A B1-insensitive High Resolution 2D T1 Mapping Pulse Sequence for Radial dGEMRIC of the Hip at 3T

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Introduction

Femoroacetabular impingement (FAI) [1] is a medical condition in which the abnormal contact between the acetabular rim and femoral neck causes labral and chondral damage that progress over time and can result in osteoarthritis (OA) of the hip. In FAI, detection of cartilage damage in its early stages is critical to the success of joint preserving surgeries aimed at correcting the bony abnormalities of FAI to prevent OA [2]. Delayed Gadolinium-Enhanced MRI of Cartilage (dGEMRIC) has been proposed as an early diagnostic tool for quantitative assessment of early biochemical changes in articular cartilage (AC) [3]. Radial MR imaging planes have been advocated for the morphologic evaluation of the acetabular labrum and adjacent AC in FAI [4]. However, radial planes are challenging for dGEMRIC, as a standard 2D multi-point IR FSE T1 mapping pulse sequence suffers from long scan times for clinical use and a recently proposed 3D GRE-based T1 mapping sequence [5] does not provide adequate spatial resolution of the cartilage when reformatted radially. Therefore our objective was to develop a new rapid 2D pulse sequence with high in-plane resolution for dGEMRIC of the hip in radially oriented planes.

Materials and Methods

We modified a fast spin-echo (FSE) pulse sequence to perform two image acquisitions. Assuming T_1 of normal cartilage at 3T to be on the order of 700-800 ms, the first image was a saturation recovery (SR) image acquired with a time delay (TD) of 700 ms and the second one was a proton density (PD) image acquired with TD = 4000 ms. T_1 was calculated pixel-wise by dividing the SR image by the PD image, to correct for the unknown equilibrium magnetization (M_0), and then solving analytically the ideal SR equation (Fig. 1). We used a B_1-insensitive saturation pulse [6] to achieve uniform T_1 weighting within the hip at 3T. Total scan time for both SR and PD acquisitions was 1 min 20 s per slice. In order to validate the T_1 measurements, we acquired four additional SR images, with TD = 350, 1050, 1750, 2450 ms (Fig. 1). Total scan time for the 4 additional SR images was 1 min 40s per slice. These additional SR images were combined with the aforementioned SR image with TD = 700 ms and the PD image, in order to perform a two-parameter (M_0, T_1) non-linear six-point fit of the ideal SR equation. In order to determine the sensitivity of the saturation pulse to B_1^+ variations within the hip, we imaged an oil phantom of known T_1 (~550 ms), with the B_1^+ scale of the saturation pulse manually adjusted from 0.8-1.2 (0.05 steps) of its nominally calibrated B_1^+ value. Ten hips (6 left, 4 right) were scanned in nine consecutive patients (mean age = 36 ± 10 years) undergoing dGEMRIC at our institution. Images (320 x 320) where acquired on a 3T MR system (Verio, Siemens Healthcare, Erlangen, Germany) using: in-plane resolution = 0.6 x 0.6 mm^2, slice thickness = 5 mm, turbo factor = 13, TR (excluding the saturation pulse and recovery time) was 143 ms, TE = 10 ms, refocusing flip angle was 180°, and receiver bandwidth = 161 Hz/pixel. A fat suppression pulse was used to avoid chemical shift artifacts at the bone-cartilage interface. All images were acquired in a radial plane that included the anterior-superior region of the acetabulum. Image processing was performed using in-house developed software. After deidentification and randomization of the patient data, two observers (RL and DK) manually segmented a region of interest (ROI) over the weight-bearing portion of the hip AC. Observer 1 (RL) repeated the image analysis after 14 days. We performed the Pearson correlation and Bland-Altman analyses to compare analytic T_1 and six-point fit T_1. Intra- and inter-observer variability was also assessed.

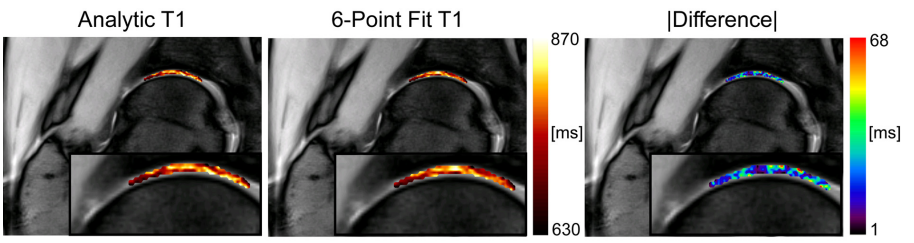
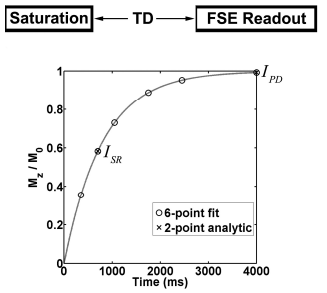


Fig. 2. For all cases, the weight-bearing portion of hip cartilage was segmented from the lateral bony edge to the edge of the acetabular fossa. T_1 maps were calculated using the analytic and the 6-point fit method and the absolute difference between the two was computed pixel-wise. RMSE was 11.8 ms for the representative case in this figure.



$$I_{SR} = M_0\left(1 - e^{-TD/T_1}\right) \qquad I_{PD} \approx M_0 \qquad T_1 = \frac{-TD}{\log\left(1 - I_{SR}/I_{PD}\right)}$$

Fig. 1. Plot of SR acquisition used in this study. The five SR acquisitions were acquired with TDs 350, 700, 1050, 1750, 2450 ms. The PD acquisition was acquired with TR = 4000 ms and without the saturation pulse. Analytical T_1 was calculated solving the equation at the bottom, using the SR image with TD = 700 ms and PD image. The two-parameter fit of the ideal SR equation was made using all six images.

Results

T_1 in the phantom was 561 ± 10 ms with the analytic method and 561 ± 11 ms with the six-point fit method. T_1 measurements with the analytic method were 567 ms, 565 ms, 561 ms, 561 ms, and 563 ms for B_{1+} variations of 0.8, 0.9, 1.0, and 1.1, and 1.2, respectively. Consistent with the previous work in the heart at 3T [6], the phantom T_1 values were similar throughout, suggesting that the saturation pulse is insensitive to B_{1+} variation as large as 20%. Analytic and six-point fit T_1 maps are shown for one representative hip in Fig. 2, together with a map of the absolute value of the difference between the two, which ranged from 1 to 68 ms (RMSE =11.8 ms). The mean analytic T_1 over 10 hips was 823 ± 189 ms, 808 ± 183 ms and 797 ± 132 ms, for the two sessions of observer 1 and the single session of observer 2, respectively. The Person correlation coefficient of determination R^2 was larger than 0.95 in all cases ($p < 0.001$), suggesting that the analytic and six-point fit T_1 measurements were strongly correlated. According to the Bland-Altman analysis, analytic and six-point fit T_1 values were in good agreement (Fig. 3). Intra- and inter-observer variability was within the 95% limits of agreement (Table 1).

TABLE I
SUMMARY OF BLAND-ALTMAN AND PEARSON ANALYSIS.

Agreement Type	Difference (ms)	Upper 95% Limit (ms)	Lower 95% Limit (ms)	R^2 (Pearson)
Analytic – 6-Point Fit (Observer 1, Session 1)	-8.7	64.5	-81.9	0.98
Analytic – 6-Point Fit (Observer 1, Session 2)	-4.3	71.5	-80.1	0.97
Analytic – 6-Point Fit (Observer 2)	18.6	77.2	-40.0	0.95
Intra-Observer (Session 2 – Session 1: Analytic in Gray, 6-Point Fit in White)	-10.4	34.1	-54.9	0.98
	-14.8	38.0	-67.6	0.98
Inter-Observer (Observer 2 – Observer 1: Analytic in Gray, 6-Point Fit in White)	11.9	118.3	-94.5	0.88
	11	144.7	-122.7	0.92

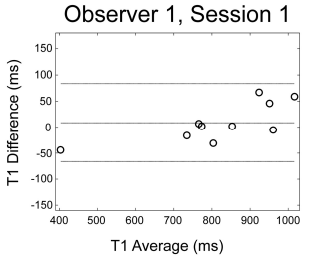


Fig. 3. Bland-Altman plot (95% confidence intervals are displayed) of the T_1 values calculated with the analytic T_1 mapping sequence vs. rigorous 6-point fitting at 3 T, for the first session of observer 1.

Discussion and Conclusions

We developed a new high-resolution 2D T_1 mapping sequence for radial dGEMRIC of the hip with a clinically acceptable scan time of 1 min 20s per slice. We showed that the T_1 measurements are accurate, repeatable and reproducible. The technique could be applied to measure cartilage T_1 in other joints and it is particularly suitable for applications at 3 Tesla, because it is insensitive to B_1^+ inhomogeneities.

References

[1] Ganz R et al, (2003) Clin Orthop Relat Res 417:112-20 [2] Beck M et al, (2004) Clin Orthop Relat Res 418:67-73 [3] Bashir A et al, (1996) MRM 36(5): 665-73 [4] Kubo T et al, (1999) J Orthop Sci 1999; 4(5): 328–32 [5] Sur S et al, (2009) JMRI 30(4): 896-900 [6] Kim D et al, (2009) MRM 62(6): 1368-78