual prosthesis to recover a limited sense of vision for these patients with the aid of implantable electronic devices. Among various proposed electronic solutions, the epi-retinal prosthesis approach attempts to provide electrical stimulation to existing viable retinal tissues -living ganglion and bipolar cells- using an array of on-chip stimulus circuits placed on the surface of the retina. The dominant mechanism for power and data communication for the current retinal prosthesis has been wireless inductive telemetry using coils.

Two-dimensional Finite-Difference based numerical methods for both electromagnetic and thermal modeling have been used to determine the influence of the Specific Absorption Rate (SAR) and stimulator Integrated Circuit (IC) power on tissue heating under different operational conditions and different hypothesis on choroidal blood flow and thermal conductivity of the complex implanted circuitry. Two- and three-dimensional 0.25mm high-resolution human head models (Fig.1) have been developed with the aid of a new semi-automatic graphical segmentation algorithm and an interpolation scheme in order to capture the finest details of the eye anatomy.

A novel multiresolution impedance method is proposed to model the spread of the current in the retina induced by the implantable microstimulator. This method will allow us to optimize the design of stimulating array and accurately determine the magnitude of the current within retina layers for various microelectrode geometries.

Finally, novel solutions for smart data telemetry are proposed and initial numerical results are presented.

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2. Methods and Results

2.A. Temperature Increase in the Eye Due to the Operation of the Prosthesis.

A two-dimensional D-H Transverse Magnetic (TM) formulation of the Finite-Difference Time-Domain (FDTD) method [1, 2] has been used to compute the induced electromagnetic energy in a 0.25 mm resolution head model derived from the "Visible Man Project." This formulation has the advantage that the Perfectly Matched Layer (PML) absorbing boundary conditions are independent of the background dielectric materials in the FDTD mesh, thus allowing the truncation of the head model as described in [1] in order to limit the computational space.

The thermal elevation in biological tissue has been computed by means of a discretized bio-heat conduction equation [3], which includes the heating effect of basal metabolism, A_0, and the cooling effect of blood perfusion, B, in the tissues. For tissue that is irradiated electromagnetically, the bioheat equation is further expanded to account for the heating effect of specific absorption rate, SAR. Furthermore, the dissipated power of the implanted stimulator IC, P_{chip}, is also expected to raise tissue temperature and is included in the bioheat equation formulation.

The current version of the telemetry system includes an extra-ocular transmitting multi-turn coil of diameter two inches located at a distance of approximately 2cm from the human eye, and an intra-ocular receiving multi-turn coil of diameter 7mm that replaces the human lens. The extra-ocular coil needs to carry a current of 2A to deliver the necessary power to the intra-ocular unit. The magnetic field associated with an external coil carrying a current of 2A has been used as the source value to expose the human head model.

The power dissipated by the implanted microchip has been both measured and computed by means of SPICE simulations. Values of dissipated power ranging from approximately 7 mW to approximately 50 mW have been observed depending upon the bias voltage, frame rate, and pulse width of the biphasic stimulus.

We have concluded that, in absence of choroidal blood flow, which corresponds to the case of blood flow rates that are not sufficient to carry away a significant amount of heat, a maximum temperature rise of 0.0685 C is induced by the external telemetry coil in the eye that does not contain the implanted microchip. Conversely, when considering choroidal blood flow, corresponding to the case of blood flow rates that are such to maintain the temperature of the choroid at a steady 37 C, a reduced maximum rise of 0.0479 C is induced by SAR. The largest temperature increase associated with the operation of the retinal prosthesis has been shown to be due to the power dissipated by the stimulator IC. A worse case temperature rise of 0.6123 C in the eye with the implant in the absence of blood flow and a reduced peak increase of 0.4349 C when accounting for blood flow has been recorded in this case. It should be noted, however, that maximum temperature increase induced on the retina was lower than 0.1876 C when the implanted microchip was collocated in the center of the eyeball. Results closely parallel recent experimental results in animals, especially for the case of absence of choroidal blood flow. This suggests that actual choroidal blood flow rates are not such to enforce a constant 37 C on the choroid, as in the case of "infinite" blood flow.

2B. Multiresolution Impedance Method for Current Spread Computation.

A novel multiresolution impedance method is proposed to efficiently compute the spread of the current induced in the human retina by the implantable microstimulator array. While the impedance method in its original form is based on the discretization of the scattering objects into equal-sized cells [4], our formulation decreases the number of unknowns by using an automatic mesh generation method that does not yield equal sized cells in the modeling space. This formulation, currently developed in two dimensions and extendable to three dimensions, will facilitate a very high resolution model in the region of the retina while maintaining a relatively coarse resolution in regions of the human head distal from the stimulating electrodes.

Results indicate that the multiresolution impedance method achieves a cell count reduction of 50 to 80 % with respect to the traditional formulation of the impedance method when all the material boundaries in the human head are modeled at a resolution of 0.25 mm and a coarser resolution is used elsewhere.

2C. Smart Telemetry Systems

While the current retinal prosthesis system supports a total of 60 electrodes, to achieve useful vision it will be necessary to increase the number of electrodes to at least 1024 (32x32 array of electrodes) and possibly more in future generations. The stimulating electrode array is characterized by a repetition rate of 60 frames/sec, with each electrode represented with a 10 bits string. Under these conditions of high data rate telemetry, it is convenient to separate the power carrier from the data carrier, essentially operating with a dual-frequency telemetry system. This permits power-efficient solutions that use back-telemetry to optimize the overall quality of the link. Thus, via detectable changes of the internal unit, the primary unit obtains information on the instantaneous power level necessary to the internal unit and possible malfunctions of electrodes.

Proposed novel solutions include a system where the implantable unit is equipped with a microstrip patch antenna for data telemetry and a coil for power delivery, or two coils operating at different frequencies for power and data telemetry. Toward the realization of these novel solutions, a new microstrip antenna of dimensions 6 x 6 x 1.5 mm and operating at the frequency of 2.44 GHz has been developed. The size of the antenna is such to render possible the implantation in the human eye, in place of the human lens. This antenna achieves a bandwidth of 30 MHz, with –30dB coupling between externally mounted antenna and internal implanted antenna.

3. Conclusions

The latest advances in computational electromagnetics as applied to the realization of a retinal prosthesis to restore the sight in the blind have been presented. It is shown that computational electromagnetics offers a viable solution for (i) establishing the thermal and electromagnetic safety of the retinal prosthesis, (ii) designing stimulating electrodes so as to induce the desired current densities in the various retinal layers, and (iii) designing novel smart telemetry systems.

4. Acknowledgements

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5. References

[1] G. Lazzi, O.P. Gandhi, and D. Sullivan. "Use of PML absorbing layers for the truncation of the head model in cellular telephone simulations". *IEEE Transactions on Microwave Theory and Techniques*, 48(11):2033–2039, November 2000.

[2] D. Sullivan. *Electromagnetic Simulation Using the FDTD Method.* IEEE Press, New York, NY, 2000.

[3] P. Bernardi, M. Cavagnaro, S. Pisa, and E. Piuzzi. "SAR distribution and temperature increase in an anatomical model of the human eye exposed to the field radiated by the user antenna in a wireless LAN". *IEEE Transactions on Microwave Theory and Techniques*, 46(12):2074–2082, December 1998.

[4] O.P. Gandhi, J.F. DeFord, and H. Kanai. Impedance method for calculation of power deposition patterns in magnetically induced hyperthermia. *IEEE Transactions on Biomedical Engineering*, 31:644-51, 1984

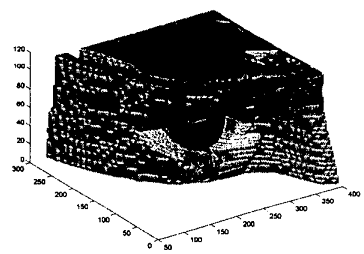

Figure 1. Three-dimensional 0.25 mm human head model section containing the right eye developed from the visible man. The eye has been separately reconstructed to identify 11 different tissue types.

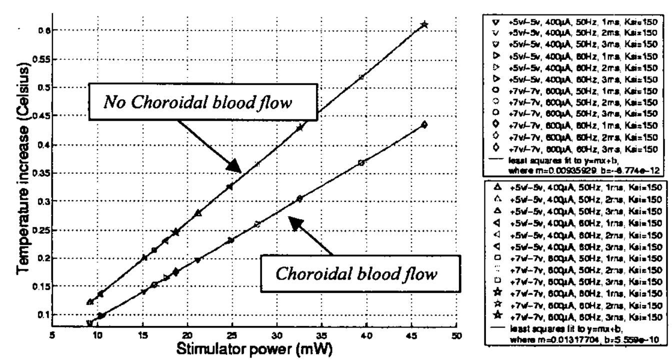

Figure 2. Comparison of predicted ocular heating versus stimulator implant power while considering the absence and presence of choroidal blood flow.