$T_{1\rho}$ Imaging with Weak B_1 Fields in the Presence of Frequency Offsets

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Introduction

Rotating frame longitudinal relaxation, $T_{1\rho}$, has been shown to be an effective contrast mechanism for assessing tumor size because it provides better contrast between normal tissue and tumors than T_1 or T_2 imaging (1). Changes in $T_{1\rho}$ have also been shown to be more sensitive in detecting response to therapy (2,3). Rotating frame relaxation weighting has also been used as a technique for indirect detection of ^{17}O labeled water during bolus transit in dynamic imaging studies (4). The commonly employed technique for generation of $T_{1\rho}$ contrast assumes that all frequency offsets, $\Delta\omega$, are small relative to the magnitude of the spin locking field, B_{1SL}. However, in imaging applications this requirement is often not fulfilled due to SAR limitations resulting in banding artifacts in the images. In the present report a simple variation of the spin locking technique is presented that corrects for frequency offsets up to $\Delta\omega = B_{1SL}$.

Methods

The basic spin locking spin preparation sequence consists of a hard excitation pulse followed by a spin locking (SL) pulse that is phase shifted by $\pi/2$. At the conclusion of the spin locking, a second hard pulse is used to return the spins to the z-axis. The $T_{1\rho}$ weighted axial magnetization is then sampled with an imaging protocol. The effects of frequency offsets during the hard pulses can be ignored because the B_1 field used for those pulses is significantly larger than any offsets present in the specimen. However, during the low power spin locking pulse the frequency offset tilts the effective field away from the spin lock axis. During spin locking, spins precess about a cone and have an arbitrary phase on this cone at the conclusion of the SL pulse resulting in banding artifacts. These artifacts can be eliminated if the excitation pulse is replaced with one that generates a flip angle that places the spins parallel to the effective field at the start of the SL pulse. This objective may be fulfilled with a $90_x - \tau - 90_y$ pulse sequence. The first pulse projects the spins into the transverse plane where they evolve for a period τ to achieve a phase dispersion proportional to their frequency offset. The spins are then projected into the yz plane by the second pulse making an angle $\tau\Delta\omega \sim \theta$ with the transverse plane when $\tau = 1/(8\gamma B_{1SL})$ and $\Delta\omega \leq \gamma B_{1SL}$. This method of spin locking has previously been shown to be effective in heteronuclear multi-dimensional high resolution spectroscopy (5). The present study is the first demonstration of the method in imaging applications.

The proposed technique was implemented on 4.7 T and 9.4 T Inova consoles (Varian, Palo Alto, CA). A phantom consisting of 3% agarose in tap water was prepared in a standard 10 mm NMR tube. After shimming, $T_{1\rho}$ spectroscopy studies were performed on the phantom (9.4 T) at a variety of frequency offsets using both of the techniques described above. $T_{1\rho}$ weighted imaging studies were also performed on tumor bearing rats (4.7 T) using both methods in order to demonstrate the effectiveness off the frequency offset correction technique.

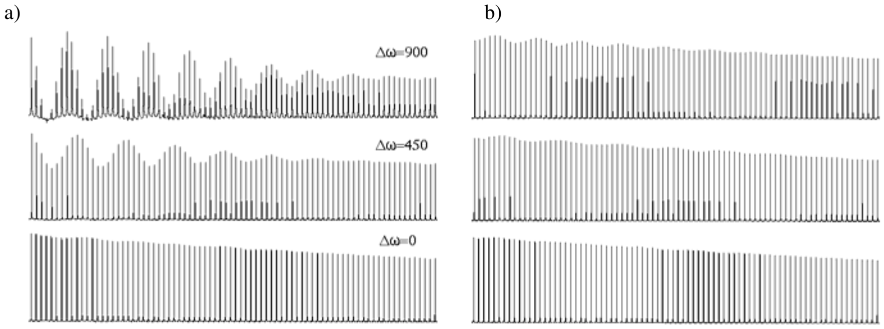

Figure 1. Spectroscopic $T_{1\rho}$ measurements acquired with a spin locking field of 900 Hz and frequency offsets of 0, 450 and 900 Hz using the basic sequence (a) and the frequency offset corrected sequence (b). Spin locking times used in the study ranged from 0.1 to 8 msec.

Results

The expected oscillations in signal intensity as a function of spin locking time were clearly observed in the spectroscopic studies using the basic pulse sequence (Fig-1a). The amplitude of the oscillations increased with frequency offset and covered the full range of the signal intensity at offsets equal to the spin locking field strength. In addition the envelope of the signal decay was faster at large frequency offsets resulting in an under estimation of $T_{1\rho}$ values under these conditions. The oscillations were largely suppressed by the frequency offset correction scheme proposed in the present study (Fig-1b) with only modest oscillations observed at frequency offsets equal to the spin locking field. $T_{1\rho}$ estimates were independent of frequency offset for offsets up to the spin locking field strength. Banding artifacts were frequently observed in $T_{1\rho}$ weighted imaging studies of rat brain using the basic sequence (Fig-2a). These artifacts were eliminated with the proposed pulse sequence (Fig-2b).

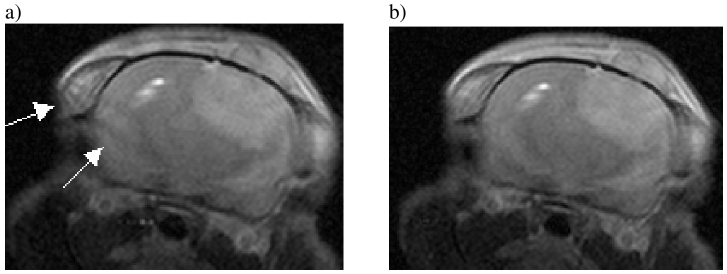

Figure 2. $T_{1\rho}$ weighted images of rat brain acquired using the basic SL sequence (a) exhibit banding artifacts (arrows) due to susceptibility effects. No such artifacts are present in the images generated with the frequency offset compensated sequence (b).

Conclusion

Adiabatic spin locking techniques have previously been proposed as a method to simultaneously address B1 inhomogeneity and frequency offset effects in SL imaging studies. However, the duration of the frequency sweep necessary to satisfy the adiabatic condition at low powers is often long relative to the desired spin locking time. Adiabatic methods are therefore not capable of making observations at short spin locking times and low spin locking powers. The method described here is easily implemented and is capable of observations at short spin locking times. The proposed pulse sequence was shown to effectively suppress artifacts in $T_{1\rho}$ weighted images acquired with low spin locking field strengths.

References

1. Aronen HJ, Ramadan UA, Peltonen TK, Markkola AT, Tanttu JI, Jaaskelainen J, Hakkinen AM, Sepponen R. Magn Reson Imag 1999;17(7):1001-1010.
2. Hakumaki JM, Grohn OH, Tyynela K, Valonen P, Yla-Herttuala S, Kauppinen RA. Cancer Gene Therapy 2002;9(4):338-345.
3. Duvvuri U, Poptani H, Feldman M, Nadal-Desbarats L, Gee MS, Lee WM, Reddy R, Leigh JS, Glickson JD. Cancer Research 2001;61(21):7747-7753.
4. Reddy R, Stolpen AH, Leigh JS. Journal of Magnetic Resonance Series B 1995;108(3):276-279.
5. Griesinger C, Ernst RR. J Magn Reson 1987;75(2):261-271.