

Proton Resonance Frequency Shift Based NMR Thermometry for Ultra-High Field RF Safety Appl

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Introduction An MR thermometry technique with sub-degree celsius accuracy is needed to measure *in vivo* temperatures vs. time in porcine brains at ultra-high fields. Porcine models are used to study thermoregulatory temperature response of the ultra-high field RF heating. The porcine hot critical temperature limit is comparable to and lower than that of humans. Also, porcine thermoregulatory mechanisms are similar to humans. Thus, conservative porcine thermoregulatory temperature responses can help develop new RF safety thresholds for ultra-high field human MRI. Sub-degree C temperature accuracy is needed since RF safety guidelines limit the maximum *in vivo* head temperature change due to RF heating to 1 °C over the core body temperature. Three-dimensional temperature maps over time are required since non-uniform RF power deposition at ultra-high fields and blood flow produce non-uniform *in vivo* temperatures with local hot spots. Thermogenic hazards are related to *in vivo* temperatures and temperature-time history – and not to the typically measured whole head average specific absorption rate.

Proton resonance frequency (PRF) shift related phase-change is routinely used to estimate *in vivo* temperature changes in thermal therapy applications. Change in temperature varies the electronic screening constant and the volume magnetic susceptibility to affect local magnetic field. This, to the first approximation, linearly changes the proton resonance frequency and thus, the proton precession rate with temperature. Typically, a constant phase-change slope of -0.01 ppm/°C is used. However, the slope values varying between (-0.0067) and (-0.0146) ppm/°C have also been reported for various tissue types. (1) To develop an MR thermometry technique with sub-degree C accuracy at ultra-high fields for porcine brains, the phase-change maps were studied at 7 T in an *ex vivo* non-perfused porcine brain.

Experiment design and Methods A porcine head was severed within two hours of the animal's death and frozen at -10 °C to preserve the porcine brain. On the day of the experiment, the head was thawed. The skin and muscle layers over the skull were removed. Further, the part of the skull where the brain resided was removed from the rest of the skull. The skull encased brain was tied to a support table and put in a cylindrical water bath. Fluoroptic temperature probes were placed in the brain, water bath, on the exterior wall of the water bath, and in the air inside the RF coil. The complete phantom (water bath + skull with brain) was placed in a 7 T magnet. (Figure 1) The temperatures of the water bath and porcine brain were varied between 34.6 and 40.6 °C using circulating heated water. The temperature of the circulating water was maintained using a temperature controller placed outside the magnet room. Removal of the skin, muscle, and rest of the skull was necessary to be able to obtain a set temperature uniformly in the brain in relatively short amount of time. The brain was kept in its cranium cavity to avoid distortion. The height of the support table in the water bath was such that it placed the cranium in the middle of the bath where the water temperature was nearly uniform. The brain fluoroptic temperature probe was inserted from the base of the skull and positioned next to the thickest part of the cranium. This location was chosen since this part of the brain would reach the steady state temperature last due to the lower thermal conductivity of the skull compared to the brain tissue.

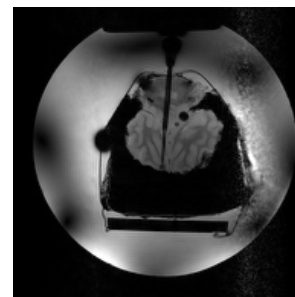


Figure 1 Cranium enclosed porcine brain with a fluoroptic temperature probe and the surrounding water bath.

The desired water bath temperature was set with the temperature controller. Once the temperature of the water bath and the brain reached steady state, images of the brain were obtained using a gradient-recalled echo sequence and an 8-channel stripline TEM transceive head coil. The RF power was transmitted with 4 channels and the signal was received from all channels. The parameters used were as follows: FOV = 17x17 cm, TR/TE = 2010/20 ms, nominal flip angle = 25°, resolution = 0.9x0.9x2 mm, slices = 80, scan time = 6.5 minutes. Phases were calculated from raw data and unwrapped. The excess magnet induced phase-drift slope was corrected for by using the surrounding water bath as a reference. The magnet induced phase drift slope was calculated by subtracting from the observed slope in the surrounding water the standard temperature induced slope of pure water of -0.01 ppm/°C. Obtaining corrected temperature induced slopes for each pixel by subtracting the excess magnet slope from the pixel-wise slopes were justified due to the uniformity of the observed slopes of the surrounding water.

Results and Discussion Figures 2 and 3 showed respectively, the phase-change slopes and the corresponding R² values in the porcine brain. The thermally induced phase-change slope varied between (-0.01 ppm/°C) to (-0.015 ppm/°C) with the R² value greater than 0.98. The exact cause of this wide variability of the phase-change slope was unknown. However, the slope values were within physiologic range. Local variation in the volume magnetic susceptibility and the macroscopic magnetic field in the porcine brain at 7T might be plausible reasons for the variability. (2) Investigations are underway to determine the exact cause. Further, no reliable data was obtained near the base of the brain. This was due to water cavities formed on the brain surface prior to the experiment with the multiple trial insertions of the fluoroptic probe and tissue distortion due to water flow. Next, Figure 4 showed the temperatures in the brain, water phantom, and on the exterior wall of the phantom. Note that it took 2.5 hours for the brain and the surrounding water bath to reach steady state.

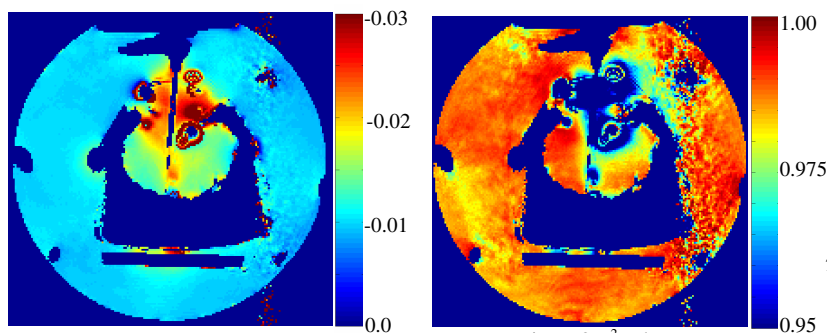


Figure 2 Phase-change slope

Figure 3 R² value

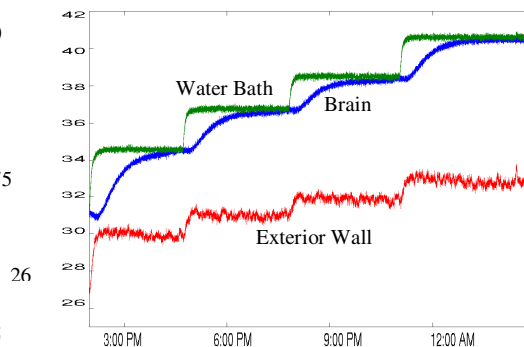


Figure 4 Temperature vs. time

Summary The PRF shift related phase-change slope varied between (-0.01 ppm/°C) and (-0.015 ppm/°C) in an *ex vivo* porcine brain at 7 T between 34.6 and 40.6 °C. A map of the phase-change slope may need to be developed for the porcine brain to acquire sub-degree C temperature accuracy.

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References (1) Peters, R.D.; Hinks, R.S.; Henkelman, R.M., MRM 40:454-459 (1998). (2) Peters, R.D.; Hinks, R.S.; Henkelman, R.M., MRM 41:909-918 (1999).