Measuring T1 in the presence of very high iron concentrations with SWIFT

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Introduction

Iron oxide magnetic nanoparticles (MNPs) are widely used in MRI as a T2- and T2*-shortening contrast agent. Quantifying high concentrations of MNPs (1 – 10 mg Fe/ml) is crucial in magnetic fluid hyperthermia for cancer therapy (1). Efforts to quantify MNP concentration have relied on T2* mapping; however, signal loss is a severe obstacle to quantifying high concentrations of MNPs based on traditional MRI methods. Above ~0.1 mg Fe/ml, MR signal is virtually zero (1), making quantification impossible. Here we use the Sweep Imaging With Fourier Transform (SWIFT) (2) pulse sequence to accomplish T1 measurement of solutions with very high iron concentration and show how the measured T1 value may be used in place of T2* to quantify high concentrations of MNPs. SWIFT has a dead time of less than 8 μs, so T2*-weighting is negligible, and the T1 shortening effect of the MNPs can be probed. This gives the advantage of having positive contrast due to the presence of MNPs instead of negative contrast for traditional pulse sequences.

One major difficulty in measuring T1 in the presence of high iron concentrations is that spins with very short T2 values do not experience the same flip angle as do spins with long T2 values. This makes flip angle based T1 measurement difficult. Inversion recovery methods are also difficult since spins with very short T2 values do not completely invert. Here we used a Look-Locker saturation recovery method to measure T1 with an adiabatic half passage (AHP) followed by a spoiler gradient to achieve saturation. The AHP pulse gives a 90° flip even for spins with very short T2 values.

Methods

We created a phantom composed of six NMR tubes with commercially available iron oxide nanoparticles with concentrations ranging from 0.3 – 1.5 mg Fe/ml in 1% agarose gel. They were immersed in distilled water and imaged with a volume coil at 9.4 T. After the AHP saturation pulse, 4096 SWIFT projections were acquired using SWIFT with TR = 1 ms; flip = 5°; bandwidth = 104 kHz. A total of 512k radial views were acquired to fill 3D k-space. The projections along the saturation recovery curve were binned in groups of 64 to obtain 64 images with varying recovery times. Then the images were fit pixel-by-pixel to a Look-Locker saturation recovery curve, giving estimates for T1.

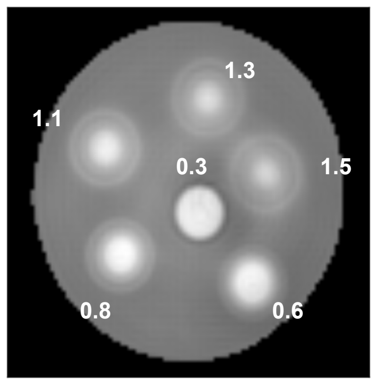

Figure 1 T1-weighted image (concentration in mg/ml).

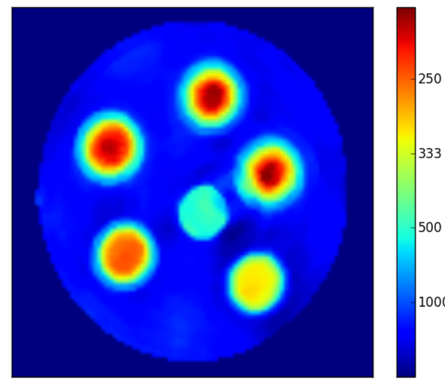

Figure 2 Measured T1 map (in seconds).

Results

Figure 1 shows the T1-weighted image reconstructed from all acquired projections. It clearly shows the positive contrast generated from very high iron concentrations. The pixels within the tubes were only noise in conventional GRE and SE images (data not shown). As the concentrations go up the T2 values get so short that they cause blurring in the SWIFT image. Figure 2 shows the T1 map generated by fitting the saturation recovery curve. It can be seen that increasing the iron concentration decreases T1. However, the blurring caused by very short T2 values complicates the interpretation of the highest concentrations.

The measured relaxation rate, R1 = 1/T1, is plotted vs. the iron concentration in Figure 3. Theoretically a linear relationship is expected. At concentrations above 0.5 mg/ml, this relationship breaks down. One possible explanation is that the very short T2 values associated with these high concentrations makes the effective flip angle of the SWIFT excitation smaller than what is being used in the Look-Locker equations. This effect will be corrected for in future work. Another factor is the blurring of the signal from spins with very short T2 values. This blurring gives greater variability within the area of uniform MNP concentration, as evidenced by the error bars on the plot.

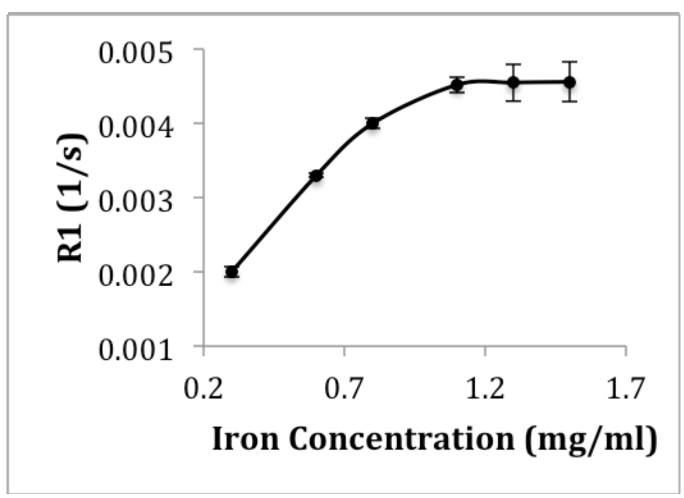

Figure 3 Measured relaxation rate (1/T1) vs. iron concentration.

Discussion

Despite the breakdown of the linear relationship at very high concentrations, this preliminary work shows that SWIFT can be used to measure T1 values at iron concentrations previously inaccessible to MRI. Further refinement is expected to enable T1 measurements to quantify MNP concentrations well above the linear range shown in Figure 3. These concentrations can in turn be used in cancer treatment with magnetic fluid hyperthermia.

References

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Acknowledgements

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