

Radio-Frequency Heating in Swine with an 8 Channel, 7 T (296 MHz) Head Coil

D. Shrivastava¹, J. Kulesa¹, J. Tian¹, G. Adriany¹, L. DelaBarre¹, and J. T. Vaughan¹

¹CMRR, University of Minnesota, Minneapolis, MN, United States

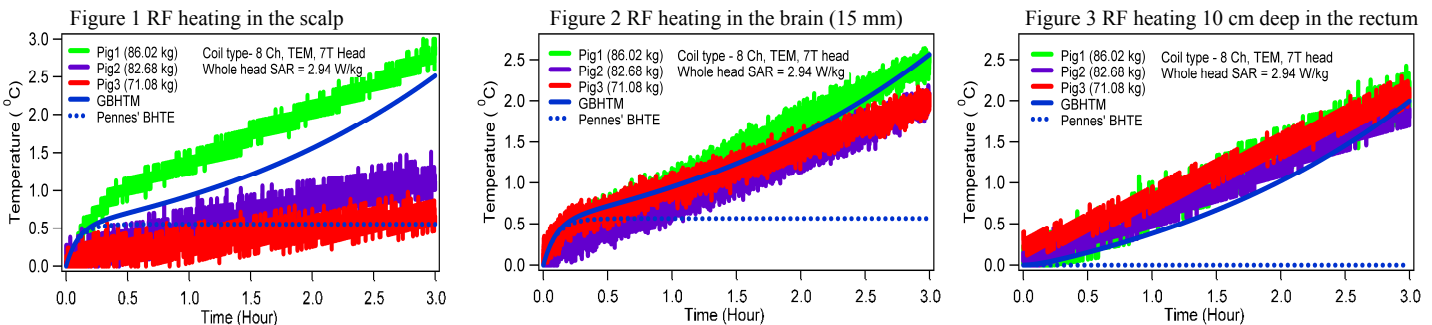
Introduction In vivo temperature responses were fluoroptically measured in the scalp, brain, and rectum of three swine (N = 3) due to power deposition with a 7T (Larmor frequency of 296 MHz) head coil, and numerically simulated using the new Generic Bioheat Transfer Model (GBHTM) (1) and ‘gold standard’ Pennes’ bioheat transfer equation (BHTE). The direct in vivo RF heating measurements and the numerical simulations were done to better understand radio-frequency (RF) heating in ultra-high fields, develop correlations between the whole head average specific absorption rate (SAR) and in vivo temperatures, and identify thresholds for adverse temperature responses. RF heating and its thermo-physiologic responses are not well understood at ultra-high fields (≥ 3 T) (2). Studying these are important for human safety assurance since non-uniform RF energy distribution and blood flow may produce non-uniform in vivo temperatures in imaged tissues with the possibility of local hot spots (2,3). The effect of non-uniform brain temperatures on the mammalian thermo-regulatory control mechanisms is unknown.

Current international RF safety guidelines limit the maximum in vivo temperature change to 1 °C and the maximum whole head average SAR to 3 W/kg (averaged over any 6 minutes) in the human head (4). MR systems monitor the SAR alone to assure safety since no non-invasive means are available to determine in vivo temperatures with the required accuracy and precision of less than 0.5 °C. Additionally, local distribution of RF power (local SAR) is routinely calculated in standard human geometries to design RF coils such that to meet allowable maximum local SAR guidelines. Cellular thermogenic hazards are related to in vivo temperatures and temperature-time history – not to the maximum whole head average and local SAR. 3 W/kg of the whole head average SAR when deposited for a ‘long’ duration may produce a temperature-over-time response in an imaged tissue to adversely affect the thermo-physiology of mammals. Thus, safety at ultra-high fields will be better assured by studying RF heating and its thermo-physiologic consequences in thermoregulatorily conservative, human relevant animal models at appropriate frequencies.

Experiment design and Methods The animal experiment protocol was approved by the Institutional Animal Care and Usage Committee of the University of Minnesota. In vivo temperatures were measured as a function of time in the sub-cutaneous layer of the scalp; 5 mm, 10 mm, 15 mm, 20 mm, and 25 mm deep in the brain after the dura; and 10 cm deep in the rectum in three anesthetized swine (mean animal weight = 79.93 kg, SD = 7.84 kg) using fluoroptic probes. To measure scalp skin temperature, an 18G catheter was used to place a fluoroptic probe in the sub-cutaneous layer of the scalp. 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. Next, an 18G catheter was used to puncture the dura and the fluoroptic probes were slipped through the dura to appropriate depths. The pigs were kept anesthetized using 1.5-2.5% Isoflurane in 50% air – 50% O₂. The room temperature and humidity, and the animals’ heart rate, blood pressure, respiratory rate, end tidal CO₂, and the % inspired/expired anesthetic agent were recorded manually every 30 minutes. A pig was chosen as a thermoregulatorily conservative model of a human for its human comparable mass, perfusion, thermal properties, and thermo-regulatory reflexes as well as cost and availability. Swine have critical, hot temperature limit comparable to and lower than that of humans.

Continuous wave RF energy (mean whole head average SAR = 2.94 W/kg, SD = 0.31 W/kg) was deposited to swine for ~3 hours (mean RF heating duration = 3.16 hours, SD = 0.05 hours) using a 9” internal diameter (ID), 8 channel, TEM volume head coil at 296 MHz (i.e., Larmor water proton frequency at 7 T). Temperatures were recorded for ~3 hours before the RF exposure started (pre-RF epoch), for ~3 hours during the RF exposure (RF-epoch), and for ~3-4 hours after the RF exposure stopped (post-RF epoch). The net average coil input power (forward- reverse) was measured at the coil by a power meter (Giga-tronics Universal Power Meter, model #8652A). The net SAR was calculated by measuring the animal’s severed head weight after the animal was euthanized (mean head weight = 4.76 kg, SD = 0.51 kg) and the coil efficiency. The number of animals was chosen as N = 3 since a minimum of N = 3 animals was required for each group to have >90% power with P<0.05 (two-sided). The RF heating was simulated using the GBHTM and Pennes’ BHTE assuming the mean animal weight of 79.93 kg, and uniform power deposition and tissue.

Results Figures 1-3 present the measured and simulated RF power induced temperature changes in the scalp, 15 mm deep in the brain, and 10 cm deep in the rectum. The measurements showed that the RF power induced temperature changes in the scalp varied from 0.57-2.80 °C after 3 hours of the power deposition (Figure 1). The RF power induced temperature changes in brain were statistically insignificantly different from each other for all locations and the average temperature change was 2.10 °C (SD = 0.27 °C, Figure 2) after 3 hours of the power deposition. The rectal temperature change was 1.96 °C (SD = 0.17 °C, Figure 3) after 3 hours of the power deposition. The brain temperature change approached 1 °C within 1.0 hour of continuous heating (Figure 2). Temperatures kept increasing and no plateau (i.e., steady state) was achieved within 3 hours of the heating (Figures 2-3) (2,3). Statistically insignificant differences were detected between the slopes of the pre and post-RF temperatures suggesting no thermoregulatory alterations. Next, the simulations showed that the new GBHTM predicted RF heating more accurately than the ‘gold standard’ Pennes’ BHTE. Accurate modeling using the GBHTM allowed the improved quantification of the net RF power in the tissue. Comparing RF heating studies at ultra-high fields, the current 7T RF heating study produced significantly different heating compared to our earlier 7T and 9.4T RF heating studies with different head coils. All RF heating studies showed spatially unique RF power induced temperature changes in the brain and rectum (3). The results suggested that the heating was coil dependent; however, the effect of the head positioning and subject-to-subject variability on the RF heating was not significant for a given weight range and RF coil.



Summary A temperature change of 2.1 °C was measured in the porcine brain due to a continuous wave RF power deposition for three hours at the whole head average SAR of ~ 3 W/kg with an 8 channel TEM, 296 MHz (7T) volume head coil. The GBHTM simulated RF heating more accurately than the Pennes’ BHTE. Further studies into the brain temperature-time response are underway using swine, other head coils, and the new GBHTM to better understand and assure RF safety.

Acknowledgments R01 EB007327, R01 EB000895, BTRR - P41 RR08079, R01 EB006835, R01 EB 00454, CA94200, CA94318, C06 RR17557-01, C06 RR12147-01, and the Keck foundation. **References** 1) Shrivastava et al., J Biomech Eng – T ASME 2009, 131(7):074506. 2) Shrivastava et al., MRM 2009,62(4):888-895. 3) Shrivastava et al., MRM 2008, 59(1):73-78. 4) ICNIRP, Health Phys, 2004, 87(2):197-216.