

SAR Distribution and Thermal Elevation in a Human Head Model due to the operation of the Data Telemetry Link and Implanted Chip in a Retinal Prosthesis

Keyoor Gosalia* and Gianluca Lazzi

Department of Electrical and Computer Engineering, NC State University, Raleigh, NC

1 Introduction

Retinal prosthesis is a rehabilitative device being designed to replace the functionality of damaged photoreceptors in patients suffering from outer retinal degeneration caused by diseases like retinitis pigmentosa (RP) or age related macular degeneration (AMD). Clinically, it has been shown that pattern electrical stimulation, when provided on the surface of the retina, can lead to the perception of simple shapes and forms in human subjects [1], thus partially reversing the visual loss. The retinal prosthesis, in its current stage of development is a dual unit device. The extraocular unit comprises of the video capturing and processing chips and an amplifier and primary coil. Intraocular unit contains the secondary coil, rectifier and signal processing chips and an electrode array [2]. Conventionally, power and data communication between the external and internal units of such prosthetic devices has been accomplished by a single low frequency telemetry link using inductive coupling between a pair of coils. In [3], mutually exclusive power and data transfer was proposed and the viability of a high bandwidth microwave data telemetry link was computationally demonstrated for a retinal prosthesis.

In this work, we use the 3-D Finite Difference Time Domain (FDTD) method to investigate the microwave data telemetry link at two widely different frequencies and examine the power deposition in the head-eye tissues quantified as peak 1-g SARs for an estimated maximum transmitted power. A 3-D thermal analysis is also performed to determine the increase in the steady state temperature distribution in the head-eye tissues due to the operation of the implanted chip.

2 Methods

2.1 Head Model and Antenna Design

In order to accurately represent the tissues of the head and eye, a 0.25 mm resolution head model was developed from the set of 1 mm resolution cross sections obtained from the National Library of Medicine (NLM) "Visible Man Project". A total of 25 different tissue types were identified in the portion of the model extracted to be used in the computational domain and their dielectric properties were obtained at two different frequencies of 1.45 GHz and 2.44 GHz from the online database of the Italian National Research Council as noted in [3].

Owing to the nature of the application, both the antennas—transmitting (extraocular) and receiving (intraocular) had to be very compact, robust and lightweight radiating structures and hence microstrip patch antennas were selected and designed with a high dielectric constant of $\epsilon_r = 9.2$. The extraocular antenna was designed to have dimensions within 25×25

mm to fit on a pair of glasses to be worn by the patient. The intraocular antenna was to be designed with dimensions less than 6×6 mm to accommodate it within the sclera muscles of the eye (5–6 mm posterior to the cornea). In the first case, as reported in [3], both the antennas were designed with the above mentioned dimensions to resonate at 2.44 GHz. At such a high frequency of 2.44 GHz, the receiver architecture (preceding the IF amplifier stage in the signal processing chips) becomes exceedingly complex and difficult to implement in the experimental stage. Hence, the performance of the data telemetry link was also investigated at a much lower frequency of 1.45 GHz. Hence, for this second case also, extraocular and intraocular antennas were designed with the same dimensional restrictions (as noted above) as for the first case. Compact designs for the intraocular antenna at 2.44 GHz and 1.45 GHz (extremely compact) were realized by employing several size reduction techniques. Strategically placed slots (inductive loading) and shorting pins were utilized to realize and implement these compact designs for the intraocular antenna.

These pairs of transmit-receive antennas at both the frequencies of 2.44 GHz and 1.45 GHz were introduced in the head model and the intraocular antenna was covered by a 0.5 mm insulating material and embedded between the sclera muscles of the eye. The extraocular antenna was kept in front of the eye (in free space) at a distance of 25 mm from the intraocular antenna as depicted in Figure 1. The entire system was modelled using an in house 3-D FDTD code and the coupling performance between the antennas was characterized at both the frequencies of 2.44 GHz and 1.45 GHz.

2.2 SAR and Thermal Elevation Measurements

Calculations measuring SAR were performed at the frequencies of 2.44 GHz and 1.45 GHz at which the coupling performance of the data telemetry link was characterized. Peak 1-voxel and peak 1-g SAR values were obtained for an estimated maximum radiated power of 50 mW. The thermal elevation in the biological tissue was computed by means of the bioheat equation which includes heating effects of basal metabolism A_0 and the cooling effect of the blood perfusion B in the tissues. In this work, influence of the SAR on heating was not considered and only the worse case power dissipation of the implanted stimulator IC was considered as the source of heat inside the head model. The resulting expanded bio-heat equation is given as:

$$C\rho\frac{\partial T}{\partial t} = \nabla \cdot (K\nabla T) + A_0 - B(T - T_b) + \underbrace{P_{chip}^{(density)}}_{HeatSource} \quad \left[\frac{W}{m^3} \right] \quad (1)$$

where $\nabla \cdot (K\nabla T)$ is the thermal spatial diffusion term, for Celsius temperature, T , thermal conductivity, K , specific heat, C , mass density, ρ , and blood temperature, T_b , assumed constant at 37°C. And the equation governing the convective exchange of the heat at the boundary of the tissues is given as:

$$K\frac{\partial T}{\partial n}(x, y, z) = -H_a(T_{(x,y,z)} - T_a) \quad \left[\frac{W}{m^2} \right] \quad (2)$$

where $T_{(x,y,z)}$ is evaluated on the surface, n is the surface normal, H_a is the convection coefficient for heat exchange with the environmental ambient temperature. Equations 1 and 2 are spatially and temporally discretized based upon the derivation in [4]. The chip is

modelled as a $4 \times 4 \times 0.5$ mm in size hinged between the sclera muscles and in this study, choroidal blood flow was not assumed to be fixed at 37°C but allowed to vary naturally. Temperature elevation in various portions of the head model was computed for a maximum chip power dissipation of 12.4 mW for 48 minutes.

3 Results

For the same size transmitting (extraocular) antennas and receiving (intraocular) antennas at both frequencies of 2.44 GHz and 1.45 GHz, coupling observed is as shown in Figure 2. At 2.44 GHz, computed coupling is -33.5 dB and at 1.45 GHz, it is -48.2 dB for a distance of 25 mm between external and internal antennas. This deterioration in the coupling performance is attributed to the decrease in the efficiency of the antenna system due to increased compactness at 1.45 GHz.

Current SAR results show that for a maximum antenna transmitted power of 50 mW, the peak 1-g SAR at 2.44 GHz is 1.592 W/kg and at 1.45 GHz is 0.834 W/kg as reported in Table 1. Also, at both frequencies, maximum deposition of energy takes place in the tissues of the forehead just above the eye and it may be due to the fact that this region of the head model is closest to the radiating extraocular antenna. In the thermal elevation analysis, an ambient temperature of 24°C was considered and the chip was allowed to dissipate 12.4 mW of power for 48 minutes. Contribution of SAR to heating has not been considered in the present study. Figure 3 shows the relative increase in temperature at various regions in the model. A maximum increase of 1.086°C was observed at a point on the chip's insulating surface. After 48 minutes of heating, the temperature increase on the retina and in the vitreous cavity remained within 0.2°C while temperature increase of portions of white matter in the brain and head sinuses remained within 0.1°C.

4 Conclusion

Coupling performance of a microwave data telemetry link at frequencies of 2.44 GHz and 1.45 GHz has been computationally examined. Coupling deteriorates by almost 15 dB as frequency is reduced (-33.5 dB at 2.44 GHz to -48.2 dB at 1.45 GHz) while keeping the antenna sizes constant. This decrease is attributed to degradation in antenna efficiency at 1.45 GHz (due to extreme compactness of the intraocular antenna). SAR measurements were also carried out at both the frequencies of interest and it was observed that for an estimated maximum antenna transmitted power of 50 mW, peak 1-g SAR was within 1.6 W/kg as stipulated in the safety guidelines. An investigation of the thermal elevation in the various tissues of the head-eye region due to the operation of an implanted chip shows a maximum temperature increase of 1.086°C on the chip after 48 minutes of power dissipation of 12.4 mW. Temperature increase of the retinal tissue was observed to be below 0.2°C and in the brain tissue to be below 0.1°C. Future work will involve characterization of the coupling performance for different antenna designs and also SAR and thermal elevation measurements for the complete prosthetic system including the low frequency power coupling coils. It should also be noted that coupling between external and internal antennas increases considerably when the distance between the two antennas is reduced. This and other aspects of the design will also be subject of future studies.

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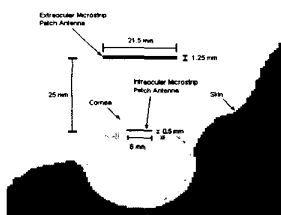


Figure 1: A 2-D view of the model showing the relative location of the Extraocular and Intraocular antennas.

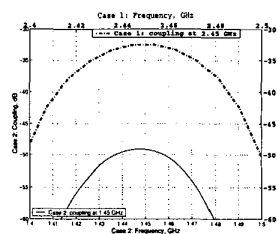


Figure 2: Computed coupling performance of the antenna system at 2.44 and 1.45 GHz

Table 1: SAR values at both frequencies

Frequency (GHz)	Peak 1-voxel (W/kg)	Peak 1-g (W/kg)
2.44	8.949	1.592
1.45	14.206	0.834

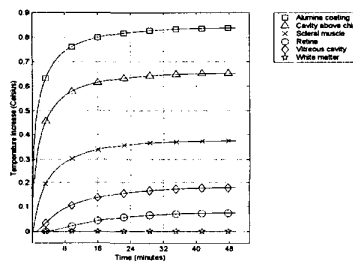


Figure 3: Simulated heating due to chip dissipated power of 12.4 mW