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T2 Measurements of Cartilage in Osteoarthritis Patients With Meniscal Tears

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Abstract

OBJECTIVE.—The objective of this study was to quantitatively assess cartilage degeneration via T2 mapping to compare patients with and those without meniscal tears.

SUBJECTS AND METHODS.—Thirty-seven patients (18 men, mean age $\pm$ SD, 65.7 ± 7.8 years; 19 women, mean age, 63.8 ± 12.0 years) with clinical symptoms of osteoarthritis were studied on 3-T MRI using a 2D multiecho spin-echo sequence for T2 mapping. Meniscal signal and morphology were qualitatively graded and correlated to the T2 values of cartilage. Analysis of covariance, Bonferroni multiple comparison correction, and Spearman's correlation coefficients were used for statistical analysis.

RESULTS.—Patients with meniscal tears (median $\pm$ interquartile range, 50.1 ± 6.1 milliseconds) had significantly ($p = 0.021$) higher T2 values of cartilage than those without meniscal tears (45.7 ± 4.8 milliseconds). T2 values of cartilage were significantly higher in the medial compartment than in the lateral compartment in patients with medial meniscal tears ($p = 0.018$).

CONCLUSION.—T2 measurements are increased in patients with meniscal tears; this finding adds support to the theory of an association of osteoarthritis with damage to both the menisci and hyaline cartilage.

Keywords

cartilage; meniscal tears; MRI; osteoarthritis; T2 mapping

Although meniscal tears are often associated with trauma, most are degenerative phenomena [1]. A prior study reported that meniscus tears were present in 86% of the patients with symptomatic osteoarthritis [2, 3]. The prevalence of meniscal tears increases with patient age [4–6] and with the severity of osteoarthritis [1, 4]. Meniscal tears are associated with an accelerated progression of cartilage degeneration in knee osteoarthritis compared with individuals with osteoarthritis but without tears presumably because of the crucial role that

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the meniscus plays within the knee joint: distributing joint forces, load bearing, and enhancing joint stability [7].

MR sequences to evaluate cartilage qualitatively [8-11] and quantify cartilage volume [12, 13] thickness have been introduced. Cartilage loss and clinical symptoms are preceded by collagen–proteoglycan matrix damage and elevated cartilage water content [14]. Therefore, a sensitive technique for detecting these structural and functional changes during the early stages of osteoarthritis could be valuable for identifying the need for early treatment, monitoring response to treatment, and assessing efforts to prevent disease progression.

Quantitative T2 mapping provides information about the interaction of water molecules and the collagen network within the articular cartilage [15]. Alterations in T2 values have been shown to correlate with changes in water content, as well as collagen structure, orientation, and organization, and to be associated with changes in hyaline cartilage and its degradation [16-18]. T2 mapping can be performed in a relatively short time if high-field MRI units are available to ensure sufficient signal-to-noise ratio and high spatial resolution at reasonable scanning times.

Using semiquantitative MRI with arthroscopic correlation, Hunter and colleagues [19] found a strong association of pathologic meniscal changes with cartilage loss in symptomatic knee osteoarthritis. In a more recent study [20], investigators used delayed gadolinium-enhanced magnetic resonance imaging of cartilage (dGEMRIC) and found significant correlations between the T1 values of the meniscus and the T1 values of the articular cartilage. To our knowledge, T2 mapping has not been used to quantify cartilage changes associated with meniscal tears in patients with osteoarthritis.

The purpose of this study was to quantitatively assess articular cartilage using T2 mapping of the femorotibial joints in patients with clinical symptoms of osteoarthritis with and those without meniscal tears.

Subjects and Methods

Study Population

Institutional review board approval and written, informed consent to collect data on the study population were obtained. Body height and weight for the calculation of the body mass index (BMI) were obtained from all subjects. Patients with a BMI of greater than 24.9 were classified as overweight, and patients with a BMI of more than 29.9 were classified as obese. The mean BMI of the patients included in this study was 27.6 ± 3.0 (SD). The BMI was within the normal range in four patients (11%); 21 patients were overweight (57%) and 12, obese (32%).

In total, 37 femorotibial joints in 37 patients with osteoarthritis were prospectively investigated.

Only patients with clinical symptoms of osteoarthritis (pain and age > 50 years, stiffness, or crepitus) and standing semiflexed knee radiographs obtained within 1 month of MRI were included in the study. Osteoarthritis severity was rated using the Kellgren-Lawrence score [21]. In five patients, the Kellgren-Lawrence score was 1; in 10, a score of 2; in 12, a score of 3; and in 10, a score of 4. All the patients had been referred to radiography by a rheumatologist because of clinical symptoms of osteoarthritis [22, 23].

Subjects with congenital disorders, primary or secondary tumors, infections, inflammatory arthropathies, fractures, or prior knee surgery were excluded from the study. Subjects with

known contraindications for MRI were also excluded. Age of between 40 and 90 years was an inclusion criterion as well.

The mean age of the study population was 65 ± 10 years. Eighteen patients were male (mean age, 65.7 ± 7.8 years) and 19, female (mean age, 63.8 ± 12.0 years).

Image Acquisition

All MRI experiments were performed on a 3-T clinical MR scanner (Magnetom Tim Trio, Siemens Healthcare). An 18-cm-diameter, 8-channel transmit–receive phased-array knee coil was used for all the imaging measurements.

A sagittal 2D multiecho spin-echo sequence with fat saturation was used with the following parameters: TR, 4,000 milliseconds; TEs, 16.5, 33, 49.5, 66, 82.5 milliseconds; field of view, 15×15 cm; matrix, 256×128 (interpolated to 256×256); bandwidth, 130 Hz per pixel; and slice thickness, 1.5 mm (interslice gap = 100%). The acquisition time was 8 minutes 30 seconds.

Image Evaluation

Meniscal lesions were graded on the multiecho spin-echo images by an experienced musculoskeletal radiologist with 20 years of experience using the following grading system: grade 0, normal meniscus; grade 1, increased signal intensity of the meniscus without evidence of a tear; grade 2, small radial meniscal tear; grade 3, nondisplaced single meniscal tear; grade 4, nondisplaced complex meniscal tear; grade 5, meniscal tear with displaced component; and grade 6, macerated meniscus [24, 25]. Patients with meniscal changes graded as 0 or 1 were assigned to the control population; patients with meniscal changes graded as 2–6 on MRI were assigned to the study population.

For the cartilage evaluation four regions were defined: the medial femoral condyle, the lateral femoral condyle, the medial tibial plateau, and the lateral tibial plateau. The femoral trochlea was considered part of the medial femoral condyle. The boundary between the medial femoral condyle and lateral femoral condyle was defined by a plane aligned with the lateral wall of the femoral notch [25]. An in-house-developed routine (Matlab, version 7.1, The Mathworks) was used for offline processing of the acquired MR images including cartilage segmentation and calculation of regional T2 values. The signal intensities of the T2-weighted images were fitted on a pixel-by-pixel basis using a linear least-squares method:

$$\ln \left| \frac{S(\text{TE})}{S_0} \right| = \left(\frac{-\text{TE}}{T_2} \right) + C$$

where $S(\text{TE})$ is the measured signal intensity of the image at a particular TE, S_0 is the signal intensity at the shortest TE, and C is an intercept. Stimulated echoes, which are created by imperfect refocusing pulses in the multiecho spin-echo sequence, lead to overestimation of the T2 values; to minimize this error, the first echo of the multiecho spin-echo sequence was excluded from the T2 calculation.

For the calculation of the T2 values, the image acquired with the shortest TE was used to estimate the relative spin density. Once that value was known, the natural logarithm of the multiecho spin-echo images could be calculated, which reduced the relation between the observed signal intensities and the T2 values to a linear dependence. Then a linear curve fit in the least-squares sense was applied to the transformed data on a pixel-by-pixel basis and the negative of the reciprocal of the slope gave the T2 values. Similarly, for the regional

analysis of the T2 values, regions of interest (ROIs) were manually drawn for the medial femoral condyle, lateral femoral condyle, medial tibial plateau, and lateral tibial plateau using a custom-built Matlab routine. The custom-built Matlab routine created color-coded T2 maps in which the manually segmented cartilage ROIs were overlaid on the shortest-TE images (TE = 16.5 milliseconds).

Statistical Analysis

Statistical analysis was performed using two computer programs (Excel 2003, Microsoft Office; and Medcalc, version 9.6.4.0, Frank Schoonjans). Because nonparametric analyses were conducted, results are summarized as medians $\pm$ interquartile range. Analysis of covariance (ANCOVA) based on ranks was used to compare the T2 values of the patient groups with and without meniscal tears as well as the T2 values of the patients with meniscal tears with and without abnormal BMI while adjusting for the potential confounding effects of age, sex, BMI, Kellgren-Lawrence score, and the presence of anterior cruciate ligament tears. That is, the T2 values were converted to ranks and these ranks were used as the dependent variable for the ANCOVA. Because a separate ANCOVA was conducted for each of the medial femoral condyle, lateral femoral condyle, medial tibial plateau, and lateral tibial plateau, the p values were subjected to a Bonferroni multiple comparison correction. Specifically, the p values from ANCOVA were multiplied by 4, the number of T2 measures compared. For testing the correlations between the Kellgren-Lawrence score and T2 values of cartilage as well as between meniscal tear score and T2 values of cartilage, Spearman's rank correlation coefficients were calculated. To compare T2 values of cartilage in the medial compartment with the T2 values in the lateral compartment and to compare T2 values of cartilage in the femoral condyles with the values in the tibial plateaus, paired-sample Wilcoxon's tests were performed. A p value of less than 0.05 was considered to be statistically significant.

Results

The T2 values (median $\pm$ interquartile range) of cartilage for the study group overall were 50.0 ± 7.1 milliseconds for the medial femoral condyle, 49.8 ± 7.7 milliseconds for the lateral femoral condyle, 49.1 ± 6.2 milliseconds for the medial tibial plateau, and 47.0 ± 7.1 milliseconds for the lateral tibial plateau (Table 1). The values of the medial compartment (medial femoral condyle and medial tibial plateau) were significantly higher than those of the lateral compartment (lateral femoral condyle and lateral tibial plateau; $p = 0.004$), and the values of the tibial plateaus (medial tibial plateau and lateral tibial plateau) were significantly lower than those of the femur condyles (medial femoral condyle and lateral femoral condyle; $p = 0.001$) (Table 1). Spearman's correlation coefficient between the Kellgren-Lawrence score and the T2 values of cartilage was 0.24.

Meniscal abnormalities (grades 1–6) were found in all 37 patients included in this study. Twenty-eight of the patients (76%, 28/37 patients) showed tears (grades 2–6) of the medial, lateral, or medial and lateral meniscus. Nine of the patients (24%, 9/37) showed signal changes within the menisci without a tear (grades 0 and 1) in the medial, lateral, or medial and lateral meniscus. Seven of the patients (19%, 7/37) had bilateral meniscal tears (medial and lateral meniscus).

Meniscal tears were more common in the medial meniscus (68%, 25/37 patients; 71%, 25/35 tears) than in the lateral meniscus (27%, 10/37 patients; 29%, 10/35 tears); tears were most common in the posterior horn of the medial meniscus (52%, 24/46 total tears). Twenty-seven menisci were interpreted as grade 1, three as grade 2, 14 as grade 3, 10 as grade 4, none as grade 5, and eight as grade 6.

After adjustment for covariates, patients with meniscal tears (median $\pm$ interquartile range, 50.1 ± 6.1 milliseconds) had significantly ($p = 0.021$) higher T2 values of cartilage than those without meniscal tears (45.7 ± 4.8 milliseconds) (Figs. 1 and 2). In detail, after adjusting for covariates and correcting for multiple comparisons, we found a significant difference for the medial tibial plateau ($p = 0.04$) and a trend toward significance was observed for the lateral tibial plateau ($p = 0.07$); however, no significant difference was seen for the lateral femoral condyle ($p = 0.6$) or the medial femoral condyle ($p = 0.7$). T2 values of cartilage were significantly higher in the medial (medial femoral condyle and medial tibial plateau) than in the lateral (lateral femoral condyle and lateral tibial plateau) compartment in patients with medial meniscal tears ($p = 0.0178$), whereas no such significance was observed for lateral meniscal tears ($p = 0.1229$). No correlation between the T2 values of cartilage and the severity of meniscal tears (grades 3–6) was found (Spearman's correlation coefficient = 0.02).

Twenty-seven (96%) of the 28 patients with meniscal tears were either overweight or obese. The T2 values of cartilage in patients with meniscal tears were significantly higher in the overweight and obese group than those in the group with a normal BMI ($p = 0.008$).

Discussion

T2 mapping has been shown to be able to detect changes in the water content, collagen structure, and orientation and organization of cartilage, all of which are associated cartilage degradation [16–18]. For in vivo imaging of the knee joint, an increase in T2 was associated with aging [26, 27] and the involvement of osteoarthritis [16], whereas a decrease in T2 was associated with the stress of running [28] and also with mechanical loading of the knee during MRI [29]. The results of our study support those observations: We found only a small but positive correlation between the Kellgren-Lawrence score and the T2 values of cartilage. This observation also fits the results of morphologic studies of articular cartilage; Link and colleagues [30] found a correlation between the Kellgren-Lawrence score and cartilage lesions on morphologic MR images.

We also found that T2 values of cartilage were significantly higher in the medial compartment (medial femoral condyle and medial tibial plateau) than in the lateral compartment (lateral femoral condyle and lateral tibial plateau), which typically experiences higher weight-bearing and is more likely to develop osteoarthritis [31]. Interestingly, in our study the T2 values on the femoral side (medial femoral condyle and lateral femoral condyle) of the joint were significantly higher than those on the tibial side (medial tibial plateau and lateral tibial plateau), which is consistent with the observation of Bolbos and colleagues [32]. They examined patients with early osteoarthritis and found a significant increase in T1rho and T2 values in all femoral compartments, but not at the tibia.

In this study T2 mapping was used to characterize cartilage changes in patients with clinical symptoms of osteoarthritis as compared with the presence and severity of meniscal tears. We found that the T2 values of cartilage in patients with meniscal tears were significantly higher than those in patients without meniscal tears. These results support other studies that have reported a direct interaction between meniscal and cartilaginous abnormalities [19, 33, 34], which seems reasonable because of biomechanical considerations. Hunter and colleagues [19] observed a strong association between meniscal damage and cartilage loss judged from conventional MR images in patients with osteoarthritis. To our knowledge, T2 mapping as well as T1rho and dGEMRIC have not been used to assess cartilage in patients with meniscal tears found on conventional MR images. Krishnan and colleagues [20] found a correlation between the T1 of the meniscus and the T1 of articular cartilage of the knee, but a correlation with conventional morphologic MR findings was not performed.

In this study we also observed that the T2 values of cartilage in patients with medial meniscal tears were significantly higher in the medial compartment (medial femoral condyle and medial tibial plateau) than in the lateral compartment (lateral femoral condyle and lateral tibial plateau); for the corresponding finding in the lateral meniscus, no statistical significance was found, which might in part be due to the small sample size of this pattern ($n = 3$). This might also be true for the lack of a correlation between the T2 values of cartilage and the severity of meniscal tears.

A limitation of this study is that neither the T2 values of cartilage measured in this study nor the meniscal abnormalities could be verified because the included subjects did not undergo surgery. Evaluating the menisci with fat-suppressed multiecho spin-echo images is a weakness of the study. Small meniscal tears and intrasubstance signal intensity changes might have been lost by evaluating the menisci only on fat-suppressed multiecho spin-echo images rather than using additionally dedicated high-resolution intermediate-weighted images. Another potential criticism of this work may be raised by the fact that the subjects' age and sex and the Kellgren-Lawrence scores in the patients without meniscal tears were not matched with one of the patients with meniscal tears. We also want to point out that in the literature several different ways of defining cartilage ROIs have been proposed [25, 35]. We chose to use the whole-organ magnetic resonance imaging score (WORMS), where the femoral trochlea is considered part of the medial femoral condyle (WORMS); this choice certainly affected the T2 values that we measured for the medial femoral condyle and must be taken in account when comparing this study with other studies.

Accepting these limitations, we conclude that T2 mapping of the articular cartilage was correlated to morphologic imaging findings in patients with clinical symptoms of osteoarthritis with and in those without meniscal tears. The results of this study might indicate the potential of T2 mapping to quantify pathologic cartilage changes in conditions that alter the biomechanical properties of the knee joint. We also believe that these results add credence to the argument of the association of osteoarthritis with damage to both the menisci and hyaline cartilage.

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Fig. 1.

73-year-old man with clinical symptoms of osteoarthritis of right knee.

A, Anteroposterior radiograph obtained with patient weight-bearing shows minimal joint space narrowing in medial compartment of knee and no osteophytes. Kellgren-Lawrence score is 1.

B, Sagittal multiecho spin-echo image (TE, 16.5 milliseconds) shows only mild degenerative changes in posterior horn of medial meniscus and no meniscal tear.

C, Sagittal T2 map shows no areas of severe increase of T2; overall mean T2 value of femorotibial cartilage is 43.2 milliseconds.

Fig. 2.

54-year-old woman with clinical symptoms of osteoarthritis of left knee.

A, Anteroposterior radiograph obtained with patient weight-bearing shows mild joint space narrowing in medial compartment of knee, no osteophytes, and Kellgren-Lawrence score of 2.

B, Sagittal multiecho spin-echo image (TE, 16.5 milliseconds) shows tiny oblique tear (*arrow*) in posterior horn of medial meniscus.

C, Sagittal T2 map shows areas with markedly increased T2 values at weight-bearing and posterior aspect of medial femoral condyle that are yellow and red; overall mean T2 value of femorotibial cartilage is 54.5 milliseconds.

TABLE 1

T2 Values of Cartilage in Study Group Patients

Region	T2 Values of Cartilage (ms)		
	Medial ^a	Lateral ^a	Medial and Lateral
Femoral condyles ^b	50.0 ± 7.1	49.8 ± 7.7	50.9 ± 6.2
Tibial plateaus ^b	49.1 ± 6.2	47.0 ± 7.1	48.5 ± 6.0
Femoral condyles and tibial plateaus	49.7 ± 6.3	48.7 ± 7.6	

Note—Data are medians ± interquartile range.

^aMedial versus lateral, $p = 0.004$.

^bFemoral condyles versus tibial plateaus, $p = 0.0001$.