RF heating model of active implants during MRI examinations

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Introduction

There is an increasing demand on MRI exams of the patients with active implants such as pacemakers, implantable cardioverter defibrillators (ICDs) and deep brain stimulators (DBSs). Unfortunately, patients with these implants are not allowed to have an MRI exam, because these implants are incompatible with MRI scanners. Primary reason for their incompatibility is radio frequency (RF) heating. The temperature increase at the implant lead tip may cause irreparable injury in the tissue. In the past, this problem has been analyzed with phantom, animal and human experiments. In this study, however, we have theoretically analyzed the amount of temperature rise at the lead tip of these implants and derived a simple approximate formula for the *safety index* (1) of implants, which is the temperature increase at the implant lead tip per unit deposited power in the tissue without the implant in place. This formula enables us to understand the parameters affecting the lead temperature rise and also helps us develop methods to overcome this problem.

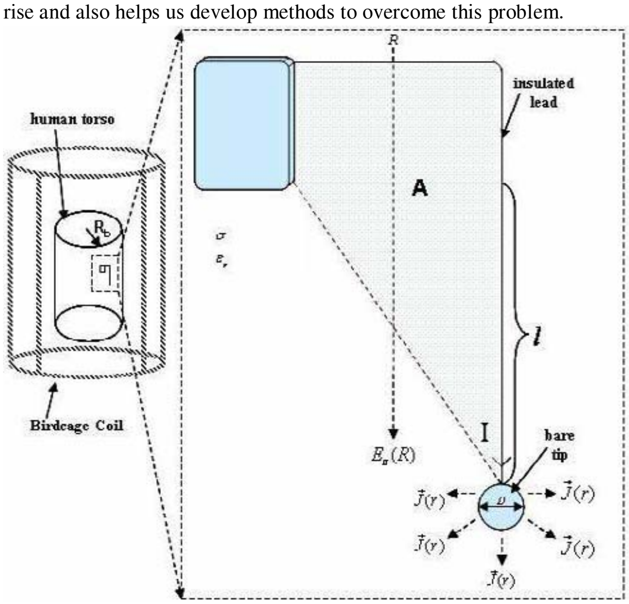

Fig. 1. Simplified implant model

Theory

Active implants are common in structure including at least one insulated lead with bare lead tip and a generator with metallic case (Figure 1). Maximum RF heating occurs at the tip of the lead. During RF application, unwanted and at the same time, unavoidable heat is deposited to the body, which is measured using specific absorption rate (SAR). Due to presence of the implant, SAR may increase significantly. In order to analyze this, we firstly calculated induced current on the lead. Assuming that this current leaves the implant at the tip of the wire uniformly in all directions, heat distribution around the tip of the lead was found. Later, this information was used to calculate the temperature distribution using the Green's function averaging technique (2). Finally, resultant peak temperature was normalized with the applied SAR to find the safety index (1). In these calculations, the electrical properties (conductivity and permittivity) and thermal properties (perfusion, heat capacity and diffusion) are assumed to be uniform around the tip of the lead. In addition, we modeled human torso as a cylindrical object. We assumed that size of the implant including its leads is significantly smaller than wavelength hence quasi-static assumptions can be used. Object is assumed to be placed at a radial distance of R from the center with an angle of θ. The results of our formulation yielded the following equation:

$$SI = \frac{\Delta T_{\max}}{SAR} = \frac{1}{2\alpha c_t}\left(l - j\frac{A}{R}e^{j\theta}\right)^2 f(D\nu)$$

where SI stands for "safety index", α and c_t are respectively the thermal diffusivity and the heat capacity of the tissue, ν is the lumped perfusion parameter (2). In this equation, l is the z-component of the distance between IPG and the electrode tip. "*A*" stands for the area of the loop generated by lead. We call $f(D\nu)$ *Perfusion Correction Factor.* Although this is a complicated function analytically, it has a simple appearance when we plot (Figure 2).

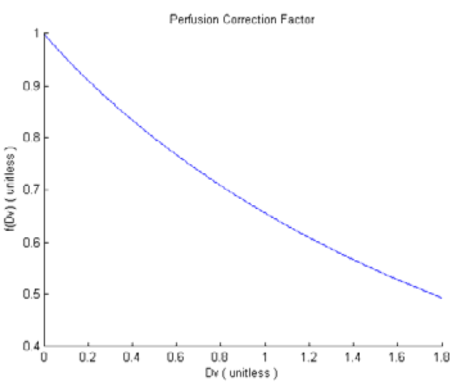

Fig. 2. Perfusion correction function.

Discussion

The above formulation gives us an easy to understand tip heating formulation. We will discuss each of the three components of the equation starting with the last component.

The perfusion correction factor approaches to 1 as the perfusion and the lead diameter, D, decrease. Note that for typical values of lumped perfusion parameter (less than 0.5 mm^{-1}) and lead tip diameters (1mm), this correction factor is between 1 and 0.5 and therefore can be ignored if a perfusion independent, worst case SI value is desired.

In typical configurations, *A/R* value is less than l, but since this is variable depending on the type of the implant and application, we selected not to ignore *A/R*. If the configuration of the implant becomes such that l and *A/R* terms are comparable, there will be angle dependence. As can be seen for the worst angle (90°), these terms adds up. This suggests that, when phantom heating experiments with implants are carried out, worst angle must be sought by rotating the phantom.

The last discussion point is on the thermal parameters α and c_t. Phantom experiments needs to be carried out with care since phantom (gel) and body thermal parameters may not match. These body thermal parameters can be found in literature and used in this equation.

For the sake of obtaining some numerical values, if we ignore the perfusion correction factor and assume a small A/R, and use typical thermal parameters ($\alpha = 1.4\times10^{-7}$ m^2/sec and c_t = 3800 Watt-sec/kg/°C), we would obtain a very simple expression SI = 0.09 l^2 where l is given in cm. In other words, while 1cm lead would not cause any significant heating, a 10cm lead heats to 9°C when it is exposed to 1 W/kg SAR.

Conclusion

To sum up, we formulated RF heating of active implants in MRI systems with a very simple formula such that it is very easy to foresee how much temperature can occur when a patient with implant needs to have an MRI exam. By adjusting power level of a specific pulse sequence, one may obtain a safe scan.

References

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