3D Segmented Elliptic-Centric Spoiled Gradient Echo Imaging for the In Vivo Quantitation of Cartilage T1rho

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Introduction Quantitative T1ρ (spin-lattice relaxation in the rotating frame) has been proposed as a diagnostic tool for the early detection of osteoarthritis [1]. However accurate assessment of cartilage T1ρ requires the implementation of a 3D sequence for the acquisition of high resolution T1ρ-weighted images. An existing steady-state (ss) 3D T1ρ sequence [1, 2] (ssT1ρ) has shown clinical promise [1], but requires knowledge of T1 for T1ρ quantitation. In addition, this sequence is SAR intensive – T1ρ preparation is played out every TR – which may preclude clinical application of ssT1ρ at 3.0T and higher. To overcome these short-comings, we propose a novel 3D pulse sequence that acquires data during the transient signal (ts) evolution immediately after T1ρ preparation (tsT1ρ).

Methods tsT1ρ, as diagrammed in Fig. 1, consists of magnetization preparation immediately followed by a 3D SPGR acquisition of a single k-space segment.

Mag Prep The mag prep section insures, at time t^- (Fig. 1, red arrow), that fat is nulled and that the magnitude of the longitudinal magnetization is the same for all acquisitions: the magnetization reset pulse (Fig 1. A.) spoils all longitudinal magnetization, and all acquisitions experience the same amount of saturation recovery, T_{rec}. T1ρ preparation (Fig 1. C.) is described in [4]. TSL, the spin lock time, determines the amount of T1ρ weighting at time t^+ (Fig 1, green arrow).

Image Acq Multiple k-space lines representing a single segment of k-space are acquired per single mag prep. The number of k-space lines acquired per mag prep (views per segment, or VPS,) is operator specified but is typically around 100. As illustrated in Fig. 2, k-space is traversed in segmented elliptic centric order, such that the center-most k-space lines are acquired at the beginning of each segment. Using an iterative Bloch simulation, SNR was maximized and blurring/edge-enhancement was minimized by calculating a flip angle train [5, 6] that provided a flat signal response for a specific prescription (TR, T_{rec},VPS), a single user-selected TSL_{opt}, the cartilage relaxation constants (Table 1), and a final flip of 90° (Fig 3). Because the flip angle train is only optimized for a single TSL, minor blurring/edge enhancement may still appear in T1ρ-weighted images where TSL is much longer or shorter than TSL_{opt}.

In-vivo T1ρ Quantitation After giving informed consent, healthy volunteers were scanned on a GE 3.0T EXCITE scanner. The tsT1ρ sequence was used to acquire images with different T1ρ-weighting by varying TSL. From these images a T1ρ map was calculated at each acquired location using a pixel-by-pixel mono-exponential fitting routine. Average T1ρ values of patella and femoral cartilage were measured from calculated T1ρ maps and compared with values found in the literature.

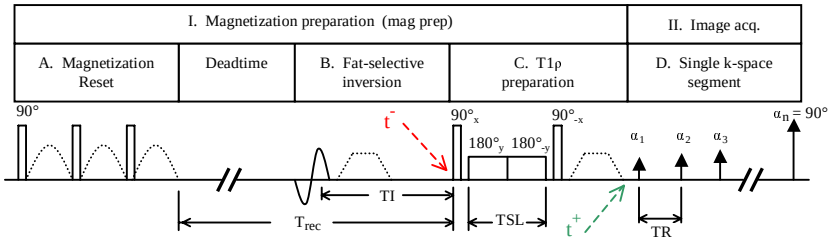

Fig 1: Pulse sequence diagram Magnetization preparation (I) and image acquisition (II) for a single segment and single TSL. Dotted lines represent z-gradient. Not drawn to scale.

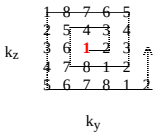

Fig 2: Segmented elliptic-centric phase encode order Phase encodes are ordered elliptic-centrically (arrow) starting from the center of k-space (red), and then segmented (numbers indicate segment), as shown here for the case of 8 segments. Note that for a typical tsT1ρ experiment, number of segments is much greater than 8 [3].

Cartilage	ms
T1	1240
T2	37
T1ρ	50

Table 1: Simulation parameters T1, T2, and T1ρ values of cartilage at 3T [1,7]. These values are used by an iterative Bloch simulation to calculate the optimal flip angle for a given TR, T_{rec}, VPS, and TSL_{opt}

Results Representative *in-vivo* images are shown in Fig 4. Axial (Fig 4. a-d) and sagittal (e-h) T1ρ-weighted images were used to calculate axial (i) and sagittal (j) T1ρ maps, respectively. All scans were performed in clinically acceptable scan times (≤ 11 min) and provided sub-mm in-plane resolution, excellent fat suppression, and superior through-plane coverage (Table 2). The average of measured T1ρ values in the patella and femoral cartilage were 46.5 and 47.6 ms, respectively, and agree with values found in the literature [1]. In some isolated areas, artificially elevated T1ρ values were found. This may have been caused by edge enhancement of cartilage at longer TSL. Further optimization of the flip angle train may help resolve this.

Discussion Unlike ssT1ρ [2], the T1ρ-weighted images in tsT1ρ are independent of T1; the images corresponding to different TSL contain the same amount of T1-weighting, and, therefore, knowledge of cartilage T1 is not required for T1ρ quantitation. In addition, with tsT1ρ, T1ρ preparation is only played out once every ~100 views, a substantial decrease in RF duty cyle and SAR compared to ssT1ρ, allowing clinical use of tsT1ρ at 3.0T. Furthermore, tsT1ρ mag prep time is less than the amount of time ssT1ρ spends on T1ρ preparation for VPS segments, when TSL > 20 ms. Therefore, tsT1ρ is faster than ssT1ρ for comparable prescriptions, and can acquire more locations for a fixed slice thickness and scan time. Also, replacing T1ρ preparation with T2Prep may be a viable option for quantitative 3D imaging of T2 relaxation.

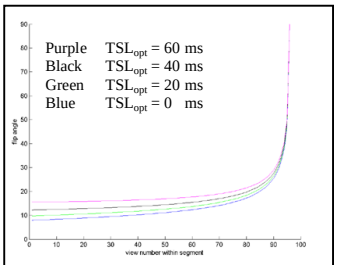

Figure 3: Flip angle train Calculated flip angle trains for different TSL_{opt} assuming relaxation parameters in Table 1 and TR, VPS, T_{rec} for the axial protocol specified in Table 2.

Conclusion A novel T1ρ-prepared segmented elliptic-centric 3D SPGR sequence that acquires data during transient signal evolution (tsT1ρ) provides accurate *in-vivo* quantitation of T1ρ with sub-mm in-plane resolution in clinically acceptable scan times. Knowledge of cartilage T1 is not need for T1ρ quantitation. ~100 views are acquired per mag prep, leading to a reducation of SAR, compared to ssT1ρ [2].

References [1] Regatte, et al., Acad Radiol. 2004 Jul;11(7):741-9 [2] Borthakur, et al., JMRI 17:730-736 (2003) [3] Bangerter, et al., ISMRM 2004 [4] Charagundla, et al., JMR 162 (2003):113-121 [5] Mugler, et al., MRM 28:165-185 (1992) [6] Epstein, et al., MRM 31:164-177 (1994) [7] Han, et al., ISMRM 2003

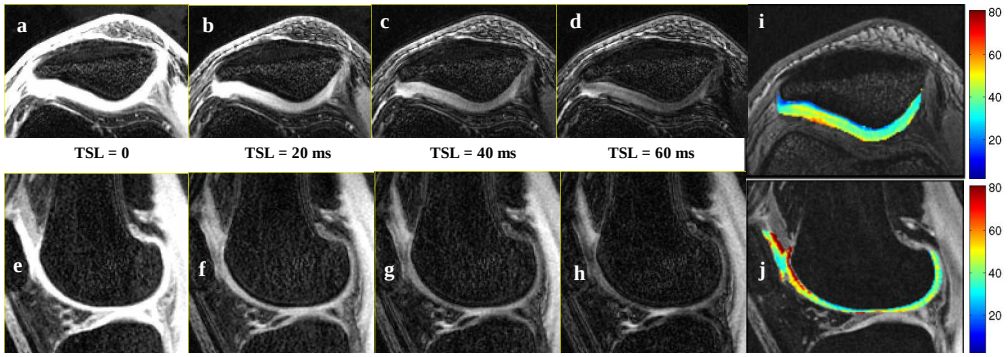

Figure 4: Example *in-vivo* T1ρ-weighted images and corresponding T1ρ maps *Top row*: Axial T1ρ-weighted images of patella cartilage (a-d) and corresponding T1ρ map overlayed on high resolution T1-weighted image (i). *Bottom row*: Sagittal T1ρ-weighted images (e-h) and corresponding T1ρ map (j). Imaging parameters listed in Table 2. All images were collected at 3.0T. Window leveling kept constant for T1ρ-weighted images.

RX	Axial	Sagittal
TE/TI/BW	Min Full / 110 ms / 32 kHz	
TR (ms)	11.8	7.9
FOV (cm)	10 x 10 x 6	14 x 14 x 9.2
Matrix	256 x 192 x 20	192 x 192 x 46
Resolution	0.4 x 0.5 x 3	0.7 x 0.7 x 2
TSL (ms)	0, 20, 40, 60	
TSL_{opt}/T_{rec} (ms)	25 / 1600	
VPS	96	192
SL_{freq} (Hz)	500	
Scan time	9:00	11:00

Table 2: Imaging parameters Prescription used to acquire images in figure 4. Blue text indicates parameters specific to tsT1ρ sequence.