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Rapid In Vivo Multicomponent T_2 Mapping of Human Knee Menisci

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Abstract

Purpose—To compare multicomponent T_2 parameters of menisci measured using Multicomponent Driven Equilibrium Single Pulse Observation of T_1 and T_2 (mcDESPOT) in asymptomatic volunteers and osteoarthritis (OA) patients with intact and torn menisci.

Materials and Methods—The prospective study was performed with Institutional Review Board approval and with all subjects signing written informed consent. mcDESPOT was performed on the knee joint of 12 asymptomatic volunteers and 14 patients with knee OA. Single-component T_2 relaxation time ($T_{2\text{Single}}$), T_2 relaxation time of the fast relaxing water component (T_{2F}), and the slow relaxing water component (T_{2S}), and fraction of the fast relaxing water component (F_F) of the medial and lateral menisci were measured. Multivariate linear regression models were used to compare mcDESPOT parameters between normal menisci in asymptomatic volunteers, intact menisci in OA patients, and torn menisci in OA patients with adjustment for differences in age between subjects.

Results—The mean mcDESPOT parameters for normal menisci in asymptomatic volunteers, intact menisci in OA patients, and torn menisci in OA patients were respectively 16.1 msec, 18.8 msec, and 22.7 msec for $T_{2\text{Single}}$; 9.0 msec, 10.0 msec, and 11.1 msec for T_{2F} ; 24.4 msec, 27.7 msec, and 31.4 msec for T_{2S} ; and 34%, 32%, 27% for F_F . There were significant differences ($P < 0.05$) in $T_{2\text{Single}}$, T_{2F} , T_{2S} , and F_F between the three groups of menisci.

Conclusion—The menisci of OA patients had significantly higher $T_{2\text{Single}}$, T_{2F} , and T_{2S} and significantly lower F_F than normal menisci in asymptomatic volunteers with greater changes in multicomponent T_2 parameters noted in torn than intact menisci in OA patients.

Meniscal tears are well described factors in the pathogenesis and progression of osteoarthritis (OA).^{1–3} The ability to noninvasively assess changes in the macromolecular

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matrix of meniscus would allow better understanding of the role of meniscal degeneration in the development of meniscal tears and the subsequent onset of OA. Quantitative magnetic resonance (MR) techniques have been developed to assess changes in the composition and ultrastructure of meniscus with disease progression.^{4–9} Among those techniques, the T_2 and apparent T_2 (T_2^*) relaxation times of meniscus have been extensively studied and have shown to be sensitive for detecting meniscal degeneration.^{4–7} However, changes in T_2 and T_2^* relaxation time of highly organized musculoskeletal tissues such as meniscus and cartilage are nonspecific parameters that are influenced by multiple factors including tissue hydration, macromolecular content, and tissue anisotropy.^{10–12}

Multicomponent T_2 and T_2^* analysis may provide more specific information regarding separate water components associated with the different macromolecular constituents of meniscal tissue.^{5,6} Juras et al⁵ found that bicomponent T_2^* mapping was superior to single-component T_2^* mapping for distinguishing between normal, degenerative, and torn menisci in human subjects. The changes in multicomponent T_2^* parameters may reflect alterations in the different water components in meniscal tissue due to degeneration and tearing. However, multicomponent T_2^* parameters are influenced by local magnetic field inhomogeneity and inherent differences in tissue susceptibility, which may change with different stages of tissue degeneration, and thus may not reflect the true T_2 characteristics of the different water components of meniscus.¹³ While multicomponent T_2 analysis of musculoskeletal tissues has been performed using Carr-Purcell-Meiboom-Gill (CPMG) sequences, these techniques require extremely long scan times for clinical useful volume coverage, which has significantly limited their use in human subjects.^{14–16}

Multicomponent Driven Equilibrium Single Pulse Observation of T_1 and T_2 (mcDESPOT) is a new technique that implements fast steady-state MRI and a two-pool water model for multicomponent T_2 mapping with high spatial resolution, large volume coverage, and short scan time.¹⁷ Previous studies have demonstrated the feasibility of using mcDESPOT to investigate the T_2 characteristics specific to the fast and slow relaxing water components of the articular cartilage of the human knee joint at 3.0T.^{18,19} This study was performed to determine the ability of mcDESPOT to provide rapid in vivo multicomponent T_2 analysis of the human knee menisci. Multicomponent T_2 parameters of meniscus measured using mcDESPOT at 3.0T were compared in asymptomatic volunteers, OA patients with intact menisci, and OA patients with torn menisci to document changes in the T_2 characteristics of the different water components of meniscus due to tissue degeneration and tearing.

Materials and Methods

Study Group

The study was performed in compliance with Health Insurance Portability and Accountability Act (HIPAA) regulations and with approval from our Institutional Review Board. All subjects signed informed consent prior to their participation in the study. The study group consisted of 12 asymptomatic volunteers (nine males between 25 and 32 years of age with an average age of 25.6 years and three females age between 20 and 38 years of age with an average age of 32.0 years) and 14 patients with knee OA (nine males between 39 and 58 years of age with an average age of 51.0 years and five females between 45 and 62

years of age with an average age of 54.5 years). All asymptomatic volunteers were selected from a database of individuals at our institution who had expressed interest in participating in MR research and had no history of prior knee pain, trauma, or surgery. All patients with knee OA were diagnosed by a fellowship-trained sports medicine physician during their routine clinical work-up using standardized criteria that included complaints of chronic knee pain and stiffness for a minimum of 6 months and the presence of definitive grade 2 osteophytes on standing anterior–posterior knee radiographs.^{20,21} The radiographs of all patients were reviewed by a fellowship-trained musculoskeletal radiologist who graded the severity of knee OA using the Kellgren-Lawrence system.²² Eight patients had grade 2 OA, while six patients had grade 3 OA.

MR Examination

All subjects underwent an MR examination of the knee joint on the same 3.0T scanner (Discovery MR750, GE Healthcare, Waukesha, WI) using an 8-channel phased-array extremity coil (InVivo, Orlando, FL). Foam padding was used to firmly secure the knee within the coil to minimize subject motion during the MR examination. All MR examinations consisted of a 3D fast spin-echo (3D-FSE) sequence and an mcDESPOT sequence performed in the sagittal plane with complete anatomic coverage of the knee joint. The 3D-FSE sequence was acquired with TR/TE=2216/23.6 msec, 16 cm field of view, 384 × 384 matrix, 1.0 mm slice thickness, 31.2 kHz bandwidth, 96 slices, one signal average, and 7-minute scan time. The mcDESPOT sequence consisted of 1) a series of eight spoiled gradient echo (SPGR) scans at varying flip angle ($\alpha=3, 4, 5, 6, 7, 9, 13, 18^\circ$) with TR/TE=4.9/2.3 msec; 2) a series of eight fully balanced steady-state free precession (bSSFP) scans at varying flip angles ($\alpha=2, 5, 10, 15, 20, 30, 40, 50^\circ$) with TR/TE=5.6/2.8 msec; and 3) an inversion recovery IRSPGR scan with TR/TE=4.9/2.3 msec, TI=450 msec, and $\alpha=5^\circ$. All scans were acquired using a 16 cm field of view, 256 × 256 matrix, 3 mm slice thickness, 83.3 kHz bandwidth, 32 slices, and one excitation. To minimize sensitivity to bSSFP signal nulls, the bSSFP scans were repeated with and without radiofrequency (RF) phase cycling to shift the nulls. Total acquisition time for the mcDESPOT sequence was 17 minutes.

Single-Component and Multicomponent T_2 Relaxation Time Mapping

The mcDESPOT images were reconstructed using an in-house software developed in MatLab (2010b, MathWorks, Natick, MA). The voxel-wise single-component T_2 relaxation time maps ($T_{2\text{Single}}$) of menisci and cartilage were created from the source images using the Driven Equilibrium Single Shot Observation of T_2 Full Modeling reconstruction method (DESPO T_2 -FM).²³ Previous studies have shown high pixel-by-pixel correlation between cartilage $T_{2\text{Single}}$ measurements obtained using mcDESPOT and conventional CPMG techniques.¹⁸ The voxel-wise multicomponent T_2 relaxation time maps for the fast relaxing water component (T_{2F}) and the slow relaxing water component (T_{2S}) and water fraction maps for the fast relaxing water component (F_F) of menisci and cartilage were created using the two-pool mcDESPOT reconstruction method.¹⁷ Image registration software (FLIRT, Functional Magnetic Resonance Imaging of the Brain Analysis Group, Oxford University, UK) was used during the reconstruction process to correct for any subject motion that may have occurred between the multiple scans.

Image Analysis

Quantitative image analysis was performed by an experienced research assistant under the supervision of a fellowship-trained musculoskeletal radiologist using an in-house segmentation software MatrixUser (MatrixUser v2.1 <http://matrixuser.sourceforge.net/>) developed in MatLab. The 3D-FSE images were used to segment the medial and lateral menisci and the articular cartilage on medial and lateral tibia plateau and the central medial and lateral femoral condyles on each MR image slice. The anterior and posterior margins of the central femoral condyles were defined as the anterior margins of the anterior horn and the posterior margins of the posterior horn of the menisci, respectively. 3D contours of each meniscus and each articular surface were created from the high-resolution 3D-FSE images and were superimposed over the lower-resolution $T_{2\text{Single}}$, $T_{2\text{F}}$, $T_{2\text{S}}$, and F_{F} maps to measure the mean MR parameters in each joint structure. The mean MR parameters of the medial and lateral cartilage weight-bearing surfaces were calculated by averaging the mean MR parameters in the medial tibia plateau and central medial femoral condyle and in the lateral tibia plateau and lateral femoral condyle respectively.

Morphologic joint analysis was performed by a fellowship-trained musculoskeletal radiologist who was blinded to whether a subject was an asymptomatic volunteer or a patient with knee OA. The radiologist used the sagittal 3D-FSE images and axial and coronal reformat images generated from the 3D-FSE source data to grade the severity of degeneration on the medial and lateral tibia plateau and the central medial and lateral femoral condyles using the Boston-Leeds Osteoarthritis Knee Scoring (BLOKS) system.²⁴ The BLOKS system uses a single three-point scale to grade osteophyte size, two three-point scales to grade the severity of cartilage loss (size and percent full-thickness), and three three-point scales to grade the severity of bone marrow edema (size, percent area bordering subchondral bone, and percent area consisting of bone marrow edema lesion versus cyst) on each articular surface. Total BLOKS scores for the medial and lateral weight-bearing surfaces were calculated by adding the BLOKS scores in the medial tibia plateau and central medial femoral condyle and in the lateral tibia plateau and central lateral femoral condyle, respectively. The radiologist also used the 3D-FSE-source and reformat images to classify the medial and lateral menisci as intact or torn according to previously described MR criteria.²⁵ In order to assess interobserver agreement, a second fellowship-trained musculoskeletal radiologist used the 3D-FSE source and reformat images to grade the severity of degeneration on the medial and lateral tibia plateau and the central medial and lateral femoral condyles using the BLOKS system and to classify the medial and lateral menisci as intact or torn for all asymptomatic volunteers and patients with knee OA.

Statistical Analysis

Statistical analysis was performed using the R programming environment (R Foundation of Statistical Imaging; Vienna, Austria; v. 2.3.1; 2006; <http://www.R-project.org>) and MatLab. For all tests, statistical significance was defined as a P -value less than 0.05.

The medial and lateral menisci were classified into three groups: normal menisci in asymptomatic volunteers ($n=24$), intact menisci in OA patients ($n=20$), and torn menisci in OA patients ($n=8$). Univariate linear regression models were used to compare $T_{2\text{Single}}$, $T_{2\text{F}}$,

T_{2S} , and F_F in normal menisci in asymptomatic volunteers, intact menisci in OA patients, and torn menisci in OA patients. Multivariate linear regression models were then used to adjust for age differences between subjects by utilizing both MR parameters and age as continuous variables to distinguish between the three groups of menisci. For those MR parameters found to be significantly different between the three groups of menisci, two-tailed Wilcoxon rank-sum tests were used for pairwise comparison between each individual set of groups with the Holm-Bonferroni correction method utilized to adjust P -values to account for Type-I error due to comparisons of multiple MR parameters between multiple groups of menisci.²⁶

Linear regression analysis was used to test the association between mean $T_{2Single}$, T_{2F} , T_{2S} , and F_F in the medial and lateral menisci and BLOKS scores in the corresponding medial and lateral weight-bearing surfaces for patients with OA. Asymptomatic volunteers were not included in the analysis since all individuals without OA had a BLOKS score of 0 in the medial and lateral weight-bearing surfaces, which would have biased the linearity of the association. Linear regression analysis was used to test the association between mean $T_{2Single}$, T_{2F} , T_{2S} , and F_F in the medial and lateral menisci and mean $T_{2Single}$, T_{2F} , T_{2S} , and F_F in the corresponding medial and lateral cartilage weight-bearing surfaces for asymptomatic volunteers and patients with OA. Kappa statistic was used to measure interobserver agreement between radiologists for grading the severity of degeneration on the medial and lateral tibia plateau and the central medial and lateral femoral condyles and for classifying the medial and lateral menisci as intact or torn.

Results

Figure 1 shows $T_{2Single}$, T_{2F} , T_{2S} , and F_F maps of an intact anterior horn and torn posterior horn of the medial meniscus in patient with knee OA. The mean mcDESPOT parameters for normal menisci in asymptomatic volunteers, intact menisci in OA patients, and torn menisci in OA patients were respectively 16.1 msec, 18.8 msec, and 22.7 msec for $T_{2Single}$; 9.0 msec, 10.0 msec, and 11.1 msec for T_{2F} ; 24.4 msec, 27.7 msec, and 31.4 msec for T_{2S} ; and 34%, 32%, 27% for F_F (Table 1). A significant difference ($P<0.001$) between the three groups of menisci was found for $T_{2Single}$, T_{2F} , T_{2S} , and F_F in univariate analysis with significant differences remaining for $T_{2Single}$ ($P=0.001$), T_{2F} ($P=0.028$), T_{2S} ($P=0.022$), and F_F ($P<0.001$) when multivariate analysis was used to adjust for age differences between subjects. There were significant differences between normal menisci in asymptomatic volunteers and intact menisci in OA patients for $T_{2Single}$ ($P=0.004$), T_{2F} ($P=0.026$), T_{2S} ($P=0.028$), and F_F ($P=0.001$) and between normal menisci in asymptomatic volunteers and torn menisci in OA patients for $T_{2Single}$ ($P=0.003$), T_{2F} ($P=0.007$), T_{2S} ($P=0.002$), and F_F ($P=0.001$). For pair-wise comparison between intact menisci and torn menisci in OA patients, a significant difference was found for F_F ($P=0.041$), but no significant difference was found for $T_{2Single}$ ($P=0.084$), T_{2F} ($P=0.367$), or T_{2S} ($P=0.232$).

There was a significant association ($P<0.001$) between $T_{2Single}$, T_{2F} , T_{2S} , and F_F in the medial and lateral menisci and BLOKS scores in the corresponding medial and lateral weight-bearing surfaces (Table 2, Fig. 2). There was also a significant association ($P<0.001$) between $T_{2Single}$, T_{2F} , T_{2S} , and F_F in the medial and lateral menisci and $T_{2Single}$, T_{2F} , T_{2S} ,

and F_F in the corresponding medial and lateral weight-bearing cartilage surfaces (Table 3, Fig. 3).

There was high interobserver agreement between radiologists for grading the severity of degeneration using the BLOKS system and for classifying the menisci as torn or intact with kappa values of 0.728 (95% confidence interval [CI] of 0.631–0.825) for osteophytes, 0.763 (95% CI of 0.659–0.867) for cartilage size, 0.802 (95% CIs of 0.646–0.958) for cartilage percent full-thickness, 0.759 (95% CI of 0.606–0.912) for bone marrow edema size, 0.837 (95% CI of 0.710–0.964) for bone marrow edema percent area adjacent to subchondral bone, 0.690 (95% CI of 0.558–0.822) for bone marrow edema percent area bone marrow edema lesion versus cyst, and 1.00 (95% CI of 1.00–1.00) for meniscus torn or intact.

Discussion

Our study demonstrated the feasibility of performing rapid in vivo multicomponent T_2 analysis of the human knee menisci in a clinically feasible scan time at 3.0T. We found two distinct fast and slow relaxing water components in meniscal tissue with T_2 relaxation times of 9.0 msec and 24.4 msec, respectively. Juras et al⁵ and Diaz et al⁶ performed multicomponent T_2^* analysis of the human knee menisci and also found two distinct fast and slow relaxing water components with T_2^* relaxation times of 1.0 msec and 15.0 msec, respectively. The T_2^* relaxation times of the fast and slow relaxing water components measured in previous studies were shorter than the T_2 relaxation times measured in our study due to the influences of local magnetic field inhomogeneity and differences in tissue susceptibility on T_2^* measurements. However, the magnitude of difference between the fast and slow relaxing water components of meniscus were relatively similar when measured using T_2^* and T_2 mapping techniques.

The exact origin of the different T_2 and T_2^* components of meniscal tissue remains unknown, as no previous study has correlated multicomponent T_2 or T_2^* parameters of meniscus with biochemical or ultrastructural parameters. Reiter et al¹⁴ identified three exchangeable water components within bovine nasal cartilage on nuclear magnetic resonance (NMR) spectroscopy: water tightly bound to collagen, water tightly bound to proteoglycan, and bulk water with T_2 relaxation times of 2.3 msec, 25.2 msec, and 96.3 msec, respectively. Zheng and Xia²⁷ and Wang et al²⁸ described three distinct water components in bovine tendon on NMR spectroscopy with T_2 relaxation times of 3.7 msec, 11.0 msec, and 26.1 msec, which were thought to represent water tightly bound within the triple helical ultrastructure of collagen, water loosely bound to collagen and other macromolecules, and bulk water, respectively. The echo time of the mcDESPOT sequence could not capture signal from the extremely short relaxing water components of cartilage and tendon measured in previous NMR studies. Since the organization of type I collagen fibers in meniscus and tendon are quite similar, the fast and slow relaxing water components of meniscus in our study most likely correspond to water loosely bound to collagen and other macromolecules and bulk water, respectively. The F_F value of 34% for normal menisci in asymptomatic volunteers in our study corresponds with the macromolecular concentration of normal healthy meniscus, which consists primarily of type I collagen and much smaller concentrations of proteoglycan, fibronectin, elastin, and glycoproteins.^{29,30}

Our study found significantly higher $T_{2\text{Single}}$, $T_{2\text{F}}$, and $T_{2\text{S}}$ and significantly lower F_{F} in torn menisci in OA patients when compared to intact menisci in OA patients and normal menisci in asymptomatic volunteers. Studies by Rauscher et al⁴ and Zarins et al⁷ also found significantly higher meniscal $T_{2\text{Single}}$ in OA patients than asymptomatic volunteers and in torn menisci than intact menisci. Juras et al⁵ performed multicomponent T_2^* mapping of human knee menisci and also found significantly higher $T_2^*_{\text{F}}$ and $T_2^*_{\text{S}}$ in torn menisci when compared to degenerative and normal menisci. In our study, F_{F} had greater ability to distinguish between normal, degenerative, and torn menisci than $T_{2\text{F}}$ and $T_{2\text{S}}$, with lower P -values for comparison between groups of menisci. These findings are similar to a previous study performed by Liu et al¹⁹ using mcDESPOT, which found that F_{F} had significantly higher diagnostic performance than $T_{2\text{F}}$ and $T_{2\text{S}}$ for distinguishing between normal and degenerative cartilage within the human knee joint. The results of both studies suggest that degeneration in human musculoskeletal tissues appears to alter the fraction of the water components to a greater extent than the T_2 relaxation time of each individual water component.

Meniscal degeneration is characterized by increased water content and decreased collagen and proteoglycan content of the tissue.³¹ Son et al³² compared quantitative MR parameters of meniscus in patients with OA with biochemical parameters and found that $T_{2\text{Single}}$ was strongly correlated with water content but only weakly correlated with proteoglycan and collagen content. The mechanisms responsible for changes in multicomponent T_2 and T_2^* parameters with meniscal degeneration and tearing is unknown. The lower F_{F} of torn and degenerative menisci in our study likely represents the combined effects of the increased water and decreased macromolecular content of degenerative meniscus. The higher $T_{2\text{F}}$ and $T_{2\text{S}}$ in torn and degenerative menisci may be due to the fact that water loosely bound to the degraded macromolecular matrix of degenerative meniscus would likely have higher T_2 relaxation time than water loosely bound to intact macromolecules and that bulk water in degenerative meniscus would likely be less restricted by the degraded macromolecular matrix than bulk water in normal meniscus, which would increase its T_2 relaxation time. Additional studies are needed to correlate multicomponent T_2 and T_2^* parameters with histological and biochemical parameters in both normal and degenerative menisci to determine the mechanisms by which meniscal degeneration and tearing leads to changes in the T_2 characteristics of the different water components of the tissue.

Our study found a significant association between $T_{2\text{Single}}$, $T_{2\text{F}}$, $T_{2\text{S}}$, and F_{F} of meniscus and the degree of cartilage degeneration in the corresponding weight-bearing surfaces assessed using both BLOKS scores and quantitative MR parameters. Rauscher et al⁴ also found a significant association between $T_{2\text{Single}}$ of meniscus and the severity of knee OA assessed using clinical pain scores, radiographs, and quantitative MR parameters. These findings reflect the important interrelationship between the meniscus and articular cartilage in normal joint health and the onset and progression of OA. The meniscus plays an important role providing shock absorption and decreasing load transmission across the articular surfaces within the knee joint.^{33,34} Meniscal tears are common in patients with knee OA and are associated with an increased progression of joint degeneration.¹⁻³ However, intact menisci in OA patients in our study also showed alterations in multicomponent T_2 parameters that were correlated with the degree of cartilage degeneration in the corresponding weight-

bearing surfaces. Thus, meniscal degeneration without structural failure may also expose the overlying and underlying articular surfaces to increased stress, which may result in a greater risk of cartilage degeneration. Additional studies are needed to compare multicomponent T_2 parameters with biomechanical properties of intact and torn menisci in OA patients to determine how changes in the T_2 characteristics of the different water components of degenerative menisci lead to changes in the mechanical strength of the tissue.

Our study has several limitations. One limitation was that the mcDESPOT method for multicomponent T_2 mapping has not been previously validated using phantoms or by comparison with CPMG methods for measuring the fast and slow relaxing water components of musculoskeletal tissues. Another limitation of our study was that all patients with knee OA had well-established Kellgren-Lawrence 2 and 3 grades of the disease. However, the presence of definitive osteophytes is the radiographic hallmark of OA.^{20,21} Thus, it was important that the initial validation of mcDESPOT for detecting differences in multicomponent T_2 parameters of meniscus between asymptomatic volunteers and patients with knee OA should include OA patients diagnosed using standard clinical and radiographic criteria. Additional studies are needed to determine whether multicomponent T_2 parameters can detect similar changes in intact and torn menisci in patients with early cartilage degeneration identified using MRI or arthroscopy. Another limitation of our study was that multicomponent T_2 parameters of meniscus were not correlated with biochemical, ultrastructural, or biomechanical parameters. Furthermore, the mean $T_{2\text{Single}}$, $T_{2\text{F}}$, $T_{2\text{S}}$, and F_{F} of the entire meniscus was measured, which prevented investigation of regional variations in multicomponent T_2 parameters in both asymptomatic volunteers and patients with OA. A final limitation of our study was that the repeatability and interobserver variability of measuring multicomponent T_2 parameters in meniscus not assessed. However, previous work has shown that mcDESPOT has high repeatability¹⁹ and high interobserver agreement¹⁸ for measuring multicomponent T_2 parameters of the articular cartilage of the human knee joint at 3.0T, and cartilage segmentation using MRI is more difficult and more prone to error than meniscus segmentation.

In conclusion, our study found that torn menisci in OA patients had significantly higher $T_{2\text{Single}}$, $T_{2\text{F}}$, and $T_{2\text{S}}$ and significantly lower F_{F} than intact menisci in OA patients and normal menisci in asymptomatic volunteers and that $T_{2\text{Single}}$, $T_{2\text{F}}$, $T_{2\text{S}}$, and F_{F} of menisci were significantly associated with the degree of cartilage degeneration on the corresponding weight-bearing surfaces. Our results suggest that multicomponent T_2 parameters measured using mcDESPOT may provide a new quantitative MR method to assess the interrelationship between meniscal and cartilage degeneration in the onset and progression of knee OA.

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FIGURE 1.

(A) 3D-FSE image, (B) $T2_{\text{Single}}$ map, (C) $T2_{\text{F}}$ map, (D) $T2_{\text{S}}$ map, and (E) F_{F} map in a patient with knee OA with an intact anterior horn (small arrow) and torn posterior horn (large arrow) of the medial meniscus. Note the increased $T2_{\text{Single}}$, $T2_{\text{F}}$, and $T2_{\text{S}}$ and decreased F_{F} in the torn posterior horn when compared to the intact anterior horn of the meniscus.

FIGURE 2.

Linear regression plots (solid regression line and dashed 95% CI lines) describing the association between mean (A) $T_{2\text{Single}}$, (B) T_{2F} , (C) T_{2S} , and (D) F_F in the medial and lateral menisci and total BLOKS scores in the corresponding medial and lateral weight-bearing surfaces. Note the significant positive association between $T_{2\text{Single}}$, T_{2F} , and T_{2S} and BLOKS scores and the significant negative correlation between F_F and BLOKS scores indicating a strong interrelationship between meniscal and cartilage degeneration within the same compartment of the knee joint.

FIGURE 3.

Linear regression plots (solid regression line and dashed 95% CI lines) describing the association between mean (A) $T_{2\text{Single}}$, (B) T_{2F} , (C) T_{2S} , and (D) F_F in the medial and lateral menisci and mean $T_{2\text{Single}}$, T_{2F} , T_{2S} , and F_F in the corresponding medial and lateral cartilage weight-bearing surfaces. Note the significant positive association between $T_{2\text{Single}}$, T_{2F} , T_{2S} , and F_F in the menisci and cartilage indicating a strong interrelationship between meniscal and cartilage degeneration within the same compartment of the knee joint.

TABLE 1

Mean and Standard Deviation of T2_{Single}, T2_F, T2_S, and F_F

MR parameter	Mean±SD		Univariate regression <i>P</i> -value	Multivariate regression <i>P</i> -value
	Normal menisci	Intact OA menisci	Torn OA menisci	
T2 _{Single} (msec)	16.1±1.8	18.8±2.3	22.7±3.2	0.001
T2 _F (msec)	9.0±0.8	10.0±1.0	11.1±1.2	0.028
T2 _S (msec)	24.4±3.0	27.7±3.2	31.4±3.0	0.022
F _F (%)	34±2	32±2	27±4	< 0.001

Normal menisci in asymptomatic volunteers, intact menisci in OA patients, and torn menisci in OA patients with associated *P*-values for comparison between groups of menisci using univariate analysis and multivariate analysis with adjustment for age.

TABLE 2

Linear Regression Coefficient and *F* Statistics

MR parameter	Linear regression coefficient		Linear regression <i>F</i> statistics		
	Slope	Intercept	<i>r</i> ²	<i>F</i>	<i>P</i> -value
T2 _{Single} (msec)	0.33±0.054	18±0.54	0.58	36	< 0.001
T2 _F (msec)	0.11±0.024	9.6±0.24	0.43	20	< 0.001
T2 _S (msec)	0.33±0.069	26±0.69	0.47	23	< 0.001
F _F (%)	−0.36±0.054	33±0.53	0.63	44	< 0.001

The association between mean T2_{Single}, T2_F, T2_S, and F_F in the medial and lateral menisci and total BLOKS scores in the corresponding medial and lateral weight-bearing surfaces.

TABLE 3

Linear Regression Coefficient and *F* Statistics

MR parameter	Linear regression coefficient		Linear regression <i>F</i> statistics		
	Slope	Intercept	r ²	F	<i>P</i> -value
T2 _{Single} (msec)	0.39±0.10	4.85±3.28	0.25	16.6	< 0.001
T2 _F (msec)	0.40±0.11	3.33±1.80	0.20	12.7	< 0.001
T2 _S (msec)	0.28±0.08	9.38±4.98	0.20	12.3	< 0.001
F _F (%)	0.61±0.17	13.41±5.17	0.20	12.8	< 0.001

The association between mean T2_{Single}, T2_F, T2_S, and F_F in the medial and lateral menisci and mean T2_{Single}, T2_F, T2_S, and F_F in the corresponding medial and lateral cartilage weight-bearing surfaces.