Skeletal Radiol (2012) 41:987–995
DOI 10.1007/s00256-011-1313-1

SCIENTIFIC ARTICLE

Evaluation of articular cartilage in patients with femoroacetabular impingement (FAI) using T2* mapping at different time points at 3.0 Tesla MRI: a feasibility study

S. Apprich · T. C. Mamisch · G. H. Welsch · H. Bonel · K. A. Siebenrock · Y.-J. Kim · S. Trattnig · M. Dudda

Received: 22 May 2011 / Revised: 11 October 2011 / Accepted: 17 October 2011 / Published online: 6 November 2011

Abstract
Objectives To define the feasibility of utilizing T2* mapping for assessment of early cartilage degeneration prior to surgery in patients with symptomatic femoroacetabular impingement (FAI), we compared cartilage of the hip joint in patients with FAI and healthy volunteers using T2* mapping at 3.0 Tesla over time.
Materials and methods Twenty-two patients (13 females and 9 males; mean age 28.1 years) with clinical signs of FAI and Tönnis grade≤1 on anterior-posterior x-ray and 35 healthy age-matched volunteers were examined at a 3 T MRI using a flexible body coil. T2* maps were calculated from sagittal- and coronal-oriented gradient-multi-echo sequences using six echoes (TR 125, TE 4.41/8.49/12.57/16.65/20.73/24.81, scan time 4.02 min), both measured at beginning and end of the scan (45 min time span between measurements). Region of interest analysis was manually performed on four consecutive slices for superior and anterior cartilage. Mean T2* values were compared among patients and volunteers, as well as over time using analysis of variance and Student's *t*-test.
Results Whereas quantitative T2* values for the first measurement did not reveal significant differences between patients and volunteers, either for sagittal ($p=0.644$) or coronal images ($p=0.987$), at the first measurement, a highly significant difference ($p\leq0.004$) was found for both measurements with time after unloading of the joint. Over time we found decreasing mean T2* values for patients, in contrast to increasing mean T2* relaxation times in volunteers.

S. Apprich · T. C. Mamisch · K. A. Siebenrock · M. Dudda
Department of Orthopedic Surgery, University of Bern,
Bern, Switzerland

S. Apprich
e-mail: sebastian.apprich@meduniwien.ac.at

T. C. Mamisch
e-mail: mamisch@bwh.harvard.edu

K. A. Siebenrock
e-mail: klaus.siebenrock@insel.ch

M. Dudda
e-mail: marcel.dudda@ruhr-uni-bochum.de

S. Apprich · T. C. Mamisch · G. H. Welsch (✉) · S. Trattnig
Department of Radiology, MR Centre of Excellence,
Medical University of Vienna,
1090, Vienna, Austria
e-mail: goetz.welsch@googlemail.com

S. Trattnig
e-mail: siegfried.trattnig@akhwien.at

G. H. Welsch
Department of Trauma Surgery, University of Erlangen-Nürnberg,
Erlangen, Germany

H. Bonel
Department of Radiology, University of Bern,
Bern, Switzerland
e-mail: harald.bonel@insel.ch

Y.-J. Kim
Department of Orthopaedic Surgery, Children's Hospital,
Harvard Medical School,
Boston, MA, USA
e-mail: young-jo.kim@childrens.harvard.edu

Conclusion The study proved the feasibility of utilizing T2* mapping for assessment of early cartilage degeneration in the hip joint in FAI patients at 3 Tesla to predict possible success of joint-preserving surgery. However, we suggest the time point for measuring T2* as an MR biomarker for cartilage and the changes in T2* over time to be of crucial importance for designing an MR protocol in patients with FAI.

Keywords Magnetic resonance imaging · Hip · Femoroacetubalar impingement · Osteoarthritis · T2* mapping

Introduction

In recent years, femoroacetabular impingement (FAI) has been described as a pathogenic factor for early onset of primary osteoarthritis (OA) of the hip in young adults [1, 2]. Cartilage damage arises from abnormal loading between the proximal femur and the acetabular rim due to a nonspherical shape of the femoral head (cam type), over-coverage by the acetabulum (pincer type), or both (mixed type) [3]. The identification of FAI as a cause of symptoms and disability may allow surgeons to correct it in its early stages, relieving symptoms and preventing progression of OA [4]. However, based on the preliminary outcome of clinical studies, the magnitude of the preceding articular cartilage damage is predictive of the final outcome of surgery [5]. The ability to evaluate cartilage precisely would improve our ability to answer the question of whether a patient would benefit long-term from joint-presevering surgery [4, 6].

Standard radiographs reveal important information about the osseous structural abnormalities of the hip [7] and, in combination with clinical evaluation, aid the investigator in the diagnosis of FAI. This method is insensitive to early damage since joint space narrowing, osteophytes, and subchondral sclerosis occur only with advanced cartilage degeneration [8], and thus it is not suitable to serve as an early diagnostic tool for planning preserving hip joint surgery.

Standard magnetic resonance imaging (MRI) and MR arthrography are currently established methods to assess the degree of damage within the joint in vivo [9]. While MR arthrography appears to be superior in the detection of labral tears to standard MRI [10], it remains challenging with both methods to make an accurate diagnosis on the morphology of the cartilage [11]. Furthermore, there is a lack of an established cartilage grading system in the hip joint. Most studies on morphological imaging of the hip cartilage use the modified outerbridge classification system [12] transferred from the knee joint. However, due to the thin and curved cartilage layers in the hip joint, this grading system appears very demanding in the hip and does not provide sufficient information for grading and staging of the defect, especially in cases of incipient cartilage degeneration (e.g., Outerbridge grade 0–2).

In order to resolve this shortcoming, recent research has focused on the development of new, more sensitive, so-called biochemical quantitative MRI sequences and the use of high field strength (≥ 3 Tesla) in a clinical setting. These sequences work to quantify changes in the molecular cartilage structure not visible on morphological images and might be a useful predictive marker for early onset of cartilage degeneration in the hip joint. Consequently, this would increase the predictability of a joint-preserving procedure already prior to the intervention, prevent unnecessary surgery, and at least delay the need for total hip arthroplasty. Furthermore, quantitative cartilage MRI might also be of great interest in longitudinal observation studies on upcoming disease-modifying drugs.

The most widely used noncontrast-based methodology sensitive to two main components of articular cartilage, collagen and water, is T2 relaxation time mapping. This technique has been reported to visualize cartilage collagen organization and water content [13, 14]. However, most reports in the literature focus on its use in the knee joint. To the best of our knowledge, only one group has investigated the application of quantitative T2 mapping for the evaluation of hip cartilage [15]. Within a clinical imaging protocol of the hip, however, this technique is still limited due to prolonged acquisition time (TA), mainly related to the spin-echo technique, and due to the restriction to two-dimensional (2D) acquisitions. Alternatively, T2* relaxation time mapping, based on a gradient-echo (GRE) sequence, might add an alternative biochemical marker. The GRE-based sequence allows shorter acquisition times and the potential of isotropic three-dimensional (3D) imaging. So far this technique has shown its feasibility in cartilage imaging with results similar to standard multi-echo spin-echo T2 [16]. First results for the evaluation of hip cartilage have been reported on a 1.5 Tesla system in FAI patients [17] and after slipped capital femoral epiphysis [18].

Since the biomechanical properties of articular cartilage are largely dependent on the interaction between water molecules and collagen fiber network, as visualized by T2 or T2* mapping, loading conditions within the joint can influence these metrics [19]. A recent article has shown that the loading state of the cartilage and the time when T2 maps are measured within the MR protocol has a significant impact on T2 values of articular cartilage [20].

Therefore the purpose of the present study was to define the feasibility of utilizing T2* mapping for assessment of early cartilage degeneration in the hip joint in FAI patients at 3 Tesla and to identify patients with a good prognosis for joint-preserving hip surgery. To take the different states of unloading of the hip joint into consideration, we assessed the differences between T2* mapping at the beginning and

at the end of the MRI examination, to suggest the best time point for T2* mapping within the protocol.

Materials and methods

Study population

Between October 2007 and April 2008, 72 consecutive patients were diagnosed with FAI based on symptoms, clinical examination, and radiographs at our clinic [1, 21]. Exclusion criteria for the study were Tönnis grade>1 [22] on x-ray, previous hip surgery, no standardized MR arthrography including radial imaging available, or complete cartilage loss on radial MRI . Thirty-one patients met the criteria and 22 of those (13 females and 9 males; mean age 28.1 years, range 16–45 years) were willing to participate in the study and underwent additional MRI. The control group consisted of 27 healthy, asymptomatic volunteers (mean age 26.6 years, 22–29 years) with no history of hip pain and no clinical signs of FAI. All experiments were performed in accordance with the 1975 Helsinki declaration and local ethics regulations. All patients gave written informed consent to use their anonymized data.

MR imaging protocol

MRI was performed on a 3 Tesla whole body MR scanner (Trio®; Siemens Medical Solution, Erlangen, Germany) with a gradient strength of 40 mT/m, using a body-matrix phased-array coil. During MRI, the lower extremities were fixed with fitting cushions in position to avoid motion during measurement and standardize hip extension and neutral rotation.

The image protocol consisted of a coronal and an oblique sagittal-oriented 3D gradient-multi-echo sequence using six echoes (TR 125, TE 4.41/8.49/12.57/16.65/20.73/24.81, FoV 160×160, scan time 4.02 min) for T2* mapping. The coronal GRE sequence was planned parallel to the femoral neck in order to display the superior part of the femoroacetabular joint (Fig. 1), while the oblique sagittal sequence was planned perpendicular to the femoral head-neck axis to reveal slices through the anterior part of the joint (Fig. 2). These two sequences were measured at the beginning (early unloading) and at the end of the examination (late unloading). Time between measurements was about 45 min to assess the effect of unloading while the subject lay in the scanner. No specific activity protocol was used prior to the MR scan. All patients and volunteers came by foot to the MR imaging site and were able to perform normal daily activity. The time delay between lying down for the MR scan and the first T2* measurement was limited to 5 min. Additional sequences were performed in between but not included in the evaluation of this study. Total scan time for both patients and volunteers was 55 min, and the MRI protocols were identical.

For assessment of morphological cartilage quality, a radial intermediate-weighted proton density (PD) turbo spin echo (TSE) sequence around the femoral neck from the standard MR arthrography protocol was used (TR/TE=1,800 ms/13 ms, BW=130 kHz, NEX=2, 4 mm slice thickness, 180 mm FOV, 512×256 matrix, TA=4.25 min).

Image analysis

Patients were classified as Tönnis grade 0 (no sclerosis, no narrowing of the joint space, no osteophytes) or grade 1 [femoral head and acetabular sclerosis, minimal joint space narrowing (< 1 mm), minimal osteophytes] on the AP radiographs [22], as a radiographic assessment of early osteoarthritis by two observers (S.A., T.C.M.) in consensus.

Morphological cartilage grading on the radial intermediate-weighted sequence was made for the anterior to superior area: cartilage was graded as normal (no thickness and no signal alterations) or damaged [surface irregularity (fibrillations, fissures, and ulcerations), signal alterations (hyperintense area), and/or cartilage substance loss] by two observers (H.B., T.C.M.) with 26 years and 10 years of musculoskel-

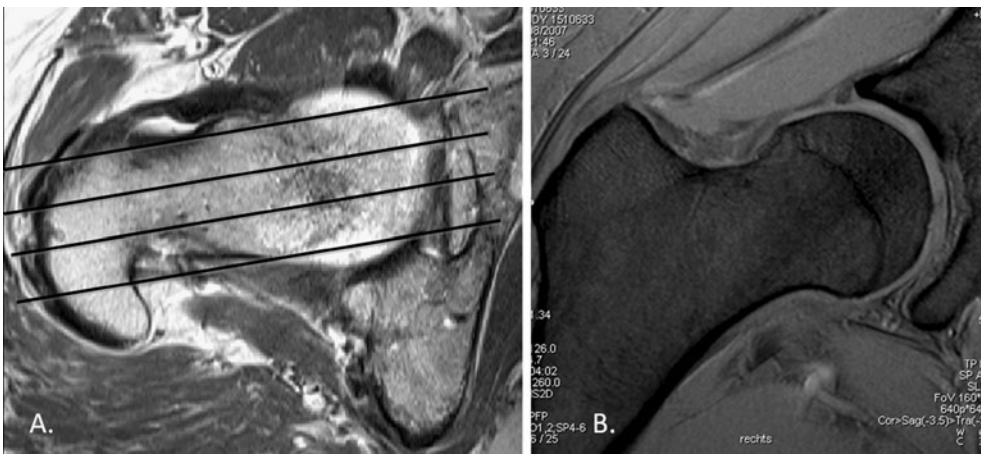

Fig. 1 Planning for the oblique coronal view of the 2D GRE sequence (second echo shown here) (**b**), along the femoral neck axis on the straight axial images (**a**)

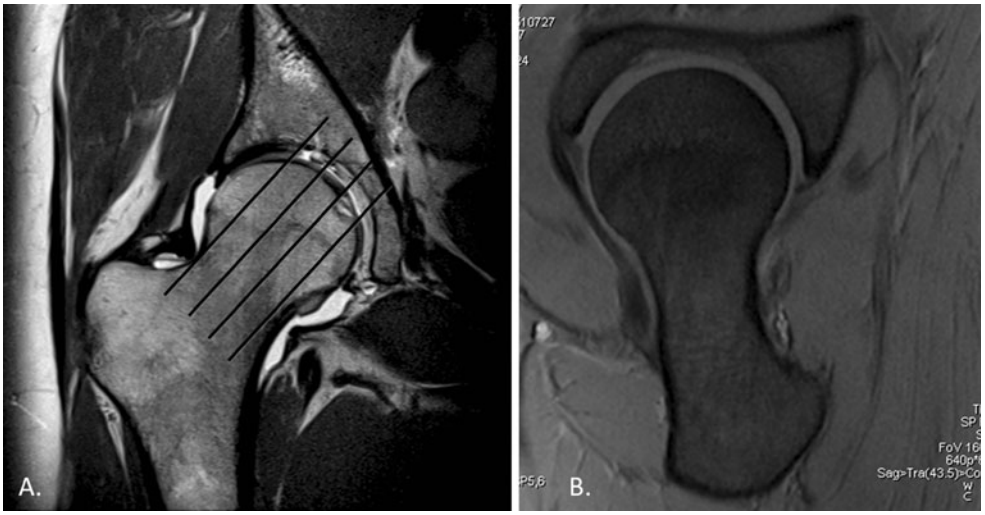

Fig. 2 Planning for the oblique sagittal view of the 2D GRE sequence (second echo shown here) (**b**), along the axis of the femoral neck on the straight coronal images (**a**)

etal (MSK) imaging reading experience in consensus. Observers were blinded to the results of T2* analysis.

T2* data sets were transferred to and processed at a Leonardo® workstation. T2* relaxation times were obtained from on-line reconstructed T2 maps using a pixel-wise, mono-exponential, non-negative least squares (NNLS) fit analysis (MapIt, Siemens Medical Solutions, Erlangen, Germany). Region of interest (ROI) analysis was performed on quantitative T2* maps for the superior and anterior section on four consecutive slices, respectively. ROIs were placed manually in the acetabular cartilage on the second echo of the 3D GRE sequence for the first measurement, which was separated from the femoral cartilage by the interposed low signal space between the two cartilage layers. The thickness of each ROI was set to a minimum of two pixels. The position of the ROI was automatically transferred to the T2* relaxation time map, and T2* values were assessed. Subsequently, ROIs were copied to the T2* maps of the second T2 measurements at the same slice position and if necessary, manually corrected for movement by anatomic landmarks. Superior, anterior, and global (whole joint) mean T2* values were calculated for the four consecutive slices for further analysis. All measurements were performed by two independent observers for interobserver agreement and repeated twice by one observer for intraobserver agreement analysis. A time gap of at least 4 weeks between the two sets of observations helped to minimize recall-bias errors. Grayscale image and T2* map of a patient are shown for both time points in Fig. 3.

In addition, to validate that the hypothesized effect of unloading on T2* values of the cartilage is not caused by an instability of the T2* measurement, we assessed the T2* relaxation times of the muscle at both time points in 10 randomly selected patients or volunteers.

Open hip surgery

Fourteen patients (63.6%) underwent surgical dislocation of the hip and reshaping and trimming of the joint within 7 months (range 0.5 and 16 months) after MR arthrography and 3.3 months (range 0.5 to 9.5 months) after T2* measurements. All surgeries were performed by the same orthopedic surgeon (K.A.S.). The acetabular cartilage was graded in these patients intraoperatively from anterior to superior as normal appearing or damaged. Damage included fibrillation, malacia, delamination, and cartilage loss. Intraoperative grading served as a standard of reference for

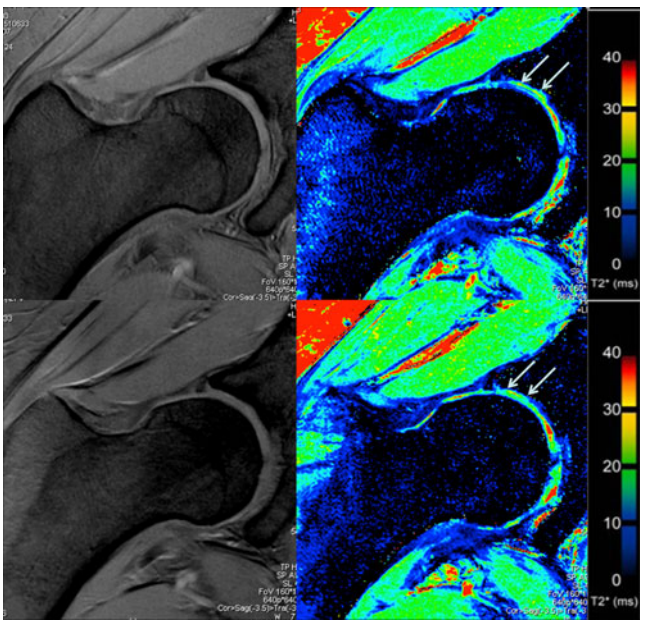

Fig. 3 Color-coded, coronal T2* maps for early and late unloading of an FAI patient. ROI analysis was performed for the acetabular cartilage at the superior section of the joint. Note mild decrease in T2* values with unloading (marked with *white arrows*)

morphological grading of the hip cartilage and for correlation with mean T2* values.

Statistical analysis

Global, superior, and anterior T2* values were compared among patient and volunteers, Tönnis grades, cartilage defect grades obtained from morphological grading, and assessment of the cartilage during surgery using a one-way analysis of variance (ANOVA). Differences between first (early unloading) and second T2* measurement (late unloading) for cartilage and muscle T2* values were tested for significance using a paired *t*-test. The association of T2* values and the individual cartilage grading methods was investigated with a Spearman's rank correlation analysis. Inter- and intraobserver analyses were performed by intraclass correalation (ICC) measurement. Sensitivity, specificity, and accuracy were calculated for morphological grading on MR arthrography images using surgery findings as the standard of reference. Statistical evaluation was performed using SPSS (version 17.0, SPSS institute, Chicago, IL, USA) for Windows assuming statistical significance at a level of $p<0.05$.

Results

Patients vs. volunteers

The comparison of global, superior, and anterior mean T2* values between FAI patients and volunteers did not show a significant difference for the first T2* measurement (early unloading: $p=0.747$, $p=0.987$, $p=0.644$, respectively) (Table 1).

In contrast, for the second measurement (late unloading), we found highly significant differences between patients and volunteers for global ($p=0.001$), superior ($p=0.001$), and anterior T2* values ($p=0.004$). While mean T2* relaxation times of the global, superior, and anterior cartilage layers for the control group significantly increased with unloading over time (Fig. 4), a slightly decreasing trend was observed in global mean T2* values for patients ($p=0.080$) (Fig. 3), revealed by paired *t*-test. These differences over time between patients and volunteers were highly significant for global, anterior, and superior T2* values ($p=0.001$, respectively). The T2* values and significances are summarized in Table 1.

T2* values were significantly higher in the anterior compared to the superior area for volunteers ($p=0.012$) and patients ($p=0.001$). This distribution of anterior and superior T2 values is displayed in Table 1.

No differences between early and late unloading were found for T2* values of the muscle as reference, either for coronal (26.1 vs. 25.9 ms; $p=0.297$) or sagittal T2* maps (26.3 vs 26.0 ms; $p=0.146$).

Intraoperative, MR arthrography, and X-ray grading

Within the diseased hip group, comparison of the intraoperative assessment revealed significant differences for T2* values between macroscopic normal cartilage (23.93± 1.7 ms first measurement, 23.29±1.4 ms second measurement) and damaged cartilage (21.05 ± 2.6 ms first measurement, 20.62±2.8 ms second measurement) for both time points ($p=0.032$; $p=0.044$). There were no significant differences for the T2* changes over time (Δ −0.64 ms normal cartilage, Δ −0.31 ms damaged cartilage; $p=0.771$).

Similarly, a trend toward lower global T2* values for damaged cartilage compared to normal cartilage was obtained with hips stratified by morphological MR arthrography findings ($p=0.083$ first measurement, $p=0.082$ second measurement), but no differences in T2* changes over time ($p=0.499$) were detected.

Table 1 Mean T2* values in milliseconds (standard deviation *in parentheses*) for the global, superior, and anterior layers of the acetabular cartilage and differences over time

Localization	Patient ($n=22$) (StD)	Volunteer ($n=27$) (StD)	*p*-value (ANOVA)
Global T2*, early unloading	21.51 (3.0)	21.75 (2.4)	0.747
Global T2*, late unloading	21.09 (2.9)	24.64 (3.1)	0.001
Global T2*, over time	Δ −0.42 (1.1)	Δ 2.89 (1.3)	0.001
p-value (paired *t*-test)	0.080	0.001	
Superior T2*, early unloading	19.53 (3.0)	19.54 (1.8)	0.987
Superior T2*, late unloading	19.10 (2.5)	22.67 (2.7)	0.001
Superior T2*, over time	Δ −0.43 (1.4)	Δ 3.12 (1.6)	0.001
p-value (paired *t*-test)	0.175	0.001	
Anterior T2*, early unloading	23.49 (3.8)	23.95 (3.5)	0.644
Anterior T2*, late unloading	23.09 (4.2)	26.64 (4.3)	0.004
Anterior T2*, over time	Δ −0.41 (1.8)	Δ 2.68 (1.6)	0.001
p-value (paired *t*-test)	0.296	0.001	

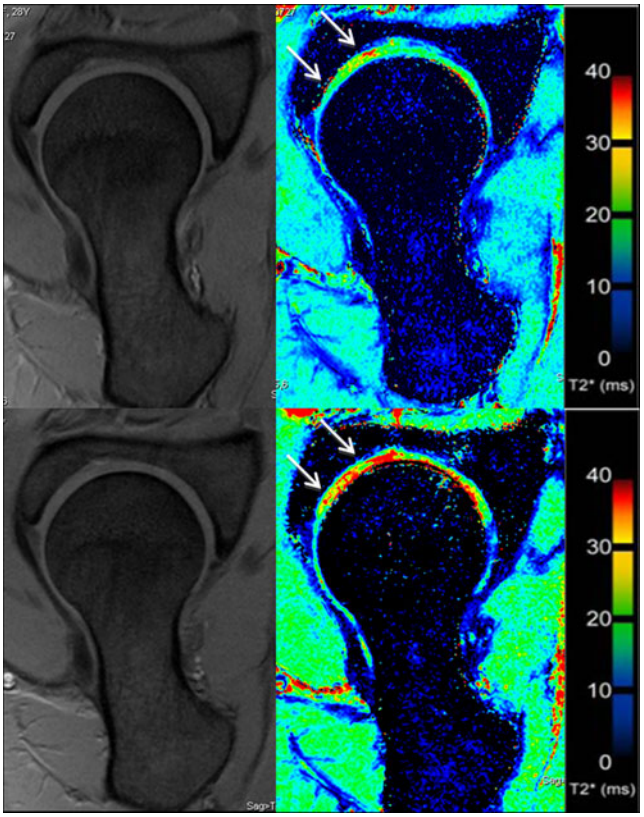

Fig. 4 Color-coded, sagittal T2* maps for early (*upper row*) and late (*lower row*) unloading of a healthy volunteer. ROI analysis was performed for the acetabular cartilage at the anterior section of the joint. Note the increase in T2* values with unloading (marked with *white arrows*)

Tönnis grading revealed a trend toward lower global T2* values for grade 1 compared to grade 0 for both time points, however no statistical significance could be reached. Also changes over time did not show statistically significant differences.

The T2* values for the intraoperative, MR arthrography, and Tönnis grading are summarized in Table 2.

The Spearman rank correlation analysis yielded a significant, moderate, and negative correlation of T2* values with cartilage grading during surgery. This correlation was lower with MR arthrography and even lower with x-ray grading, and did not reach the level of significance (Table 2).

Observer reproducibility was 0.816 for interobserver agreement and 0.860 for intraobserver agreement.

A correlation of the intraoperative grading with the MR grading (n=14) showed a sensitivity of 43%, specificity of 71%, and accuracy of 57%, respectively.

Table 2 Mean global T2* values in milliseconds (standard deviation *in parentheses*) for normal and injured acetabular cartilage, classified by intra-operative, MR arthrography, and Tönnis grading and Spearman rank correlation of T2* values and method of cartilage grading

Method of grading	Early unloading	Late unloading	Over time
Surgical grading			
Normal (n=7)	23.93 (1.7)	23.29 (1.4)	Δ −0.64 (0.7)
Damaged (n=7)	21.05 (2.6)	20.62 (2.8)	Δ −0.43 (1.7)
p-value	0.032	0.026	0.771
Spearman's rho	−0.585 (p=0.028)	−0.514 (p=0.060)	
MR arthrography grading			
Normal (n=12)	22.53 (2.6)	22.03 (2.4)	Δ −0.50 (1.3)
Damaged (n=10)	20.29 (3.1)	19.97 (3.0)	Δ −0.32 (0.7)
p-value	0.083	0.082	0.702
Spearman's rho	−0.343 (p=0.118)	−0.311 (p=0.159)	
Tönnis grading			
Grade 0 (n=14)	22.02 (2.7)	21.73 (2.5)	Δ −0.29 (0.9)
Grade 1 (n=8)	20.62 (3.5)	19.97 (3.3)	Δ −0.65 (1.3)
p-value	0.307	0.169	0.499
Spearman's rho	−0.149 (p=0.508)	−0.253 (p=0.256)	

Discussion

In the present study, T2* values of the acetabular cartilage were evaluated in patients suffering from FAI and healthy volunteers at different time points. A coronal and sagittal oblique GRE sequence (Figs. 1 and 2) was performed for each patient at the beginning and end of each MR examination, with 45 min in between.

Whereas no differences were found for FAI patients and healthy volunteers for global, superior, or anterior T2* values within the first measurements (early unloading), we found highly significant differences for the second measurement (late unloading) at the end of the MR examination. Accordingly the change in T2* values over time was also significantly different for these two groups. Hence the applicability of T2* mapping for the evaluation of symptomatic FAI hips is dependent on the time delay between the start of the MR scan and the time point when the T2* sequence is performed. This is probably the most important finding of this study, that quantitative T2* relaxation times of the articular hip cartilage appear to be time-dependent after unloading. However, native cartilage in healthy volunteers and the cartilage in FAI patients revealed an inverse behavior after unloading. Whereas the cartilage in volunteers showed a highly significant increase in T2* values, cartilage T2* relaxation times in patients suffering from FAI were found to decrease with unloading over time.

A recent study investigated the impact of unloading on quantitative T2 measurements in patients after matrix-associated autologous chondrocytes transplantation (MACT) of the knee joint [20]. The authors reported an increase in T2 values with unloading, more pronounced in the MACT tissue, involving differences between healthy cartilage and cartilage repair tissue that were only found for the late unloading measurement.

In contrast to our study, Mamisch et al. found that the significant change in T2 values with time occurred not within the healthy control cartilage, but in the more pronounced increase in T2 values within the transplant tissue. As the T2 relaxation time is not specific to a single cartilage component [23], the increase in T2 values was attributed to hydration and/or rearrangement of the collagen organization. Interestingly, in the present study the cartilage of FAI patients acted differently, as the mean T2* values decreased during the MR examination (unloading), while cartilage T2* relaxation times increased in the volunteer group. The increase in T2* within the volunteer group may be explained by a reorganization of the collagen fibers, especially in the transitional zone in which fibers normally have a perpendicular orientation and proton molecules are more moveable. Additionally, with unloading of the cartilage between the two T2* measurements, cartilage may become rehydrated and therefore increase T2*.

Two recent studies have shown inverse results regarding the effect of loading to knee cartilage T2 [24, 25]. Greater anisotropy of the superficial collagen fibers and less mobility of protons were suspected to be the cause of this decrease. However, the cause for the decrease in T2* within FAI patients with unloading can only be hypothesized. Maybe the injured cartilage layer is not capable of rehydrating or re-orienting the collagen microstructure due to loss of the charged components of the cartilage, i.e., glycosaminoglycans.

The basic difference between the unloading study of Mamisch et al. [20] and ours, besides the different joint and cartilage tissue, is of course the multi GRE sequence used in our study. The GRE sequence lacks the 180° refocusing pulse, and therefore it is more sensitive to susceptibility artifacts. These artifacts are caused by intrinsic inhomogeneities of the magnetic field occurring at the border between cartilage and underlying bone structures. These inhomogeneities contribute to a faster dephasing of the T2 signal and result in shorter T2* values [26].

The second significant finding of this study was that T2*, if measured at the late time point, is able to differentiate between healthy and FAI-injured hips, with lower T2* in the diseased hip. This is of major importance in that our patients were selected to represent a study cohort with early OA (Tönnis grade ≤1 and no gross morphological changes in MR arthrography). This drop in mean T2* between normally rated hip cartilage and degenerated cartilage has already been described using T2* maps from a 3D GRE sequence at 1.5 Tesla [17].

Currently, there are no in vitro studies comparing histological and electron-microscopical data with cartilage T2* values to clarify the role of T2* in the assessment of cartilage ultrastructure. A recent in vivo study has shown comparable results of quantitative T2* mapping with apparent T2 in cartilage imaging of patients after MACT [16] in the knee joint. Both techniques were feasible to differentiate between normal cartilage and repair tissue. However, Welsch et al. [16] hypothesized in their study that T2* might not measure the same properties of cartilage as T2. It seems that T2* is less sensitive to the water content of cartilage. Besides the collagenous architecture, T2* might also be dependent on macromolecules and their orientation [16]. Our results and the weak but significant correlation of T2* with T1 values obtained using a dGEMRIC technique by Bittersohl et al. [17] might support this hypothesis as cartilage damage is described to go along with increased water content, breakdown of the collagen fibers, and a loss of proteoglycans (PG) [27]. However, an in vitro study on the correlation of T2* relaxation times of the cartilage (e.g., of femoral head specimens after total hip arthroplasty) with histological findings would be worthwhile to clarify this problem.

Regarding the correlation of quantitative T2* values with intraoperative, MR arthrography, and Tönnis grading, we did not find any effect of unloading at all. However, what was conspicuous was the significantly lower T2* values in the macroscopically damaged cartilage, assessed intraoperatively, compared to normal native cartilage. When hips were stratified by morphologic MR findings, a trend towards the same results was observed, whereas Tönnis grading did not reveal significant differences in T2* values. These differing results may be due to the insensitivity of morphological MR and, in particular, x-ray methods in stratifying early cartilage damage in the hip joint. As the macroscopic assessment is still the gold standard in the assessment of degenerated cartilage in the hip joint, it should be noted that the most significant correlation was found between T2* values und intraoperative grading, whereas the morphological assessments on MR images and x-rays were not significantly correlated. These findings might prove our assumption that using cartilage grading based on quantitative T2* mapping detects more subtle differences in cartilage defects. In particular, incipient degeneration, not visible on morphological images, can be assessed that is not classifiable by conventional MRI.

Interestingly, we also found significant differences between the T2* values of the anterior and superior sections of the hip joint for patients and for volunteers with higher T2* values for the anterior part. Watanabe and colleagues [15] described a topographic variation for T2 relaxation times in hip cartilage with an increase near the magic angle (54.7°) in a volunteer study. It seems reasonable to assume that the different orientations of the collagen fibers in the superior and anterior sections of the hip joint might also be responsible for the different distribution of T2* values in our study. It is also possible

that differences in weight bearing between the superior and anterior section might play a role in this variation of T2*.

A general limitation of the evidence of quantitative cartilage maps is the limited applicability of absolute values, as relaxation times are dependent on the individual sequence, coil, and magnetic field strength and, in the particular case of T2/T2* mapping, the loading state of the cartilage. However, this problem can be overcome by measuring T2* relaxation times of the cartilage at the end of the scan in the unloaded state. A limitation of this study is that due to the small sample size, only 14 (64%) FAI patients underwent surgery. The application of the dGEMRIC technique to the MRI protocol in future, which depicts the GAG content of the hip cartilage and has already shown accurate results for the early detection of cartilage defects, would add additional information for validation of T2* mapping. However this will make contrast agent administration necessary. The lack of a standardized activity protocol prior to the MRI may certainly have increased variability in the loading effect, however measurements were performed consistently for all patients and volunteers. Concerning the T2* maps a higher resolution would have improved the distinction of femoral and acetabular cartilage and in some ROIs joint fluid may have been included in our analysis, leading to increased T2* values. Furthermore, since susceptibility artifacts occur at the border between cartilage and underlying bone structures, cartilage thinning might correlate with T2*.

In conclusion, the study proved the feasibility of utilizing T2* mapping as a useful predictive marker for early onset of cartilage degeneration in the hip joint in FAI patients at 3 Tesla in a reasonable acquisition time. This needs to be confirmed by prospective follow-up studies with larger patient cohorts undergoing open hip surgery for FAI. However, the time point for measuring T2* as an MR biomarker for cartilage and the changes in T2* over time are of importance to design a MR protocol.

References

1. Ganz R, Parvizi J, Beck M, Leunig M, Notzli H, Siebenrock KA. Femoroacetabular impingement: a cause for osteoarthritis of the hip. Clin Orthop Relat Res. 2003;417:112–20.
2. Notzli HP, Wyss TF, Stoecklin CH, Schmid MR, Treiber K, Hodler J. The contour of the femoral head-neck junction as a predictor for the risk of anterior impingement. J Bone Joint Surg Br. 2002;84(4):556–60.
3. Beck M, Kalhor M, Leunig M, Ganz R. Hip morphology influences the pattern of damage to the acetabular cartilage: femoroacetabular impingement as a cause of early osteoarthritis of the hip. J Bone Joint Surg Br. 2005;87(7):1012–8.
4. Beck M, Leunig M, Parvizi J, Boutier V, Wyss D, Ganz R. Anterior femoroacetabular impingement: part II. Midterm results of surgical treatment. Clin Orthop Relat Res. 2004; 418:67–73.
5. Clohisy JC, St John LC, Schutz AL. Surgical treatment of femoroacetabular impingement: a systematic review of the literature. Clin Orthop Relat Res. 468(2):555–564.
6. Murphy S, Tannast M, Kim YJ, Buly R, Millis MB. Debridement of the adult hip for femoroacetabular impingement: indications and preliminary clinical results. Clin Orthop Relat Res. 2004;429:178–81.
7. Tannast M, Siebenrock KA, Anderson SE. Femoroacetabular impingement: radiographic diagnosis—what the radiologist should know. Radiologia. 2008;50(4):271–84.
8. Locher S, Werlen S, Leunig M, Ganz R. Inadequate detectability of early stages of coxarthrosis with conventional roentgen images. Z Orthop Ihre Grenzgeb. 2001;139(1):70–4.
9. Schmid MR, Notzli HP, Zanetti M, Wyss TF, Hodler J. Cartilage lesions in the hip: diagnostic effectiveness of MR arthrography. Radiology. 2003;226(2):382–6.
10. Czerny C, Hofmann S, Urban M, Tschauner C, Neuhold A, Pretterklieber M, et al. MR arthrography of the adult acetabular capsular-labral complex: correlation with surgery and anatomy. AJR Am J Roentgenol. 1999;173(2):345–9.
11. Mamisch TC, Bittersohl B, Hughes T, Kim YJ, Welsch GH, Dudda M, et al. Magnetic resonance imaging of the hip at 3 Tesla: clinical value in femoroacetabular impingement of the hip and current concepts. Semin Musculoskelet Radiol. 2008;12(3):212–22.
12. Outerbridge RE. The etiology of chondromalacia patellae. J Bone Joint Surg Br. 1961;43-B:752–7.
13. Mosher TJ, Dardzinski BJ. Cartilage MRI T2 relaxation time mapping: overview and applications. Semin Musculoskelet Radiol. 2004;8(4):355–68.
14. Smith HE, Mosher TJ, Dardzinski BJ, Collins BG, Collins CM, Yang QX, et al. Spatial variation in cartilage T2 of the knee. J Magn Reson Imaging. 2001;14(1):50–5.
15. Watanabe A, Boesch C, Siebenrock K, Obata T, Anderson SE. T2 mapping of hip articular cartilage in healthy volunteers at 3 T: a study of topographic variation. J Magn Reson Imaging. 2007;26 (1):165–71.
16. Welsch GH, Trattnig S, Hughes T, Quirbach S, Olk A, Blanke M, et al. T2 and T2* mapping in patients after matrix-associated autologous chondrocyte transplantation: initial results on clinical use with 3.0-Tesla MRI. Eur Radiol. 2010; 20(6):1515–23.
17. Bittersohl B, Hosalkar HS, Hughes T, Kim YJ, Werlen S, Siebenrock KA, et al. Feasibility of T2* mapping for the evaluation of hip joint cartilage at 1.5 T using a three-dimensional (3D), gradient-echo (GRE) sequence: a prospective study. Magn Reson Med. 2009;62(4):896–901.
18. Miese FR, Zilkens C, Holstein A, Bittersohl B, Kropil P, Mamisch TC, et al. Assessment of early cartilage degeneration after slipped capital femoral epiphysis using T2 and T2* mapping. Acta Radiol. 52(1):106–110.
19. Liess C, Lusse S, Karger N, Heller M, Gluer CC. Detection of changes in cartilage water content using MRI T2-mapping in vivo. Osteoarthr Cartil. 2002;10(12):907–13.
20. Mamisch TC, Trattnig S, Quirbach S, Marlovits S, White LM, Welsch GH. Quantitative T2 mapping of knee cartilage: differentiation of healthy control cartilage and cartilage repair tissue in the knee with unloading-initial results. Radiology. 2010;254(3):818–26.
21. Kassarjian A, Belzile E. Femoroacetabular impingement: presentation, diagnosis, and management. Semin Musculoskelet Radiol. 2008;12(2):136–45.

22. Tonnis D. Letter: congenital hip dysplasia: clinical and radiological diagnosis (author's transl). Z Orthop Ihre Grenzgeb. 1976;114 (1):98–9.
23. Menezes NM, Gray ML, Hartke JR, Burstein D. T2 and T1rho MRI in articular cartilage systems. Magn Reson Med. 2004;51 (3):503–9.
24. Mosher TJ, Smith HE, Collins C, Liu Y, Hancy J, Dardzinski BJ, et al. Change in knee cartilage T2 at MR imaging after running: a feasibility study. Radiology. 2005;234(1):245–9.
25. Nishii T, Kuroda K, Matsuoka Y, Sahara T, Yoshikawa H. Change in knee cartilage T2 in response to mechanical loading. J Magn Reson Imaging. 2008;28(1):175–80.
26. Chavhan GB, Babyn PS, Thomas B, Shroff MM, Haacke EM. Principles, techniques, and applications of T2*-based MR imaging and its special applications. Radiographics. 2009;29 (5):1433–49.
27. Poole AR. An introduction to the pathophysiology of osteoarthritis. Front Biosci. 1999;4:D662–670.