

# Systemic In Vivo Radio-Frequency Heating in Porcine Models with a 12.5" Diameter, 8 Channel, 7 T (296 MHz) Head Coil

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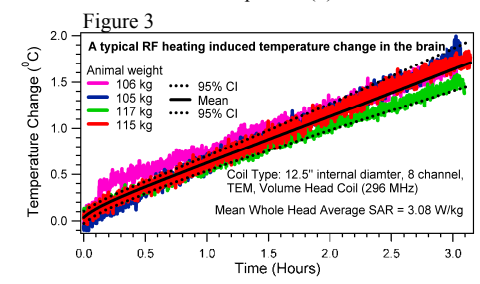
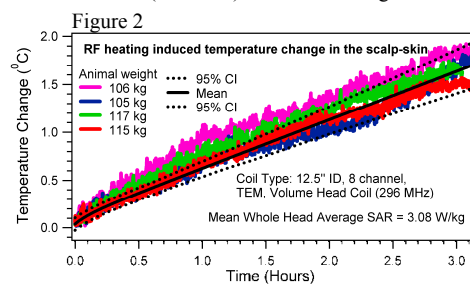
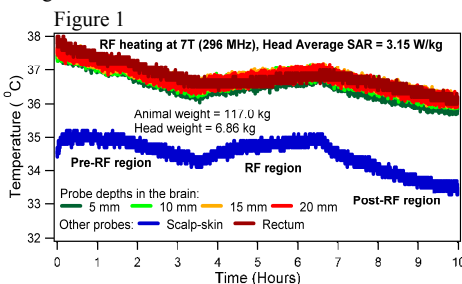
**Introduction** In vivo temperature responses were measured in the scalp, brain, and rectum of four porcine models (N = 4) with a 7T (Larmor frequency of 296 MHz) head coil to study radio-frequency (RF) heating, develop correlations between the whole head average specific absorption rate (SAR) and in vivo temperatures, and identify thresholds for adverse temperature responses. RF heating and its thermo-physiologic responses are not well understood at ultra-high fields ( $\geq 3T$ ) (1). Studying these is 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 (1,2). 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  $1^{\circ}C$  and the maximum whole head average SAR to 3 W/kg (averaged over any 6 minutes) in a human head (3). No limit exists for the maximum exposure duration for the SAR if the temperature limit is not exceeded. 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  $0.5^{\circ}C$ . Local distribution of RF power (local SAR) is routinely calculated using standard, non-perfused human geometries. However, cellular thermogenic hazards are related to in vivo temperatures and temperature-time history – not to maximum SAR. 3 W/kg of 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, and 20 mm deep in the brain after the dura; and 10 cm deep in the rectum in four anesthetized swine (mean animal weight = 110.75 kg, SD = 6.13 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. An 18G catheter was used to puncture the dura and slip fluoroptic probes to appropriate depths. Swine were kept anesthetized using 1.5-2.5% Isoflurane in 50% air – 50% O<sub>2</sub>. The room temperature and humidity, and the animals’ heart rate, blood pressure, respiratory rate, end tidal CO<sub>2</sub>, and the % inspired/expired anesthetic agent were manually recorded every 30 minutes. Swine were chosen as a thermoregulatorily conservative, human relevant animal model for their 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 SAR = 3.08 W/kg, SD = 0.09 W/kg) was deposited to porcine heads for ~3 hours (mean RF heating duration = 3.09 hours, SD = 0.05 hours) using a 12.5" 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 region, Figure 1), during the RF exposure (RF region, Figure 1), and for ~3-4 hours after the RF exposure stopped (Post-RF region, Figure 1). The net average coil input power (forward minus 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 = 7.06 kg, SD = 0.25 kg). The number of animals was chosen as N = 4 since a minimum of N = 4 animals was required for each group to have >90% power with P<0.05 (two-sided).

**Results and Discussion** A typical temperature-time response in a RF heated swine is presented in Figure 1. It is shown that temperatures dropped linearly due to anesthesia in the pre and post RF regions (1,2). Temperatures were raised over the baseline dropping temperatures in the RF region due to the RF heating (1,2). RF heating induced temperature changes in the subcutaneous layer of the scalp and 15 mm in the brain are presented in Figures 2 and 3, respectively. The temperature changes approached  $1^{\circ}C$  within 1.5 hours of continuous heating (Figures 2-3). Temperatures kept increasing and no plateau (i.e., steady state) was achieved within 3 hours of heating (Figures 2-3) (1,2). Standard multivariate analysis of variance showed that the difference in temperature changes among all pigs and all probe locations was insignificant ( $p>0.1$ ). Standard one-way analysis of variance showed that the difference in the slopes of the pre-RF and post-RF temperatures among all pigs for each probe location was insignificant ( $p > 0.1$ ). Temperature decay in pre and post RF regions was explained since Isoflurane is a known vasodilator. Insignificant temperature changes among all locations and all pigs suggested that the head coil produced systemic, uniform heating. Insignificant difference between the pre and post RF slopes among all pigs for a location suggested that the uniform RF heating up to  $\sim 1.85^{\circ}C$  in 3 hours did not significantly alter anesthesia induced thermal response in swine. In comparison, our earlier in vivo RF heating results at 400 MHz (9.4 T) with a smaller 9" ID four loop volume head coil showed non-uniform heating and altered thermal responses in swine (1). Both, the current 7T RF heating study and our previous 9.4 T RF heating study showed spatially unique RF heating induced temperature changes (2). The result 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. Parametric curves for mean and 95% CI temperature changes for all six locations (scalp-skin; 5 mm, 10 mm, 15 mm, and 20 mm in the brain; and rectum) and four pigs are presented as black curves in Figures 2-3. The curves are useful in predicting in vivo RF heating due to the head coil and were obtained using the standard solution of the new Generic Bio-heat Transfer Model (GBHTM) and the current gold standard Pennes’ Bioheat transfer equation (4).



**Summary** Systemic, uniform RF heating of  $\sim 1.85^{\circ}C$  was produced in 3 hours in swine due to a continuous wave whole head average SAR deposition of  $\sim 3$  W/kg with a 12.5" ID, 8 channel, TEM 7 T volume head coil. Further studies into the brain temperature-time response are underway using swine, smaller diameter 7T RF head coils and the new Generic Bio-heat Transfer Model to better understand and assure RF safety at ultra high fields.

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**References** 1) Shrivastava et al., MRM 2009,62(4):888-895. 2) Shrivastava et al., MRM 2008, 59(1):73-78. 3) ICNIRP, Health Phy, 2004, 87(2):197-216. 4) Shrivastava et al., J Biomech Eng – T ASME 2009, 131(7):074506.