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 B1-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, and 2450 ms (Fig. 1). Total scan time for the 4 additional SR images was 1 min 40 s 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) were 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.

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, 563 ms and 564 ms for $B_1$ variations of 0.9, 1.0, 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).

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 20 s 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

Fig. 1. Plot of SR acquisition used in this study. The five SR acquisitions were acquired with TDs 350, 700, 1050, 1750, and 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.

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.

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.