

Analysis of MR Thermometry Methods using Tm-DOTMA and Water Proton : Experimental and Numerical Results

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INTRODUCTION: There is a growing need and interest in MR Thermometry methods to obtain full volumetric maps of radiofrequency (RF) induced heating of tissue in patients with medical implants (1,2). The most commonly used methods are based on the chemical shift of the water proton (1H) signal which provides high spatial and temporal resolution, however, it has weak temperature sensitivities (~ 0.01 ppm/°C) (3) and a high sensitivity to B₀ inhomogeneity. Recent studies (3,4) have proposed the use of paramagnetic lanthanide complex, namely the thulium 1,4,7,10-tetraazacyclododecane-1,4,7,10-tetramethyl-1,4,7,10-tetraacetate (Tm-DOTMA), characterized by a high temperature sensitivity (~0.57- 0.7 ppm/°C) of the methyl peak. Here we compare the use of Tm-DOTMA vs. water proton to image the RF-induced heating of a sample metallic object. Both chemical shift imaging (CSI) and conventional water proton reference frequency (PRF) methods were used. Numerical calculations were also performed and compared to experimental results.

METHODS: MRI imaging was performed on a 4.7T (200 MHz) Bruker Biospin, Billerica, MA, USA), with a shielded 12-rung linear high-pass birdcage coil (coil length of 16 cm; coil diameter of 7.2 cm; shield diameter of 12.0 cm). A rectangular 1.0%-agar gel phantom (length = 13 cm, width = 6.5 cm, and height = 2.5 cm) filled with (or without) 7.16 mM Tm-DOTMA was used for the study. Three copper strips having 5 cm length and 1 cm width were included in one side of the phantom (Fig. 1). Two fiber optic probes (Luxtron 3100, Santa Clara, CA, USA) located near and away from the copper strips were used for reference temperature measurements. Estimation of thermal effects was made using interlaced periods of proton irradiation using a BIR4 decoupling pulse and MRI temperature measurements (32.8 sec for 32x32 chemical shift imaging (CSI) with 5.0x6.4 mm² spatial resolution and 122.9 sec for the PRF method with 60.0x76.2 mm² FOV). All simulations were performed using a commercially available software (xFDTD, Remcom, Inc, State College, PA) and analysis of the results was performed in Matlab (The MathWorks, Inc., Natick, MA). Simulation results of electromagnetic fields were normalized so that |B₁⁺| = 4μT at the coil center corresponding to a 1.5ms 90° pulse.

RESULTS: Fig. 2 shows the numerical simulation results of total electric field (|E|), rotating RF magnetic field (B₁⁺), and local SAR within the rectangular sample without (first row) and with (second row) the copper strips at 4.7T (200 MHz). The |E| and local SAR were increased near the tip of the copper strips. Figure 3 shows the experimentally measured CSI spectra using Tm-DOTMA (first row) and water proton (second row) before (first column) and after (second column) the RF heating. The temperature change map (ΔT) with 64x64 matrix and 122 sec scanning time using the PRF method with Tm-DOTMA (first row) and water proton (second row) was shown in Fig. 4.

DISCUSSION: A frequency shift of about 480 Hz (Fig. 3, first row, red) and 750 Hz (Fig. 3, first row, green) using the Tm-DOTMA corresponded to ~4°C and ~7 °C temperature change, well matched with the temperature change of 3.9 °C and 7.6 °C measured by the optic fiber probe. However, the frequency shift in water proton CSI (Fig. 3, second row) could not be detected because of the much smaller temperature sensitivity, i.e. ~0.01 ppm/°C (water proton) vs. ~0.58 ppm/°C (Tm-DOTMA). Calculations of ΔT using PRF method in Fig. 4 show that Tm-DOTMA may not be good for the large temperature change measurements because of aliasing from large phase shifts. For example, a 456° phase shift (Tm-DOTMA) from a temperature increase of 3°C, is aliased as 96° phase shift. However, a 5.4° (water proton) phase shift related to the same temperature increase (3°C) at 4.7T (200 MHz). Our results suggest that the thermometry using Tm-DOTMA is appropriate for measuring a small temperature change using CSI method. Although the PRF method can also be used, the current implementation suffers from aliasing.

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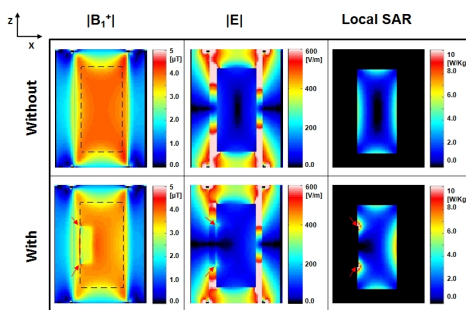


Figure 2 Calculated magnitude of rotating RF magnetic field (B₁⁺, first column), total electric field (|E|, second column) and local SAR (third column) at 4.7T (200 MHz) without and with the copper strips. Red arrows in second row indicate the edge of the copper strips.

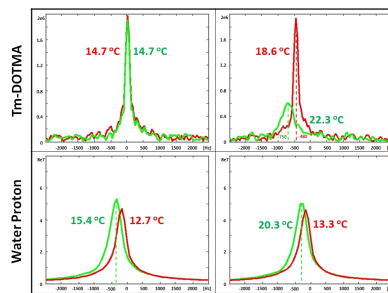


Figure 3 Experimentally measured CSI results of Tm-DOTMA (first row) and water proton (second row) before (~15 °C, first column) and after (~20 °C, second column) RF heating near (green) or away (red) from the copper strip. Note the frequency shift due to the temperature increase is observed in the Tm-DOTMA case.

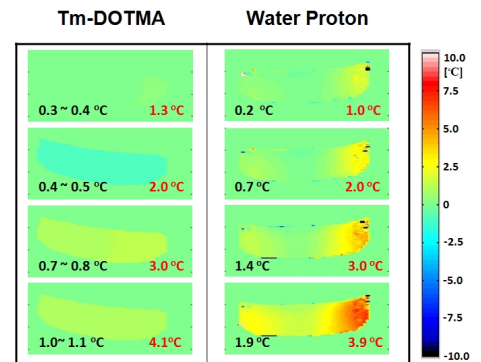


Figure 4 Experimentally measured temperature increase (ΔT) map within the agar gel sample after exposure to RF power due to the decoupling pulse with Tm-DOTMA (first column) and water proton imaging (second column). Numbers in red and black colors are the measured temperatures using fiber optic probes.

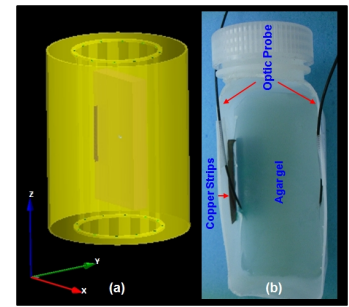


Figure 1 Setup for numerical simulation (a) and experiment (b). HP birdcage coil with an RF shield (yellow), sample (violet) and copper strips (blue) used for simulations (a). An agar gel phantom with copper strips and optic fiber probes used for the reference temperature measurement (b).