Radio-Frequency Heating in Swine due to a 3T (123.2 MHz) and 7T (296 MHz) Head Coil

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Introduction In vivo temperature responses were measured using fluoroptic probes in the scalp, brain, and rectum of eight swine due to a continuous wave (CW) power deposition with a 15 rung, 3T (Larmor frequency = 123.2 MHz) TEM head coil and an 8 channel, 7T (Larmor frequency = 296 MHz) TEM head coil (N=4 for each coil). Next, the heating was simulated using the newly derived Generic Bioheat Transfer Model (GBHTM) (1) and the 'gold standard' empirical Pennes' bioheat transfer equation (BHTE). The direct, fluoroptic in vivo RF heating measurements and the numerical simulations were done to better understand the heating, develop a first principles based validated bioheat transfer model to predict the heating, and identify safety thresholds for adverse thermogenic responses at ultra-high fields. RF heating and its thermo-physiologic responses are not well understood at ultra-high fields (≥3T) (2). No validated tools are available to predict the heating. Studying RF heating is important for human safety assurance since non-uniform RF energy distribution at ultra-high fields and blood flow may produce non-uniform in vivo temperatures (i.e., local hot spots) in imaged tissues (2-4). The effect of non-uniform brain temperatures on the mammalian thermo-regulatory mechanisms is unknown.

Current international RF safety guidelines limit the maximum in vivo temperature change to 1 ^{0}C and the maximum whole head average SAR to 3 W/kg (averaged over any 6 minutes) in the human head (5). 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 ^{0}C. 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 eight anesthetized swine using fluoroptic probes (Coil = 3T, mean animal weight = 75.8 kg, SD = 5.6 kg; Coil = 7T, mean animal weight = 79.9 kg, SD = 7.8 kg) (N=4 for each coil). 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% O_2. The room temperature and humidity, and the animals' heart rate, blood pressure, respiratory rate, end tidal CO_2, 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 was deposited to swine with the head coils for three hours to produce heating. 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) (Coil = 3T, mean coil input power = 43.2 W, SD = 0.5 W; Coil = 7T, mean power to the 7T coil = 42.4 W, SD = 1.0 W). Comparable coil input power was provided to the coils to study coil-load coupling. The number of animals was chosen as N = 4 for each coil since a minimum of N = 4 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, and uniform power deposition and tissue.

Results and Discussion Figures 1-2 present the RF power induced temperature changes due to the 3T head coil at 15 mm deep in the brain and 10 cm deep in the rectum, respectively. Figures 3-4 present the RF power induced changes due to the 7T head coil at 15 mm deep in the brain, and 10 cm deep in the rectum, respectively. The measurements showed that the RF power induced temperature changes were unique for a given coil and location. Unique temperatures for a location suggested that 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. RF heating in the brain was higher than in the rectum. Thus, rectal temperatures may not be used to gauge heating in the brain during head imaging. The temperatures kept increasing and no plateau (i.e., steady state) was achieved within 3 hours of the heating (Figures 1-4) (2-4). Thus, imaging time should be minimized to minimize heating. The simulations showed that the new GBHTM predicted RF heating more accurately than the 'gold standard' Pennes' BHTE. Accurate modeling using the new, validated GBHTM promises improved quantification of the in vivo RF heating and thus, improved safety during head imaging at ultra-high fields.

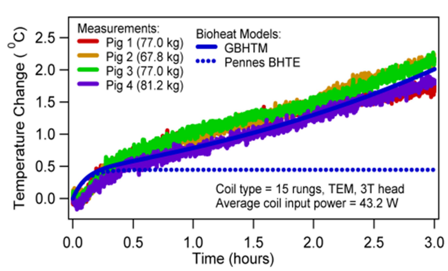

Figure 1 RF heating 15 mm deep in the brain after the dura due to a 15 rung, 3T head coil.

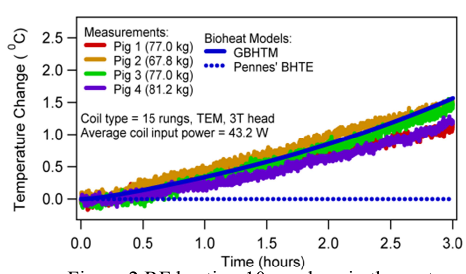

Figure 2 RF heating 10 cm deep in the rectum due to a 15 rung, 3T head coil.

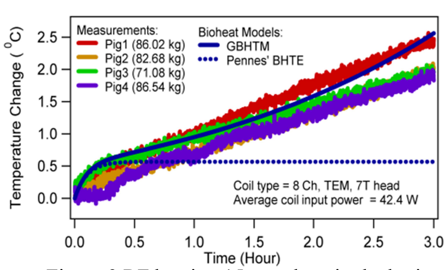

Figure 3 RF heating 15 mm deep in the brain after the dura due to an 8 channel, 7T head coil.

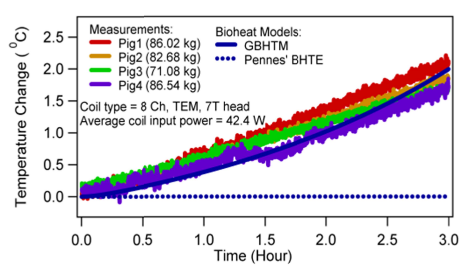

Figure 4 RF heating 10 cm deep in the rectum due to an 8 channel, 7T head coil.

Summary The RF power induced temperature changes are unique for a given coil and location. The temperatures kept increasing and no plateau (i.e., steady state) was achieved within 3 hours of the heating. The GBHTM simulated in vivo RF heating more accurately than the Pennes' BHTE.

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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) Shrivastava et al., MRM 2011, 66(1), 255-63. 5) ICNIRP, Health Phy, 2004, 87(2):197-216.