Investigating RF heating of pacemakers in MRI using a safety index

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Introduction

In the United States, there are approximately 750,000 patients with cardiac pacemakers or implantable cardioverter defibrillators (ICDs), and this number is growing. Among these patients, 60,000 require an MRI examination every year [1]. Unfortunately, MRI scanners are incompatible with these implants.

MRI is known to be a safe diagnostic procedure; however, three magnetic field sources (the static magnetic field, the RF pulse, and the gradient field) may become the sources of safety problems in MRI. Possible safety issues, related to cardiac pacemakers and ICDs are: 1) the possibility of dislocation of the pacemaker due to static magnetic field; 2) the possibility of undesired pacing of the heart by the induced currents to the pacing leads; 3) the possibility of causing malfunction in the electronic circuit of the pulse generator due to interference from the MRI electromagnetic field; 4) the possibility of changing the mode of the pacemaker by causing the switching on/off of the reed relays in the implant; and 5) the possibility of excessive heating around the implant due to the concentration of the electromagnetic field around the pacemaker.

Previous work on this subject involved experiments in which patients using cardiac pacemakers were scanned in an MR scanner [2],[3] and the ECG signal was recorded simultaneously. Although no serious acute injuries occurred, alterations in the ECG signal were observed in certain patients, implying that further investigation is necessary. In our study, the RF safety of a cardiac pacemaker is considered as two separate problems: 1) the safety of the leads; and 2) the metallic case of the pacemaker. RF heating of wires in interventional MRI has been investigated [4] and the results are applicable to pacemaker leads. The intention of this study was to further investigate RF heating on cardiac pacemakers by analyzing the pacemaker's case.

Methods

Software was written using MATLAB (version 6.5, Mathworks Inc., Natick, MA) to investigate the heating effect of cardiac pacemakers under the RF field in MRI. The Finite Difference Time Domain (FDTD) method was used in the software and the computation domain was terminated using Mur's Absorbing Boundary Condition (ABC).

In order to verify this software, an experiment was conducted using the setup in Figure 1. Three temperature probes were placed and data were recorded for 10 minutes. A GE Signa 1.5T MR scanner was used, with all the gradients shut off and a body coil was used to irradiate the phantom. A cylindrical phantom (20cm diameter, 45 cm height), containing 22gm/liter of NaCl solution was used. The pacemaker (Medtronic Kappa 700) was located 6 cm from the top of the cylinder. All the probes were oriented in the longitudinal direction, and probes A and B were placed tangential to the pacemaker. The radial distance from the center to probes A and C was the same. Thus, heating observed due to the pacemaker could be compared with regard to the reference probe C. Both numerical and experimental values were compared afterward and verified.

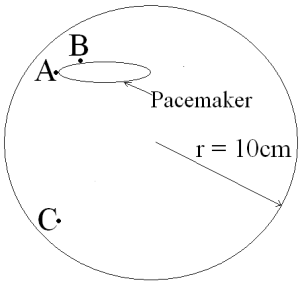

Fig1: Cross section of experimental setup (A,B,C represents temperature probes)

Having verified the results of the computational simulation with the experimental results, the study was extended to a more realistic phantom, a frequency-dependent tissue model (human dosimetry model), developed by the United States Air Force Research Laboratory (AFRL) [5], as seen in Figure 2. From the SAR distribution, the temperature distribution was calculated using the Bioheat equation. For local heating, the Bioheat equation is treated as a linear shift-invariant system, similar to the Green's function approach in interventional MRI [6], with the following assumptions: 1) the thermal parameters (α: diffusivity, k: thermal conductivity , v: perfusion) are constant in the local region of interest; and 2) the pacemaker is small with respect to the body. The perfusion value of the resting muscle cell was used, which was assumed to be independent of temperature. The safety index was calculated, which is the in vivo temperature increase caused per unit of applied SAR (W/kg).

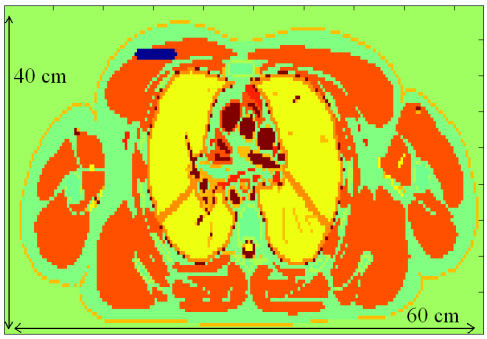

Fig2: Cross-section of AFRL dosimetry model including a cardiac pacemaker

Results

Perfusion is not accounted for in the experimental setup, thus the derivative of the temperature with respect to time is proportional to the SAR distribution according to the Bioheat equation. Finally, the SAR gain, i.e., the ratio of SAR distribution with the pacemaker to the SAR distribution without the pacemaker, can be found by taking the ratios of the derivatives of probe A data to probe C. The FDTD results lay within the error margin of the experiment, as seen in Table 1.

Probe	Experiment	FDTD
A	2.85	2.87
B	0.85	0.68
C	Ref	Ref

Table 1: SAR gain values for the Experiment and FDTD method

Using the AFRL human dosimetry model [5], for 1W/kg of total SAR applied to the body, a temperature change of 1.82°C was observed (Figure3),which is equal to the safety index(°C/W/kg). Thus, according to the United States Food & Drug Administration's (FDA) 2 °C temperature increase limit in the trunk, we conclude that the SAR applied should not exceed 1.1W/kg, in order to ensure a tolerable temperature increase.

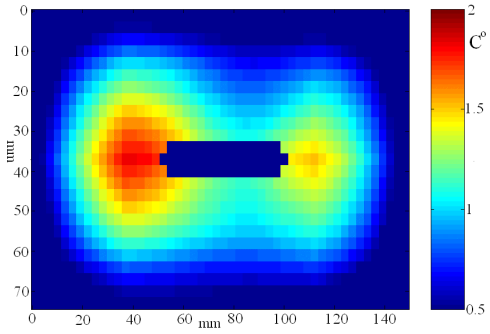

Fig3: Temperature distribution (transverse plane) around the pacemaker (70*150mm region) placed in AFRL human dosimetry model for 1W/kg input power.

Discussion and Conclusion

RF safety criteria for a pacemaker's case have been proposed theoretically. In vivo experiments to determine the temperature distribution are necessary. According to the results obtained here, the safety index was found to be 1.82°C/W/kg, whereas a safety index around 10 °C/W/kg was observed for the wires [4]. Therefore, RF safety should be considered based on the pacemaker leads. In this study, RF safety was investigated separately for the pacemaker case and leads. In order to gain a more extensive understanding of the problem, investigation of the problem as a whole is necessary.

References: [1] http://www.gemedicalsystems.com **[2]** Roguin A et al. Modern Pacemaker and Implantable Cardioverter-Defibrillator Systems can be MRI safe: In vitro and in vivo assessment of safety and function at 1.5 Tesla. American Heart Association Scientific Sessions; Orlando, Florida, 200 Circulation 2003; 108(17): IV-372 **[3]** E. T. Martin et al. ISMRM 2003, #2445 **[4]** Yeung CJ, Susil RC, Atalar E, RF Safety of Wires in Interventional MRI: Using a Safety Index, MRM. 47:187-193, 2002. **[5]** www.brooks.af.mil/AFRL/HED/hedr **[6]** Yeung CJ, Atalar E, A Green's Function Approach to Local SAR Averaging for Interventional MRI, Medical Physics 28:826-832, 2001.

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