In Vivo Micron-Scale Arthroscopic Imaging of Human Knee Osteoarthritis With Optical Coherence Tomography: Comparison With Magnetic Resonance Imaging and Arthroscopy

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Abstract

Current treatments for osteoarthritis are pain relief and total joint arthroplasty. There is a clinical need for early osteoarthritis diagnostic methods for potential preventive interventions. The resolution achieved with radiography, magnetic resonance imaging (MRI), and arthroscopy is too limited for the assessment of early disease. The high resolution, small fiber-optic probes, and real-time imaging of optical coherence tomography (OCT) makes this method ideal for assessing articular cartilage.

In this article, we describe in vivo human arthroscopic OCT with qualitative baseline comparisons made with MRI and arthroscopy. Two-year MRI follow-ups are under way to quantitatively compare OCT with MRI and to assess the long-term outcomes of changes noted in the OCT images.

Osteoarthritis (OA) is a major cause of morbidity.[1] The disorder is treated primarily with symptom relief or joint arthroplasty. Optimally, OA is diagnosed at an early stage, and potential therapeutics can be evaluated.[2,3] Current diagnostic technologies, limited primarily by their resolution or penetration, are used mainly in detecting OA at its later stages, when the articular cartilage is severely diseased.[4,5] Therefore, there is a clinical need for a diagnostic technology capable of identifying early OA.[6]

Optical coherence tomography (OCT) has a demonstrated potential for assessing early OA.[7-11] OCT and ultrasound are analogous imaging technologies, with OCT using infrared light and ultrasound using acoustic waves.[12] In OCT, the time that light takes to be reflected back, or echo delay time, is used to measure distances. The intensity of back-reflection is plotted as the function of depth. The beam is then scanned across the sample to create 2- or 3-dimensional data sets.

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OCT has several advantages over other imaging modalities. First, its resolution is up to 25 times higher than that of anything else used in clinical medicine.[12] Second, it is based on fiber-optic technology, which allows the design for arthroscopies as small as 0.017 inch.[13] Third, its data are acquired at a video rate up to 120 frames per second.[14] Fourth, it is compact and portable; its size is similar to that of an ultrasound machine. Fifth, it can be combined with a range of spectroscopic techniques, including polarization spectroscopy (PS-OCT), which measures collagen content.[8,15]

OCT can identify cartilage thickness on a micron scale. In addition, assessment of collagen through birefringence is also a potentially powerful PS-OCT tool. Most tissue in the body is not birefringent or sensitive to the polarization state of incident light. For tissue with highly organized structures, back-reflection intensity varies with the polarization state of the incident light—visualized with an organized banding pattern. As loss of

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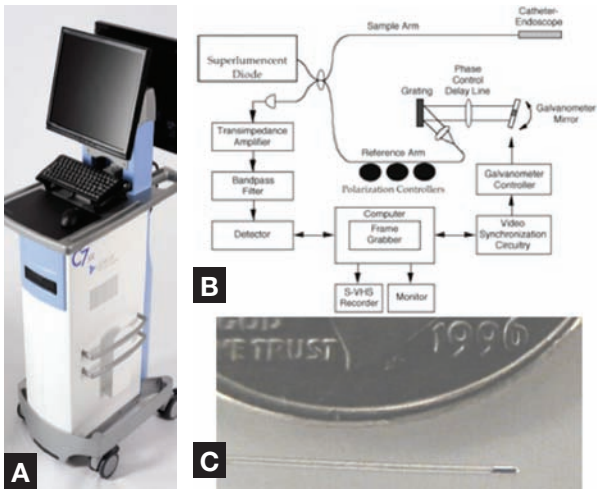

Figure 1. Image (A), schematics (B), and catheter (C) of LightLab optical coherence tomography imaging engine (LightLab Imaging, Westford, Mass).

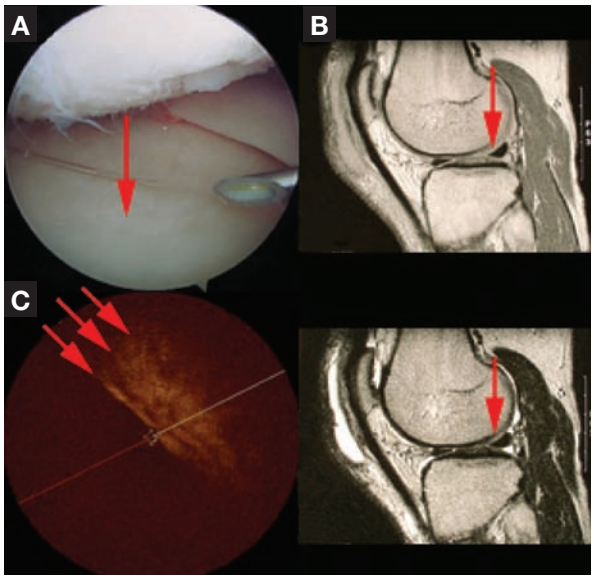

Figure 2. (A) Arthroscopic image of normal medial tibial cartilage. Red arrow represents section of smooth, normal-looking cartilage. (B) Magnetic resonance imaging of joint using T_1 and T_2 (top to bottom) relaxation states. Sagittal cross-section shows uniformly homogeneous articular layer at indicated point. (C) Optical coherence tomography image of area represented by arthroscopic image shows uniform banding pattern, indicative of healthy cartilage.

collagen organization is one of the first pathophysiologic changes of OA, reduction or disappearance of tissue birefringence, as visualized with PS-OCT, is an early marker of cartilage breakdown.[8,15] Therefore, PS-OCT can be used not only for micron-scale structural assessment of cartilage but for identification of collagen breakdown before cartilage thinning.

Strong in vitro correlations have been found between OCT images of cartilage and histopathology—including high-resolution assessments of cartilage thickness, loss of the bone–cartilage interface, and presence of fibrocartilage.[7,8,10,11] In addition, the ability of PS-OCT to identify collagen breakdown in cartilage prior to cartilage thinning has been demonstrated.[8,9] In vivo human studies have been

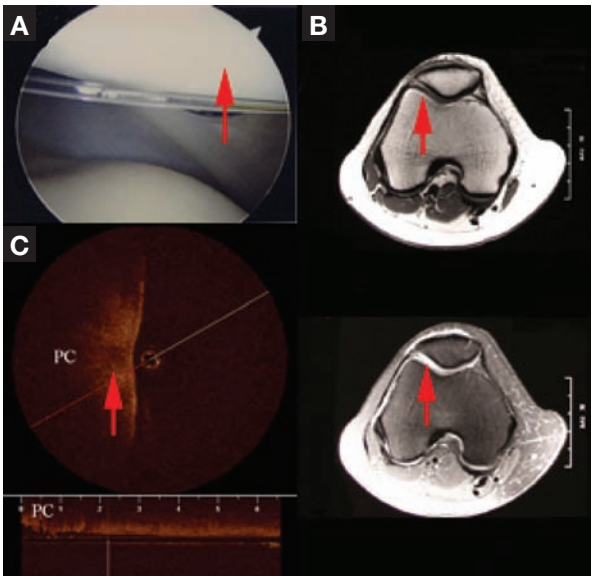

Figure 3. (A) Arthroscopic image of normal-looking patellar cartilage. Red arrow represents section of smooth, homogenous cartilage. (B) Magnetic resonance imaging of joint using T_1 and T_2 (top to bottom) relaxation states. Transverse cross-section shows uniformly homogeneous articular layer at indicated point. (C) Optical coherence tomography image of area represented by arthroscopic image shows relative loss of uniformed banding pattern, suggesting breakdown of collagen matrix.

conducted with a handheld probe in open joints as well as in rats; in these studies, development of arthritis was followed as a function of time.[8-11] These data support a role for OCT and PS-OCT in assessing cartilage pathology.

Minimally invasive assessment of joints is an important step in OCT development. In the present study, we performed in vivo human arthroscopic OCT. Contrast MRI and charge coupled device arthroscopic images were obtained for comparisons. Preliminary images demonstrated that OCT can be performed arthroscopically within a human joint—which supports potential use of OCT and PS-OCT in early assessment of cartilage pathology at a resolution higher than that of any clinical imaging technology.

Patients and Methods

There were several inclusion criteria: already identified for routine arthroscopic partial meniscectomies, not appropriate for meniscal repair, male or female between 30 and 60 years of age, preserved joint space on radiographs, meniscal tear confirmed by MRI, symptomatic for less than 6 months, and medically cleared for routine arthroscopy/meniscectomy/MRI. All patients volunteered for the study and provided informed consent. The institutional review board at Brigham and Women's Hospital approved the protocol and consent forms.

OCT was performed with a LightLab OCT imaging engine (LightLab Imaging, Westford, Mass) (Figure 1). This engine uses a wideband light source of 12 mW. The imaging was captured at a rate of 10 frames per second at a resolution of 800×304 pixels. The engine has axial resolution of 12 μm and lateral resolution of

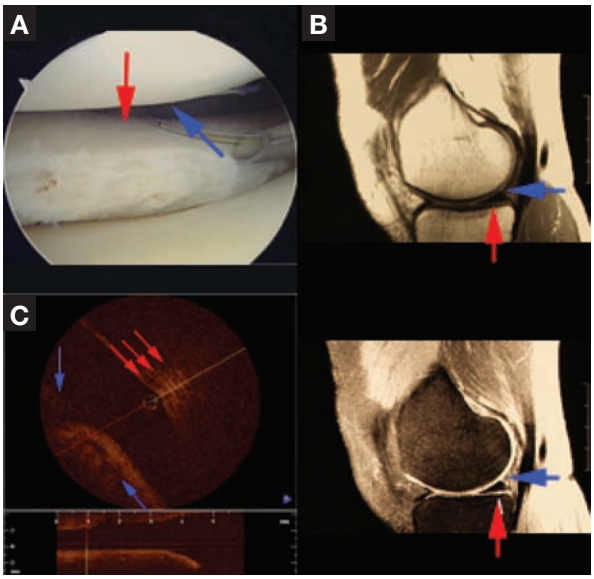

Figure 4. (A) Arthroscopic image of normal meniscal cartilage and mildly diseased femoral cartilage. Red arrow represents section of meniscus, and blue arrow represents section of mildly diseased cartilage. Both sections look normal. (B) Magnetic resonance imaging of joint using T_1 and T_2 (top to bottom) relaxation states. Sagittal cross-section shows heterogeneous articular layer at blue arrow and normal meniscus at red arrow. (C) Optical coherence tomography image of area represented by arthroscopic image shows relative loss of uniformed banding pattern at blue arrow, indicative of collagen breakdown in cartilage, but also tight, uniform banding pattern at red arrow, indicative of healthy, highly organized meniscus.

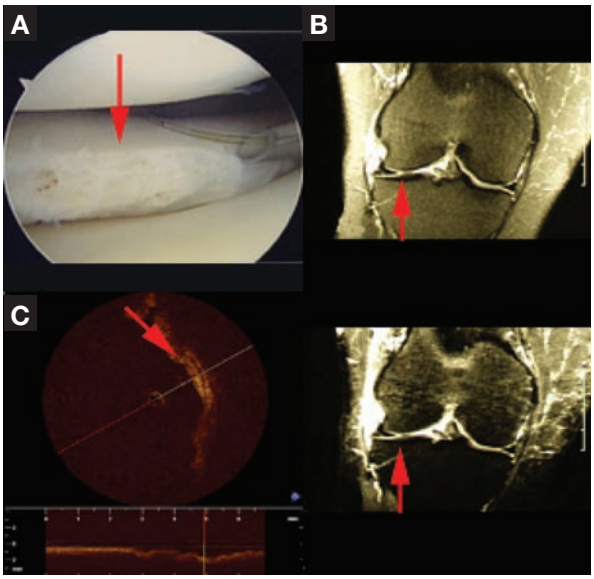

Figure 5. (A) Arthroscopic image of resected meniscus. (B) Magnetic resonance imaging of joint using T_1 and T_2 (top to bottom) relaxation states. Coronal cross-section shows bright spot at arrow, indicating meniscal flap. (C) Optical coherence tomography image of area represented by arthroscopic image shows resected meniscus with irregular surface but relatively regular banding pattern.

25 µm. It uses a sterile imaging endocatheter/arthroscope with a cross-sectional diameter of 0.017 inch and a focal length of 1.2 mm. The endocatheter/arthroscope has an internal pullback rate of 0.5 mm/s, which allows the data to be formatted into a video stream.

Baseline 3.0 Tesla MRI of the joint was obtained for patients. OCT was performed during the arthroscopic procedures. An 18-gauge spinal needle was introduced through a standard 7-mm anteromedial utility portal (Becton, Dickinson and Company, Franklin Lakes, NJ). The tip of the sterile OCT endocatheter/arthroscope was introduced through the spinal needle, and images were obtained within the knee joint and scanned medial to lateral with the help of the visible OCT aiming beam (infrared light is not visible to the eye). All images were taken through normal saline arthroscopic medium.

Results

Figures 2 through 6 show human knee joint images obtained with in vivo arthroscopic OCT. These qualitative data of normal and diseased articular and meniscal cartilage are interpreted in comparison with previous OCT imaging of cartilage and organized tissue and related histopathology as a baseline for the utility of the approach. The OCT images are also presented with arthroscopic and contrast MRI images for qualitative comparison.

Figure 2 examines normal medial tibial cartilage with the 3 modalities (red arrows). In the arthroscopic image, the cartilage is smooth and normal-looking; in the contrast MR image, it has a thick, uniform appearance, representative of healthy cartilage; the OCT image shows a homogeneous banding pattern that has been demonstrated by previous research in humans and animals to be histologically normal cartilage.

Figure 3 examines moderately to severely diseased cartilage (red arrows) using the 3 modalities. In the arthroscopic image, the cartilage is smooth and uniform; the contrast MR image also demonstrates a normal-looking, thick, uniform layer of articular cartilage; in contrast, the OCT image shows a relative loss of banding patterns, consistent with loss of collagen organization.

Figure 4 examines healthy meniscus (red arrows) and mildly diseased cartilage (blue arrows) with the 3 modalities. In the arthroscopic image, the healthy meniscus has a uniform surface, even though it is near resected meniscus (this image also shows normal-looking cartilage); the contrast MR image shows cartilage heterogeneity, normal meniscus, decreased thickness, and areas of signal drop-out illustrating thinning and abnormal cartilage; the OCT image shows the healthy meniscus with an organized, tight banding pattern and a smooth surface, representing normal meniscal cartilage (however, this image also shows mildly diseased femoral cartilage, as indicated by a relative loss of uniform banding patterns).

Figure 5 examines resected meniscus with the 3 modalities (red arrows). The arthroscopic image shows an irregular surface caused by resection of diseased meniscus; the contrast MRI image shows a thinning, abnormal cartilage (result of the trauma); the OCT image shows the irregular surface seen in the arthroscopic image but also a relatively regular banding pattern that suggests viable remaining meniscus (ie, complete resection of degraded meniscus).

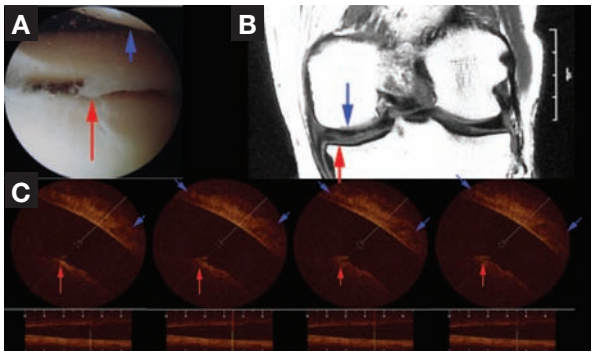

Figure 6. (A) Arthroscopic image of meniscal tear. Red arrow represents meniscal tear, and blue arrow represents smooth, uniform, adjacent articular surface. (B) Magnetic resonance imaging of joint using T_1 and T_2 (top to bottom) relaxation states. Coronal cross-section shows uniformly thick layer of cartilage. (C) Sequential optical coherence tomography images of area represented by arthroscopic image from posterior to anterior (left to right) show progression through meniscal tear and loss of clear banding pattern in cartilage.

Figure 6 examines a meniscal tear (red arrows) and mildly diseased adjacent cartilage (blue arrows) with the 3 modalities. The arthroscopic image clearly shows a meniscus tear and a uniform, smooth articular surface; the contrast MR image also shows an irregular meniscal surface indicative of a meniscal flap or tear and a uniformly thick layer of cartilage; the OCT image shows sequential imaging from posterior to anterior through the meniscal tear and visualizes the articular surface. The series of OCT images clearly shows tear progression but more interestingly shows loss of a clear banding pattern (blue arrow) consistent with cartilage breakdown adjacent to the degraded meniscus.

Discussion

There is a clinical need for a method of high-resolution in vivo imaging of articular cartilage. This study is the first to demonstrate in vivo human arthroscopic imaging with OCT. Representative images of this technology were qualitatively compared with conventional arthroscopic and MR images for reference. Although the critical roles of these other modalities in joint management cannot be understated, the extremely high resolution of OCT and the ability of OCT to measure collagen breakdown make it a potentially powerful technology for joint integrity evaluation and sequential monitoring of therapeutics. In vivo arthroscopic OCT imaging was an important step in this direction.

Imaging was performed at a video rate that allowed large areas of the joint to be assessed while not dramatically increasing operation procedure time. In addition, imaging was performed with an endocatheter/arthroscope less than 0.017 inch in diameter. The small size of this instrument allowed not only for its relatively easy use in combination with conventional arthroscopy but also for its potential introduction into the joint space through a small-gauge needle (<18 gauge). Identification of collagen breakdown with use of PS-OCT and its endocatheter/arthroscope is important. Studies are under way to examine how cartilage, demonstrated abnormal by PS-OCT, changes as a function of time.

With this technology being introduced, the limitations of this article are quantitative comparisons with histopathology and other imaging modalities, as well as long-term follow-up as to what abnormalities in OCT images predict. Interpretations of images were based on a database generated from studies spanning a decade. As already stated, we are following our patient population for at least 3 years to determine the significance of changes seen with PS-OCT. In addition, patients are being examined with OCT, contrast MRI, and arthroscopy in increasing numbers to generate quantitative comparisons using double-blinded studies beyond the introduction of a technological advance in this paper. Thus, this article presents preliminary data from a pilot study. The small number of patients in this study does not provide the opportunity to categorize individuals into demographics. In the future, large-scale trials will be focused more on demographic distribution.

Conclusions

The in vivo arthroscopic OCT imaging of the human joint represents a new and potentially powerful method for identifying early OA and longitudinally assessing therapeutics. Future efforts will advance the technology and evaluate its long-term prognostic value.

Authors' Disclosure Statement

The authors report no actual or potential conflict of interest in relation to this article.

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