Prediction of Implant Tip Heating Using Modified Transmission Line Method (MoTLiM) under MRI

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INTRODUCTION:
Radio frequency (RF) heating is a serious problem for patients with medical implants during MRI examination. The maximum temperature rise due to RF induced currents typically appears at the tip of the implant leads and may cause tissue burns. Although this problem has been shown multiple times in the literature both by experimentally [1] and computer simulations [2], an analytical model has never been developed. The lack of an analytical model creates difficulties in the design of MRI compatible implant leads. In this study we demonstrate the use of Modified Transmission Line Method (MoTLiM) [3] to solve SAR gain and temperature rise around the implant lead.

THEORY:
MoTLiM is a method which models the implant lead in a similar way with lumped element model of transmission line. To solve induced currents knowledge of incident E-field pattern, electrical parameters of medium and lead properties are required. In MoTLiM, current along the lead is found analytically for a known E field by solving a second order differential equation with constant coefficients. By carrying on some electromagnetic analysis charge distribution and total E field along the lead is found. This information is used to calculate SAR and SAR amplification. Finally bio-heat equation is used to calculate the temperature rise by applying Green's function as described in [4]. The block diagram of the overall method is shown in Fig 1.

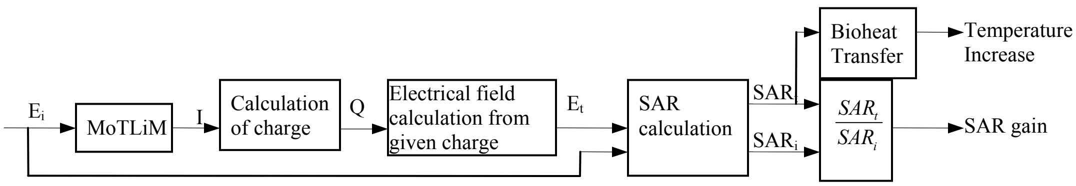

Figure-1 Block diagram representation of calculation procedure of SAR gain and temperature

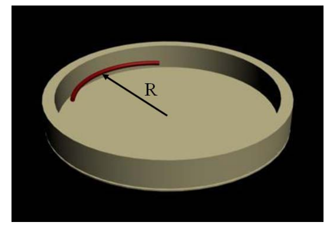

Figure-2 Position of lead inside phantom. This design produces a uniform E-field along the lead

EXPERIMENTAL VERIFICATION:
For experimental verification of our method, a cylindrical phantom with height of 8cm and radius of 18.5cm was utilized. Measured conductivity of phantom is 0.65S/m and relative permittivity is 92. Electrical properties of phantom were measured using the proposed method in reference [5]. During experiments a bare lead with length of 16cm and diameter of 0.65mm was positioned 16 cm far from the center of phantom as seen in Fig 2. This design ensures that lead is exposed to uniform E field. As seen in Fig 1 incident E-field, E_i, is the only parameter needed to solve temperature increase and SAR gain. For this specific phantom geometry E-field is in the circumferential direction and can be calculated as $E_\rho = -iB_{10}R\omega f(t)/2$ where $f(t)$ is the envelope, B_{10} is the magnitude, ω is radial frequency of the applied RF field and R is the distance of wire from center of the cylindrical phantom as seen in Fig 2. B_{10} can be calculated from equation $\alpha = \gamma B_{10}\int f(t)dt$ where α is the flip angle and γ is the gyromagnetic ratio. It should be noted that α is calculated through actual flip angle method [6].

SAR along the lead can be calculated using above calculated E_i by carrying on simple electromagnetic analysis. Temperature increase can be found by convolving calculated SAR with Green's function. Green's functions are solutions of tissue bioheat equation, therefore heating of the lead tip must be calculated as if it is located in a tissue. Brains thermal diffusivity, 0.143 cm^{-2}/sec, and thermal conductivity, 0.5 W/m, values were used.

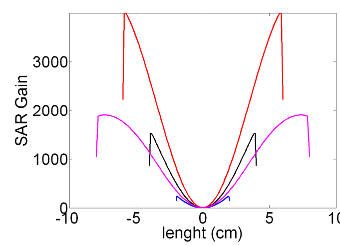

Figure 3 SAR gain calculated using MoTLiM on the surface of bare wires with lengths of 4, 8, 12 and 16cm

In [1] it is proposed that the steady state temperature of perfused tissue can be predicted with to temperature measurement using a perfusionless phantom at the time point which is equal to the tissue perfusion time constant. Relying on this method, the experimental data from a gel phantom was used to predict steady state heating of a tissue. Brains time constants, 72-150 sec, were used.

RESULTS:
Theoretically calculated SAR gain values, under 3T static field, for different lengths of leads in a medium with conductivity 0.4S/m and relative permeability of 80 are shown in Fig 2.

Predicted temperature increase is 4.8°C for time constant 72 sec and 6°C for 150 sec and these two are the upper and lower bounds as seen in Fig 4. Whereas, calculated steady state temperature increase is 10°C which is above the predicted range, so there is 40 % error between calculation and predicted temperature increase. Up to 30% error may be originating from used prediction method [1]. Also probe positioning and probe sensitivity are the other possible sources of error. Our temperature probe (NeoOptix, CITY, COUNTRY) is has a 5mm long sensitive region. However, theoretical calculations were done for much smaller area.

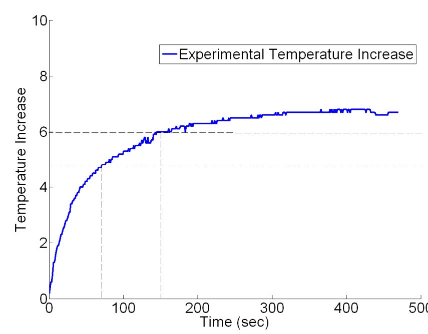

Figure-4 Experimental Heating as a function time. Note that when object is perfused the steady state temperature will be approximately equal to the temperature value at the perfusion time constant [1].

CONCLUSION:
Using MoTLiM, implant tip heating calculation is straightforward with known incident E field pattern. It easily predicts tip heating for different patient positioning. MoTLiM gives an analytical solution which contains all tissue and lead parameters. So using MoTLiM, lead tip heating problem can solved in a straightforward way and intuition on the design can be obtained.

REFERENCES:
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