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Clinical Optical Coherence Tomography of Early Articular Cartilage Degeneration in Persons with Degenerative Meniscal Tears

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Abstract

Objective—Quantitative and nondestructive methods for clinical diagnosis and staging of articular cartilage degeneration are important to evaluation of potential disease modifying treatments for osteoarthritis. Optical Coherence Tomography (OCT) is a novel imaging technology that can generate microscopic resolution cross-sectional images of articular cartilage in near real time. This study tests the hypotheses that OCT can be used clinically to identify early cartilage degeneration, and that OCT correlates with MRI T2 values and arthroscopy.

Methods—Patients undergoing arthroscopy for degenerative meniscal tears were recruited under IRB approved protocols. 30 consecutive subjects completing preoperative 3.0T MRI, arthroscopy, and intraoperative OCT comprised the study group. Qualitative and quantitative OCT, and MRI T2 values were compared to modified Outerbridge cartilage degeneration scores (0–4) assigned by arthroscopy.

Results—Arthroscopic grades showed cartilage abnormality in 23/30. OCT grades were abnormal in 28/30. Both qualitative and quantitative OCT strongly correlated (Kruskal-Wallis $p=0.004$ and $p=0.0002$, respectively) with arthroscopy. Neither superficial nor deep T2 values correlated with arthroscopy (Kruskal-Wallis $p>0.05$). Quantitative OCT correlated with superficial T2 (Pearson $r=0.39$, $p=0.03$).

Conclusion—These data show that OCT can be used clinically to provide qualitative and quantitative assessments of early articular cartilage degeneration strongly correlating with arthroscopy. The correlation between quantitative OCT and superficial T2 values further supports the utility of OCT as a clinical research tool providing quantifiable microscopic resolution data on articular cartilage structure. New technologies for nondestructive quantitative assessment of human articular cartilage degeneration may facilitate development of strategies to delay or prevent the onset of osteoarthritis.

Keywords

Cartilage; Osteoarthritis; Optical Coherence Tomography (OCT); Magnetic Resonance Imaging (MRI); Cartilage Injury; Cartilage Degeneration; T2 Map

INTRODUCTION

Osteoarthritis is reaching epidemic proportions as the population ages (12). Post-traumatic osteoarthritis occurs more frequently in younger age groups during the prime work years rendering osteoarthritis a leading cause of disability worldwide (6). While osteoarthritis is of multifactorial etiology and eventually involves the entire joint, the central pathologic feature has traditionally been attributed to progressive loss of articular cartilage (11). Consequently, there is great clinical need for early diagnosis and treatment of cartilage degenerative processes.

Historically, osteoarthritis has been diagnosed radiographically by characteristic bone changes that account for the “osteo” portion of the name that occur at advanced stages of cartilage loss and degeneration (16). When the cartilage is already gone, the disease is too advanced for efforts to protect or restore articular cartilage. There currently are no FDA approved disease-modifying osteoarthritis drugs.

Arthroscopy is the current clinical standard for evaluating preosteoarthritic cartilage lesions also referred to as chondrosis. These lesions do not yet involve bone and frequently are not visible by radiographic examination (8,17). The described arthroscopic changes begin with subjective identification of cartilage “softening” by palpation, followed by superficial surface fibrillations that progress to involve the full thickness of the cartilage and then the underlying bone (23). There is increasing evidence that these descriptions pertain to a continuum of cartilage loss culminating years later in the characteristic bone and joint changes of osteoarthritis (30).

Conventional MRI has been shown to be useful in identifying later stages of chondrosis manifested by changes in cartilage morphology consisting of partial thickness and full thickness fissuring and defects, but cannot reliably differentiate between healthy and diseased cartilage with intact articular surfaces (27). Newer quantitative MRI evaluations such as MRI T2 mapping of articular cartilage have been shown to be dependent on collagen orientation and tissue hydration.(2,7,19). Unlike standard MRI, T2 mapping can provide quantitative information about subsurface articular cartilage structure and biochemical integrity (26).

Barriers to development and assessment of chondroprotective and disease modifying agents include identification of cartilage disease before the development of irreversible changes. The earliest signs of cartilage injury and degeneration include potentially reversible metabolic perturbations accompanied by microstructural changes occurring prior to visible breakdown of the articular surface (25). While these changes can be detected in the laboratory through histological, biochemical and metabolic studies of tissue biopsies, they can elude detection by conventional arthroscopic surface inspection and probing or structural MRI (3,4,22,28,31). These changes therefore are not currently identifiable clinically except perhaps by histopathology (18), which is not practical for early diagnosis because it requires removal and destruction of the cartilage being examined.

Optical Coherence Tomography is a novel nondestructive imaging technology that can be incorporated into arthroscopes to generate cross-sectional images of articular cartilage in near real time at resolutions (10–20 μm) that are comparable to low power histology (5,14,15). OCT has also been shown to be sensitive to collagen architecture resulting from both acute trauma and degeneration (4,15,24). Recent studies show that OCT can identify changes in cartilage birefringence associated with potentially reversible metabolic changes implicated in the pathogenesis of osteoarthritis (4). This study was performed to test the hypotheses that Optical Coherence Tomography (OCT) can be used clinically to identify

early cartilage degeneration, and that OCT assessments correlate with MRI T2 values and conventional arthroscopy.

PATIENTS AND METHODS

Human Subjects

Patients indicated for arthroscopic meniscal surgery provided informed consent according to an Institutional Review Board approved protocol. The primary diagnosis of degenerative meniscal tear was defined by two criteria: (1) having a complex, horizontal or radial meniscal tear pattern on clinical magnetic resonance imaging (MRI) scan, and (2) having either normal or near normal tibiofemoral joint spaces (Grade 0, 1) on standing AP and 45° flexed posteroanterior radiographs (1). Thirty consecutive human subjects undergoing arthroscopic treatment for degenerative meniscal tears who completed preoperative 3.0 Tesla quantitative MRI, conventional arthroscopic exam, and arthroscopic Optical Coherence Tomography (OCT) exam comprised the sample for this study. There were 13 females and 17 males with a mean age of 42.5 ± 13.8 years (range 18–68 years), and mean BMI of 28.0 ± 5.9 (range 20–43).

MRI

Pre-operative study MRI was performed on a Siemens whole body MAGNETOM Trio 3T MR imager (Siemens, Erlangen, Germany) using the NIH sponsored Osteoarthritis Initiative (OAI) sequences and scanner (www.oai.ucsf.edu), and a standard extremity coil, within 1 month prior to surgery. Multi-slice sagittal 2-D T2 mapping images were acquired using a fast spin-echo sequence with 7 echo images (TEs) ranging from 10–80 ms and a repetition time (TR) of 2700 ms. The 2-D images were collected in a 12 cm field of view (FOV) with a 384×384 matrix for $313 \times 313 \mu\text{m}$ in-plane resolution. Twenty-seven to 30 slices (3mm thick) were collected. The bandwidth was 250 Hz/pixel, and scan time was approximately 10 minutes.

Prior to T2-curve fitting, the TE images were down-sampled using cubic interpolation in Matlab (TheMathWorks, Natick, MA) to increase the signal to noise ratio (SNR), creating an effective resolution of $416 \times 416 \mu\text{m}$ in-plane. T2 maps were generated for a single section from the center of the medial femoral condyle (MFC) using MRMapper software (© Beth Israel Deaconess and MIT 2006) running on a Matlab platform. The shortest echo image (TE = 10ms) was not included in the T2 curve-fitting routine. A small full-thickness region of interest (ROI) in the center of the medial femoral condyle was manually segmented for each section mapped. These ROI were further subdivided into 2 approximately equal sections to examine zonal T2 variations: a deep zone (extending from the subchondral bone to the center of the tissue to encompass the bottom half of the tissue thickness) and a superficial zone (extending from the center of the tissue to the articular surface). The average T2 values for the superficial and deep zone ROI were recorded.

Arthroscopic Evaluations

During surgery, targeted standard arthroscopic and arthroscopic OCT exams were conducted on the study areas in the central weight bearing region of the medial femoral condyle. Visual landmarks consisting of the top of the notch, the posterior border of the condyle when the knee is flexed at 90°, and the medial and lateral borders of the condyle were used to define the central weight bearing region and the mid-sagittal plane of the medial femoral condyle. Arthroscopic grades were assigned to the area by the treating surgeon (CRC) using a modified Outerbridge scale (0-firm; 1-softening; 2- partial thickness defect, superficial fissures; 3-fissuring to subchondral bone; 4-exposed subchondral bone). The arthroscopic

exam and grading was performed at the beginning of the case and recorded prior to OCT imaging.

Arthroscopic OCT images were acquired using a hand-held arthroscopic probe fitted with the sample arm of a fiber optic OCT imager (Imalux Niris Imaging System, Cleveland, OH). The light source consisted of a super luminescent diode with a center wavelength and spectral bandwidth of 1310 nm and 55 nm respectively. The optical power of the probe was < 6mW and generated echographs of infrared light with horizontal and depth resolutions of 10–20 μ m. The OCT probe was capable of generating cross-sectional images measuring 2mm wide by 1.5 mm deep of the articular cartilage directly in line with the face of the probe. Clinical imaging of the weight bearing region of the medial femoral condyle was performed by advancing the probe through a standard anteromedial knee arthroscopy portal.

Cartilage OCT imaging was performed according to published methods (4). Briefly, the study areas were scanned by sequentially rotating the handheld OCT probe through 4 different radial orientations at 45° apart. The resulting image series constituted the OCT exam for each study area.

Grading of OCT Images

OCT images were randomized for blinded grading by two independent observers weeks to months following image acquisition. OCT images were graded according to the following criteria. Tissue demonstrating clearly distinguishable banding patterns (Figure 1b) in at least one radial orientation was classified as retaining OCT form birefringence (OCT Grade 0). Tissue with partial banding in any of the four orientations was classified as intermediate (OCT Grade 1). Tissue that did not demonstrate the characteristic multi-laminar pattern in any of the four orientations were classified as being without OCT form birefringence (OCT Grade 2). Tissue with surface incongruity were classified as irregular articular surface (OCT Grade 3).

Quantitative Analysis of OCT Images

Custom image analysis software was used to automatically extract image feature data from the OCT images (32). The automated feature generation process consisted of three main steps. First, cartilage tissue regions were segmented from the images, second a non linear smoother was used to enhance the edge structures, and finally edge measurements that assess the intensity variations in the cartilage were conducted. Variation statistics were used to produce an automatic scoring for each OCT image. Details of the ‘feature’ generation process were as follows:

1. The total variation (29) edge-preserving filtering function was applied to each image at 2 scales: a fine scale ($\lambda = 0.05$, removing high frequency noise only) and a coarser scale ($\lambda = 0.10$, small local variation are suppressed revealing larger scale intensity trends in the image).
2. Using the gradient information in each $\lambda=0.05$ filtered image the cartilage interface was detected using the Spectral Rounding algorithm (32). The area under the interface was taken as the cartilage measurement area (CMA).
3. A matched quadrature pair filter bank (13) was then applied to each $\lambda=0.10$ smoothed image measuring the intensity contrasts at multiple scales and orientations.
4. Finally two features were extracted and combined: the average squared edge intensity over all orientations and the horizontal edge variance, both restricted to

the CMA. These statistics were then used to predict the Arthroscopic score associated with the sample.

Statistical Analyses

Subjective OCT grades, quantitative OCT feature data and T2 values (superficial and deep) were compared to the surgeon's arthroscopic grade as the standard. OCT grades, OCT feature data and T2 values were grouped according to arthroscopic grade and non-parametric Kruskal-Wallis tests were used to assess the variation of each parameter with the arthroscopic grade. The arthroscopy data was then dichotomized and post-hoc pairwise non-parametric Mann-Whitney tests were used to detect differences between groups. Two tailed t-test was used to analyze for T2 differences between superficial and deep zones, and to test for quantitative differences between subjects with arthroscopic grade 0 and grade 1 tissue. Linear regression was used to examine the relationship between T2 relaxation time and OCT numerical feature data. Kruskal-Wallis and Mann-Whitney tests were performed with SPSS (SPSS Inc., Chicago, IL. All other statistical analyses were performed with Excel (Microsoft, Redmond, WA).

RESULTS

The arthroscopy, subjective and quantitative OCT, and T2 data are provided for each individual human subject sorted by arthroscopic grade in Table 1. Representative images of arthroscopy, OCT and MRI T2 are shown in Figure 1.

Arthroscopy

Arthroscopic surface imaging and palpation revealed 50% (15/30) of the subjects had intact articular surfaces in the central weight bearing region of the medial femoral condyle. The distribution of arthroscopic scores is shown in Figure 2 and was: Grade 0 (Firm) = 7, Grade 1 (Soft) = 8, Grade 2 (fissuring <50% of cartilage thickness) = 6, Grade 3 (fissuring > 50% of cartilage thickness = 6), and Grade 4 (exposed bone) = 3. The mean modified Outerbridge score was 1.6 ± 1.3 , and the median score was 1.5.

OCT vs. Arthroscopy

The distribution of subjective OCT grades binned by arthroscopic grade (Figure 2) reveals that 5/7 subjects with arthroscopically firm (scope grade 0) cartilage were graded abnormal by OCT (OCT grade > 0). Subjective OCT grades increased with increasing arthroscopic grade (Kruskal-Wallis $p=0.004$, Figure 3a), and discriminated between tissue with an intact articular surface and tissue with surface defects (arthroscopic grades 0, 1 v arthroscopic grades 2–4; Mann-Whitney $p=0.001$). The two independent graders agreed on the subjective OCT grade 90% of the time ($\kappa=0.88$). Subjective OCT grades were not significantly different for both firm and softened tissue with intact articular surfaces (arthroscopic grade 0 v 1, Mann-Whitney $p=0.19$). Quantitative feature data was found to vary with arthroscopic grade (Kruskal-Wallis $p = 0.0002$) and to discriminate between tissues with an intact surface and tissues with surface defects (Mann-Whitney $p<<0.001$). Quantitative OCT values demonstrated a trend toward differentiating arthroscopically firm (scope grade 0) cartilage from softened tissue (scope grade 1) by 2-tailed t-test ($p=0.057$), but not by a more conservative statistical analysis (Mann-Whitney, $p = 0.12$).

T2 vs. Arthroscopy

Neither superficial nor deep T2 values varied significantly with cartilage degeneration as assessed by conventional arthroscopy (Kruskal-Wallis $p=0.11$, $p=0.10$, respectively, Figure 3c). Comparison of T2 values in different tissue zones revealed that T2 values in the deep

half of articular cartilage (37 ± 6 ms, mean $\pm$ STD) were 24% lower than those in the corresponding superficial half of the tissue (48 ± 8 ms), T-test $p < 0.001$, Figure 4a. Superficial T2 values discriminated (Mann-Whitney $p = 0.04$) between tissues with intact articular surfaces (arthroscopic grades 0, 1; $T2 = 45 \pm 7$ ms, mean $\pm$ STD) and those showing surface defects in the study location (arthroscopic grades 2, 3, 4; $T2 = 51 \pm 7$ ms, Figure 4b). Deep T2 values did not (Mann-Whitney $p = 0.87$). T2 values in arthroscopically firm cartilage (grade 0) were found in the middle of the range of all observed T2 values while diseased cartilage (arthroscopic grades 1 to 4) demonstrated increasing superficial T2 with increasing disease level. No correlation was observed between deep tissue T2 values and arthroscopic grade.

T2 vs. OCT

Neither superficial nor deep T2 values varied significantly with subjective OCT grade (Kruskal-Wallis $p = 0.59$, $p = 0.46$, respectively). Quantitative OCT derived feature scores showed a correlation with superficial T2 values (Figure 5). The Pearson r correlation between superficial T2 relaxation times and OCT numerical features was 0.39 ($p = 0.03$), while the Pearson r correlation between deep T2 values versus OCT features was 0.13 ($p = 0.50$).

DISCUSSION

This study shows that OCT can be used clinically to identify early cartilage degeneration in patients with degenerative meniscal tears, and that OCT strongly correlates with conventional arthroscopic assessment. Both qualitative evaluation of OCT birefringence patterns and quantitative OCT image data showed strong correlation with grades assigned by conventional arthroscopy. Quantitative OCT also correlated with superficial MRI T2 map values, providing construct validity as both modalities generated quantitative cross-sectional information on cartilage subsurface properties. Clinical OCT provided cross-sectional images of a small area of articular cartilage at resolutions comparable to low power microscopy without the need to damage or remove the tissue. The ability shown in this study to obtain quantifiable microscopic resolution data on cartilage subsurface matrix characteristics in the clinical setting is important to advancing the study of early cartilage degeneration in humans.

Patients with a meniscal tear and minimal radiographic signs of osteoarthritis have been shown in long-term clinical studies to be a pre-osteoarthritic population (10). Meniscal injury and meniscal surgery are established risk factors for osteoarthritis of the knee (9,10). Meniscal tears can be classified as traumatic or degenerative based on the pattern of the tear. Longitudinal and vertical tears involving the periphery of the meniscus are considered traumatic. Tearing of the meniscus substance generates complex, horizontal and flap tear patterns that are described as degenerative, and it has been postulated that this type of meniscal tear may be a presenting sign of early osteoarthritis (10).

Data from this multi-modal clinical imaging study are consistent with prior studies showing strong associations between degenerative meniscal tear and preradiographic osteoarthritis. Mild chondrosis encompasses arthroscopic grades 1 (softening) and 2 (fissures less than 50% of the cartilage depth). The mean and median arthroscopic grades of 1.6 and 1.5, respectively, are consistent with early chondrosis and the absence of significant osteoarthritis in this study group.

In this clinical study of persons with degenerative meniscal tears, the OCT findings are potentially consistent with ex vivo studies suggesting that OCT may be more sensitive than conventional arthroscopy in identifying early cartilage degeneration. All of the subjects

identified by arthroscopy as having abnormally softened cartilage received abnormal OCT cartilage grades. Interestingly, while 7/30 subjects showed no arthroscopically detectable signs of cartilage abnormality to the study area, only 2/30 subjects had detectable OCT form birefringence by OCT, a property shown in ex vivo studies to be associated with normal cartilage structural and metabolic properties (2,4,24). While the concept that persons with degenerative meniscal tears form a preosteoarthritic population lend support to the notion that the high incidence of OCT cartilage signal abnormality observed in this study may indicate subtle early cartilage degeneration (10), this question cannot be answered through a single cross-sectional study. Similar to the study of any new assessment technology, longitudinal clinical studies to see if areas of OCT abnormality progress to cartilage fissuring and tissue loss as well as additional ex vivo studies comparing OCT signal abnormalities with structural, biochemical, and metabolic abnormalities are needed.

Because arthroscopy is the current nondestructive clinical standard, it remains unclear whether the relative absence of OCT birefringence in this study was due to clinical OCT detecting degenerative changes at an earlier stage than arthroscopy, or if these findings represent a false positive. Previous studies have shown that cartilage appearing “normal” to arthroscopic exam and visual inspection can be biochemically and histologically abnormal (22,28). Due to ethical considerations, biopsies of “normal appearing cartilage” were not obtained to perform histological, biochemical, or metabolic assessments in this study. Several ex vivo studies of nonhuman articular cartilage suggest that OCT birefringence patterns may reflect alterations to collagen microstructure (14,24,33,35). Similar findings were noted in a study using human articular cartilage (2). While further study is needed, another ex vivo human tissue study using the same OCT system as this study, showing the absence of detectable OCT birefringence to be associated with cartilage metabolic changes found in early osteoarthritis (4), provide additional insight into interpretation of these clinical findings.

This study provides additional support for the feasibility of using OCT to image articular cartilage clinically in humans during arthroscopic surgery (4). The use of infrared light permits ultra-high resolution imaging far exceeding that of current clinical MRI and comparable to low power histology. OCT imaging is also rapid, with detailed cross-sectional images obtained in near real time. The area of cartilage imaged in this study was comparable to the histology from a 2 mm biopsy but with depth penetration of approximately 1–1.5 millimeters. While the superficial cartilage was well imaged, the penetration depth of OCT is insufficient to assess the deeper layers of human cartilage or the subchondral bone interface. This means that to image articular cartilage, the OCT probe cannot image through skin and must be placed against or extremely close to the cartilage through an incision.

Clinical magnetic resonance imaging permits noninvasive macroscopic resolution imaging of articular cartilage and other joint structures but is considered limited in ability to detect cartilage injury and degeneration prior to breakdown of the articular surface (27). For quantitative evaluation of subsurface degeneration, MRI T2 mapping at 3.0 Tesla was used in the current study (20,21). Consistent with previous reports in the literature, zonal variations in T2 were observed in this study (34). As a second and independent measure of cartilage extracellular structure, superficial MRI T2 mapping was found in this study to discriminate between tissue with intact articular surfaces (Arthroscopic Grade 0–1) and tissue with surface defects (Arthroscopic Grades 2–4), and to correlate with quantitative OCT. While neither superficial nor deep T2 values from the protocols used correlated with arthroscopic grades in this study population where half of the subjects had intact articular surfaces, the finding that superficial T2 values correlated with quantitative OCT supports additional work to improve the sensitivity of MRI for early detection of cartilage abnormalities with either higher resolution or improved image contrast.

This clinical study additionally showed that both OCT and MRI T2 mapping provide quantifiable data on cartilage subsurface matrix properties. While both qualitative and quantitative OCT strongly correlated with arthroscopic assessment of early cartilage degeneration, the superficial T2 MRI values showed a more modest level of correlation with quantitative OCT. This is likely due to the differences in resolution between OCT (micrometer) and MRI (millimeter). In contrast, conventional arthroscopy provides micrometer resolution surface imaging over a macroscopic area which potentially improves correlation with both cross-sectional imaging modalities. The larger surface area facilitates comparison with MRI while the high fidelity facilitates comparison with OCT.

Another contributing factor to weak or absent correlations could be the difficulty in ensuring precise registration in the clinical setting. While the use of embedded fiduciary markers, tracking devices, and scoring of the cartilage would better ensure study of the same cartilage sites, these methods are not readily justifiable for use in patients clinically indicated for arthroscopic partial meniscectomy. Despite the registration challenges, this clinical study still showed several important correlations between the three metrics. These findings highlight the importance and potential benefit of multi-modal assessments to enhance diagnosis and staging of early cartilage degeneration.

Clinical study of the natural history of cartilage injury and degeneration prior to breakdown of the articular surface is critically important to identification of potentially reversible cartilage pathologies (4). A novel imaging technology, OCT, was found to strongly correlate with arthroscopy when used clinically to study articular cartilage. Conventional arthroscopy, the current nondestructive clinical standard for evaluation of articular cartilage, permits high fidelity surface imaging and subjective tactile probing but does not provide quantitative data on cartilage subsurface structure. Current MRI and MRI T2 map protocols lack the speed and resolution of arthroscopy or OCT, but permits noninvasive macroscopic imaging of cartilage subsurface matrix and other joint structures. While the MRI T2 values in this study did not correlate with arthroscopy, the finding that superficial T2 values correlated with OCT numerical features, two independent quantitative measures of cartilage subsurface properties, supports continued evaluation of both modalities for the study of early cartilage degeneration.

This study shows that OCT can potentially be used as a clinical research tool to complement arthroscopy by providing quantifiable, microscopic resolution cross-sectional information on cartilage subsurface characteristics that may be important to improved evaluation and staging of early cartilage injury and degeneration in humans. Continued research and development of noninvasive and nondestructive clinical tools for biochemical and quantitative evaluation of cartilage health are needed. Early diagnosis may provide the basis for development of new treatments to delay or prevent the onset of osteoarthritis.

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Figure 1. Example Images

Column 1 (a) Arthroscopically firm (b) OCT with birefringence, (c) T2 map (superficial T2 = 54 ± 9 ms; deep T2 = 49 ± 11 ms). **Column 2** (d) Arthroscopically firm (e) OCT without birefringence (f) T2 map (superficial T2 = 55 ± 9 ms; deep T2 = 45 ± 8 ms). **Column 3** (g) Arthroscopically “softened”, (h) OCT without birefringence (i) T2 map (superficial T2 = 46 ± 11 ms; deep T2 = 43 ± 13 ms). **Column 4** (j) Arthroscopic fissured (k) OCT fissured, (l) MRI T2 map (superficial T2 = 55 ± 9 ms; deep T2 = 45 ± 8 ms).

Figure 2. Subjective OCT grade distribution by Arthroscopic grade

In this study of persons with degenerative meniscal tears, 5/7 subjects with arthroscopically firm (Scope Grade 0) articular cartilage were abnormal by OCT (OCT Grade > 0). All subjects with cartilage graded slightly abnormal (Scope Grade 1) by arthroscopy were abnormal by OCT. The proportion of higher OCT grades reflecting increasing abnormality increased with increasing arthroscopic grade.

Figure 3. OCT and MRI metrics compared to arthroscopic grade as the standard

(a) Subjective grading of OCT images based on characterization of birefringence pattern and surface smoothness shows that OCT grade varies with arthroscopic grade (Kruskal Wallis $p=0.004$). (b) Mean quantitative OCT values strongly correlate to arthroscopic disease severity grades (Kruskal Wallis $p = 0.0002$, $R=0.85$). (c) Mean T2 values demonstrate a complex relationship to arthroscopic grade. The mean superficial T2 value (open circles) is lowest in softened but intact tissue (scope grade 1) and increases with increasing degeneration (scope grades 2–4). Superficial T2 values of healthy tissue (scope grade 0), however, fall in the middle of the range of observed superficial T2s. The mean deep T2 value (closed circles) is lowest in tissue with partial thickness defects and surface fissures.

Neither superficial nor deep T2 values varied significantly with cartilage degeneration as assessed by conventional arthroscopy (Kruskal-Wallis $p=0.11$, $p=0.10$, respectively). Error bars are $\pm$ SEM.

Figure 4. MRI T2 Mapping

(a) T2 values measured in the superficial half of cartilage were found to be 24% higher on average than those measured in the deep half of tissue T-test $p < 0.0001$, error bars ± 1 SEM). (b) Superficial T2 values discriminated between cartilage with intact articular surfaces and cartilage with surface defects (Mann-Whitney $p = 0.04$, error bars ± 1 SEM).

Figure 5. Superficial T2 values (open circles) correlate to quantitative OCT values (Pearson $r = 0.39$, $p=0.03$). No correlation is seen between deep T2 values (closed circles) and quantitative OCT values (Pearson $r = 0.13$, $p=0.50$).

Table1

Study Data Sorted by Arthroscopic Grade

Subject	Scope grade	Subjective OCT grade	Quantitative OCT feature score	T2 superficial, ms	T2 deep, ms
A	0	1	0.76	42	40
B	0	0	0.00	54	49
C	0	2	1.16	52	39
D	0	0	0.00	40	33
E	0	2	0.98	51	33
F	0	2	0.86	55	45
G	0	2	1.29	42	35
H	1	2	1.48	41	32
I	1	2	0.75	36	31
J	1	2	0.95	49	31
K	1	3	1.73	53	40
L	1	1	0.63	41	39
M	1	2	1.61	31	29
N	1	2	1.25	46	43
O	1	2	1.38	43	36
P	2	1	0.73	51	29
Q	2	2	1.89	51	36
R	2	2	1.84	60	33
S	2	3	2.08	49	31
T	2	3	1.88	40	31
U	2	3	1.58	45	39
V	3	2	2.01	51	30
W	3	3	2.45	48	34
X	3	3	3.59	55	42
Y	3	3	4.00	50	36
Z	3	3	3.03	47	41
AA	3	3	3.28	56	36

Subject	Scope grade	Subjective OCT grade	Quantitative OCT feature score	T2 superficial, ms	T2 deep, ms
BB	4	3	3.27	45	37
CC	4	3	3.53	64	46
DD	4	3	2.57	63	46