T1rho imaging of cartilage in high-field scanner: effects of field inhomogeneity

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Introduction

$T_{1\rho}$ is the time constant for the longitudinal relaxation in the rotating frame, effectively being T_1 at the low B_1 field strength. It has been shown to be sensitive to the low-frequency interaction between macromolecules and water and $T_{1\rho}$ measurements have been used to assess changes in the proteoglycan content of cartilage, which is associated with osteoarthritic cartilage degeneration[1]. The $T_{1\rho}$ value is measured by spin locking the magnetization in the transversal plane, and for obtaining quantitative $T_{1\rho}$-maps, scans with a number of locking times must be performed. The method is, however, sensitive to inhomogeneities in the static magnetic field. The inhomogeneity typically increases with higher magnetic field strength and, therefore, considerations on the influence of inhomogeneities are more important when doing $T_{1\rho}$ measurements at high field strength.

The purpose of the present study was to quantitatively investigate the errors in $T_{1\rho}$ measurements introduced by field inhomogeneity using a conventional and a self-compensating composite pulse sequence.

In an off-resonance condition, a 90° excitation pulse along the *y*-axis does not bring the magnetization (*M*) to lie exactly along the *x*-axis, but rather it will be placed at a certain phase angle from the *x*-axis. A subsequent spin-locking pulse played along the *x*-axis will bring the off-resonance magnetization to oscillate around this axis and the amount of longitudinal magnetization after the restoring -90° pulse will depend on which time in the locking cycle the restoring pulse is played out. A composite excitation pulse sequence consisting of a $90°_x$ pulse followed by a $135°_y$ pulse will position *M* in the *xz*-plane near the effective locking B_1 causing *M* to be fixed and not oscillating during the locking period. The magnetization is brought back to the *z*-axis by playing out the two pulses in reversed order. This has been described by Dixon[2].

Methods

Spin-locking pre-pulses were added to a 3D spin echo sequence on a 7 T Varian scanner. In order to investigate the signal fluctuation after spin-locking, phantom experiments were done using a water bottle. Acquisitions were made with spin locking times ranging from 0 to 40 ms in steps of 0.4 ms. The spin locking strength was 440 Hz and both the standard and the composite pulse sequences were run. A B_0 field map was calculated by subtraction of the phase images from two gradient echo scans with echo times of 5.1 and 6.5 ms. Based on this, numerical simulations of the Bloch equation were performed to confirm the experiments. For quantifying the signal fluctuations during spin locking as function of off-resonance, we did simulations with off-resonance frequency ranging from 0 to 670 Hz.

Using the 3D spin echo sequence with both the conventional and the composite pulses, $T_{1\rho}$ measurements were performed in an ex vivo patella sample from the knee of a pig. Pixel size was 0.5x0.25 mm^2, slice thickness 3 mm and TE/TR was 12/600 ms. Spin locking frequency was 440 Hz with locking times from 0 to 50 ms in 10 ms steps.

Results

Field mapping scans on a patella sample showed that B_0 typically varied up to 300 Hz (1 ppm) over the specimen. The signal variation after locking at 145 Hz offset is shown in Fig 1. Signal curves from in vitro measurements and simulations are shown for both the conventional and the composite sequences.

Fig. 2 shows the signal fluctuation amplitude as function of off-resonance frequency. If, for example, fluctuation up to 30% were allowed, the offset must be below 145 Hz and 580 Hz with the conventional and the composite sequences, respectively.

Example patella $T_{1\rho}$-weighted images are shown in Fig. 3. Notice the difference in homogeneity at the arrows for the conventional and composite sequences. $T_{1\rho}$ in the cartilage was around 45 ms.

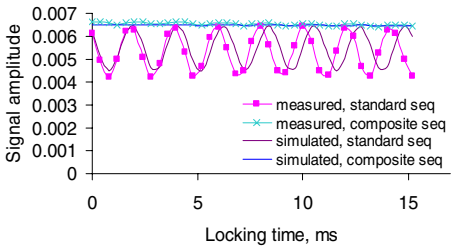

Figure 1. Measured signal curves from phantom measurements at a position with 145 Hz off-resonance. Scans with both the standard and composite sequences were made and signal curves from simulations at the same off-resonance are also shown.

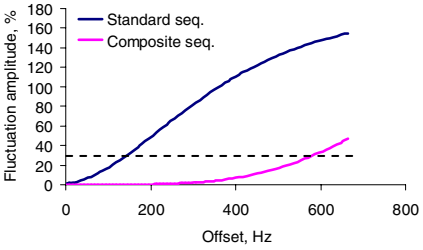

Figure 2. Signal fluctuation amplitude as function of off-resonance frequency for the conventional and the composite sequences.

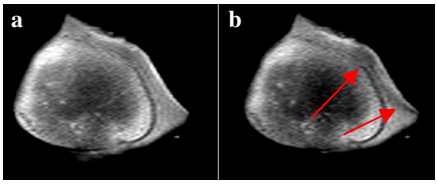

Figure 3. T1ρ-weighted cartilage images acquired with the composite (a) and conventional (b) sequences. Shown images are at 30 ms locking time.

Discussion

The study has shown that the B_0 homogeneity is a critical issue when doing $T_{1\rho}$ measurements or $T_{1\rho}$-weighted imaging. Using composite excitation, as shown here, reduces the fluctuation of the longitudinal magnetization after spin locking significantly, proving that this sequence is much more robust towards inhomogeneity. Unfortunately, this method increases SAR, which is not an issue for ex vivo or animal studies, but is of concern for human use. The error introduced by inhomogeneity could also be reduced by using higher locking frequency, but the sensitivity to proteoglycan content is assumed to be optimal with a locking frequency around 440 Hz.

Another way to reduce the signal fluctuation would be to synchronize the signal sampling with the locking frequency, but the simulations showed that the frequency of the oscillating signal varies slightly with the offset field, and therefore this is not a reliable approach.

In conclusion, inhomogeneities in the magnetic field can induce significant errors in $T_{1\rho}$-weighted scanning. It is important to assure that the field is sufficiently homogeneous or to use a self-compensating composite pulse.

References

Regatta R et al. Radiology 2003, 229:269-274.

Dixon T et al. MRM 1996, 36:90-94.