Radiofrequency Heating during Body Imaging in a 3T Body Coil and Patient Safety

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Target Audience All MR personnel including MR manufacturers, Clinicians, Researchers, Patients, Human Research Subjects, and Regulatory Bodies.

Purpose In vivo radiofrequency (RF) heating was simulated using the new, first principles based generic bioheat transfer model (GBHTM) in a digital pig (weight = 71.48 kg) and measured using fluoroptic probes in the scalp, brain, simulated hot regions in the body, and rectum of anesthetized swine due to power deposition from a 3T body coil [1]. The simulations and fluoroptic measurements were performed to develop a validated bioheat transfer model to accurately predict and better understand RF energy transport and related heating in vivo to make high (1.5T) and ultra-high field (≥ 3T) MRI safer yet even more powerful.

'Excessive' local and systemic RF heating of the skin and deep tissue (i.e., tissue away from the skin and its thermal receptors) is a safety concern in high and ultra-high field MRI. Excessive heating can be produced since RF power deposition and blood flow are non-uniform in the body. Additionally, present limits for 'safe' local and global RF power densities (i.e., specific absorption rate or SAR) were overestimated by implementing unvalidated Pennes bioheat model inaccurately to simulate 'safe' temperatures and temperature changes, as defined by international regulatory guidelines[2]. The traditional implementation of the Pennes bioheat model overestimated tissue to blood heat transfer rate in deep tissues by artificially (and non-physically) keeping the blood at a constant temperature and by assuming 100% effectiveness of tissue to blood energy exchange. The assumptions resulted in higher local as well as global SAR numbers for the same 'safe' deep tissue temperature changes and thus, overestimated 'safe' SAR limits. Deep tissue heating cannot be 'felt' and thus, avoided by the patient intervention in high and ultra-high fields.

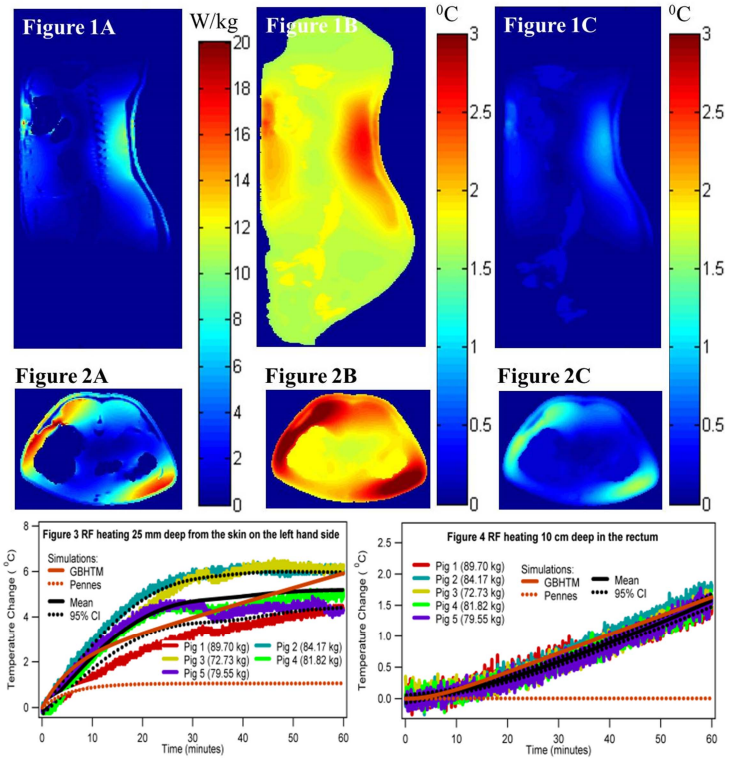
Present international RF safety guidelines limit the maximum whole body average SAR to 4 W/kg averaged over any six minutes of power deposition from volume transmit coils (e.g., body coils in clinical scanners). The maximum whole-body average SAR of 4 W/kg can be delivered for up to 60 minutes. The guidelines assume that this amount of RF energy deposition will result in safe in vivo temperature changes (i.e., core temperature ≤ 1 ^{0}C and local temperature ≤ 3 ^{0}C in non-febrile) [2].

Methods – The Digital Pig Model and GBHTM Simulations A digital pig model was developed by acquiring 1.5 mm isotropic, whole-body anatomic images of a ~73.61 kg euthanized pig with computed tomography (CT). The images were segmented in six tissue types (i.e., skin, fat, muscle, bone, lungs, and internal air) using MIMICS software (Materialise, Belgium). Appropriate electromagnetic and thermal properties were assigned to the tissues. The digital pig had a mass of ~71.48 kg.

Local temperature changes were simulated by solving the GBHTM (In Vivo Temperatures LLC, Roseville, MN 55113), which was derived based on the conservation of energy. The GBHTM allowed blood temperature to change based on the thermal interaction with the surrounding tissue and thus promised to provide better estimates for the heating. Necessary local SAR distribution was obtained by importing the digital pig in REMCOM finite difference time domain software (State College, Pennsylvania, USA) and solving Maxwells equations for the digital pig centered in a 3T body coil. The 3T (~123.2 MHz) body coil was modeled as a 16 channel, high pass, 50 cm long, 60 cm internal diameter (ID) bird cage coil shielded with a 120 cm long and 65 cm ID faraday cage.

Methods – Experimental Design The animal experiment protocol was approved by the Institutional Animal Care and Usage Committee of the University of Minnesota. RF heating was measured as a function of time using fluoroptic probes in the sub-cutaneous layer of the scalp; 15 mm and 25 mm deep in the brain after the dura; in the subcutaneous layer of the skin in the plane of the isocenter, 5 mm lateral to the midline; 25 mm and 50 mm deep in the plane of the isocenter, 5 mm lateral to the midline (simulated hot regions); 25 mm deep in the plane of the isocenter on the left hand side (LHS) of the body closest to the MR table (simulated hot region); and 10 cm deep in the rectum. The measurements were made in five anesthetized swine (N= 5, mean animal weight = 81.59 kg, SD = 6.23 kg). Temperatures at the scalp and skin were measured by placing fluoroptic probes in the sub-cutaneous layer with an 18G catheter. To measure brain temperatures, an ~18G hole was drilled into the swine cranium perpendicular to the coil plane 45 mm away from the back of the skull and 5 mm lateral to the midline and fluoroptic probes were slipped through the dura to appropriate depths. Other tissue temperatures were measured by placing fluoroptic probes at appropriate depths using 18G catheters. The pigs were kept anesthetized using 1.5-2.5% Isoflurane in 50% air – 50% O_2 during the experiment. A pig was chosen as a thermoregulatorily conservative model of a human for its human comparable mass, perfusion, electromagnetic and thermal properties, thermo-regulatory reflexes, and World Health Organization's recommendation.

The RF heating was produced in a clinical 3T scanner due to an hour long turbo spin echo (TSE) sequence (whole body average SAR = 2.77 W/kg, SD = 0.26 W/kg). Temperatures were recorded for ~1 hour before the RF exposure started, for ~1 hour during the RF exposure, and for 0.75 hour after the RF exposure stopped. The number of animals was chosen as N = 5 since a minimum of 4.0 animals was required to have >95% power with P<0.01 (two-sided).



Results Figures 1A and 2A present the local SAR distribution in the sagittal and axial planes of the digital pig due to the RF power deposition from the 3T coil, respectively. Figures 1B and 2B present the associated local temperature change distribution at the end of the RF deposition simulated using the GBHTM. Figures 1C and 2C present the associated local temperature change distribution at the end of the RF deposition simulated using the traditional Pennes model. Figures 3 and 4 present the validation of the GBHTM predictions (and the limitations of the Pennes predictions) against fluoroptic measurements at the LHS 25 mm deep hot region under the skin and rectum, respectively.

Discussion The GBHTM simulated the in vivo RF energy transport and heating more accurately. Pennes model, as expected, underestimated the RF heating. Whole-body average SAR of 2.77 W/kg may produce local temperature changes well above the defined 'safe' temperature changes in < 15 minutes of RF deposition. Similar 'hot' regions can be produced in deep tissues away from the skin and its receptors in patients making patient sensory based intervention difficult unless too late. Mean rectal temperature change during this time was < 0.3 ^{0}C and thus, may not be used to gauge heating in the human body.

Summary The GBHTM's accurate predictive ability of the in vivo RF energy transport and related heating paves the possibility of in vivo temperature based RF safety implementation in patients wearing/ not wearing conductive medical devices in the MR scanners of future. The implementation will allow clinicians and researchers to use more SAR for shorter scans (<10 min) without exceeding 'safe' temperature limits making MRI safer yet more powerful. Current local and global 'safe' SAR limits are overestimated and do not satisfy local and global 'safe' temperature change limits for scan times longer than 10 minutes.

Acknowledgments R01 EB007327, P41-EB015894. **References** 1) D. Shrivastava et al., JBME **131** (7), 074506 (2009). 2) IEC, **60601-2-33-ed3.0b** (2010).