9.4 T RF Heating: In Vivo Thermoregulatory Temperature Response in Porcine Models

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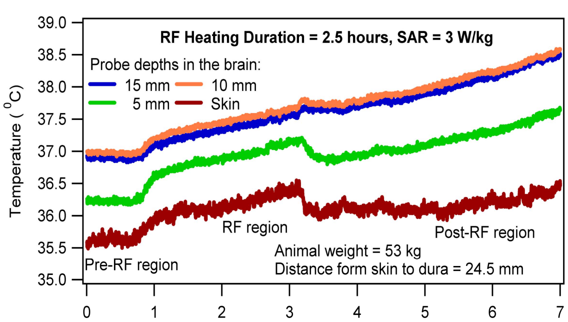
Introduction Thermoregulatory temperature response to RF heating at ultra-high fields (UHFs) (≥3T) is unknown. Studying this temperature response is important for human safety since non-uniform RF energy distribution and blood flow produce local hot spots deep in the imaged tissue. (1,2) Additionally, there are unknown safe limits to how much excess temperature-over-time a body can tolerate in an imaged tissue before reacting adversely to it.

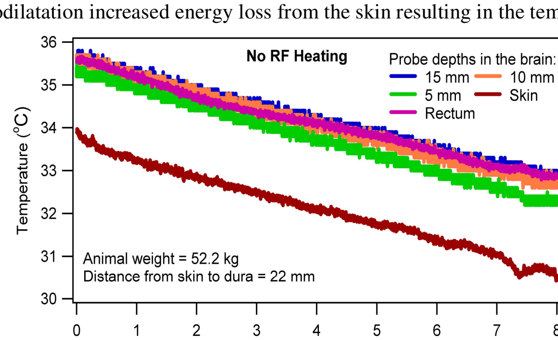
Current RF safety guidelines limit the maximum *in vivo* temperature change to 1 ^{0}C and the maximum SAR to 3 W/kg (averaged over 10 minutes) in a human head. (3) No limit exists for the maximum exposure duration for the SAR if the temperature limit is not exceeded. However, MR systems monitor the SAR only. No means exist to monitor *in vivo* temperatures with the required accuracy of less than 0.5 ^{0}C. No correlations between the temperatures and the SAR exist in perfused human geometries to estimate the maximum duration of SAR exposure before the temperature limit is exceeded. Local distribution of RF power (local SAR) is routinely calculated in realistic, 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 (~3hours) may produce a temperature-over-time response in an imaged tissue to overwhelm the thermoregulatory system of mammals. The rise of *in vivo* temperatures due to overwhelmed thermoregulatory mechanisms under excessive thermal loads (e.g., high ambient temperatures, exercise, hyperthermia, etc.) is known for centuries in mammals. To identify possible excessive RF energy deposition limits at the highest field (i.e., 9.4 T), *in vivo* temperature responses were measured in the scalp and brain of eight human-sized porcine models.

Experiment design and Methods Temperatures were measured as a function of time in the brain and surrounding cutaneous layer of eight human sized, anesthetized swine (4 RF heated and 4 sham RF heated swine, mean animal weight = 53.6 kg, SD = 7.7 kg). Pigs were chosen for their human comparable mass, perfusion, thermal properties, and thermo-regulatory reflexes as well as cost and availability. Additionally, swine have critical, hot temperature limit comparable to and lower than that of humans. Brain temperatures were recorded using an inline fluroptic probe (3 transducers 5 mm apart) placed at 15 mm, 10 mm, and 5 mm depths from the dura inside the brain. An ~18G hole was drilled into the anesthetized animal's cranium perpendicular to the coil plane to place the inline probe. Skin temperature was recorded using a separate fluroptic probe placed in the head cutaneous layer using an 18G catheter. The animal was kept anesthetized during experiments using 2-3% 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 manually recorded every 30 minutes.

In RF heated swine, continuous wave RF energy (mean SAR = 2.9 W/kg, SD = 0.14 W/kg) was deposited to porcine heads for 2.5-3.4 hours (mean RF heating duration = 3.1 hours, SD = 0.4 hours) using a four loop RF head coil at 400 MHz (9.4 T) (N = 4, mean weight = 57.4 kg, SD = 4.2 kg). Temperatures were recorded for ~3 hours before the RF exposure started (Pre-RF region in Figure 1), during the RF exposure (RF region in Figure 1), and for ~3-4 hours after the RF exposure stopped (Post RF region in 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. In sham RF heated swine, temperatures were recorded for the typical duration of a heating experiment (~8hours) to understand thermoregulatory effects of anesthesia (N = 4, mean weight = 49.8 kg, SD = 9.1 kg). The number of animals was chosen as N=4 for each group. This was so because a minimum of N=4 animals was required for each group to have >90% power with $P<0.05$ (two-sided). The animal experiment protocol was approved by the Institutional Animal Care and Usage Committee of the University of Minnesota.

Results and Discussion Typical temperature-time responses in the RF heated swine and the sham RF heated swine were presented in Figures 1 and 2, respectively. It was shown in Figure 1 that 3 W/kg of SAR at 400 MHz when continuously deposited for more than 2.5 hours caused *in vivo* temperatures to rise after the RF exposure stopped. The observation was found true in three out of four RF heated swine with RF heating duration exceeding 2.5 hours (mean RF heating duration = 3.1 hours, SD = 0.4 hours). Swine have critical hot temperature limit comparable to and lower than that of humans. Thus, the brain temperature-time response produced by the '3 W/kg of SAR for 3.1 hours' RF energy may represent an upper conservative safe temperature-time limit for humans at 9.4 T. The measured maximum temperature change due to the SAR (i.e., the temperature change in the RF region) was less than a degree at all measured locations. However, the non-uniform RF energy distribution at 9.4 T and blood flow produce non-uniform temperature distribution and thus, local hot spots. The development of an appropriate bioheat model is underway to determine the safe maximum temperature-time history at 9.4 T. Next, anesthesia caused a linear temperature drop in sham RF heated swine (Figure 2). Isoflurane is a known vasodilator. An increased blood vessel surface area due to vasodilatation increased energy loss from the skin resulting in the temperature drop.





Summary 3 W/kg of SAR at 400 MHz when continuously deposited for 3.1 hours caused *in vivo* temperatures to rise after the RF exposure stopped in three out of four swine. Future studies into the brain temperature-time history and thermoregulatory temperature response are underway using swine and new bioheat thermal models to better understand RF safety at ultra high fields.

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References

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