Heating near Deep Brain Stimulation (DBS) Lead Electrodes during Imaging with a 3T Transceive Head Coil in Cadaveric Porcine Heads

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Introduction Development of a clinically feasible protocol is of significant interest to place the extra-cranial portion of a deep brain stimulation (DBS) lead such that to minimize heating near DBS electrode-tissue contacts during an MRI. Additionally, a validated engineering tool is needed to determine maximum heating near the electrodes to verify patient safety after a sequence. Harmful heating near DBS lead electrode-tissue contacts is a safety concern during a high and ultra-high field MRI. Placement of the extra-cranial DBS lead with respect to a head coil is expected to influence the heating significantly due to its relative closeness to the coil.

This preliminary work, first, studies the effect on the heating due to various placements of the extra-cranial DBS lead by measuring temperatures using fluoroptic probes near DBS lead electrodes during imaging with a 3T, transceive, volume head coil in cadaveric porcine heads. Measurement in cadaveric heads serves as an upper limit to the maximum heating in vivo due to the absence of the blood flow. Swine are recommended by the World Health Organization as appropriate thermo-physiologic models of humans due to comparable electromagnetic and thermal properties.

Second, a proton resonance frequency (PRF) shift based MR thermometry method is used together with a thermal model to develop a validated engineering tool to determine peak temperature changes near the lead during imaging. MR thermometry methods are regularly used to image in vivo temperatures; however, these methods are ineffective next to conductive devices due to susceptibility artifacts. A new theoretical bioheat model the generic bioheat transfer model (GBHTM) (1) has recently been developed and validated to determine in vivo heating at ultra-high fields; however, the model requires power density in the device or the boundary temperatures near the conductive device as inputs to simulate heating next to the device. Due to the ability to provide complementary pieces of information by the MR thermometry (i.e., temperatures outside the artifact region) and the GBHTM (i.e., temperatures inside the artifact region) the two methods are combined herein to develop a 'hybrid' approach to determine heating around conductive devices and evaluate patient safety right after an imaging sequence, while the patient waits in the scanner.

Experiment design and Methods A DBS lead with four electrodes at the distal end was implanted in cadaveric porcine heads (N= 3, mean animal head weight = 5.78 kg, SD = 0.32 kg). One fluoroptic probe each was taped to the scalp and two distal electrodes (i.e., electrodes one and two). Another fluoroptic probe was placed 6 mm away from the distal most, first electrode in the brain to validate MR thermometry outside the susceptibility artifact range. Heating was measured in each porcine head for the following four extra-cranial lead placements: lead looped at the top, side, and back of the head; and lead placed parallel to the coil axial direction. The area of the loop was maximized to maximize heating. Next, the instrumented head with the desired extra-cranial lead placement was placed in a 3T, tranceive head coil. A low whole head average SAR (<0.1 W/kg) gradient recalled echo (GRE) sequence was run to obtain baseline phase information near the device to conduct PRF shift based MR thermometry (scan time = 28 s). The susceptibility artifact range near the DBS lead for the GRE sequence was measured as ~<5 mm. Afterwards, a 641s long turbo spin echo (TSE) sequence was run at the maximum allowable whole head average SAR of ~3.2 W/kg (mean SAR = 3.16 W/kg, SD = 0.03 W/kg) to produce heating. Another GRE sequence was run right after the heating sequence to image phase changes and thus, temperature changes. The average maximum imaged temperature change outside the artifact range (i.e., 6 mm away from the first electrode) was used as input to the GBHTM. The GBHTM was used to simulate the temperature changes around DBS electrodes during imaging. The simulated temperatures were compared to the fluoroptic temperatures to validate the 'hybrid' approach.

Results and Discussion Figure 1 presents the effect of the extra-cranial DBS lead placement on the heating near DBS lead electrodes in cadaveric porcine heads. The heating was significantly reduced when the lead was placed parallel to the coil axial direction (peak temperature change = 1.5-3.2 ^{0}C) compared to when the lead was looped (peak temperature change = 5.1-24.7 ^{0}C) since the parallel placement minimized the rate of change of magnetic flux through the lead. The result presents a clinically plausible approach to minimize heating during imaging with the 3T head coil. Figure 2 presents a comparison of the temperatures outside the susceptibility artifact range imaged using the MR thermometry method and simulated using the GBHTM. Comparable temperatures demonstrated the promise of the 'hybrid' approach in simulating accurate heating near conductive devices (i.e., inside and outside the artifact range). Figure 3 presents the temperatures simulated by the GBHTM and measured using fluoroptic probes at and near DBS lead electrodes. Validating the hybrid approach, the simulated and measured transient temperatures near the scalp, electrode 2, and 6 mm distal from electrode 1 were comparable. Relatively large deviation in the simulated and measured temperatures near electrode 1 was attributed to the strong temporal and spatial temperature gradients and the placement of the fluoroptic probe near the electrode.

Next, the maximum temperature change should be ~< 4.0 ^{0}C (i.e., absolute temperature <41 ^{0}C) in clinical settings near conductive devices to avoid stressing/damaging surrounding tissue. This ~four times reduced maximum heating near the electrodes will result in more than four times lower temperature change outside the artifact range due to blood perfusion (~< 1.0 ^{0}C) in a patient. Accuracy of the PRF based in vivo MR thermometry has been shown to be > 1^{0}C. Therefore, an MR thermometry technique is needed to image temperatures outside the susceptibility artifact range with the accuracy better than 0.2 ^{0}C to satisfactorily implement the presented 'hybrid' technique. Exogenous contrast (e.g., TmDOTA$^-$) based MR thermometry may be a viable option to determine heating (2).

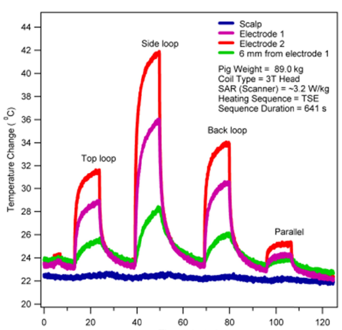

Figure 1 A typical heating near DBS lead electrodes during imaging with a 3T head coil in the cadaveric porcine head.

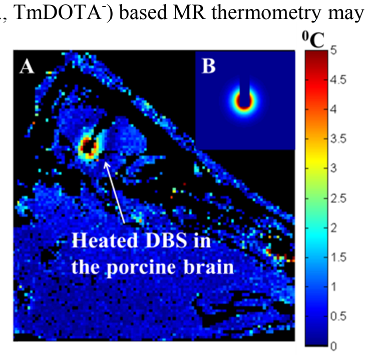

Figure 2 Imaged (Figure 2A) and simulated (Figure 2B) temperature change near DBS lead electrodes in the porcine brain.

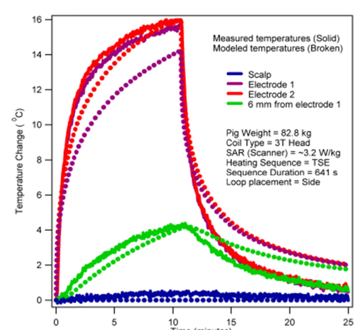

Figure 3 A typical comparison between measured and simulated temperatures in the porcine head.

Summary Heating near DBS electrode-tissue contacts during imaging with a 3T head coil was minimized by placing the extra-cranial lead parallel to the coil axial direction. Thus, design of clinically plausible implantation protocols for the extra-cranial DBS lead may be feasible for a given coil and device to minimize heating near the device during an MRI. An MR Thermomerty-GBHTM based 'hybrid' approach is shown to determine accurate heating near DBS electrodes during imaging at 3T.

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References 1) Shrivastava et al., Magn. Reson. Med 2011, 66(1), 255-63. 2) Hekmatyar et al., Int. J. Hyperthermia, 2002, 18(3), 165-179.