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A Novel MR-based Method for Detection of Cartilage Delamination in Femoroacetabular Impingement Patients

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Abstract

In this study, quantitative magnetic resonance based measurements were used to evaluate $T_{1\rho}$ and T_2 mapping and heterogeneity in femoroacetabular impingement (FAI) patients with acetabular cartilage delamination and to determine the ability of these quantitative MR-based measurements in detecting delamination. Unilateral hip joint MR-scans of 36 FAI patients with arthroscopically-confirmed acetabular cartilage delamination and 36 age, gender and BMI matched controls were obtained. $T_{1\rho}$ and T_2 mapping and heterogeneity of the hip joint articular cartilage were assessed in both groups using voxel-based relaxometry (VBR). Quantitative MR-based measurements were compared using statistical parametric mapping (SPM). Receiver operating characteristic (ROC) analysis was used to assess the ability of these quantitative measurements in detecting delamination by calculating the area under the curve (AUC). Pearson partial correlations (r) were used to assess for associations between $T_{1\rho}$ and T_2 radial heterogeneity with the alpha angle in FAI patients. $T_{1\rho}$ and T_2 global acetabular values were significantly higher in FAI patients with a focal increase within the posterior acetabular cartilage. FAI patients exhibited increased anterior superior acetabular $T_{1\rho}$ and T_2 heterogeneity and both of these measures demonstrated a strong ability to detect acetabular cartilage delamination ($T_{1\rho}$ AUC: 0.96, $p<0.001$; T_2 AUC: 0.93, $p<0.001$). FAI patients with a larger alpha angle exhibited increased anterior superior acetabular $T_{1\rho}$ ($r=0.48$, $p=0.02$) and T_2 ($r=0.42$, $p=0.03$) heterogeneity. $T_{1\rho}$ and T_2 heterogeneity within the anterior superior acetabular cartilage was shown to be a sensitive measure in detecting

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delamination and may prove beneficial to clinicians in determining optimal interventions for FAI patients.

Keywords

Voxel Based Relaxometry (VBR); Radial Heterogeneity; Femoroacetabular Impingement; Delamination; $T_{1\rho}/T_2$

INTRODUCTION

Femoroacetabular impingement (FAI) is a morphological disorder of the hip joint, which causes abnormal joint loading patterns and may cause acetabular cartilage delamination[1–4]. Delamination is a separation of the acetabular cartilage layer from the subchondral bone[3,5,6] and is strongly associated with the cam-type deformity[1–4]. More specifically, it was shown that FAI patients with an alpha angle of at least 65° have a 4-fold increase in risk of acetabular cartilage delamination[2]. This injury pattern is ascribed to increased shear forces within the hip joint, as a result of the geometric impingement of the cam lesion. Chronic impingement may then cause enlargement of the cartilage flap and lead to complete detachment from the adjacent cartilage thereby producing loose bodies, full-cartilage thickness defects, and eventually progressive osteoarthritis[1,3,6,7]. Delamination occurs in approximately 30 – 52% of FAI patients[1,8,9] and is usually detected arthroscopically, as delamination is difficult to diagnose radiologically[6,10]. An improved method of detecting acetabular cartilage delamination in FAI patients prior to surgery would benefit the orthopaedic community and may aid in improving surgical treatment options[9,11].

MR-arthrograms are considered the gold standard in detecting labral abnormalities in FAI patients[12,13] yet radiological detection of acetabular cartilage delamination may still be difficult for radiologists to detect even with MR-arthrograms[1,6,10]. This may be due to the limited amount of distensibility in the hip joint[10], thereby causing difficulty in viewing the separation between the acetabular and femoral cartilage surfaces. Previous work by Pfirrmann *et al* (2008) demonstrated that when using MR arthrography in detecting acetabular cartilage delamination, fluid under the delaminated cartilage is a specific yet uncommon sign of delamination, while a hypo-intense signal in the acetabular cartilage may be a useful sign to help diagnose cartilage delamination[9]. Overall, radiologists encounter difficulty in assessing delamination due to various factors and therefore, a more quantitative and precise method of detecting delamination through non-invasive imaging methods would benefit the orthopaedic community.

Quantitative MR-imaging (QMRI) techniques such as $T_{1\rho}$ and T_2 mapping have gained increased use in assessing hip joint cartilage composition in FAI patients[14–17]. Voxel based relaxometry (VBR) allows for the examination of the local distribution of $T_{1\rho}$ and T_2 mapping and has recently been used to assess both hip[18] and knee[19,20] joint cartilage composition. VBR analysis of the acetabular and femoral cartilage layers of the hip joint was shown to be consistent with a traditional region of interest (ROI) based method in those with hip osteoarthritis (OA)[18] and was shown to be more sensitive in detecting local patterns of $T_{1\rho}$ elevation compared to a traditional ROI based assessment[19]. This suggests that VBR

may provide for a more sensitive ability to detect localized differences in articular cartilage composition in FAI patients as well. Also, it is important to understand the effects of FAI on spatial distribution (heterogeneity) of cartilage relaxation times, using texture based analysis, as previous studies have shown that the spatial distribution of cartilage relaxation times may be a sensitive enough measure to discriminate between those with and without OA[21–23].

Therefore, the aims of our study were to: 1) assess the global and local characteristics and heterogeneity of biochemical composition within the acetabular and femoral cartilage using absolute $T_{1\rho}$ and T_2 VBR and standard deviation of the VBR mapping in subjects with and without FAI, 2) determine whether these quantitative MR-based measurements are sensitive enough to identify acetabular cartilage delamination and 3) determine whether there is an association between acetabular cartilage $T_{1\rho}$ and T_2 heterogeneity with the cam-type morphology in FAI patients with delamination. We hypothesized that when compared to healthy controls, $T_{1\rho}$ and T_2 cartilage mapping and heterogeneity within the anterior acetabular cartilage layer, would be altered in FAI patients; further we hypothesized that anterior acetabular cartilage $T_{1\rho}$ and T_2 heterogeneity would be able to reliably detect delamination and would be associated with the cam-type morphology.

METHODS

Patient Demographics

This case-control study (Level III) was approved by the Committee for Human Research at our institution. All subjects provided written informed consent prior to testing. A total of 72 study participants were enrolled in the current study: 36 FAI patients with acetabular cartilage delamination and 36 age, gender and body mass index (BMI) matched controls were recruited for the current study. Acetabular cartilage delamination was verified arthroscopically during surgical treatment of FAI patients (Figure 1).

All FAI patients were recruited from the Sports Medicine Clinic at our institution and were tested (approximately one month) prior to hip arthroscopy. Each FAI patient exhibited an alpha angle > 55°[24] and/or a lateral center edge (LCE) angle > 35°[25] as well as other morphological abnormalities including cartilage and labral abnormalities, osseous bump formation or acetabular over-coverage. The alpha and lateral center edge angles were measured on oblique axial MR-images and standard anterior-posterior pelvis radiographs, respectively. Each FAI patient also demonstrated a positive flexion adduction internal rotation (FADIR) test[26] upon examination by an orthopaedic surgeon (A.L.Z.). Participants were excluded from this study if they possessed a BMI > 35kg·m^{-2}, previous hip surgery on the affected side, radiographic indication of osteoarthritis (Kellgren-Lawrence grade[27] > 1 and less than 2mm of joint space) or contraindications to MRI (i.e. pregnancy, coronary stent, etc.). It should be noted that all control participants demonstrated negative FADIR tests, indicating no clinical signs of impingement.

MR-Image Acquisition

Each study participant underwent a unilateral MR-scan, using a 3 Tesla MR scanner (GE MR750, GE Healthcare, Waukesha, WI) and an 8-channel cardiac coil (GE Healthcare,

Waukesha, WI). For all scans, each participant's feet were aligned in neutral rotation and secured in place to reduce hip movement. The MRI protocol included morphological sequences consisting of T_2 fast spin echo (FSE) images and a combined $T_{1\rho}$ and T_2 sequence[28,29], which were used to assess morphological abnormalities and cartilage relaxation mapping, respectively.

The T_2 intermediate-weighted, fat-suppressed, FSE images were obtained with a repetition time of 2400–3700ms, echo time of 60ms, field of view (FOV) of 14 – 20cm, matrix size of 288 × 224 and a slice thickness of 3 – 4mm. These T_2 FSE images were obtained in the sagittal, oblique axial and coronal planes and were used to assess for cartilage and labrum abnormalities, osseous bump formations and acetabular over-coverage in all study participants. In the current study, $T_{1\rho}$ and T_2 MR-images were obtained using the following sequence parameters: FOV of 14cm, matrix size of 256 × 128 pixels, slice thickness of 4mm, recovery time of 1.2s, views per segment of 64, bandwidth of 62.5kHz, no gap, in-plane spatial resolution of 0.5mm, in-plane pixel spacing is [0.5469,0.5469] mm and the out of plane slice thickness is 4 mm, time spin lock of 0/15/30/45ms, spin lock frequency of 300Hz and an acquisition time of 13:47.

MR-Image Processing and Analysis

A previously published method used to implement VBR to assess hip joint cartilage composition[18] was used in the current study and is briefly explained below. Each study participant's MR-data was registered to a single reference participant's MR-data, which provided for the comparison of similar anatomic areas across all participants. The reference data was selected through an iterative process that minimized the global deformation (i.e. minimum deformation template) across participants. Morphological differences across the participants required the use of non-rigid registration applied using the Elastix Toolbox[30]. Non-rigid registration was performed using an iterative process that aimed in reducing the overall differences in femoral head shape between the reference image and in each participant's image. The femoral head center in the reference image and in each participant's image was determined using the Hough transform[31,32], a method of object detection based on the transformation of all points of an object as defined by a specific equation. For the current study, the femoral head was modeled as a circle, which represented a section of the femoral head in 2D space. The deformation field computed on the first $T_{1\rho}$-weighted image (TSL=0) was then applied to all the later $T_{1\rho}$-weighted and T_2-weighted images, allowing for the fitting of $T_{1\rho}$ and T_2 maps aligned to the template of each subject. Acetabular and femoral cartilage ROIs manually defined on the reference image were then applied to all the deformed cases creating a fully automatic segmentation procedure.

A radial local standard deviation filter was applied on the $T_{1\rho}$ and T_2 maps to compute local heterogeneity. We modeled the 2D coronal section of the femoral head as a circle. Prior to the application of the kernel, the 3D $T_{1\rho}$ and T_2 maps were converted into cylindrical coordinates [ρ, θ, z] (polar coordinates in the coronal plane) and the kernel applied as a standard deviation filter was [3×1], with 1 in θ and 3 in the ρ direction and followed the circular shape of the femoral head within the 2D section. After the filter's application, each voxel assumes the value of the standard deviation of the [3×1] voxel neighborhood. Radial

symmetry padding was used for the voxels lying on the cartilage borders. This filtering technique returned maps that represent the $T_{1\rho}$ and T_2 local radial heterogeneity.

Statistics

Group demographics, alpha and lateral center edge angles were compared using independent t-tests, where a p-value of less than 0.05 was considered significant. Global differences in $T_{1\rho}$ and T_2 mapping and heterogeneity between the FAI and control groups in both the acetabular and femoral cartilage layers were assessed using independent t-tests. VBR based group comparisons were performed using Statistical Parametric Mapping (SPM), which provided an assessment of the local differences in $T_{1\rho}$ and T_2 mapping and heterogeneity between both groups. Group comparisons of the VBR measurements (i.e. mean and standard deviation) were performed using independent t-tests and used to obtain the volumetric p-value SPMs. Also, the percent of significant voxels (PSV) and the average p-value within the significant cluster ($p < 0.05$) of the acetabular and femoral cartilage layers were computed. Random field theory was used to account for any false positives due to multiple comparisons[33].

The ability of the global and local $T_{1\rho}$ and T_2 mapping and heterogeneity in discriminating between FAI patients with delamination and healthy controls was assessed using the area under the curve (AUC) of the receiver operating characteristic (ROC) analysis. The max-efficiency cut-off values were also determined for each of the global and local $T_{1\rho}$ and T_2 MR-based parameters. The significance of the discriminations ($p < 0.05$) was assessed using one-tailed independent t-tests.

The association between alpha angle with $T_{1\rho}$ and T_2 mapping and heterogeneity within the anterior superior acetabular cartilage of the FAI patients was assessed using a Pearson partial correlation coefficient (r), adjusting for age, gender and BMI, where a p-value of less than 0.05 was considered significant. The Jarque-Bera test was performed to check for normality of the $T_{1\rho}$ and T_2 data distribution[34].

RESULTS

As the FAI patients and healthy controls were matched for age, gender and BMI, these demographics along with the alpha and lateral center edge angles of all study participants were found to be similar ($p > 0.05$) (Table 1).

The FAI patients exhibited significantly higher global acetabular $T_{1\rho}$ values (FAI: 34.5±4.0 ms, Control: 32.8±2.6 ms, $p = 0.04$) yet no differences were exhibited in global femoral $T_{1\rho}$ values (FAI: 34.7±3.6 ms, Control: 34.8±3.5 ms, $p = 0.93$) (Figure 2A). More specifically, the FAI patients demonstrated a significant $T_{1\rho}$ elevation within the posterior acetabulum (Figure 2B; PSV: 8.64%; $p = 0.03$). The FAI patients exhibited increased global $T_{1\rho}$ heterogeneity within both the acetabular (FAI: 9.81±2.03 ms, Control: 8.39±1.54 ms, $p = 0.001$) and femoral (FAI: 8.66±1.46 ms, Control: 7.57±1.46 ms, $p = 0.002$) cartilage layers (Figure 2C). When assessing the local $T_{1\rho}$ heterogeneity, the FAI patients exhibited increased $T_{1\rho}$ heterogeneity within the anterior-superior acetabular (PSV: 10.6%; $p = 0.02$)

and anterior femoral (PSV: 10.5%; p = 0.02) cartilage layers (Figure 2D). All global and local based QMRI measurements are summarized in Table 2.

Similar to the global $T_{1\rho}$ results, the FAI patients exhibited significantly higher global acetabular T_2 values (FAI: 28.8±4.6 ms, Control: 26.5±2.2 ms, p = 0.01) and similar global femoral T_2 values (FAI: 31.3±4.1 ms, Control: 30.9±2.5 ms, p = 0.65) (Figure 3A). The increased acetabular T_2 values occurred in the posterior region of the acetabular cartilage (Figure 3B; PSV: 14.7%; p = 0.02). Global T_2 heterogeneity in the FAI patients was increased in both the acetabular (FAI: 10.1±1.93 ms, Control: 7.91±1.79 ms, p < 0.001) and femoral (FAI: 8.54±2.13 ms, Control: 6.88±1.95 ms, p = 0.001) cartilage layers (Figure 3C). Within both the anterior superior acetabular and anterior femoral cartilage layers, local T_2 heterogeneity was increased and demonstrated a similar amount of significantly different voxels within these regions (PSV=24%, p = 0.02) when compared to healthy controls (Figure 3D).

The ROC analysis (Figure 4) demonstrated that the local heterogeneity of $T_{1\rho}$ (cut-off: 8.96ms, AUC: 0.96, p<0.001) and T_2 (cut-off: 8.16ms, AUC: 0.93, p<0.001) within the anterior-superior acetabular cartilage better discriminated those with delamination compared to any of the other QMRI based measurements (Table 3).

Within the FAI patients, a larger alpha angle was associated with an increase in $T_{1\rho}$ (r = 0.48, p = 0.02) and T_2 (r = 0.42, p = 0.03) radial heterogeneity within the anterior superior acetabular cartilage. Although both the $T_{1\rho}$ and T_2 radial heterogeneity displayed moderate associations with the alpha angle, T_2 radial heterogeneity demonstrated a slightly larger amount of significant voxels that were associated with the alpha angle within FAI patients ($T_{1\rho}$ PSV: 2.05%, T_2 PSV: 3.38%). The correlation map between T_2 radial heterogeneity and alpha angle in the FAI patients, along with the scatterplot of the average T_2 radial heterogeneity and alpha angles within the anterior superior acetabular cartilage are shown in Figure 5.

DISCUSSION

The results of the current study demonstrated that a VBR analysis of quantitative MR-based measurements was able to reliably detect acetabular cartilage delamination within FAI patients. More specifically, $T_{1\rho}$ and T_2 radial heterogeneity were able to better detect delamination compared to global $T_{1\rho}$ and T_2 mapping. These results suggest that $T_{1\rho}$ and T_2 radial heterogeneity may be a more sensitive measure than global $T_{1\rho}$ and T_2 mapping in detection of delamination. In addition, the $T_{1\rho}$ and T_2 radial heterogeneity within the anterior superior acetabular cartilage layer, the area of the hip joint in which delamination occurs, was moderately associated with the cam impingement (i.e. alpha angle) and helps to validate previous work suggesting that there is an association between the cam impingement and delamination[1–4].

In the current study, both the acetabular and femoral global $T_{1\rho}$ and T_2 relaxation times in the FAI patients were similar to previously published $T_{1\rho}$ and T_2 relaxation times in FAI patients[14,15]. The FAI patients in the current study exhibited significantly higher global

acetabular $T_{1\rho}$ and T_2 relaxation times compared to the healthy controls with no differences in femoral $T_{1\rho}$ and T_2 relaxation times. These results indicate altered acetabular cartilage composition and are supported by previous work that demonstrated a strong association between acetabular cartilage abnormalities and increased hip joint loading during gait in FAI patients[35]. These FAI patients may potentially be applying larger loads within the hip joint and these loads seem to be affecting the acetabular cartilage composition more so than the femoral cartilage composition. The increase in $T_{1\rho}$ and T_2 relaxation times may be driven by a more focal difference in the $T_{1\rho}$ and T_2 mapping of the posterior acetabular cartilage, where approximately 8 – 14% of voxels within the posterior acetabular cartilage layer demonstrated significantly increased $T_{1\rho}$ and T_2 relaxation times in FAI patients when compared to healthy controls. The altered cartilage composition present in the posterior acetabulum of FAI patients may be due to increased shear stresses present within this region of the acetabular cartilage during activities of daily living such as a squatting task[36] and may be indicative of the contre-coup lesion[3,37]. Future studies combining quantitative MR-imaging and finite element analyses may provide an ability to understand the mechanical loading patterns during squatting, walking, etc. that may lead to altered hip joint cartilage composition within FAI patients.

Both global acetabular and femoral $T_{1\rho}$ and T_2 radial heterogeneity are increased in FAI patients compared to healthy controls but more specifically, the FAI patients in the current study exhibited significantly increased $T_{1\rho}$ and T_2 radial heterogeneity within the anterior superior acetabular cartilage corresponding to the area where delamination is typically observed[9]. Although there were no differences in local $T_{1\rho}$ and T_2 mapping within the anterior superior acetabular cartilage, the results of the current study suggest that $T_{1\rho}$ and T_2 radial heterogeneity within the anterior superior region may be more affected by the FAI pathology and/or the presence of cartilage delamination. It is plausible that the shear forces applied to the anterior superior acetabular cartilage by the cam lesion, the same force thought to lead to delamination[3], may cause disruption of the extracellular matrix architecture in FAI patients. Also, in FAI patients with a cam lesion, provocative motions into hip flexion and internal rotation increases during both static and dynamic activities and the largest pressures and stresses are observed in the anterior superior acetabular cartilage[36,38]. Over time, these increased stresses applied to the anterior superior acetabular cartilage may cause a disruption in the $T_{1\rho}$ and T_2 spatial distribution of neighboring voxels (increased heterogeneity) and may indicate cartilage damage[21].

ROC analysis demonstrated that the $T_{1\rho}$ and T_2 radial heterogeneity within the anterior superior acetabular cartilage layer were able to better detect delamination compared to any of the other $T_{1\rho}$ and T_2 based parameters analyzed in this study. The anterior superior acetabular $T_{1\rho}$ and T_2 radial heterogeneity demonstrated similar AUC values ($T_{1\rho}$: 0.96, T_2: 0.93) and suggest that both of these parameters may be useful in detecting acetabular cartilage delamination. Also, the results of the current study help to support the notion that cam impingement is associated with acetabular cartilage delamination[1–4]. More specifically, the FAI patients with worse cam impingement (higher alpha angle) exhibited increased anterior superior acetabular $T_{1\rho}$ and T_2 radial heterogeneity. Local voxel based assessment of the $T_{1\rho}$ and T_2 radial heterogeneity exhibited that T_2 radial heterogeneity showed a larger percentage of voxels ($T_{1\rho}$ PSV: 2.05%, T_2 PSV: 3.38%) within the anterior superior

acetabular cartilage that were moderately correlated with the alpha angle compared to $T_{1\rho}$ radial heterogeneity. These results may suggest that T_2 radial heterogeneity may be slightly more affected by the cam lesion that leads to acetabular cartilage delamination.

The limitations of the current study should be considered when interpreting the findings. The global and local $T_{1\rho}$ and T_2 mapping and heterogeneity were assessed within the central portion of the hip joint and not in the medial and lateral portions, due to the curved surface of the hip joint, which causes challenges in image processing in the far medial and lateral surfaces of the joint[39]. The relatively low resolution of the $T_{1\rho}$ and T_2 sequences used in this study (pixel spacing $0.5459 \times 0.5459 mm^2$) needs to be acknowledged as a study limitation. The average cartilage plate for the reference hip consists of 4.41 voxels, thereby limiting the number of standard deviation observations made along the radial direction. In this study, we used the assumption of a circular shape for the reference hip, while the registration of the entire dataset on a single template make this assumption true for all the subjects, future work should consider more complex flattening techniques to model the local variation in the curvature of the femoral head surface. These analyses were only performed on FAI patients with arthroscopic validation of delamination and a sample of control subjects who were assumed to have normal hip joint cartilage. A similar study should be performed in FAI patients without delamination that undergo hip femoroplasty, in order to understand the potential differences in hip joint cartilage radial heterogeneity between FAI patients with and without delamination. Also, it is unknown when delamination occurs in these FAI patients and therefore, it is difficult to suggest how radial heterogeneity within the anterior superior cartilage may differ as an effect of time in FAI patients with delamination. In addition, the cross-sectional nature of this study allows for the establishment of associations between MR-based measures and delamination yet a prospective approach is required to help establish the causation of delamination and whether or not MR-based measures, such as $T_{1\rho}$ and T_2 heterogeneity, would aid in determining early markers of delamination.

In conclusion, quantitative MR-imaging and use of voxel-based relaxometry provide a useful and beneficial assessment of hip joint cartilage composition that may be associated with FAI. More so, using these techniques to quantify the radial heterogeneity within the anterior superior acetabular cartilage was shown to be associated with radiological measurements (alpha angle) and may help clinicians better assess the possibility of an FAI patient exhibiting acetabular cartilage delamination. The approach used in this study can potentially be applied in a clinical setting and may help clinicians and surgeons in determining optimal surgical treatment options for FAI patients.

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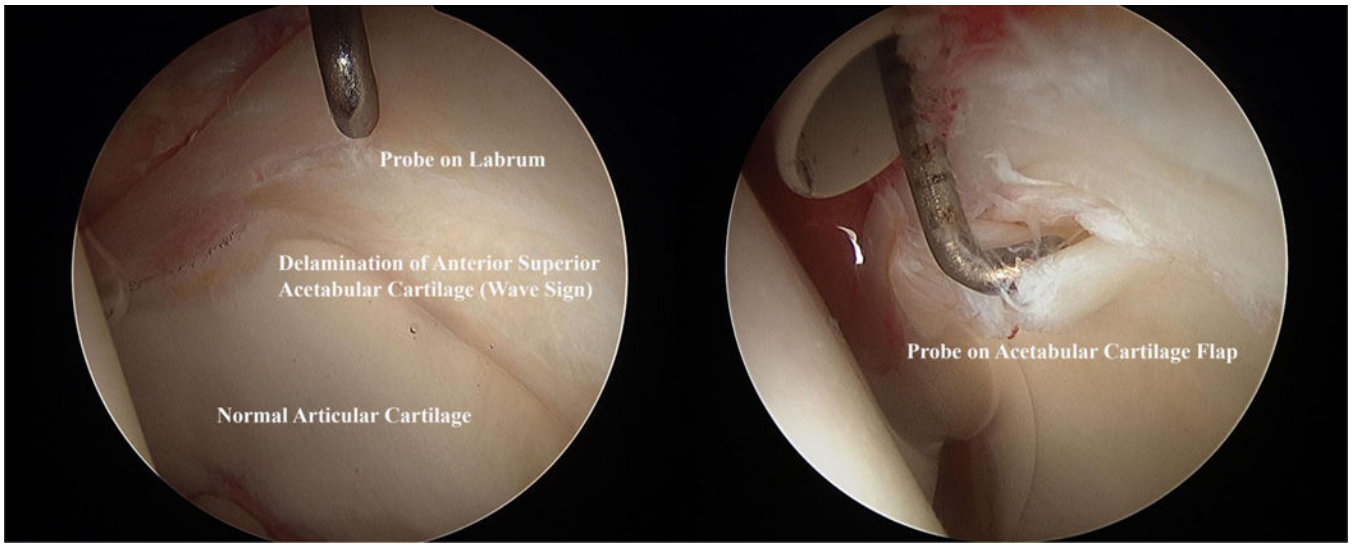

Figure 1.

Arthroscopic images of a femoroacetabular impingement patient that underwent hip arthroscopy in which the surgeon is probing the region of delamination (left) and showing the separation of the acetabular cartilage from the subchondral bone (right).

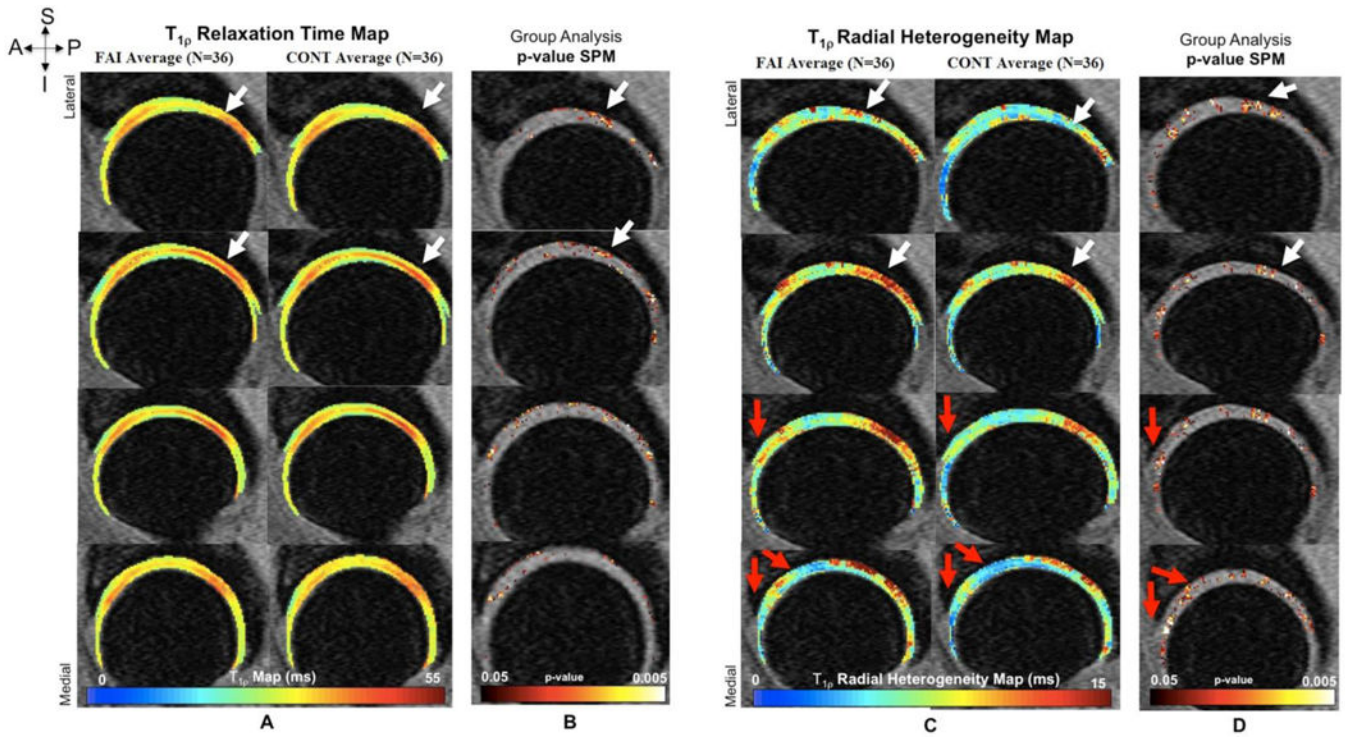

Figure 2.

$T_{1\rho}$ relaxation mapping (2A – 2B) and radial heterogeneity (2C – 2D) for the femoroacetabular impingement (FAI) and controls (CONT) groups in the acetabular and femoral cartilage layers. The red and white arrows indicate clusters of voxels with significant elevation in $T_{1\rho}$ relaxation mapping or radial heterogeneity within the anterior and posterior regions, respectively.

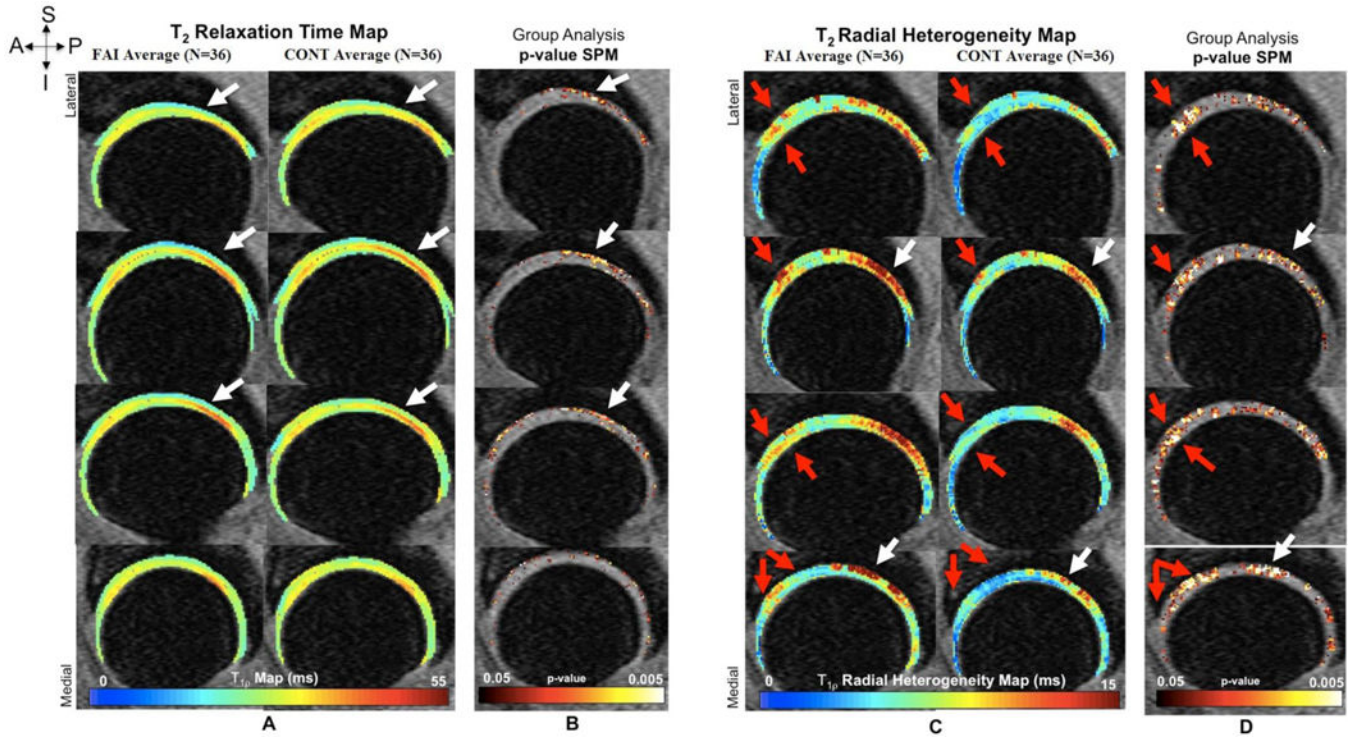

Figure 3.

T_2 relaxation mapping (3A – 3B) and radial heterogeneity (3C – 3D) for the femoroacetabular impingement (FAI) and controls (CONT) groups in the acetabular and femoral cartilage layers. The red and white arrows indicate clusters of voxels with significant elevation in T_2 relaxation mapping or radial heterogeneity within the anterior and posterior regions, respectively.

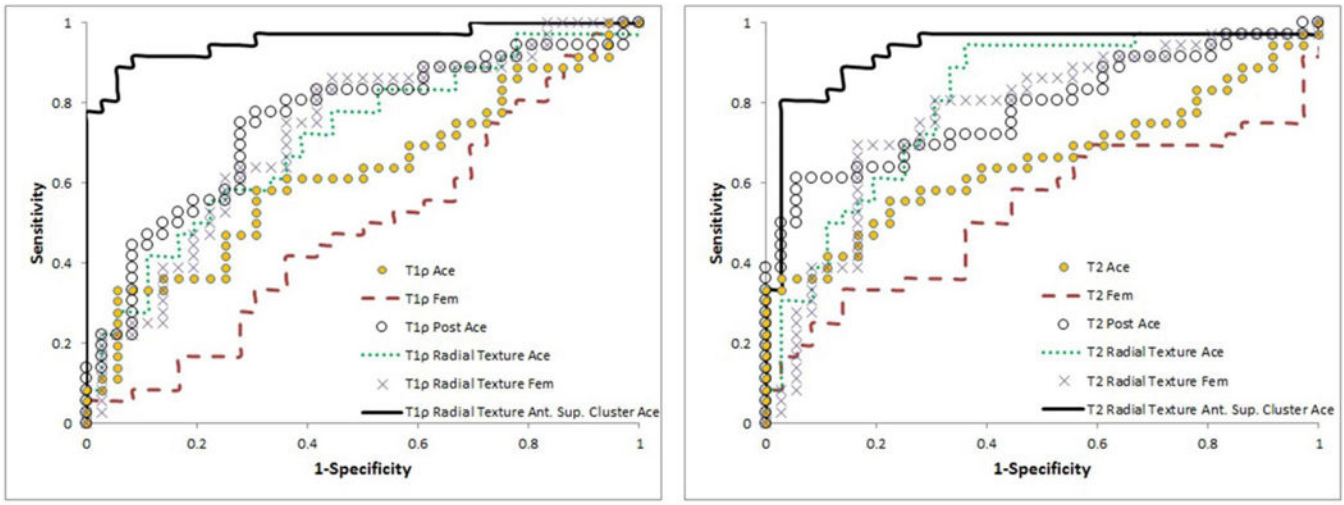

Figure 4.

The receiver operating characteristic (ROC) curves for the $T_{1\rho}$ (left) and T_2 (right) acetabular (ACE) and femoral (FEM) MR-based measurement. $T_{1\rho}$ and T_2 radial texture within the anterior superior (Ant. Sup.) acetabular cartilage were found to be the most sensitive predictors of delamination in femoroacetabular impingement patients.

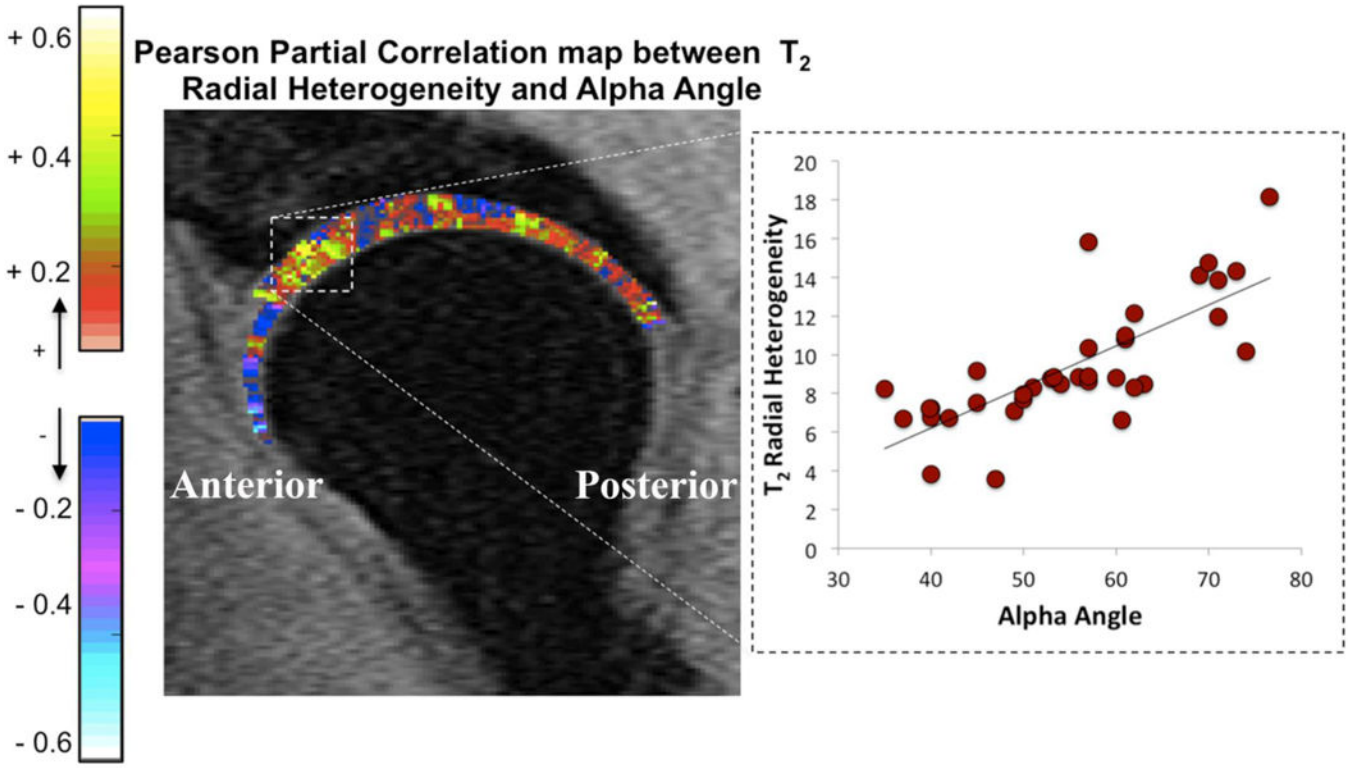

Figure 5.

The Pearson partial correlation map of the T_2 radial heterogeneity (ms) and alpha angle (degrees) within the FAI patients is shown (left). The average T_2 radial heterogeneity within the anterior cartilage (boxed region) demonstrates a high positive correlation with alpha angle measurements (right).

Table 1

Demographics and hip joint morphology (mean±standard deviation) for the femoroacetabular impingement (FAI) patients and healthy controls (CONT).

	FAI (N=36)	CONT (N=36)	p-value
Age (years)	35.7±9.4	39.1±10.2	0.14
Gender (Males:Females)	19:17	19:17	1.00
Body Mass Index ($kg \cdot m^{-2}$)	24.1±3.2	23.8±3.1	0.83
Alpha Angle (Degrees)	55.3±11.4	52.0±11.5	0.23
Center Edge Angle (Degrees)	33.4±7.8	30.9±5.9	0.13

Table 2

$T_{1\rho}$ and T_2 mapping and heterogeneity measurements (ms) in the acetabular (ACE) and femoral (FEM) cartilage layers for controls (CONT) and femoroacetabular impingement (FAI) patients, represented as average(standard deviation). An * represents statistically significant values ($p < 0.05$).

	FAI (N=36)	CONT (N=36)	p-value
$T_{1\rho}$			
Global ACE	34.5(4.0)	32.8(2.6)	0.04*
Global FEM	34.7(3.6)	34.8(3.5)	0.93
Posterior ACE	35.3(4.2)	31.9(2.7)	<0.001*
Radial Heterogeneity ACE	9.81(2.02)	8.39(1.54)	0.001*
Radial Heterogeneity FEM	8.66(1.46)	7.57(1.46)	0.002*
Radial Heterogeneity Ant. Sup. ACE	11.2(2.3)	7.12(1.24)	<0.001*
T_2			
Global ACE	28.8(4.6)	26.5(2.2)	0.01*
Global FEM	31.3(4.1)	30.9(2.5)	0.65
Posterior ACE	29.6(5.3)	24.9(2.1)	<0.001*
Radial Heterogeneity ACE	10.1(1.93)	7.91(1.79)	<0.001*
Radial Heterogeneity FEM	8.54(2.13)	6.88(1.95)	0.001*
Radial Heterogeneity Ant. Sup. ACE	10.6(2.4)	6.70(1.44)	<0.001*

Anterior Superior: Ant. Sup.

Table 3

Receiver operating characteristic (ROC) analysis of the various $T_{1\rho}$ and T_2 mapping and heterogeneity measurements in the acetabular (ACE) and femoral (FEM), with the corresponding area under the curve (AUC: average [95%CI]) and max efficiency cut-off values (ms). An * represents statistically significant values ($p < 0.05$).

		AUC	Cut-off Value	p-value
$T_{1\rho}$				
	Global ACE	0.62[0.49 0.75]	33.3	0.04*
	Global FEM	0.49[0.35 0.62]	34.6	0.43
	Posterior ACE	0.75[0.63 0.86]	33.0	<0.001*
	Radial Heterogeneity ACE	0.71[0.59 0.83]	8.89	0.001*
	Radial Heterogeneity FEM	0.72[0.60 0.84]	7.91	<0.001*
	Radial Heterogeneity Ant. Sup. ACE	0.96[0.91 1.00]	8.96	<0.001*
T_2				
	Global ACE	0.66[0.53 0.79]	27.3	0.01*
	Global FEM	0.53[0.39 0.67]	31.8	0.32
	Posterior ACE	0.79[0.70 0.89]	26.1	<0.001*
	Radial Heterogeneity ACE	0.81[0.70 0.91]	8.91	<0.001*
	Radial Heterogeneity FEM	0.77[0.65 0.88]	7.69	<0.001*
	Radial Heterogeneity Ant. Sup. ACE	0.93[0.86 0.99]	8.16	<0.001*

Anterior Superior: Ant. Sup.