The feasibility of characterizing the spatial distribution of cartilage $T_2$ using texture analysis

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Summary

Objective: The purpose of this study was (1) to characterize the spatial distribution of cartilage $T_2$ in postmenopausal osteoarthritis (OA) patients and age-matched healthy subjects using second order texture measures at baseline, and (2) to analyze changes in the texture of cartilage $T_2$ after 9 months.

Methods: 3.0 T-MRI of the knee was performed in 8 mild OA patients and 10 age-matched controls at baseline and after 9 months. Cartilage $T_2$, volume, and average thickness were calculated in all patients. Texture analysis, based on the gray level co-occurrence matrix, was performed on the cartilage $T_2$ maps. Texture parameters, including entropy and angular second moment, were calculated at 0° (corresponding to the anterior–posterior axis) and at 90° (corresponding to the superior–inferior axis), with pixel offsets ranging from 1 to 3 pixels.

Results: Least squares mean analysis showed that mean $T_2$ values, their standard deviation (SD), and their entropy were greater ($P < 0.05$) in OA patients than in controls. Over 9 months, the SD and entropy of cartilage $T_2$ significantly ($P < 0.05$) decreased in OA patients, while no significant changes were evident in cartilage thickness or volume.

Conclusion: The mean cartilage $T_2$ values, their SD, and their entropy were greater in OA patients than in controls, indicating that the $T_2$ values in osteoarthritic cartilage are not only elevated, but also more heterogeneous than those in healthy cartilage. The longitudinal results demonstrate that changes in texture parameters of cartilage $T_2$ may precede morphological changes in thickness and volume in the progression of OA.

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Key words: Magnetic resonance imaging, Osteoarthritis, Cartilage $T_2$, Texture analysis, GLCM.

Abbreviations: MRI Magnetic Resonance Imaging, OA osteoarthritis.

Introduction

Osteoarthritis (OA) is a heterogeneous and multi-factorial disease characterized by the progressive loss of hyaline articular cartilage and the development of altered joint congruency, subchondral sclerosis, intraosseous cyst formation, and osteophytes. It affects approximately 14% of the adult population† and is the second most common cause of permanent disability among subjects over the age of 50‡. The incidence of OA increases with age, and is more prevalent in females than males over the age of 50§. The prevalence of knee OA is 20–40% in people aged 75 years and older¶.

The initial stages of OA include proteoglycan loss, increased water content, and disorganization of the collagen network. With further degeneration, cartilage tissue becomes ulcerated causing proteoglycans to diffuse into the synovial fluid, thus decreasing water content in cartilage. The intermediate stages of OA include cartilage thinning, fibrillation, and decreased proteoglycan and water content. In the late stages of OA, collagen, proteoglycan, and water content are further reduced, and the collagen network is severely disrupted¶.

Quantitative $T_2$ relaxation time has been used as a non-invasive marker of cartilage degeneration, as it is sensitive...
to tissue hydration and biochemical composition. In early cartilage degeneration, changes in the extracellular matrix (e.g., disorganization and breakdown of collagen network) increase the mobility of water, thus increasing $T_2$ relaxation time. Previous studies have demonstrated elevated $T_2$ relaxation time in OA subjects as compared to healthy subjects$^6,7$, reported spatial variations in $T_2$ values from the radial zone to the articular cartilage surface$^8$, and shown different visual patterns of $T_2$ values in prearthritic, early arthritic, and healthy hip cartilage$^9$. Dray et al.$^{10}$ found no difference between mean $T_2$ values in osteoarthritic cartilage; however, they showed visual differences in the spatial distribution of the $T_2$ values. These results demonstrate the necessity to characterize and quantify the spatial distribution of cartilage $T_2$ values.

Texture analysis based on the gray level co-occurrence matrix (GLCM) is a method developed by Haralick et al.$^{11}$ that can be used to examine the spatial distribution of pixel values in an image. This method has been used to characterize trabecular bone structure$^{12}$ and breast tissue$^{13}$. Texture analysis would supplement standard measures of cartilage $T_2$ (such as mean and standard deviation [SD]), by providing information on the variation between neighboring pixels. Texture analysis directly quantifies the distribution of cartilage $T_2$, which may change with disease progression. Recent studies have characterized the distribution of cartilage pixel values in anatomic images$^{14,15}$ and $T_2$ relaxation maps$^3$. Blumenkrantz et al.$^{15}$ demonstrated that mild OA patients ($n=8$) had significantly elevated GLCM entropy and reduced angular second moment (ASM) of cartilage $T_2$ than controls ($n=14$). Based on these results, we hypothesize that texture measures can be used to characterize and quantify cartilage degeneration in early OA and may complement measures of mean cartilage $T_2$.

The purpose of this study was (1) to characterize the spatial distribution of cartilage $T_2$ in postmenopausal OA patients and age-matched healthy subjects using second order texture measures at baseline, and (2) to analyze changes in the texture of cartilage $T_2$ after 9 months.

**Methods**

**SUBJECTS**

Eight female OA patients (age = 55.7 ± 7.3 years) and ten age-matched female controls (57.6 ± 6.2 years) participated in the study. In all subjects, standing anteroposterior radiographs of the knee were obtained and evaluated using the Kellgren Lawrence (KL)$^{16}$ grading scale for OA severity. The inclusion criteria required that patients had a KL score of 2 or 3 in one knee, and an equal or lower KL score in the contralateral knee; frequent knee symptoms (pain, aching or stiffness), or used medication (all types) to treat knee pain on most days during the past year; and a body mass index (BMI) > 30 kg/m$^2$. The OA patients were not undergoing any type of treatment during the study. The inclusion criteria required that control subjects did not have radiological and clinical evidences of knee OA in either knee (KL score 0) and had a BMI < 30 kg/m$^2$. This study was performed in accordance with the rules and regulations from the local Human Research Committee, and all subjects provided informed consent.

**MAGNETIC RESONANCE (MR) IMAGING**

MR imaging was performed on a 3.0 T system (Signa, GE Medical systems, Waukesha, WI, USA) using a knee coil that was specifically developed for this study (Clinical MR Solutions, Brookfield, WI, USA). Subjects were positioned supine in the scanner and imaged at baseline and 9 months.

High-resolution, fat-suppressed, three-dimensional (3D) spoiled gradient-echo (SPGR) sagittal MR images (TE = 7.5 ms, TR = 20 ms, resolution = 0.293 × 0.293 × 1.5 mm$^3$, FOV = 15 cm) were acquired for assessing cartilage morphology. Two-dimensional (2D) dual echo fast spin echo (FSE) sagittal images (TE$_1$/TE$_2$ = 8.5/34.1 ms, TR = 3600 ms, resolution = 0.625 × 0.625 × 3 mm$^3$, FOV = 16 cm) were acquired for measuring cartilage $T_2$ relaxation time and to determine the Whole-Organ Magnetic Resonance Imaging Scores (WORMS)$^{17}$.

**IMAGE ANALYSIS**

All images were analyzed using a Sun Workstation (Sun Microsystems, Palo Alto, CA, USA). Knee cartilage was segmented from the SPGR images using a spline-based, semi-automatic technique (Bezier splines and edge detection)$^{18}$ developed using Matlab (Mathworks, Natick, MA, USA). Five regions were defined: medial and lateral tibia, medial and lateral femur, and trochlea. Shape-based interpolation was used to generate isotropic voxels from which 3D cartilage thickness and volume maps were computed. $T_2$ maps were computed on a pixel-by-pixel basis from the dual echo, FSE images, using the following equation:

$$S(TE) = e^{-\exp(-TE/T_2)}$$

The $T_2$ maps were registered to the SPGR images using a rigid-body algorithm (to reduce the effects of knee movement from the SPGR sequence to the $T_2$ mapping sequence). The segmented regions of interest were resampled and superimposed on the $T_2$ maps. Any segmented regions of interest that had partial volume effects due to fluid were manually excluded.

Texture analysis was performed on a slice-by-slice basis on the cartilage $T_2$ maps. This method is based on the GLCM as described by Haralick et al.$^{11}$. The GLCM determines the frequency that neighboring gray level values occur in an image. An image can be represented at a defined orientation (e.g., 0° and 90°) and a defined spacing (e.g., spacing = 1 for nearest-neighbor pixels). Texture parameters including ASM and entropy were calculated from the co-occurrence matrix. ASM is a measure of order in an image, while entropy is a measure of disorder in an image. The equation for ASM and entropy are shown below. $P$ represents the probability of the co-occurrence of pixel values $i$ and $j$ in an image, $N$ represents the number of distinct gray levels in the quantized image, and $R$ is a normalizing constant (Harrlick et al.$^{11}$).

$$ASM = \sum_{i=1}^{N} \sum_{j=1}^{N} \frac{P(i,j)}{R}$$

$$Entropy = \sum_{i=1}^{N} \sum_{j=1}^{N} P(i,j)(-\ln P(i,j))$$

Texture analysis was performed on the cartilage $T_2$ maps in the lateral femur, lateral tibia, medial femur, medial tibia, and trochlea. A GLCM was defined for each cartilage region and used for texture analysis. Second order texture measures, including entropy and ASM, were calculated at 0° (corresponding to the anterior–posterior axis) and at 90° (corresponding to the superior–inferior axis), with pixel offsets ranging from 1 to 3 pixels. The pixel offset range was chosen based on the fact that approximately 3–4 pixels span the cartilage thickness$^{18,20}$.

**Statistical analysis**

At baseline, t tests were used to compare texture parameters in OA patients and controls. A one-way analysis of variance (ANOVA) was employed to evaluate texture parameters in different cartilage compartments (using JMP software, SAS institute, Cary, NC, USA). Pearson correlations were calculated to determine the relationship between (1) ASM and entropy of cartilage $T_2$, (2) texture parameters at different orientations, and (3) texture parameters at different pixel offsets. Paired t tests were used to compare texture parameters of cartilage $T_2$ in OA patients at 0° and 90°.

The reproducibility (root mean square coefficient of variation percentage [CV%]) for cartilage segmentation and $T_2$ quantification was less than 5% and is described in detail by Stahl et al.$^{19}$.

The longitudinal data analysis was performed using SAS Version 9.1 software (SAS Institute, Cary, NC). Least square means (LSMeans) and standard errors (SEs) at baseline and 9 months were estimated for mean cartilage $T_2$, SD of $T_2$, entropy and ASM of $T_2$, and cartilage volume.
and thickness. These variables were compared with multivariate ANOVA (MANOVA) after adjusting for the effects between visits and among measurement locations, and after excluding the repeated measurement errors in the same subjects with SAS GLM procedure. The changes in outcome variables between baseline and 9 months were evaluated using the same MANOVA model.

**Results**

**BASELINE PATIENT CHARACTERISTICS**

The OA subjects (n = 8) and controls (n = 10) were similar in age (OA subjects = 55.7 ± 7.3 years, controls = 57.6 ± 6.2 years, P = 0.574), but had significantly different BMIs (OA subjects = 34.4 ± 4.9, controls = 23.2 ± 2.1, P < 0.0001). Four OA subjects had a KL score of 2, and the other four had a KL score of 3.

**Baseline results**

At baseline, the mean and the SD of cartilage T2 values were greater in OA subjects than in controls (P < 0.05 in the lateral femur and in all compartments combined). There were no significant differences in cartilage thickness or volume between patients and controls at baseline (P > 0.05).

The ASM of cartilage T2 was greater in control subjects than in OA patients in the lateral femur (P < 0.05 for 90°, 3 pixel offsets), medial tibia (P < 0.05 for 90°, 1 pixel offset), and all compartments combined (P = 0.05 for 0°, 1 pixel offset). Entropy of cartilage T2 was greater in OA patients than in control subjects in the lateral femur (P < 0.05 for 0°, 1–3 pixel offsets; and for 90°, 2–3 pixel offsets), medial tibia (P < 0.05 for 90°, 1–3 pixel offsets), and all compartments combined (P < 0.05 for 0°, 1–3 pixel offsets). Representative examples of images and texture parameters from two OA patients (with cartilage WORMS scores of 5 and 1) and a control subject are shown in Fig. 1. Figure 2 illustrates the differences in entropy and ASM of cartilage T2 (at 0° and 90°) between OA patients and controls.

In OA patients, entropy and ASM of cartilage T2 were significantly different between cartilage compartments. ASM of cartilage T2 was greatest in the medial tibia and lowest in the medial femur. ASM (0°, 1 pixel offset) was significantly greater in the lateral femur than both the medial femur and trochlea (P < 0.05). ASM (0°, 1 pixel offset) was significantly greater in the medial tibia than both the medial femur and the trochlea. Entropy of cartilage T2 was greatest in the medial femur and lowest in the medial tibia. Entropy (0°, 1 pixel offset) was significantly greater in the medial femur than the medial tibia, lateral femur, and lateral tibia (P < 0.05). Entropy (0°, 1 pixel offset) was significantly greater in the trochlea than both the medial tibia and the lateral femur (P < 0.05). Significant differences between 0° and 90° in ASM and entropy of cartilage T2 were demonstrated in the lateral tibia, medial tibia, and trochlea.

**CORRELATIONS BETWEEN MEASUREMENTS**

A positive relationship was demonstrated between texture parameters at different pixel offsets. In addition, strong positive correlations were found between texture parameters at different orientations (0° and 90°). Negative correlations were demonstrated between ASM and entropy (Table I).

A positive correlation was established between entropy (90°, 2 pixel offsets) of cartilage T2 and the SD of cartilage T2 (r = 0.313, P < 0.05). A negative correlation was established between mean cartilage T2 and SD of cartilage T2 (r = 0.307, P < 0.05).

No significant correlations were evident between baseline texture parameters and longitudinal changes in cartilage thickness and volume.

**WORMS SCORING**

Texture parameters were evaluated in patients with different degrees of cartilage degeneration (determined by cartilage WORMS). Cartilage WORMS was determined in each cartilage compartment. The subject cohort was subdivided into three groups: controls, those with a WORMS of 1, and those with a WORMS of ≥2 (corresponding to normal, inhomogeneous cartilage signal, and morphologic cartilage degeneration, respectively). Cross-sectional analysis of the combined data from baseline and follow-up showed that entropy was greatest (and ASM was lowest) in patients...
with the greatest WORMS. Representative examples are shown in Fig. 1. The mean \( \pm \) SE of ASM (0°, 1 pixel offset) was 0.877 \( \pm \) 0.004 in controls, 0.868 \( \pm \) 0.014 in patients with WORMS of 1, and 0.858 \( \pm \) 0.006 in patients with WORMS \( \geq \) 2 (\( P = 0.03 \)). The mean \( \pm \) SE of entropy (0°, 1 pixel offset) was 0.192 \( \pm \) 0.006 in controls, 0.208 \( \pm \) 0.020 in patients with WORMS of 1, and 0.226 \( \pm \) 0.009 in patients with WORMS \( \geq \) 2 (\( P = 0.009 \)).

**Longitudinal results**

**MEAN AND SD OF CARTILAGE T2**

Using the combined data from baseline and 9 months, the LSMean analysis showed significant differences (\( P < 0.05 \)) in mean and SD of cartilage \( T_2 \) between OA patients and controls (Table II). Overall, the mean \( T_2 \) was 42.329 \( \pm \) 0.521 ms in patients and was 40.035 \( \pm \) 0.485 ms in controls (\( P = 0.002 \)). The SD of cartilage \( T_2 \) was 14.259 \( \pm \) 0.275 ms in patients and was 12.884 \( \pm \) 0.256 ms in controls (\( P < 0.001 \)).

The LSMean model demonstrated longitudinal decreases in mean \( T_2 \) (all compartments combined), which approached significance (\( P = 0.060 \)) in OA patients, but not in controls (\( P > 0.05 \)). The SD of cartilage \( T_2 \) significantly (\( P = 0.032 \)) increased from baseline to 9 months in OA patients (Table III). No significant (\( P > 0.05 \)) longitudinal changes in the SD of cartilage \( T_2 \) were evident in controls.

**CARTILAGE THICKNESS AND VOLUME**

Using the combined data from baseline and 9 months, LSMean analysis showed that cartilage volume and thickness were not significantly different between OA patients and controls (Table II). Overall, the mean cartilage thickness

| Table I: Correlations between texture parameters of cartilage \( T_2 \) |
|-------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Texture parameter       | Orientation     | Pixel offset    | Texture parameter | Orientation     | Pixel offset    | Correlation     | \( P \)        |
| Effects of pixel offset | ASM             | 0               | ASM             | 0               | 2               | 0.997           | <0.0001        |
|                        | ASM             | 0               | ASM             | 0               | 3               | 0.993           | <0.0001        |
| Effects of orientation  | ASM             | 90              | ASM             | 0               | 1               | 0.618           | <0.0001        |
|                        | ENT             | 90              | ENT             | 0               | 1               | 0.497           | <0.0001        |
| Effects of texture parameter | ASM | 0               | ENT             | 0               | 1               | 0.986           | <0.0001        |
|                        | ASM             | 90              | ENT             | 90              | 1               | 0.985           | <0.0001        |
patients and controls, demonstrating that these parameters may be able to differentiate osteoarthritic from healthy cartilage. The mean $T_2$ values, their SD, and their entropy were greater in OA patients than in controls, indicating that the $T_2$ values in osteoarthritic cartilage are not only elevated, but also more heterogeneous than those in healthy cartilage. Over 9 months, the SD and entropy of cartilage $T_2$ significantly ($P < 0.05$) decreased in OA patients, while no significant changes were evident in cartilage thickness or volume. The longitudinal results demonstrate that changes in texture parameters of cartilage $T_2$ may precede morphological changes in thickness and volume in the progression of OA.

The results of this study are consistent with those of previous studies, which have reported elevated $T_2$ values in OA cartilage\textsuperscript{5,7}, and increased entropy and decreased ASM of cartilage $T_2$ and $T_1p$ values in OA subjects compared to controls\textsuperscript{20}. $T_2$ relaxation time in cartilage has been associated with many factors including the mobility of water\textsuperscript{21} (which is affected by the breakdown of the extracellular matrix), water content\textsuperscript{22}, and collagen fiber orientation\textsuperscript{21}. Both in vitro\textsuperscript{24} and in vivo studies\textsuperscript{21,25–27} have observed differences in $T_2$ values from the deep to superficial layers of cartilage. Characterizing the heterogeneity of $T_2$ values (using SD and texture analysis) provides a means to quantify their distribution. SD, which evaluates the deviation of $T_2$ values from their mean, characterizes the spread of $T_2$ values, while GLCM texture measures examine the differences in neighboring $T_2$ pixel values. Together, these measurements can be used to quantify the distribution of cartilage $T_2$ values on both a global and focal scale, which is essential, given the heterogeneity of biochemical changes that occur in osteoarthritic cartilage. Based on the cross-sectional data, the mean, SD, and entropy of cartilage $T_2$ values were elevated in OA subjects as compared to controls. The increases in mean cartilage $T_2$ suggest that the mobility of water is elevated in osteoarthritic cartilage; the increases in SD and entropy suggest that the changes to the extracellular matrix are both globally and spatially heterogeneous throughout the degenerated cartilage.

Longitudinally, the SD and entropy of cartilage $T_2$ significantly decreased in OA patients. There were no significant changes in mean, SD, ASM or entropy of cartilage $T_2$ in controls. The mechanisms responsible for the longitudinal decreases of cartilage $T_2$ entropy are difficult to isolate in an in vivo imaging study. These longitudinal results were unexpected; however, we speculate that decreased entropy of cartilage $T_2$ in OA patients over 9 months is related to swelling of cartilage in the early stages of OA, or short-term changes in disease progression. For example, Fig. 4 illustrates the progression of cartilage degeneration in an OA patient from baseline to 9 months. At baseline, the cartilage signal is inhomogeneous, and at 12 months, a cartilage defect (which has a more homogeneous signal) has developed. The changes in intensity and spatial distribution of pixel values are evidenced by decreased entropy of cartilage $T_2$. These results demonstrate that changes in cartilage $T_2$ are heterogeneous during the evolution of OA.

The goal of this study was to establish a method that can be used to quantify and compare the distribution of $T_2$ pixels in osteoarthritic and healthy cartilages. Since GLCM texture analysis yields a numerical result, it facilitates a simple means for comparison between subject groups. The short-term changes in the spatial distribution of cartilage $T_2$ values motivate a long-term follow-up study. A further study with a larger patient cohort, and multiple follow-up durations (such as the Osteoarthritis Initiative) is therefore clearly

### Table II

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control Patient (LSMean $\pm$ SE)</th>
<th>OA Patient (LSMean $\pm$ SE)</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASM</td>
<td>0.851 $\pm$ 0.003</td>
<td>0.841 $\pm$ 0.003</td>
<td>0.037</td>
</tr>
<tr>
<td>Entropy</td>
<td>0.243 $\pm$ 0.004</td>
<td>0.257 $\pm$ 0.005</td>
<td>0.034</td>
</tr>
<tr>
<td>$T_2$ SD (ms)</td>
<td>12.884 $\pm$ 0.256</td>
<td>14.259 $\pm$ 0.275</td>
<td>0.0003</td>
</tr>
<tr>
<td>$T_2$ Mean (ms)</td>
<td>40.035 $\pm$ 0.485</td>
<td>42.329 $\pm$ 0.521</td>
<td>0.002</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>1.565 $\pm$ 0.039</td>
<td>1.570 $\pm$ 0.036</td>
<td>0.914</td>
</tr>
<tr>
<td>Volume (cm$^3$)</td>
<td>1.615 $\pm$ 0.067</td>
<td>1.716 $\pm$ 0.072</td>
<td>0.307</td>
</tr>
</tbody>
</table>

was 1.570 $\pm$ 0.036 mm in patients and was 1.565 $\pm$ 0.033 mm in controls ($P = 0.914$) in all compartments. The mean cartilage volume was 1.716 $\pm$ 0.072 cm$^3$ in patients and was 1.615 $\pm$ 0.067 cm$^3$ in controls ($P = 0.307$).

Cartilage thickness and volume decreased in OA patients over time; however, these differences were not significant ($P = 0.701$ for thickness and $P = 0.715$ for volume) (Table III). Cartilage volume and thickness increased in control subjects over time; however, these differences were also insignificant ($P = 0.473$ for thickness and $P = 0.912$ for volume).

### Table III

<table>
<thead>
<tr>
<th>Variable</th>
<th>Patient (LSMean $\pm$ SE)</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASM</td>
<td>0.835 $\pm$ 0.004</td>
<td>0.847 $\pm$ 0.004</td>
</tr>
<tr>
<td>Entropy</td>
<td>0.268 $\pm$ 0.007</td>
<td>0.247 $\pm$ 0.007</td>
</tr>
<tr>
<td>$T_2$ SD (ms)</td>
<td>14.89 $\pm$ 0.388</td>
<td>13.70 $\pm$ 0.388</td>
</tr>
<tr>
<td>$T_2$ Mean (ms)</td>
<td>43.37 $\pm$ 0.736</td>
<td>41.40 $\pm$ 0.736</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>1.585 $\pm$ 0.051</td>
<td>1.557 $\pm$ 0.051</td>
</tr>
<tr>
<td>Volume (cm$^3$)</td>
<td>1.744 $\pm$ 0.102</td>
<td>1.691 $\pm$ 0.102</td>
</tr>
</tbody>
</table>

### Discussion

This study demonstrated the feasibility of using texture analysis to characterize the spatial distribution of $T_2$ values in articular cartilage in OA patients and controls. Entropy and ASM showed significant differences between mild OA
warranted, and would be essential to understand the time-course of $T_2$ changes in OA. There were no significant cross-sectional differences or longitudinal changes in cartilage thickness or volume in OA patients and controls. This may be because the time-course of cartilage volume and thickness changes are slower than changes in mean, SD, and texture of cartilage $T_2$ in OA.

The limitations of this pilot study include a small subject sample size (8 OA patients and 10 controls), short follow-up duration (9 months) and the use of two echo times in calculating the $T_2$ map. While additional echo times would increase the accuracy of cartilage $T_2$ and texture quantification, two echo times were used due to constraints in imaging duration. Due to the limited spatial resolution of the $T_2$ mapping sequence, only approximately 3–4 pixels spanned the cartilage thickness. Increased spatial resolution would decrease partial volume effects at the cartilage–bone surface and would improve the accuracy of the texture analysis particularly perpendicular to the cartilage surface. Because the patient’s knee cannot be in an identical

Fig. 3. Increased ($P < 0.10$) cartilage $T_2$ ASM was evident in OA patients from baseline to 9 months. Decreased ($P < 0.10$) cartilage $T_2$ entropy was evident in OA patients from baseline to 9 months.

Fig. 4. Sagittal $T_2$-weighted FSE images (top row) and cartilage $T_2$ maps overlayed on $T_2$-weighted FSE images (bottom row) of an OA patient at baseline and 9 months. At baseline, the cartilage signal at the posterior lateral tibia (arrow) is inhomogeneous (a) and at 9 months, an extensive cartilage defect with a more homogeneous signal has developed in the same area (arrow in [b]). An extensive adjacent bone marrow edema pattern is also evident. Visually, there is a decrease in the heterogeneity of $T_2$ values from baseline to follow-up.
position during the baseline and follow-up scans, registration of these scans would ensure that the same region of cartilage is evaluated at both visits. Therefore, improved registration and segmentation techniques would increase the accuracy of cartilage volume, thickness, and T₂ measurements. Another limitation to this study is the fact that the OA patients had a significantly greater mean BMI than controls. The excess fat tissue in the knee may affect the calculated T₂ values. Future studies should be designed to include both age and BMI-matched patients and controls.

In this study, the orientation of the texture analysis was performed with respect to the imaging plane, rather than with respect to bone surface. Therefore, 0° may not be considered parallel to the bone surface, especially given the curvature of the femoral condyles. Future studies will define the texture analysis coordinates with respect to the bone surface – 0° will be parallel to the bone surface, while 90° will be perpendicular. This could be accomplished by flattening out the cartilage, thereby facilitating texture analysis at a greater pixel offset in the horizontal plane.

A recent study by Qazi et al. quantified the homogeneity of cartilage signal from T₁-weighted knee images obtained on a 0.18 T scanner. This study calculated first order entropy of cartilage using a histogram-based method, and demonstrated a significant difference in cartilage entropy between mild OA patients and healthy controls. Though both studies evaluate the pixel distribution of OA cartilage, the field strength, thus the contrast-to-noise, resolution and other factors are different between our study and the above-mentioned study, which makes direct comparison difficult. However, future studies could combine histogram and co-occurrence-based measurements to investigate their collective sensitivity to cartilage degeneration.

In summary, the results show that OA patients have higher and more heterogeneous cartilage T₂ values than healthy controls. Over 9 months, the SD and entropy of T₂ values decreased in OA patients, which may reflect the change of heterogeneity in cartilage structure in the evolution of OA. The T₂ quantification sequence, number of echos, fitting routine, and impact of noise are all factors, which may affect the calculation of texture parameters. While we have established the feasibility of using texture measures to quantify regional heterogeneity in cartilage T₂, the time-course and evolution of these measures are likely to be complex; therefore, further studies examining texture analysis in a larger cohort are warranted.

References