Heating of bilateral hip prostheses in a human body model induced by a multi-axis gradient coil set

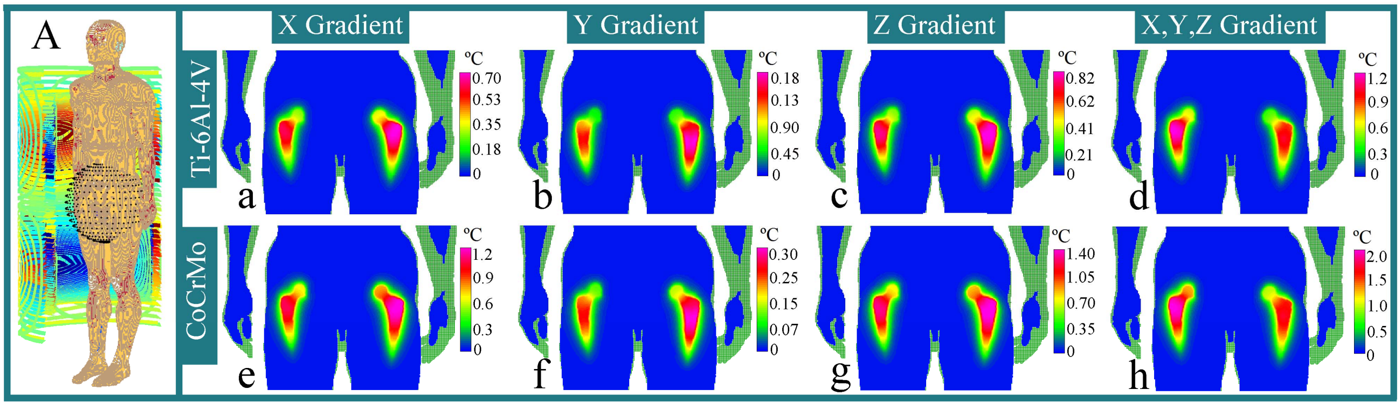
Hector Sanchez-Lopez[1], Luca Zilberti[2], Oriano Bottauscio[2], Jeffrey Hand[3,4], Annie Papadaki[5], Fangfang Tang[1], Mario Chiampi[6], and Stuart Crozier[1]
[1]School of Information Technology & electrical Engineering, The University of Queensland, Brisbane, QLD, Australia, [2]Istituto Nazionale di Ricerca Metrologica, Torino, Torino, Italy, [3]Centre for the Developing Brain, Kings College London, London, United Kingdom, [4]Division of Imaging Sciences and Biomedical Engineering, Kings College London, London, United Kingdom, [5]Neuroimaging Analysis Centre, University College London Hospitals, London, United Kingdom, [6]Dip. Energia, Politecnico di Torino, Torino, Italy

Target Audience: This work will be of interest to those engineers and clinicians dedicated to safety issues related to gradient coil fields and their interactions with large metallic implants.

Purpose: This study aims to determine the impact of 30 mT/m conventional gradient coils driven at 1 kHz on the temperature of two different types of hip implants. The need for MRI compatible prostheses is increasing particularly with the use of hybrid scanners and robotic interventions. Material geometry and electrical properties used in the prostheses are important not only for MRI scanners but also for patient safety. Limited attention has been given to the impact of these rapidly varying fields on large implants such as hip prostheses. A previous study demonstrated temperature increments up to 2 °C in an aluminum hip implant resulting from exposure to large duty cycle gradient fields [1]. The temperature increase in an implant depends on the prosthesis geometry, physical dimensions, material properties, pulse sequence and the relative position of the implant with respect to the DSV and here is a need to investigate ways of mitigating heating in large implants. This work studies the impact of a conventional multi-axis gradient set simultaneously driven at 1 kHz on temperature in two different materials used in a typical bilateral hip implant. The hip implant was inserted into the skeletal structure of a human phantom and a non-commercial frequency-domain code based on hybrid finite element (FE) - boundary element (BE) method was used to calculate the current density and the temperature distribution in the implant and surrounding tissues.

Method: Three whole-body shielded gradient coils were designed [2] to produce 30 mT/m within a 500 mm spherical DSV. The DUKE voxel model [3] of resolution 2x2x2 mm^3 was segmented into 77 tissue types and hip prostheses 168 mm long and with a 24 mm diameter femoral head were inserted into the skeletal structure to simulate a bilateral implant. The femoral head and the femoral stem reside within the DSV but close to the boundaries of the 500 mm DSV. Two materials were considered: Ti-6Al-4V alloy and CoCrMo alloy with electrical and thermal conductivities of $5.8\cdot10^5$ Sm^{-1} and 7.2 Wm^{-1}°C^{-1} and $1.16\cdot10^6$ Sm^{-1} and 14 Wm^{-1}°C^{-1}, respectively. The hybrid FE-BE method solves the electric vector potential within the human body and the scalar magnetic potential in the whole domain including air. The voxels on which the phantom is discretized are used as the finite element mesh, while the voxel faces on the body boundary are the surface elements for the BE technique [4]. The power dissipated by induced currents within the prostheses is the forcing term for the thermal simulation. Starting from basal conditions, the bioheat equation is solved by FE method under steady-state conditions, in terms of the temperature elevation [5], avoiding any assumption on the value of metabolic heat, blood and surrounding air temperatures. Simulations of the human phantom considered were: a) exposure to the changing magnetic field of each gradient coil driven alone at 1kHz.; b) exposure to the resultant magnetic field produced by all coils simultaneously driven in phase at 1 kHz.

Results: Figure A, shows the modified DUKE model facing the *x*-coil, the three gradient coils and the DSV covering the phantom hips. Figures a)-h) describe the temperature increment in a coronal section due to each gradient field and to the combined fields for Ti-6Al-4V and CoCrMo alloy prostheses, respectively.



Discussions and Conclusions: Figures a), b), e) and f) demonstrate that there is a strong dependency of the patient/implant positioning with respect to the individual gradient coil axes. The *x*-coil produces nearly four times more temperature increase than that produced by the *y*-coil due to the model positioning. Due to the enclosed structure of the *z*-coil the temperature increment is slightly larger than that produced by the *x*-coil. It is also noticeable that in one of the implants, the temperature rises slightly more than in other one, possibly due to small differences in the positions of the prosthesis stems within the femurs. In typical current sequences such as fat-sat or 3D-True-FISP, all three gradients are used intensively and therefore the temperature rise under these conditions is of concern. Temperature increments up to 1.7 times larger than those produced by the *x*-coil are predicted for the combined gradient fields (figures d) and h)). The results also demonstrate that the temperature increase associated with Ti6Al4V prostheses is smaller than that for CoCrMo prostheses.

This preliminary study is of importance as it contributes to the understanding of the gradient coil–implant interactions and the concomitant temperature rises. The modified phantom model together with powerful electromagnetic software provides a virtual testing lab capable of investigating flexible scenarios to answer diverse research questions such as: Can we modify the gradient coils to minimize the inductive coupling with the hip implant? What is the optimal material to produce a hip implant that it is tissue compatible, light, and strong and at the same time minimizes the induced currents? How could we tailor the gradient pulse sequences to control the temperature increases? How much temperature increase is produced in split gradient coils? We anticipate answering these research questions in an extended study.

References

[1] H. Graf, et al, J Magn Reson Imaging. 26(5),pp.1328-33. 2007.
[2] H. Sanchez, et al J Magn Reson, vol. 199, pp.48-55, 2009.
[3] A. Christ, et al, Physics in Medicine and Biology, vol. 55, Issue 2, pp. N23–N38, 2010.
[4] O. Bottauscio et al., "A GPU Computational Code for Eddy-Current Problems in Voxel-Based Anatomy", submitted to CEFC2014.
[5] L. Zilberti et al., Proc. 2013 Int. Conf. Electromagnetics in Advanced Applications (ICEAA), Torino, Sept. 2013, pp. 895-898.