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Cartilage damage in femoroacetabular impingement (FAI): preliminary results on comparison of standard diagnostic vs delayed gadolinium-enhanced magnetic resonance imaging of cartilage (dGEMRIC)

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Summary

Objectives: To study the three-dimensional (3D) T1 patterns in different types of femoroacetabular impingement (FAI) by utilizing delayed gadolinium-enhanced magnetic resonance imaging (MRI) of cartilage (dGEMRIC) and subsequent 3D T1 mapping. We used standard grading of OA by Tonnis grade on standard radiographs and morphological grading of cartilage in MRI for comparative analysis.

Methods: dGEMRIC was obtained from ten asymptomatic young-adult volunteers and 26 symptomatic FAI patients. MRI included the routine hip protocol and a dual-flip angle (FA) 3D gradient echo (GRE) sequence utilizing inline T1 measurement. Cartilage was morphologically classified from the radial images based on the extent of degeneration as: no degeneration, degeneration zone measuring <0.75 cm from the rim, >0.75 cm, or total loss. T1 findings were evaluated and correlated.

Results: All FAI types revealed remarkably lower T1 mean values in comparison to asymptomatic volunteers in all regions of interest. Distribution of the T1 dGEMRIC values was in accordance with the specific FAI damage pattern. In cam-types ($n = 6$) there was a significant drop ($P < 0.05$) of T1 in the anterior to superior location. In pincer-types ($n = 7$), there was a generalized circumferential decrease noted. High interobserver (intra-observer) reliability was noted for T1 assessment using intra-class correlation (ICC):intra-class coefficient $= 0.89$ (0.95).

Conclusions: We conclude that a pattern of zonal T1 variation does seem to exist that is unique for different sub-groups of FAI. The FA GRE approach to perform 3D T1 mapping has a promising role for further studies of standard MRI and dGEMRIC in the hip joint.
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Key words: MRI, Hip, Cartilage, FAI, dGEMRIC.

Introduction

Abnormal morphology in femoroacetabular impingement (FAI) leads to a mechanical impaction involving the proximal femur and acetabular rim inducing labral failure and varying degrees of cartilage damage[1]. Based on morphology, FAI can be divided into two types; cam and pincer. In cam FAI, the cause of impaction is a non-spherical shape of the femoral head along with insufficient femoral head−neck offset. In pincer FAI, the impact arises from acetabular over-coverage[1] or due to the shape or orientation of the acetabulum[2−4]. Combined variants are common[5].

Untreated FAI can lead to premature osteoarthritis (OA) of the hip[1,6,7] and surgical treatment is often necessary to delay the onset of the same as well as for managing symptoms[8]. The outcome of surgical intervention depends on the degree of pre-existing OA with obvious poor results in patients with advanced changes[7,9,10].

Magnetic resonance (MR) arthrography is an excellent tool to assess extent and character of joint changes[11]. MR arthrography has been proven accurate in detecting labral pathologies such as degeneration, cysts and tears[12−15] but is not so specific for diagnosing cartilage damage especially at the early stages[16,17].

Biochemical imaging techniques such as delayed gadolinium-enhanced MR imaging (MRI) (dGEMRIC) may help to overcome this barrier. dGEMRIC represents a technique of cartilage T1-relaxation assessment after gadolinium administration. By injecting the anionic, negatively charged contrast agent gadolinium-diethylene-triamine-pentaacetic-acid ($Gd\text{-}DTPA^{2-}$) the gadolinium penetrates into the cartilage inversely to the concentration of glycosoaminoglycan (GAG). The dGEMRIC method has been established both *in vitro*[18−20] and *in vivo*[21−26].

The purpose of this study was to answer the following questions: is three-dimensional (3D) T1 mapping a reliable means of assessing the status of hip joint cartilage? Is there

any regional variation (i.e., anterior–posterior (AP) or peripheral–central) in the mapping values? Therefore, we performed comparative analyses of these readings with dGEMRIC and standard radiography in both symptomatic FAI cases and a control group of asymptomatic young-adult volunteers. We further analyzed the data to outline any differences of 3D T1 patterns for different types of FAI namely cam-type, pincer-type, and mixed-type.

Method

STUDY POPULATION

A total of 26 patients (18 males, eight females) who presented with symptomatic FAI based on clinical examination and plain radiographic findings were subsequently recruited in this prospective study. Symptomatic FAI was verified clinically by the anterior impingement sign[27] performed in supine position by flexing the hip to 90° during adduction and simultaneous internal rotation. The test was considered positive (inclusion criterion for patients, exclusion criterion for volunteers) if it would reproduce the sharp groin pain similar to their primary complaint of hip pain. Exclusion criteria were; patients with previous hip surgery, associated dysplasia and patients with other hip problems. The mean age was 32.1 ± 8.8 years, ranging from 17 to 49 years. The control group involved 10 asymptomatic young-adult volunteers (three males, seven females, mean age 26.5 ± 2.1 years, and range 24–31 years) who took part in the clinical evaluation and underwent MRI as well. Informed consent was obtained in all cases and this study was approved by the local ethics committee.

MEDICAL HISTORY AND PHYSICAL EXAMINATION

During the interview, patients were questioned regarding presence and severity of pain, stiffness in the hip and the ambulatory status and scored according to the Merle D'Aubigné system[28]. On physical exam, range of hip flexion and internal rotation was noted in all cases.

PLAIN RADIOGRAPHIC EVALUATION

Plain radiographic evaluation was used to divide the patients into three cohorts (cam-, pincer-, and mixed-type) for T1 dGEMRIC analysis and to assess the osteoarthritic degeneration based on the radiographs for comparison to the T1 dGEMRIC findings. Therefore, an AP radiograph of the pelvis was performed with a standard technique in supine position with neutral rotation of pelvis with the beam centered on the symphysis pubis equidistant from either anterior–superior iliac spines (ASISs) and an axial cross-table radiograph[29] was performed. To assess the hip joint morphology, the following radiographic assessments were performed on the AP radiograph: lateral center edge (LCE) angle of Wiberg[30], acetabular index of Tonnis[31], femoral head extrusion index of Heyman and Herndon[32], presence of a coxa profunda[33] as well as cross-over and posterior wall signs[2]. On the axial cross-table radiograph, the alpha angle[34] was measured to evaluate asperity at the femoral head–neck junction. Sub-types of FAI (cam, pincer and mixed) were classified based on these quantitative and qualitative assessments according to previously published criteria[35]. Tonnis grade[31] and joint space width (JSW) at the central weight-bearing zone and also at the periphery close to the acetabular rim on the AP radiograph were used as the radiographic assessment of OA. Radiographic analyses and FAI classifications were performed by two experienced orthopedic surgeons (KS and MB) who were blinded to MRI findings.

MRI

A 0.4 ml per kg body weight of FDA approved gadolinium contrast agent Gd-DTPA^{2-} (Magnevist, Schering AG, Berlin, Germany) was administered intravenously. Prior to MRI, the subjects were asked to walk for 15 min and then to wait another 30 min (a total of 45 min) until MRI was performed to facilitate adequate penetration of gadolinium into the cartilage[22]. MRI was performed in supine position at a 1.5 T system (Magnetom Avanto, Siemens, Erlangen, Germany) using a body matrix-phased array coil.

The MR protocol included: (1) axial two-dimensional (2D) turbo spin echo (TSE) with T1-weighting (repetition time (TR)/echo time (TE) = 491 ms/13 ms, 3 mm slice thickness, 160 mm field of view (FOV), 512 × 256 matrix, acquisition time (TA) = 4.14 min), (2) coronal oblique 2D TSE with proton-density (PD)-weighting (TR/TE = 3060 ms/9.1 ms, 2 mm slice thickness, 130 mm FOV, 256 × 205 matrix, TA = 5.35 min), (3) sagittal 2D TSE with PD-weighting (TR/TE = 2900 ms/9.1 ms, 2 mm slice thickness, 130 mm FOV, 256 × 205

matrix, TA = 5.35 min), (4) axial 2D fast low angle shot (FLASH) with T1-weighting (TR/TE = 250 ms/12 ms, 2 mm slice thickness, 120 mm FOV, 256 × 205 matrix, TA = 3.52 min), and (5) radial 2D TSE with PD-weighting around the femoral neck and perpendicular to the acetabular rim (TR/TE = 1800 ms/13 ms, 4 mm slice thickness, 180 mm FOV, 512 × 256 matrix, TA = 4.30 min). The radial sequence was planned on the sagittal–oblique and the coronal–oblique localizer image to minimize saturation effects.

In addition to the MR protocol, an FA 3D gradient echo (GRE) sequence with volumetric interpolated breathhold examination (VIBE) utilizing inline T1 measurement was performed (TR/TE/FA = 25 ms/3.6 ms/10° and 35°, 0.78 mm slice thickness, 200 mm FOV, 256 × 256 matrix, voxal size = 0.78 mm^3 (isotropic), slab = 96, TA = 8.46 min). This FA GRE technique [as an alternative to the inversion recovery (IR) method for T1 mapping] has been previously validated for the hip in phantom and *in vivo* studies[36,37]. The complete MRI examination including Gd-DTPA^{2-} injection, then 45 min of waiting time prior to MR arthrography (~30 min) and FA scans for T1 mapping (~10 min) took approximately 90 min.

MRI ANALYSES

MRI analyses were performed independent to the radiographic analyses by two experts in musculoskeletal imaging (SW and TM).

Femoroacetabular cartilage was evaluated from the radial 2D TSE PD-weighted MR images at eight positions around the femoral neck as previously described by Locher *et al.*[15]: (1) anterior–inferior, (2) anterior, (3) anterior–superior, (4) superior–anterior, (5) superior, (6) superior–posterior, (7) posterior–superior, and (8) posterior. Cartilage was graded based on the extent of degeneration as similarly used by Pfirrmann *et al.*[11] for assessment of cartilage damage in different types of FAI: 0 as no degeneration, 1 as degeneration extending not more than 0.75 cm medially from the acetabular rim, 2 as degeneration extending medially for more than 0.75 cm. Degeneration was defined as any evidence of cartilage damage ranging from substance irregularities to focal thickness loss of acetabular cartilage. Total cartilage loss was defined as grade 3 and excluded for T1 analysis (Fig. 1).

For T1 measurement of cartilage the 3D data sets (morphological 3D VIBE and corresponding 3D T1 maps) were transferred to a Leonardo® workstation (Siemens, Erlangen, Germany) for further processing and analyses. By using multi-planar-reconstruction (MPR) software, a reference imaging plane through the center of the femoral head and perpendicular to the femoral neck axis in both coronal and sagittal plane was defined. On this reference image, eight radial VIBE and T1 map reformats (see above) were created (Fig. 2). Thus, similar to the radial 2D PD TSE for assessment of cartilage morphology, T1 relaxation was assessed at various zones: (1) anterior–inferior, (2) anterior, (3) anterior–superior, (4) superior–anterior, (5) superior, (6) superior–posterior, (7) posterior–superior, and (8) posterior.

Fig. 1. Radial PD-weighted TSE image with an indirect arthrography effect (white arrows). Note the cartilage damage at the acetabular rim.
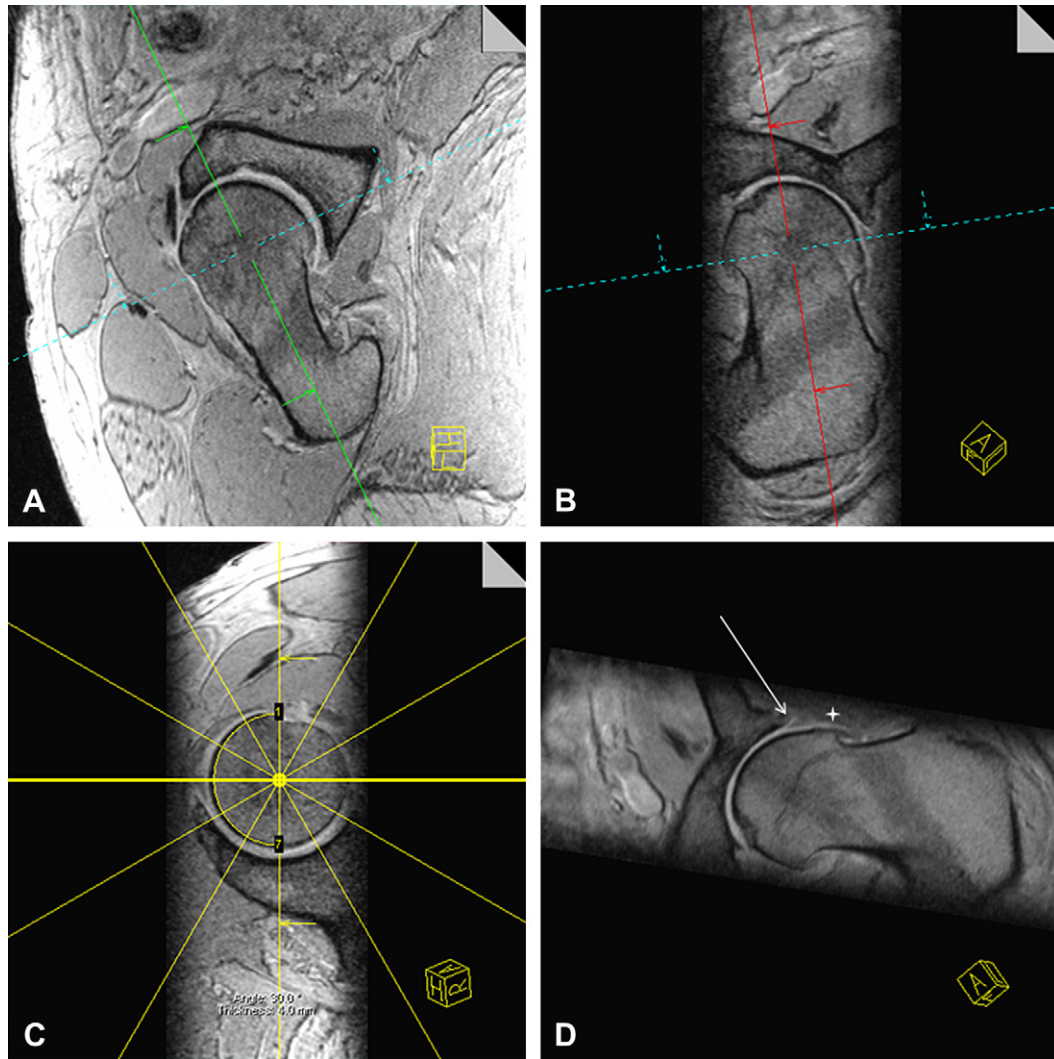
Fig. 2. MPR that is performed to create a plane that is perpendicular to the femoral head–neck (A, B) and in the center of the femoral head. On this plane (C) radial reformats with an interval of 30° were generated for accurate assessment of morphology and changes of degeneration (C). The coronal oblique plane (highlighted yellow line in C) depicting the superior zone is illustrated in (D). Note the non-spherical nature of the femoral head (white star) and a corresponding tear at the base of the labrum (line of high signal intensity).

Two regions of interests (ROIs) were drawn within each T1 radial reformat. One ROI was set peripherally and the second ROI was placed centrally that reflected the morphological cartilage grading upon the extent (<0.75 and >0.75 cm) of cartilage damage (Fig. 3).

The image resolution was limited hence the acetabular and femoral cartilage layers were not reliably distinguishable. If significant amounts of joint fluid are trapped between the cartilage layers, the average T1 value would be further lowered. The size of the peripheral and central ROI varied minimally due to differing cartilage thickness. However, we took care to respect the cartilage boundaries. Ultimately, 16 ROIs were studied within each hip.

To compare the distribution of our results to previously published studies[11], the alpha angle was assessed at the eight radial positions as described by Nötzli et al.[34] and the acetabular coverage was assessed by measuring the acetabular depth on the axial reformat. As described and reported previously[11], acetabular depth was expressed as the distance between a line drawn joining the anterior and posterior acetabular horns and the center of the femoral head.

STATISTICAL ANALYSES

Continuous data was expressed as mean and standard deviations (SD) (±). To determine whether or not statistically significant differences were present between FAI patients and the asymptomatic control group and between the different sub-groups of FAI the Student's t test (parametric variables, independent samples) or the Wilcoxon rank sum test (non-parametric variables, exact significance, one-sided) was utilized. Based on radiographic analyses, the three FAI sub-groups (cam/pincer/mixed) were compared amongst each other using the univariate analysis of variance (ANOVA). P-values below 0.05 were considered to be statistically significant. For reliability assessment, plain radiograph and MRI measurements were repeated by two other observers (BB and SS) in 10 randomly selected patients. One observer only (BB) further repeated the analyses in these 10 randomly selected patients after 4 weeks. Subsequent, inter-observer and intra-observer agreement was evaluated by intra-class correlation (ICC) testing. SPSS® software (Version 16.0, SPSS Inc., Chicago, IL, USA) was used for statistical analysis.

Results

RELIABILITY ANALYSIS

ICC reliability analysis included parametric plain radiographic (JSW, LCE, Tonnis index, extrusion index, and alpha angle) and MRI measurements (alpha angle, acetabular depth, and T1 relaxation). Intra-class coefficients for inter-observer (intra-observer) reliability were as follows:
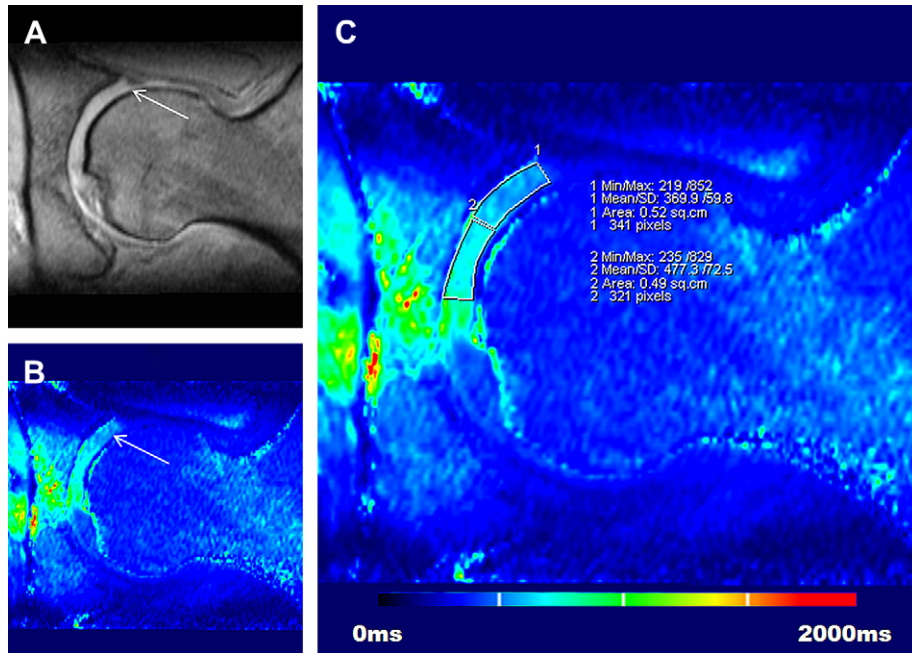
Fig. 3. Morphologic VIBE reformat (A) and the corresponding T1 maps (B, C) depicting the superior zone in a cam-type hip. T1 values are visualized in a color scale (simplified bright colors − high T1 values, dark colors low T1 values), and quantified by ROI analyses. Note the drop in T1 (∼370 ms) at the acetabular rim indicates a high Gd-DTPA^{2-} infiltration due to GAG loss and cartilage degeneration. The medial zone is, in that case, less affected (∼477 ms).

JSW central 0.68 (0.77), JSW peripheral 0.68 (0.86), LCE 0.86 (0.97), Tonnis index 0.95 (0.98), femoral head extrusion index 0.90 (0.97), alpha angle radiograph 0.73 (0.95), alpha angle MRI 0.82 (0.88), acetabular depth 0.82 (0.87), and T1 relaxation 0.89 (0.95).

HISTORY AND PHYSICAL EXAMINATION FINDINGS

In comparison with the control group, all FAI sub-groups were noted to have statistically significant differences in Merle D'Aubigné scores ($P < 0.01$), pain duration ($P < 0.01$), and range of hip flexion ($P < 0.01$). Internal rotation was significantly limited in the cam- and mixed-FAI groups ($P < 0.01$) but not in the pincer-FAI group ($P = 0.44$). Considering the mean Merle D'Aubigné scores that ranged from 14.4 to 15.2, the subjective state of health was considered as relatively good in all FAI patients. Our findings are summarized in Table I.

PLAIN RADIOGRAPHS

Out of 26 FAI patients, six were classified as cam-type, seven as pincer-type, and 13 as mixed-types. Tonnis grading and JSW assessment did not reveal any evidence of advanced OA. There were nine cases of Tonnis grade 0 and 17 cases of Tonnis grade 1. The distribution of T1 values from the dGEMRIC scans for hips of various Tonnis grades and different types of FAI are shown in Table III and Fig. 4. The T1 values were significant lower for cam-type and pincer-type impingement ($P < 0.05$) at all positions in hips with FAI but no radiographic evidence of OA (Tonnis grade 0) compared to the asymptomatic volunteers, with a more severe decrease for pincer-type cases. For hips with Tonnis grade 1 OA, all types of FAI had significantly lower T1 values ($P < 0.05$) with a zonal variation for the cam-type impingement cases, with a drop of values from anterior−superior to superior.

MRI DATA

Morphologic data on every symptomatic FAI patient including alpha angle and acetabular depth are shown in Table II, and showed a distribution as similar to the one described by Pfirrmann *et al.*[11]. Alpha angles were significantly higher in cam-types at the anterior ($P = 0.012$), anterior−superior ($P = 0.017$), and superior−anterior

Table I

*Merle D'Aubigné score, as well as range of flexion and internal rotation in symptomatic FAI patients and asymptomatic volunteers. Note: continuous data being expressed as mean values and SD (±), *P-values of <0.05 and **P-values of <0.01 were considered as significant for analyzing the differences between the FAI sub-groups calculated using the Student's t test*

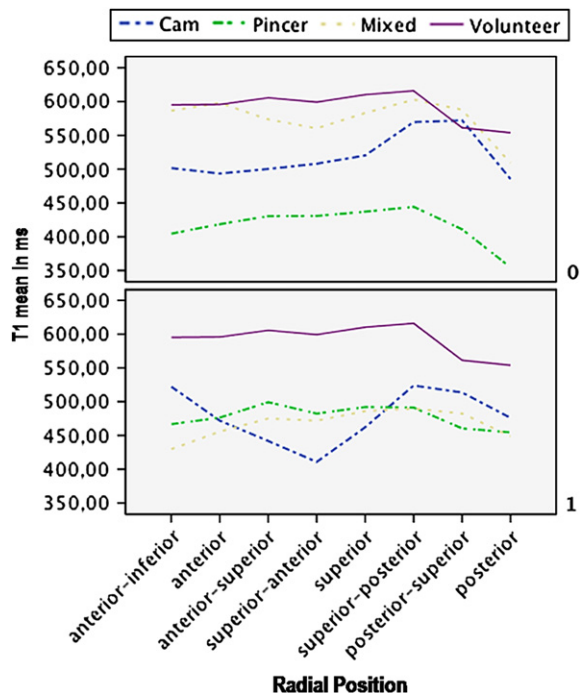|	Cam-type, $N = 6$	Pincer-type, $N = 7$	Mixed-type, $N = 13$	Volunteers, $N = 10$
Merle D'Aubigné	15.2 ± 1.0**	14.4 ± 2.0**	14.9 ± 1.3**	18
Pain duration (months)	22.5 ± 13.7**	14.6 ± 8.9**	29.5 ± 26.6**	0
Flexion (°)	98.3 ± 7.5**	103.6 ± 9.5**	103.5 ± 12.7**	122.5 ± 7.1
Internal rotation (°)	10.0 ± 9.5**	22.9 ± 13.5	10.4 ± 8.8**	27.5 ± 7.1

Fig. 4. T1 distribution throughout the hip joint with various radiographic grades (Tonnis grades) of OA in different types of FAI. Note the difference in T1 patterns between the cam-type and pincer-type with significantly lower T1 values when compared to the control group of asymptomatic volunteers.

($P = 0.016$) positions. In mixed-type patients, all mean alpha angles except for those in the posterior region were significantly higher with P-values ranging from <0.01 to 0.045. No significant differences could be noted for the pincer-type group. Cam-type cases revealed a statistically significant lower acetabular depth index ($P = 0.017$).

In cam-type cases, cartilage lesions were mainly present in the anterior−inferior to superior−anterior zones (50−67%). In pincer-type cases, cartilage lesions were more frequent in the anterior−inferior to superior locations (57−86%). It is important to note that cartilage damage in pincer-type cases was more in the periphery while those in cam-types were more extensive toward the center of the joint. Further, lesions on the posterior aspect were

more common in pincer-FAI patients (29−43%) than in cam-type patients (17−33%). In mixed-type cases, cartilage lesions were more frequent in the anterior−inferior to superior zones (extending from periphery toward the center) (54−77%) and also noted in the posterior regions (23−39%). Few asymptomatic volunteers did show mild cartilage changes in the anterior to superior−anterior locations (20−30%).

For dGEMRIC and T1 mapping a total of 576 ROIs were analyzed. Mean ROI size and SD was 0.30 ± 0.12 cm^2 in the periphery and 0.29 ± 0.12 cm^2 in the central location. The maximum difference noted between peripheral and central ROI size was 0.06 cm^2 (mean difference 0.022 ± 0.016 cm^2).

For global T1 dGEMRIC values for the different grades of morphological MR analysis, there was for normal graded cartilage a drop of values in the anterior−superior portion for the cam-type cases and no changes for the mixed- and pincer-type cases. This is shown in Fig. 6. For grade 1 cartilage lesions there was a drop from anterior to superior for the cam-type patients and overall decreased values for the pincer-type and mixed-type cases. For grade 2 cartilage lesions there was an overall significant drop ($P < 0.05$) of T1 values for all types of impingement with no differences within the cam-, pincer- and mixed-type group (Table IV and Fig. 5).

For zonal variation from peripheral to central in the cam-type group a statistically significant decrease of T1 values for the peripheral locations was found in the anterior to superior zones (P-values anterior to superior: 0.019, 0.003, 0.006, 0.002). In the central locations, T1 values were significantly lower for anterior−superior ($P = 0.011$), superior−anterior ($P = 0.011$), and superior ($P = 0.043$) zones. In pincer-types all T1 values except for those on peripheral anterior and peripheral posterior locations were significantly lower (P-values reported in Table V). In the mixed-type cohort statistically lower T1 values occurred in only three locations. At the peripheral portion the difference was statistically significant in the superior ($P = 0.048$) and central portion at two positions; anterior ($P = 0.049$) and superior−anterior ($P = 0.014$). For the asymptomatic volunteer group there was an increase of T1 values noted toward the superior regions except for a slight drop in the superior−anterior location. The radial distribution of T1 values in FAI patients as compared to asymptomatic volunteers in peripheral and central locations is shown in Table V and illustrated in Fig. 6.

Table II

Morphological assessment of the hip including alpha angle and acetabular depth in symptomatic FAI patients and asymptomatic volunteers obtained with MRI. Note: acetabular depth was measured on the axial 3D reformat as distance between femoral head center and a line joining anterior and posterior acetabular rim. *P-values <0.05 and **P-values <0.01 indicating statistically significant difference between the FAI group and the control group of asymptomatic young volunteers.

	Cam-type, $N = 6$	Pincer-type, $N = 7$	Mixed-type, $N = 13$	Volunteers, $N = 10$
	Alpha angle, °	Alpha angle, °	Alpha angle, °	Alpha angle, °
Anterior−inferior	47.0 ± 16.5	35.3 ± 2.8	44.5 ± 9.8**	35.1 ± 4.3
Anterior	58.3 ± 12.6*	39.1 ± 4.0	49.9 ± 6.6**	39.0 ± 4.0
Anterior−superior	62.2 ± 14.7*	39.6 ± 2.6	54.2 ± 6.9**	41.5 ± 4.8
Superior−anterior	64.5 ± 17.7*	40.1 ± 6.1	51.1 ± 11.9**	39.3 ± 5.0
Superior	49.3 ± 20.0	37.7 ± 5.6	41.3 ± 4.4*	36.4 ± 3.9
Superior−posterior	45.5 ± 17.5	35.1 ± 4.9	38.0 ± 4.8*	34.6 ± 2.4
Posterior−superior	43.9 ± 15.4	33.4 ± 4.7	37.6 ± 4.8*	32.4 ± 1.4
Posterior	41.5 ± 12.7	34.7 ± 3.2	39.1 ± 9.1	33.6 ± 4.5
Total	51.5 ± 17.0**	37.0 ± 4.8	44.5 ± 9.7**	36.2 ± 4.8
Acetabular depth (cm)	0.96 ± 0.18*	0.56 ± 0.21	0.77 ± 0.25	0.70 ± 0.17

Table III

T1 results of cam-, pincer- and mixed-type cases with various radiographic grades of joint damage according to the Tonnis grading system. Continuous data are being expressed as mean values and SD ($\pm$). To evaluate if significant difference is present between the FAI group and the control group of asymptomatic young volunteers, the Student's t test (independent values) was performed. *P-values of <0.05 and **P-values <0.01 for the statistical significant difference between FAI patient and asymptomatic volunteer

	Tonnis grade 0			Tonnis grade 1			Volunteers
	Cam-type, $N=2$	Pincer-type, $N=2$	Mixed-type, $N=5$	Cam-type, $N=4$	Pincer-type, $N=5$	Mixed-type, $N=8$	$N=10$
Anterior−inferior	501.7 ± 70.5	404.6 ± 60.0*	586.5 ± 202.2	522.3 ± 150.5	466.7 ± 98.8*	429.8 ± 98.7**	595.2 ± 99.6
Anterior	493.6 ± 70.6	418.6 ± 29.0*	598.0 ± 197.7	472.0 ± 100.8	476.5 ± 110.5	455.8 ± 66.0**	595.7 ± 95.5
Anterior−superior	500.4 ± 111.7	430.5 ± 51.1*	573.7 ± 183.3	441.9 ± 21.9**	499.3 ± 92.7	475.2 ± 73.8**	605.6 ± 82.9
Superior−anterior	508.1 ± 98.9	430.9 ± 76.0*	560.4 ± 166.2	410.9 ± 76.4**	482.4 ± 80.9*	471.9 ± 89.8**	599.2 ± 73.7
Superior	520.3 ± 97.7	437.1 ± 59.3*	583.2 ± 162.0	462.2 ± 68.9**	492.2 ± 71.6*	486.2 ± 89.3*	610.3 ± 69.1
Superior−posterior	569.7 ± 61.4	444.4 ± 4.9*	602.9 ± 173.5	524.0 ± 130.4	491.3 ± 104.1*	489.8 ± 87.5**	616.0 ± 73.9
Posterior−superior	572.1 ± 20.0	411.0 ± 17.2*	588.0 ± 186.9	513.6 ± 149.7	460.5 ± 110.1	482.6 ± 134.6	561.3 ± 97.6
Posterior	485.5 ± 30.5	354.8 ± 11.1*	509.1 ± 170.1	476.0 ± 126.2	454.6 ± 90.7	448.8 ± 146.1	553.9 ± 116.9

Discussion

FAI can cause premature OA if appropriate intervention is not performed early[1,6]. Aids to diagnosis include a detailed medical history and physical examination, radiographs and MR arthrography with radial scanning. The clinician has to recognize the limitation of motion, type of anatomic pathomorphology and degree of cartilage damage. Since the success of treatment and prevention of early osteoarthrosis is based on the timing of intervention, diagnostic tools that will identify the earliest of articular cartilage changes, both biologically and radiologically, are warranted. In the presented study we explored the potential of dGEMRIC as a tool to identify the loss of GAG within cartilage at an early stage[18−23,25,26].

Based on our results we conclude that 3D T1 mapping can be a reliable means of assessing the status of hip joint cartilage. The comparative analyses of dGEMRIC and standard radiography in symptomatic FAI cases and the control group of asymptomatic young-adult volunteers revealed that 3D T1 mapping can assess the differences in degeneration as classified by radiography and morphological MR grading. In addition there exists a pattern of zonal variation that seems to be unique for a sub-group of FAI lesions.

Using dGEMRIC, all FAI cases revealed a trend of lower T1 mean values in the entire joint as compared to asymptomatic volunteers. The occurrence of a significant difference in certain ROIs, depending on the type of FAI, despite the low number of cases in this study outlines the potential of a higher sensitivity of the dGEMRIC technique which has to be shown in correlation to intra-operative results. Our findings of dGEMRIC and T1 mapping in some ways resonate with previous reports depicting cartilage changes in hip dysplasia or patients with early OA[24,38]. In the report by Kim *et al*.[24] the T1 values were noted to be lower relative to the grade of dysplasia and ranged from 570 ± 90 (with no signs of dysplasia) to 550 ms (with mild dysplasia), 500 ms (moderate) and 420 ms (with severe dysplasia). In the study of Tiderius *et al*.[38] the T1 values ranged approximately from ~540 ms in asymptomatic volunteers to ~420 ms in patients with early OA. However, in both studies the limitation was that only coronal T1 maps could be obtained by using fast-spin echo with IR.

By using radial T1 mapping it was possible to perform precise T1 evaluation around the entire hip joint. Based on the morphologic MRI data of our study cohorts, we noted that cartilage lesions in cam-type cases were more frequent in the anterior−inferior to superior−anterior locations. In pincer-type cases cartilage lesions were also notable in

Table IV

T1 results of cam-, pincer- and mixed-type cases with various MRI grades of joint damage according to the extent of cartilage damage (0 = normal, 1 ≤ 0.75 cm, 2 > 0.75 cm). Continuous data are being expressed as mean values and SD ($\pm$). Note that the presence of one unique cartilage grade within each hip was acquired for classification and analysis. These data are kept descriptive according to the low number of cases

|	Grade 0			Grade 1			Grade 2			Volunteers
	Cam-type, $N=1$	Pincer-type, $N=0$	Mixed-type, $N=3$	Cam-type, $N=1$	Pincer-type, $N=3$	Mixed-type, $N=2$	Cam-type, $N=4$	Pincer-type, $N=3$	Mixed-type, $N=2$	$N=10$
Anterior−inferior	551	−	599 ± 118	592	462 ± 69	545 ± 117	462 ± 75	431 ± 96	404 ± 97	595 ± 100
Anterior	543	−	595 ± 143	552	471 ± 60	535 ± 179	452 ± 24	444 ± 95	431 ± 78	596 ± 96
Anterior−superior	579	−	605 ± 120	442	502 ± 46	533 ± 156	436 ± 41	449 ± 85	447 ± 92	606 ± 83
Superior−anterior	577	−	599 ± 109	465	504 ± 37	506 ± 119	404 ± 39	418 ± 37	444 ± 100	599 ± 74
Superior	589	−	610 ± 100	548	524 ± 61	547 ± 117	437 ± 58	412 ± 42	463 ± 97	610 ± 69
Superior−posterior	613	−	615 ± 139	605	532 ± 71	559 ± 112	479 ± 80	405 ± 32	466 ± 92	616 ± 74
Posterior−superior	586	−	561 ± 168	621	506 ± 73	539 ± 171	472 ± 84	365 ± 29	465 ± 82	561 ± 98
Posterior	597	−	553 ± 102	619	473 ± 90	542 ± 167	437 ± 68	362 ± 80	425 ± 112	554 ± 117
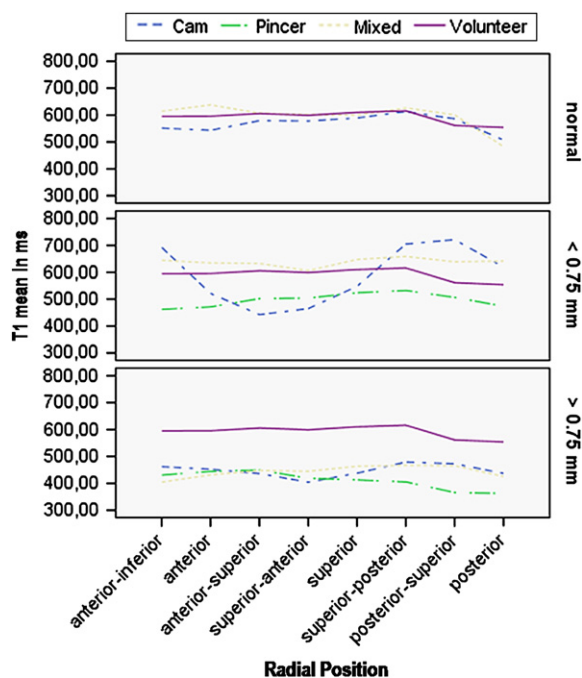
Fig. 5. Distribution of T1 values throughout the hip joint with various MRI grades based on the extent of cartilage damage for different types of FAI. Note the difference in T1 patterns between the cam-type and the pincer-type with significantly lower T1 values when compared to the control group of asymptomatic volunteers. Also note the significant T1 drop at the anterior−superior to superior region in the cam-type with a cartilage lesion extent <0.75 mm.

the posterior aspect. However, the defect appeared more circumferential and less-extensive toward the center of the joint. These findings of differences in the extent of cartilage damage as well as frequency and location of cartilage lesions are consistent with previously published reports[5,11]. The morphological pattern of lesions is further substantiated by the T1 distribution findings in our study. In our cases with cam-type FAI, there was a significant drop of T1 in the anterior to superior location (both centrally and peripherally) that reflects the existing damage pattern in this type of FAI. An example of the specific damage pattern in cam-types is illustrated in Fig. 7. In pincer-types, there was no drop in the T1 values at a specific region but a circumferential decrease was noted that was statistically significant in almost all radial regions. This again corresponds with the morphologic damage pattern noted in our current study and in other previous reports[5,11]. However, based on the T1 findings in peripheral and central locations, cartilage degeneration did not seem to be singularly restricted to the acetabular rim as partly shown in our study and other previous studies[5,11]. This zonal variation assessed by T1 dGEMRIC has possible clinical applications in decision making for joint preserving surgery[7,9,10].

At this point in time we are not aware of any clinical reports investigating mixed component of FAI with dGEMRIC. In our series there were 13 such cases. As expected, the findings in these cases revealed a damage pattern with combined cam and pincer findings. The cartilage damage was most frequent in the anterior−inferior to superior locations with lesion sizes that were larger than 7.5 mm. This damage pattern was well localized and reflected by the T1 value distribution. The differences in T1 values between mixed-type FAI patients and

asymptomatic volunteers reached a statistically significant level only at three regions: superiorly in the peripheral zone and anteriorly and suiperioanteriorly in the central zone. This could possibly be explained by the anatomical variations in this cohort that led to a conglomeration of more or less degenerated cartilage. The presence of high SD in the mixed cohort also points toward this.

There are limitations in this study. Our study population was relatively small with 26 patients, and due to the subdivision into three groups according to the type of impingement the number of patients within each group was further decreased, which significantly reduces the numbers for a power analysis. However, findings of medical history[4], range of motion[4,39], plain radiographs[1−4], alpha angles on MRI[11,34], as well cartilage findings[5,11] in our study closely resemble those as in previous reports. Therefore, we believe our results demonstrate typical findings in patients with FAI. Despite the inclusion of patients with only mild articular changes as per the Tonnis grades and JSW, we noted a wide range of findings on the MRI. Limitations of the control group were that although all volunteers were interviewed for history of hip pathologies and were clinically examined before inclusion, few cases of cartilage changes were still identified in this asymptomatic group albeit not excluded from the study. One major limitation was the absence of a diagnostic gold standard such as intra-operative correlation or histology. In addition, the cartilage grading based on an indirect arthrography, which is not comparable to direct arthrography. With direct MR arthrography labral tears and cartilage clefts may be better identified through the contrast filling into the clefts. Therefore, we may have missed lesions, which could explain some differences between cartilage grading and the T1 dGEMRIC. It was not possible to differentiate between acetabular and femoral cartilage layers at an image resolution obtained with 1.5 T. Therefore, in our study ROI analysis included acetabular and femoral cartilage as one combined entity. In some areas of severe or considerable damage it was difficult to differentiate between joint effusion and cartilage. However, any inclusion of joint fluid mapping would actually lower the T1 value, which would depict more severe cartilage damage. Finally, ROI analysis obtains only mean values that represent the entire encircled area and, therefore, minor but remarkable changes may have been possibly underestimated. Hence, to minimize the obliteration effect within each radial reformat we created peripheral and central sub-divisions for T1 assessment.

In summary, the T1 distribution reflected the FAI damage pattern and was consistent with earlier reports. Additionally, the FA GRE approach in our study allowed shorter scanning time and the ability to perform 3D T1 mapping including T1 assessment at any desired location. High ICC was noted for T1 assessment. Therefore, we believe that this study demonstrates a reproducible method for further studies of dGEMRIC and T1 in the hip joint. The assessment of zonal variation of cartilage damages for different types of FAI and also for different stages of cartilage degeneration may have important clinical implications: It can help to better understand the histopathology of cartilage degeneration in FAI and the development of progressive OA based localized lesions of FAI. This may help to define a time-point of treatment, and it can possibly lead to an improved staging of FAI for planning of the appropriate therapy, e.g. the decision on open surgery vs arthroscopic approach. Future studies should involve a larger study population and a diagnostic gold standard like intra-operative correlation or histology for comparison. In addition the use of 3 T MRI in future studies can
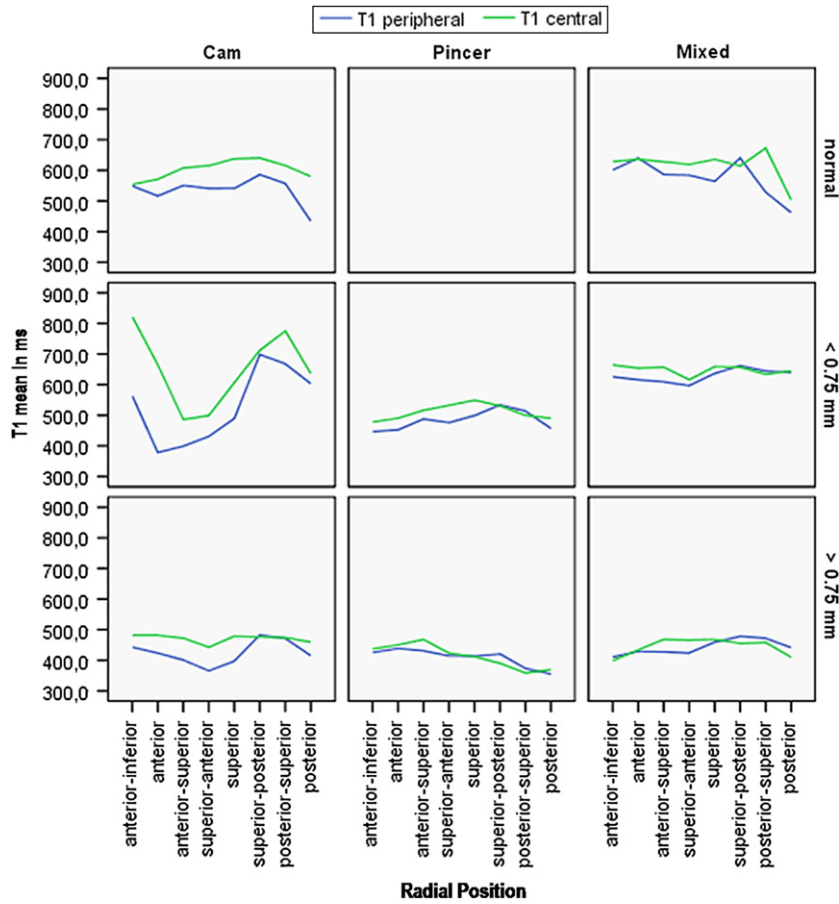
Fig. 6. Zonal variation of T1 values in different types of FAI at various grades of cartilage damage. Note the significant difference for cam-type impingement in cartilage damage <0.75 mm with more severe lesions at the peripheral zone.

Table V

Cartilage lesions based on PD TSE on different radial locations and T1 values in symptomatic FAI patients and asymptomatic volunteers at the same radial location for all ROI in degenerated and normal graded cartilage. T1 values are being expressed as mean and SD ($\pm$). Statistical differences between patients and volunteers for the extent of cartilage damage were calculated with the Wilcoxon rank sum test. For analysis of T1 means, the Student's t test was utilized. Note *P-values of <0.05 and **P-values of <0.01 were considered to prove statistical difference

| | Cam-type ($N = 6$) | | | | Pincer-type ($N = 7$) | | | |
| | Cartilage lesion | | dGEMRIC value (ms) | | Cartilage lesion | | dGEMRIC value (ms) | |
	<7.5 mm	>7.5 mm	Peripheral	Central	<7.5 mm	>7.5 mm	Peripheral	Central
Anterior−inferior	1 (16.7%)*	3 (50.0%)	480 ± 83	551 ± 167	3 (42.9%)*	2 (28.6%)	438 ± 115*	460 ± 70**
Anterior	1 (16.7%)	3 (50.0%)	432 ± 76*	527 ± 118	4 (57.1%)*	2 (28.6%)	447 ± 111	473 ± 85**
Anterior−superior	1 (16.7%)	3 (50.0%)	426 ± 65**	497 ± 74*	4 (57.1%)	2 (28.6%)	464 ± 100*	496 ± 71**
Superior−anterior	1 (16.7%)	2 (33.3%)	406 ± 80**	481 ± 103*	3 (42.9%)	2 (28.6%)	450 ± 75*	486 ± 85**
Superior	0	2 (33.3%)	437 ± 74**	527 ± 83*	2 (28.6%)	2 (28.6%)	463 ± 57**	490 ± 84**
Superior−posterior	0	2 (33.3%)	536 ± 94	543 ± 127	0	3 (42.9%)	485 ± 81**	471 ± 98*
Posterior−superior	0	1 (16.7%)	518 ± 93	548 ± 148	0	3 (42.9%)	454 ± 93*	439 ± 96*
Posterior	0	1 (16.7%)	450 ± 87	509 ± 116	0	2 (28.6%)	414 ± 88	439 ± 94*
	Mixed-type ($N = 13$)				Volunteers ($N = 10$)			
Anterior−inferior	2 (15.4%)*	5 (38.5%)	488 ± 153	493 ± 174	0	0	577 ± 111	614 ± 95
Anterior	3 (23.1%)*	6 (46.2%)	506 ± 144	515 ± 151*	2 (20.0%)	0	565 ± 108	627 ± 94
Anterior−superior	3 (23.1%)*	7 (53.9%)	492 ± 129	534 ± 134	3 (30.0%)	0	585 ± 94	626 ± 84
Superior−anterior	4 (30.8%)*	6 (46.2%)	488 ± 140	524 ± 125*	2 (20.0%)	0	559 ± 88	640 ± 68
Superior	1 (7.7%)*	6 (46.2%)	511 ± 112*	536 ± 148	0	0	594 ± 70	626 ± 75
Superior−posterior	1 (7.7%)	4 (30.8%)	544 ± 131	523 ± 138	0	0	627 ± 83	605 ± 79
Posterior−superior	1 (7.7%)	4 (30.8%)	512 ± 144	534 ± 186	0	0	562 ± 91	561 ± 109
Posterior	0	3 (23.1%)	477 ± 161	468 ± 149	0	0	529 ± 124	579 ± 113
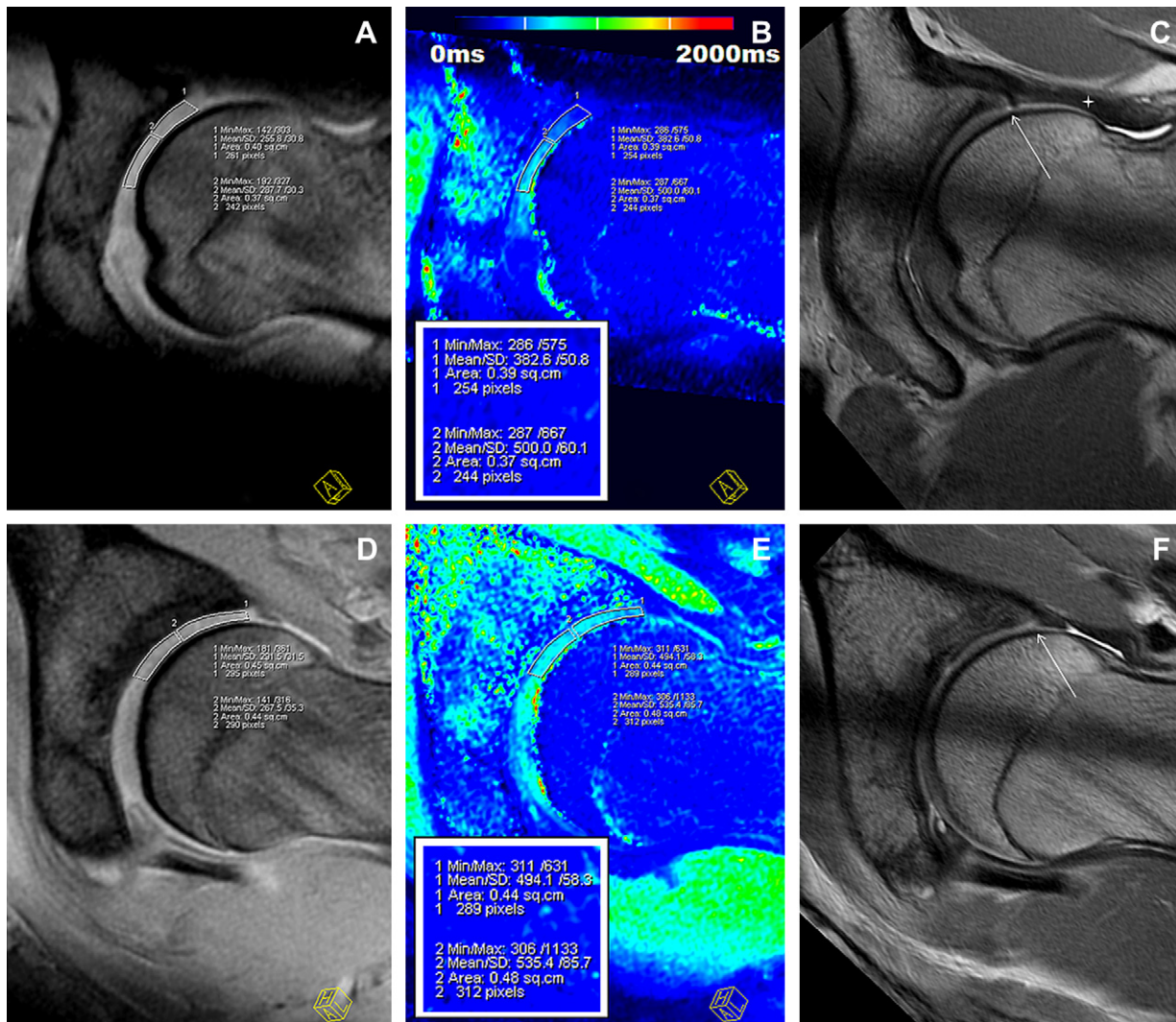
Fig. 7. Morphologic VIBE (A) and corresponding T1 reformat (B) at the superior location in a cam-type patient. Note the visual coloring quantified by the low T1 value that is pronounced peripherally at the acetabular rim (B). The PD-weighted radial image (C) demonstrates a nonspherical femoral head along with reduced head–neck offset and a basal labral tear (white arrow). Interestingly, there are no clear signs of cartilage damage in this scan. In the same patient at the posterior–superior location (D–F), T1 is mildly lowered (E). A basal labral tear (white arrow) was identified at the same location (F).

substantially improve morphological cartilage diagnosis by higher resolution and dGEMRIC technique by differentiation of the acetabular and femoral cartilage layers.

Conflict of interest

Acknowledgments

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