OPTIMIZED SIGNAL INTENSITY AND T1r BASED NMR THERMOMETRY FOR ULTRA-HIGH FIELD RF SAFETY APPLICATIONS

D. Shrivastava[1], T. Liimatainen[2], U. Goerke[2], J. Kulesa[2], T. Hanson[3], S. Michaeli[2], and J. T. Vaughan[3]

[1]CMRR, Radiology, University of Minnesota, Minneapolis, MN, United States, [2]University of Minnesota, Minneapolis, MN, United States, [3]University of Minnesota

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 conservative thermo-physiologic models of humans. Conservative porcine thermoregulatory temperature responses can help develop new RF safety thresholds for ultra-high field human MRI. Sub-degree C temperature accuracy for MR thermometry 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.

Traditionally, non-invasive MR thermometry is conducted by measuring temperature dependent changes in the MR parameters the proton resonance frequency shift (PRF), spin-lattice relaxation time T_1, spin-spin relaxation time T_2, the proton density, and the water diffusion coefficient. Temperature measurement accuracy on the order of 1^0C has been obtained in non-perfused phantoms. The PRF based thermometry technique is found as the most accurate and reliable. However, note that the PRF technique is prone to large errors (> 2 ^{0}C) due to subject motion, susceptibility artifacts, field drifts, and SNR issues related to RF penetration, or field inhomogeneities.(1-4) This preliminary study investigates the use of the signal intensity (SI) and longitudinal magnetization relaxation rate constant in the rotating frame (i.e., T_{1r}) to measure in vivo temperatures in a porcine brain with sub-degree Celsius accuracy.

Experiment design and Methods A human sized porcine model (weight = 82.3 kg) was immobilized using ~6 g/kg of Telazol (Tiletamine HCL + Zolzepam HCL). This was followed by intubation. Swine were kept anesthetized during the experiment (~ 9 hrs) using 1.5-2.5% Isoflurane in 50%-50% air-O2. Respiratory rate was set to 12-13 cycles/min using a ventilator (Ohmeda 7000). Minute volume was set between 6-8 l/min. Saline (0.9% NaCl) was provided through an ear vein to keep swine hydrated during the experiment. Next, a fluoroptic probe was placed 10 cm deep in the rectum to monitor the core temperature. At the end of the experiments, animals were euthanized using a saturated KCL solution.

Anesthesia causes linear temperature drop uniformly all over the brain. Additionally, the brain and rectal temperatures are within 0.2 degrees of each other in an anesthetized animal. (5) Thus, it was assumed that the rectal core temperature is the average brain temperature and no fluoroptic probes were placed in the brain. To determine useful TR, TE, and flip angle such that the sensitivity of signal intensity to temperature was maximized, the expression for the signal intensity of a 2D gradient-recalled echo (GRE) sequence was differentiated with respect to temperature and equated to zero. It was found that the sensitivity increased with a decrease in TR and TE. Further, the flip angle between 30 and 60 degrees was found appropriate. Thus, the following parameters were used for a 2D GRE sequence to obtain the signal intensity: FOV=256 X 256, Slice thickness = 3.5 mm, TR = 100 ms, TE = 3.1 ms, flip angle = 45 degrees, slice = 64, time = 2.08 min. Average signal intensity value was read for the entire brain in a slice using the software MRIcro and plotted against the core temperatures (Figure 2). To determine T_{1r} for a slice, adiabatic HS1 (pulse duration = 8.96 ms, band width X pulse duration=20) pulses were employed in a pulse train with different number of pulses (0, 4, 8, 12, 16) prior to a segmented 2D GRE acquisition with the following parameters (TR = 4000 ms, TE = 5.0 ms, FOV= 250 X 250, flip angle = 25 degrees, number of segments = 8). The acquisition time was 1.06 min for the T_{1r} pulse sequence. Fitting was performed by linear model into linearized T_{1r} data as a function of pulse train duration. The average T_{1r} value was calculated over the entire brain in a slice and average T_{1r} values were plotted as a function of the core temperature (Figure 4).

Results Figure 1 shows anatomical details of a porcine head slice as obtained by the optimized 2D GRE sequence (slice 45). Figure 2 presents correlations between the optimized average signal intensity for the entire brain in a slice and core rectal temperature for two porcine head slices (slice 45 and slice 50). Figure 3 shows anatomical details in a porcine head slice as obtained by the first of the 2D GRE sequence in the T_{1r} acquisition. Figure 4 presents correlations between the average T_{1r} for the entire brain in the slice and core rectal temperatures. Good correlations were obtained between the rectal temperatures, and the optimized signal intensities and the T_{1r}s. When correlations were used to back predict the in vivo temperatures, an error of the ≤0.25 degree C was obtained. Thus, the optimized signal intensity and T_{1r} have potential to predict in vivo porcine brain temperatures with sub-degree Celsius accuracy.
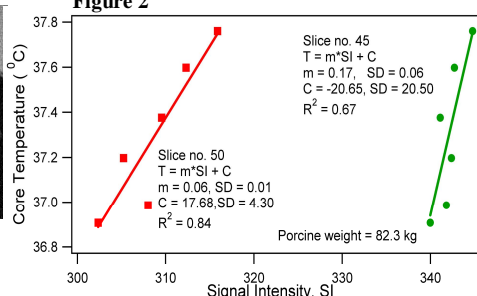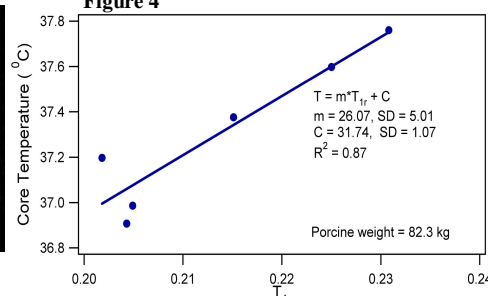
Figure 1

Figure 2

Slice no. 45
T = m*SI + C
m = 0.17, SD = 0.06
C = -20.65, SD = 20.50
R^2 = 0.67

Slice no. 50
T = m*SI + C
m = 0.06, SD = 0.01
C = 17.68, SD = 4.30
R^2 = 0.84

Porcine weight = 82.3 kg

Figure 3

Figure 4

T = m*T_{1r} + C
m = 26.07, SD = 5.01
C = 31.74, SD = 1.07
R^2 = 0.87

Porcine weight = 82.3 kg

Summary Optimized signal intensity and longitudinal magnetization relaxation rate constant in the rotating frame (i.e., T_{1r}) were well correlated with the core rectal temperatures in an in vivo porcine brain. The correlations were obtained for ~ 1degree C change in the porcine core temperature. The use of the signal intensity and the T_{1r} to estimate porcine brain temperature in an ultra-high field RF heating experiment seems promising.

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