Visualization of RF Heating Using a Na₄HTm[DOTP] Doped Agarose Phantom

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Introduction

The advantages of high field MR Imaging have brought with it the disadvantages of increased power delivered to MRI coils. For a transmit/receive surface coil, the conservative electric field density is highest surrounding the capacitors. This is due to the high voltage drop across the loop gap. There is also an induced electric field, arising from the interaction of these electric fields with a conductive material that produces heating. Na₄HTm[DOTP] is a compound which has previously been shown to have temperature dependent proton and phosphorous chemical shifts. We have discovered a 0.5 PPM/°C temperature dependent Na chemical shift coefficient for Na₄HTm[DOTP]. Such a frequency shift generates a phase shift governed by Δψ, where T is the total pre-acquisition delay time. Our goal was to construct a Na₄HTm[DOTP] doped agarose phantom which would employ this characteristic to probe the heating caused by the coil during the MRI experiment. By comparing the phase difference maps of the image before and after an appropriate MRI scan, areas of heating will become visible.

Materials and Methods

Two Na₄HTm[DOTP] sample types were made to measure the temperature dependent chemical shift. One was an aqueous sample and the other a 6% agarose gel. Both contained 40 mM Na₄HTm[DOTP]. Spectroscopy was performed on a 9.4 tesla Bruker system. Each sample was heated in the magnet from room temperature (24 °C for the gel, 26 °C for the solution) to 46 °C in steps of 2 °C and the frequency was recorded. The imaging phantom was constructed to have the identical contents as the agarose gel sample. A conductivity for this sample can be approximated using the formula σ = 1.74 x 10⁻²⁰ where x is the sodium concentration in wt/wt %. This yields a conductivity of 0.38 S/m at 45 MHz. The conductivity of muscle at 45 MHz is slightly higher.

All imaging was performed on a 4.0 Tesla GE Signa Scanner at the Hospital of the University of Pennsylvania. Four single tuned, 10 cm diameter transmit/receive surface coils were used. All four had different degrees of distributed capacitance, ranging from 1 capacitor gap up to four capacitor gaps. The imaging protocol involved 1) acquiring a 3 minute, low power image, 2) acquiring a 5 minute high power image, and 3) acquiring another low power image. Low power refers to a time power of 25.0 W. "Na data sets were acquired as such: 3D FGRE, TR = 13 ms, TE = 2 ms, flip angle = 70 degrees, 0.63 mm in plane resolution, slice thickness = 12 mm. Each coil was matched to 50 Ω with the sample loaded, on both a Wavetek and a Marconi Instruments network analyzer. The experimental setup is shown in Figure 1.

Results and Discussion

We have discovered a 0.5 PPM/°C temperature dependent Na chemical shift coefficient for Na₄HTm[DOTP]. This coefficient is 50 times higher than that of water protons. At 4.0 Tesla, this translates into a 22 Hz/°C shift. The data for both the solution and gel samples are shown in Figure 2. As the sodium linewidth is on the order of 10's of Hz, this small change is difficult to measure via spectroscopy. However, one degree phase shift can be more easily measured and corresponds to 0.06 °C. This number is computed using the equation:

\[ Δψ = 360 \times K \times (γR) \times TF \times ΔT \]

where Δψ is the phase difference, K is the shift coefficient, TE is the echo or delay time and ΔT is the temperature difference.

Refocusing of the dephasing spins is unwanted in this situation, so we chose to use a 3D fast gradient echo sequence. Figure 3 shows the effect of a power intensive MRI experiment using a surface coil with capacitance distributed at two loop gaps. The same sagittal slice from the center of the 3D data set is pictured, as both the phase difference map and the real image. Signal intensity in the phase image is maximum at the edges and falls off towards the middle of the image. The maximum signal intensity corresponds to a temperature rise of ~ 6 °C. These edge regions correspond exactly to the placement of the capacitors. Increasing the distributance of capacitance decreases the dropoff from edge to center in other data sets.

These experiments clearly demonstrate the ability of a Na₄HTm[DOTP] doped agarose gel to indicate areas of heating in a phantom caused by an MRI experiment. This technique to probe power deposition can be used for any coil type or geometry. As there are temperature dependent chemical shifts for 'H and ³¹P as well, this method is also applicable for those imaging modalities. Optimization of this technique can be achieved by using a higher concentration of Na₄HTm[DOTP], thereby increasing the signal and allowing shorter acquisition times. Not only would this increase the conductivity, making the phantom more analogous to tissue, but it would capture localized heating better as heat would have less time in which to dissipate. Research in this direction is currently underway.

Figure 1. Experimental imaging setup for a surface coil with capacitance distributed at two loop gaps.

Figure 2. A) phase difference map for the 2 capacitor imaging experiment; b) Image of doped agarose phantom.

Figure 3. Chemical shift versus temperature for the solution and gel samples.

1 Chen and Hoult, MRM 29: 386-390 (1993).
3 Shapiro et al., JACS submitted.