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Multicomponent T_2 Analysis of Articular Cartilage With Synovial Fluid Partial Volume Correction

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Abstract

Purpose—To investigate the use of a three-pool model to account for the confounding effects of synovial fluid on multicomponent T_2 analysis of articular cartilage using Multicomponent Driven Equilibrium Single Shot Observation of T_1 and T_2 (mcDESPOT).

Materials and Methods—mcDESPOT was performed on the knee of eight asymptomatic volunteers and eight patients with osteoarthritis at 3.0T with multicomponent T_2 maps created using the two-pool model and a three-pool model containing a nonexchanging synovial fluid water pool. The fraction of the fast-relaxing water component (F_F) and the T_2 relaxation times for the fast-relaxing (T_{2F}) and slow-relaxing (T_{2S}) water components were measured in the superficial and deep layers of patellar cartilage using the two-pool and three-pool models in asymptomatic volunteers and patients with osteoarthritis and were compared using Wilcoxon signed rank tests.

Results—Within the superficial layer of patellar cartilage, F_F was 22.5% and 25.6% for asymptomatic volunteers and 21.3% and 22.8% for patients with osteoarthritis when using the two-pool and three-pool models, respectively, while T_{2S} was 73.9 msec and 62.0 msec for asymptomatic volunteers and 72.0 msec and 63.1 msec for patients with osteoarthritis when using the two-pool and three-pool models, respectively. For both asymptomatic volunteers and patients with osteoarthritis, the two-pool model provided significantly ($P < 0.05$) lower F_F and higher T_{2S} than the three-pool model, likely due to the effects of synovial fluid partial volume averaging.

Conclusion—The effects of partial volume averaging between superficial cartilage and synovial fluid may result in biased multicomponent T_2 measurements that can be corrected using an mcDESPOT three-pool model containing a nonexchanging synovial fluid water pool.

The extracellular matrix of articular cartilage is a complex network of type II collagen, proteoglycan, and water.¹ Quantitative magnetic resonance imaging (MRI) methods have been used to evaluate the composition and ultrastructure of articular cartilage.² Among these techniques, the transverse relaxation time constant (T_2) has been the most extensively

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studied and has been shown to be sensitive for detecting cartilage degeneration.^{3,4} However, T_2 relaxation time is a nonspecific parameter influenced by multiple factors including tissue anisotropy, hydration, and macromolecule content.^{5–7} Multicomponent T_2 mapping methods have been proposed to improve the specificity of cartilage T_2 analysis.^{8–10} Previous studies using nuclear magnetic resonance (NMR) have identified three water components within cartilage, which were assigned to extremely fast-relaxing water bound to collagen ($T_2 = 2$ msec, fraction = 6%), fast-relaxing water bound to proteoglycan ($T_2 = 25$ msec, fraction = 15%), and slow-relaxing bulk water ($T_2 = 96$ msec, fraction = 79%).⁸

Multicomponent T_2 analysis is typically performed using multiecho spin-echo techniques.^{8–10} Previous studies have shown that the fraction of the fast-relaxing water component (F_F) is a sensitive and specific measure of the proteoglycan content of cartilage and that the T_2 relaxation time of both the fast-relaxing (T_{2F}) and slow-relaxing (T_{2S}) water components change with enzymatic degradation of cartilage.^{8,9} However, spin-echo techniques require a long acquisition time, which have limited cartilage assessment to a single slice of ex vivo specimens. An alternative method called Multicomponent Driven Equilibrium Single Pulse Observation (mcDESPOT) has recently been proposed to accelerate multicomponent T_2 analysis using rapid 3D steady-state imaging.^{11,12} mcDESPOT can be used to characterize the fast- and slow-relaxing water components of articular cartilage with complete anatomic coverage of the human knee joint at 3.0T in a clinically feasible scan time.^{12–14}

One confounding factor in the two-pool mcDESPOT analysis is synovial fluid partial volume averaging with superficial cartilage. The extremely slow-relaxing synovial fluid water (T_2 in the range of seconds) can cause a significant increase in T_2 relaxation time as well as an underestimation of the water fraction of the fast-relaxing water component.¹⁵ Thus, there is a need to account for synovial fluid in the mcDESPOT model to better assess superficial cartilage and to avoid biased multicomponent T_2 measurements. Three-pool models have been recently proposed for mcDESPOT¹⁵ and quantitative magnetization transfer (MT) imaging¹⁶ to improve the characterization of neural tissues in the presence of partial volume averaging with cerebrospinal fluid (CSF). Specifically, a mcDESPOT three-pool method introduces a third nonexchanging water component to model the partial volume averaging effects of CSF, which has been shown to be effective at correcting CSF contamination in brain imaging.¹⁵ This study was performed to investigate the use of the three-pool mcDESPOT model to account for the confounding effects of synovial fluid on multicomponent T_2 analysis of the articular cartilage of the knee joint in human subjects.

Materials and Methods

Study Group

The study group consisted of eight asymptomatic volunteers (five males and three females with an average age of 31.2 years) and eight patients with knee osteoarthritis (six males and two females with an average age of 49.3 years). All asymptomatic volunteers had no history of prior knee pain, trauma, or surgery. All patients with osteoarthritis complained of chronic knee pain and stiffness for a minimum of 6 months and had Kellgren–Lawrence (KL) grade 2 osteoarthritis on standing flexion anterior–posterior knee radiographs assessed by a

fellowship-trained musculoskeletal radiologist.¹⁷ The study was performed with approval from our Institutional Review Board and in compliance with Health Insurance Portability and Accountability Act (HIPAA) regulations. All subjects signed written informed consent.

MR Examination

An MR examination of the knee was performed on all subjects using a 3.0T scanner (Discovery MR750, GE Healthcare; Waukesha, WI) and 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. To assess the repeatability of cartilage multicomponent T_2 measurements obtained using the mcDESPOT two-pool and three-pool methods, the MR examination was performed twice on the same knee of five asymptomatic volunteers and five patients with osteoarthritis with the subjects taken out of the scanner and allowed to rest in a sitting position for 10 minutes between scans.

A series of scans necessary for mcDESPOT analysis were performed on all subjects which included: 1) eight spoiled gradient-echo (SPGR) scans with repetition time/echo time (TR/TE) = 4.6/2.2 msec over a range of flip angles ($\alpha = 3, 4, 5, 6, 7, 9, 13, 18^\circ$); 2) 16 fully-balanced steady-state free-precession (bSSFP) scans with TR/TE = 5.0/2.5 msec over a range of flip angles ($\alpha = 2, 5, 10, 15, 20, 30, 40, 50^\circ$) repeated with radiofrequency phase cycling $\psi = 0^\circ$ and 180° ; and 3) an inversion recovery (IR)-SPGR scan with TR/TE = 4.6/2.2 msec, TI = 450 msec, and flip angle $\alpha = 5^\circ$ for estimating the flip angle error caused by transmitting B1 field inhomogeneity. All scans were performed in the sagittal plane with a 16 cm field of view, 256×256 matrix, 3 mm slice thickness, 32 slices, one excitation, $0.6 \times 0.6 \times 3.0$ mm voxel size, and total scan time of 17 minutes. A sagittal fat-suppressed radial bSSFP sequence with TR = 4.6 msec, TE = 0.3 msec and 1.8 msec, $\alpha = 15^\circ$, 16 cm field of view, $384 \times 384 \times 384$ matrix, 0.4 mm slice thickness, one excitation, $0.4 \times 0.4 \times 0.4$ mm voxel size, and 6-minute scan time was also performed on all subjects.¹⁸ In addition, a sagittal 3D fat-suppressed fast spin-echo (3D-FSE) sequence with TR/TE = 2216/23 msec, $\alpha = 90^\circ$, 16 cm field of view, 384×384 matrix, 1 mm slice thickness, 96 slices, one excitation, $0.4 \times 0.4 \times 1.0$ mm voxel size, and 7-minute scan time was performed on all patients with osteoarthritis. The radial bSSFP sequence was performed on all subjects since it was better suited for cartilage segmentation due to its ability to acquire higher isotropic resolution images, while the 3D-FSE sequence was performed on patients with osteoarthritis since it provided better visualization of superficial cartilage lesions.

Multicomponent T_2 Relaxation Time Analysis

Image processing and model fitting were performed using an in-house program developed in MatLab (2013a, MathWorks, Natick, MA). Prior to model fitting, image registration software Elastix¹⁹ was used to correct for any subject motion which may have occurred between the multiple scans. Single-component T_2 relaxation time maps ($T_{2\text{single}}$) of cartilage were created using the Driven Equilibrium Single Shot Observation of T_2 Full Modeling method (DESPOT2-FM).²⁰ Water fraction maps for the fast-relaxing water component (F_F) and T_2 relaxation time maps for the fast-relaxing (T_{2F}) and slow-relaxing (T_{2S}) water components of cartilage were created for all subjects using both the mcDESPOT two-pool

model¹¹ and the mcDESPOT three-pool model, which contained a nonexchanging extremely slow-relaxing water component for modeling synovial fluid.¹⁵ Water fraction maps for synovial fluid (F_{SF}) were also created for all subjects using the three-pool model. In addition, normalized model fitting residual error maps reflecting the voxel-by-voxel accuracy of model fit for the mcDESPOT two-pool model and mcDESPOT three-pool models were created for a single slice through the center of the knee joint in all asymptomatic volunteers.

Cartilage Segmentation and Quantitative Image Analysis

The articular cartilage on all radial bSSFP images through the patella of all subjects was segmented semiautomatically using in-house software developed in MatLab by an experienced research assistant under the supervision of a fellowship-trained musculoskeletal radiologist. The cartilage masks were downsampled using the nearest-neighbor method and divided into superficial and deep cartilage layers with equal thicknesses. The cartilage masks were then superimposed over the multicomponent T_2 maps created using the two-pool and three-pool models to measure the average F_F , T_{2F} , T_{2S} , and $T_{2Single}$ within patellar cartilage and within the superficial and deep layers of patellar cartilage for all subjects. As using a threshold is a common postprocessing method for eliminating the effects of synovial fluid partial volume averaging during quantitative cartilage analysis, the average F_F , T_{2F} , T_{2S} , and $T_{2Single}$ within patellar cartilage were also obtained from multicomponent T_2 maps created using the two-pool model after postprocessing was performed to remove cartilage voxels having a $T_{2Single}$ greater than a threshold value of 75 msec. The cartilage masks were also superimposed over the normalized model fitting residual error maps to measure average residual errors within the superficial and deep layers of patellar cartilage and residual errors within each individual voxel of the superficial and deep layers of patellar cartilage on a single slice through the center of the knee joint in all asymptomatic volunteers.

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 $P < 0.05$.

To minimize type-I error, Friedman's tests were first used to compare F_F , T_{2F} , and T_{2S} within the superficial and deep layers of patellar cartilage for the two-pool model, three-pool model, and two-pool model with threshold for both asymptomatic volunteers and patients with osteoarthritis. For those parameters in which there was a significant difference between the three models, Wilcoxon signed rank tests were used for pairwise comparison between the two-pool model and three-pool and between the two-pool model and two-pool model with threshold. Wilcoxon signed rank tests were also used to compare $T_{2Single}$ within the superficial and deep layers of patellar cartilage for the two-pool model and two-pool model with threshold. Wilcoxon rank sum tests were used to compare F_F , T_{2F} , and T_{2S} within patellar cartilage between asymptomatic volunteers and patients with osteoarthritis for the two-pool model, three-pool model, and two-pool model with threshold.

Wilcoxon signed rank tests were also used to compare average normalized model fitting residual errors within the superficial and deep layers of patellar cartilage between the two-pool model and three-pool model. F-tests were used to compare the normalized model fitting residual errors within each voxel of the superficial and deep layers of patellar cartilage between the two-pool model and three-pool model. Coefficients of variation were used to assess the repeatability of F_F , T_{2F} , and T_{2S} measurements for patellar cartilage obtained on repeat scans using the two-pool model and three-pool models for both asymptomatic volunteers and patients with osteoarthritis.

Results

Figures 1 and 2 demonstrate the effects of partial volume averaging between superficial cartilage and synovial fluid which may bias multicomponent T_2 measurements when using the two-pool model. As shown in Fig. 1, there was decreased F_F and increased T_{2S} within superficial patellar cartilage located adjacent to synovial fluid on the two-pool model maps in an asymptomatic volunteer. The synovial fluid partial volume averaging was not present on the F_F and T_{2S} three-pool model maps. As shown in Fig. 2, there was high F_{SF} on the three-pool model maps within superficial cartilage of the patella and femoral condyle located adjacent to synovial fluid in three asymptomatic volunteers. Within the areas of high F_{SF} , F_F was lower on the two-pool model map than on the three-pool model map, indicating that synovial fluid partial volume averaging resulted in underestimation of F_F in superficial cartilage. As shown in Fig. 3, there was decreased F_F and increased T_{2F} and T_{2S} on the two-pool model maps within a partial-thickness cartilage lesion on the femoral trochlea in a patient with osteoarthritis, which persisted on the three-pool model maps, indicating that the changes in multicomponent T_2 parameters were due to cartilage degeneration and not synovial fluid partial volume averaging.

Tables 1 and 2 show average F_F , T_{2F} , T_{2S} , and $T_{2\text{Single}}$ within patellar cartilage and within the superficial and deep layers of patellar cartilage for the two-pool model, three-pool model, and two-pool model with threshold for asymptomatic volunteers and patients with osteoarthritis. There was a significant difference ($P < 0.05$) between the two-pool model, three-pool model, and two-pool model with threshold for F_F , T_{2F} , and T_{2S} within the superficial cartilage layer in both asymptomatic volunteers and patients with osteoarthritis. Within the superficial cartilage layer in both asymptomatic volunteers and patients with osteoarthritis, the two-pool model provided significantly lower ($P < 0.05$) F_F and significantly higher ($P < 0.05$) T_{2S} than the three-pool model and significantly lower ($P < 0.05$) F_F and significantly higher ($P < 0.05$) T_{2F} and T_{2S} than the two-pool model with threshold. For both asymptomatic volunteers and patients with osteoarthritis, the two-pool model provided significantly higher ($P < 0.05$) $T_{2\text{Single}}$ in the superficial cartilage layer than the two-pool model with threshold. There was a significant difference ($P < 0.05$) in multicomponent T_2 parameters within patellar cartilage between asymptomatic volunteers and patients with osteoarthritis when using the three-pool model for F_F and when using the two-pool model and three-pool model for T_{2F} .

As shown in Fig. 4, the two-pool model provided better curve fit for the deep cartilage layer than the superficial cartilage layer of the patella, while the three-pool model provided

equally good curve fit for both the superficial and deep cartilage layers. The average normalized model fitting residual error for the two-pool model was 0.75 (standard deviation [SD] of 0.79) for the superficial cartilage layer and 0.13 (SD of 0.53) for the deep cartilage layer. The average normalized model fitting residual error for the three-pool model was 0.26 (SD of 0.32) for the superficial cartilage layer and 0.15 (SD of 0.37) for the deep cartilage layer. The three-pool model had significantly lower ($P < 0.05$) average residual error than the two-pool model for the superficial cartilage layer, indicating a more accurate model fit. When normalized model fitting residual errors were directly compared in each voxel of patellar cartilage, the three-pool model had significantly lower ($P < 0.05$) residual errors than the two-pool model for 1.3% of voxels in the deep cartilage layer and 11.2% of voxels in the superficial cartilage layer.

There was high repeatability of F_F , T_{2F} , and T_{2S} measurements for patellar cartilage obtained on repeat scans using the two-pool model and three-pool models for both asymptomatic volunteers and patients with osteoarthritis. The coefficients of variation for multicomponent T_2 measurements in asymptomatic volunteers were 3.3% and 4.5% for F_F , 4.1% and 5.8% for T_{2F} , and 6.3% and 5.2% for T_{2S} when using the two-pool model and three-pool model, respectively. The average coefficients of variation for multicomponent T_2 measurements in patients with osteoarthritis were 4.7% and 3.7% for F_F , 5.2% and 5.1% for T_{2F} , and 6.0% and 5.3% for T_{2S} when using the two-pool model and three-pool model, respectively.

Discussion

Due to the need to acquire multiple scans with different imaging parameters, mcDESPOT and other quantitative MR techniques are limited by relatively low spatial resolution and thick slices, which may lead to both in-plane and through-plane partial volume averaging between articular cartilage and adjacent joint structures. Our study has shown that the effects of partial volume averaging between superficial cartilage and synovial fluid may result in biased multicomponent T_2 measurements. In particular, the two-pool mcDESPOT model provided significantly lower ($P < 0.05$) F_F and significantly higher ($P < 0.05$) T_{2S} within the superficial cartilage layer of the patella located adjacent to synovial fluid in both asymptomatic volunteers and patients with osteoarthritis, which could be misinterpreted as areas of cartilage degeneration. Therefore, the effects of synovial partial volume averaging may lead to reduced specificity for multicomponent T_2 analysis of cartilage when using the two-pool mcDESPOT model.

Our results demonstrated the feasibility of reducing the effects of synovial fluid partial volume averaging by using a three-pool mcDESPOT model, which introduces a nonexchanging synovial fluid water pool. This nonexchanging synovial fluid water component is likely misinterpreted as the slow-relaxing water component in the mcDESPOT two-pool model, as it provides steady-state signal that is closer to the slow-relaxing water component. This may be the reason why the two-pool model provided significantly lower ($P < 0.05$) F_F and significantly higher ($P < 0.05$) T_{2S} within the superficial cartilage layer in our study while providing similar T_{2F} when compared to the three-pool model. The mcDESPOT three-pool model reduced synovial fluid contamination of superficial cartilage, thereby

providing a more accurate model fit and allowing decreased F_F and increased T_{2S} of cartilage due to partial volume averaging to be distinguished from similar changes due to cartilage degeneration. The mcDESPOT three-pool model also showed high repeatability for measuring multicomponent T_2 parameters with coefficients of variation that compare favorably with other quantitative cartilage imaging techniques.^{21,22}

A common postprocessing method for eliminating synovial fluid partial volume averaging is to simply remove voxels from superficial cartilage using a threshold. Similar to the three-pool model, the threshold method provided significantly higher ($P < 0.05$) F_F and significantly lower ($P < 0.05$) T_{2S} within the superficial cartilage layer of the patella when compared to the two-pool mcDESPOT model. However, a problem with using the threshold method is the increased uncertainty, as it is difficult to justify the “correct” threshold value. The threshold method may also eliminate cartilage voxels with MR parameters above or below the threshold value, which are due to cartilage degeneration and not partial volume averaging with synovial fluid. This may be the reason why statistically significant differences in multicomponent T_2 parameters within patellar cartilage between asymptomatic volunteers and patients with osteoarthritis could not be detected using the threshold method in our study. Furthermore, combining a threshold method with quantitative MRI could not be used to identify early cartilage degeneration in clinical practice, as removal of voxels in superficial cartilage would create a distorted articular surface. On the other hand, the mcDESPOT three-pool model reduces synovial fluid partial volume contamination by modeling synovial fluid in the steady-state signal equation, which maintains data from all image voxels and allows the method to be used for both clinical and research purposes.

A model-based approach may also potentially be used to reduce the effects of partial volume averaging between articular cartilage and bone marrow fat at the cartilage–bone interface. The mcDESPOT model could be expanded to include a fourth pool consisting of a nonexchanging fat component, although doing so would increase the complexity of the model fit. In addition, chemical shift of fat must also be considered in the mcDESPOT model in order to perform accurate fat partial volume correction. Furthermore, multiple fat peaks with different chemical shift frequencies may potentially extend the complexity of the MR signal model, leading to challenges in stable and accurate model solutions. Future work will involve incorporation of both fat and synovial fluid partial volume correction in the mcDESPOT model in order to provide more accurate cartilage multicomponent T_2 analysis.

Our study has several limitations. First, our study focused only on the knee joint and involved a relatively small number of asymptomatic volunteers and patients with a single Kellgren–Lawrence grade of osteoarthritis. Furthermore, depth dependency analysis was performed only on patellar cartilage due to the thin cartilage on the other articular surfaces of the knee joint. In addition, the synovial fluid water pool was considered to be nonexchanging in the mcDESPOT three-pool model, although dynamic exchange between synovial fluid and the slow-relaxing bulk water component of cartilage is thought to occur during joint loading.^{23,24} However, such exchange between water components would likely be minimal while the subject is lying supine during the MR examination. Nevertheless, additional work is needed to investigate the effect of increasing the complexity of the

mcDESPOT three-pool model to take into account possible exchange between synovial fluid and the slow-relaxing water component of cartilage. Finally, the mcDESPOT model did not account for the MT effect, which has been shown to influence steady-state signal.^{25,26} Previous studies have demonstrated that mcDESPOT parameters could be potentially modulated in a complex way due to the MT effect.^{27,28} A technique called mcRISE has recently been proposed to correct bias caused by MT modulation in mcDESPOT and has been successfully implemented for cartilage imaging.²⁸ Further investigation is needed to determine whether combining both MT and partial volume averaging correction in the mcDESPOT model can provide more accurate cartilage multicomponent T_2 analysis.

In conclusion, our study has shown that the effects of partial volume averaging between superficial cartilage and synovial fluid may result in biased multicomponent T_2 measurements which can be corrected using an mcDESPOT three-pool model containing a nonexchanging synovial fluid water pool. However, additional studies with surgical or histological correlation are needed to determine whether the potentially more accurate parameter estimation of the mcDESPOT three-pool model may improve the specificity of cartilage multicomponent T_2 analysis by allowing changes in F_F and T_{2S} due to partial volume averaging to be distinguished from similar changes due to cartilage degeneration.

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FIGURE 1.

Comparison of multicomponent T_2 maps of patellar cartilage created using the mcDESPOT two-pool model and mcDESPOT three-pool model in an asymptomatic volunteer. a: Radial bSSFP image shows synovial fluid located adjacent to patellar cartilage where it can cause a partial volume averaging effect. b,e: There is increased F_F within the superficial cartilage layer as shown by the white arrows for the three-pool model when compared to the two-pool model. c,f: There is no visible difference in T_{2F} within patellar cartilage between the two-pool model and three-pool model. d,g: There is decreased T_{2S} within the superficial cartilage layer as shown by the white arrows for the three-pool model when compared to the two-pool model.

FIGURE 2.

Comparison of F_F maps between the mcDESPOT two-pool model and mcDESPOT three-pool model. The first column shows radial bSSFP images that demonstrate the anatomical references of the knee in three asymptomatic volunteers. The white arrows indicate areas within the patellofemoral and tibiofemoral compartments of the knee joint where synovial fluid is located adjacent to cartilage where it can cause a partial volume averaging effect. The second and third columns show the F_F maps created using the two-pool model and three-pool model, respectively. The F_{SF} maps created using the three-pool model are shown in the fourth column, where the white arrows illustrate areas of high synovial fluid water fraction. The last column shows the F_F two-pool model maps subtracted from the F_F three-pool model maps. The white arrows illustrate areas where F_F within the superficial cartilage layer is lower for the two-pool model than the three-pool model due to the effects of synovial fluid partial volume averaging.

FIGURE 3.

Comparison of multicomponent T_2 maps of cartilage on the femoral trochlea created using the mcDESPOT two-pool model and mcDESPOT three-pool model in a patient with osteoarthritis. a: 3D-FSE anatomical image shows a superficial partial-thickness cartilage lesion on the femoral trochlea identified by a white arrow. b–d: There is decreased F_F and increased T_{2F} and T_{2S} within the cartilage lesion on the two-pool model maps. e–g: The decreased F_F and increased T_{2F} and T_{2S} within the cartilage lesion persist on the three-pool model maps, indicating that the changes in multicomponent T_2 parameters are due to cartilage degeneration and not synovial fluid partial volume averaging.

FIGURE 4.

Comparison of model fit between the mcDESPOT two-pool model and mcDESPOT three-pool models in regions of interest placed within the superficial and deep layers of patellar cartilage in an asymptomatic volunteer. For the SPGR scans, bSSFP scans with radiofrequency phase cycling $\psi = 0^\circ$, and bSSFP scans with radiofrequency phase cycling $\psi = 180^\circ$, the two-pool model provides better fit for the deep cartilage layer than the superficial cartilage layer, while the three-pool model provided equally good fit for the deep and superficial cartilage layers.

TABLE 1

Average Multicomponent T2 Parameters Within Patellar Cartilage of Eight Asymptomatic Volunteers When Using the mcDESPOT Two-Pool Model, mcDESPOT Three-Pool Model, and mcDESPOT Two-Pool Model With Threshold

Patella	Average F _F [%] mean (standard deviation)			Average T2 _F [msec] mean (standard deviation)			Average T2 _S [msec] mean (standard deviation)			Average T2 _{Single} [msec] mean (standard deviation)	
	2-pool	3-pool	2-pool w/threshold	2-pool	3-pool	2-pool w/threshold	2-pool	3-pool	2-pool w/threshold	w/othreshold	w/threshold
Entire	29.3 (3.0)	30.5 (2.5)	30.2 (3.0)	14.6 (2.1)	14.6 (2.4)	14.2 (2.0)	62.0 (6.3)	53.2 (6.9)	54.8 (6.2)	34.0 (3.5)	32.0 (3.9)
Deep	33.8 (3.9)	33.5 (2.5)	34.0 (3.5)	13.4 (2.3)	13.5 (2.4)	13.2 (2.1)	49.1 (7.6)	48.6 (7.4)	48.4 (7.4)	27.4 (5.0)	27.0 (4.4)
Superficial	22.5 (2.3)	25.6 (2.4)	24.1 (2.2)	16.5 (2.1)	16.7 (2.5)	15.9 (2.1)	73.9 (7.9)	62.0 (6.5)	64.9 (6.1)	44.4 (5.0)	40.4 (3.6)

TABLE 2

Average Multicomponent T2 Parameters Within Patellar Cartilage of Eight Patients With Osteoarthritis When Using the mcDESPOT Two-Pool Model, mcDESPOT Three-Pool Model, and mcDESPOT Two-Pool Model With Threshold

Patella	Average F _F [%] mean (standard deviation)			Average T2 _F [msec] mean (standard deviation)			Average T2 _S [msec] mean (standard deviation)			Average T2 _{Single} [msec] mean (standard deviation)	
	2-pool	3-pool	2-pool w/threshold	2-pool	3-pool	2-pool w/threshold	2-pool	3-pool	2-pool w/threshold	w/o threshold	w/threshold
Entire	26.6 (3.1)	27.3 (2.4)	27.3 (2.7)	16.9 (2.1)	17.2 (2.1)	16.4 (1.8)	64.7 (8.8)	57.6 (8.0)	57.3 (7.5)	40.0 (6.7)	37.7 (5.1)
Deep	30.2 (3.4)	30.3 (2.6)	30.4 (3.0)	16.0 (2.0)	16.3 (2.0)	15.7 (1.6)	54.9 (7.8)	54.7 (7.9)	54.6 (8.0)	34.8 (6.3)	33.7 (4.9)
Superficial	21.3 (3.9)	22.8 (3.1)	22.3 (3.6)	18.4 (2.9)	18.9 (3.0)	17.7 (2.6)	72.0 (13.0)	63.1 (11.5)	63.3 (10.7)	48.1 (9.9)	44.6 (7.8)