Imaging of the Rotator Cuff With Optical Coherence Tomography

TIMOTHY HARTSHORN, MD; JIAN REN, PHD; C. THOMAS VANGSNESS JR, MD

This study evaluated the utility of optical coherence tomography (OCT) in imaging porcine and human rotator cuff (RTC) tissue, analyzed its effectiveness in identifying clinical pathology, and correlated these findings with histologic examination. Twelve human cadaveric and 6 porcine shoulders were evaluated. Six-millimeter–wide bone sections were harvested from the proximal humerus of each specimen, with each containing the entire enthesis of the respective RTC tendon, as well as 2 cm of tendon medial to the enthesis. Only the supraspinatus tendon was evaluated in the human specimens, whereas the enthesis of multiple RTC tendons were evaluated in the porcine model. All specimens were imaged using OCT and correlated with histologic evaluation. Optical coherence tomography evaluation of macroscopically healthy tissue consistently showed an easily identifiable banding pattern (birefringence) in contrast to a disorganized, homogeneous appearance in grossly diseased tissue. Optical coherence tomography was more effective for qualitative evaluation of RTC tissue, identification of bursal-sided RTC tears, and localization of calcific deposits, whereas intrasubstance tendon delaminations and partial articular-sided tendon avulsion lesions were relatively more difficult to identify. Optical coherence tomography correlated well with histologic evaluation in all specimens. Optical coherence tomography provides high-resolution, subsurface imaging of rotator cuff tissue in real-time to a depth of up to 4 mm with excellent correlation to histology in a cadaveric model. Optical coherence tomography could be an effective adjunctive tool for the identification and localization of rotator cuff pathology. The use of OCT in arthroscopic shoulder surgery potentially provides a minimally invasive modality for qualitative assessment of rotator cuff pathology. This may allow for a decrease in soft tissue dissection, improved qualitative assessment of cuff tissue, and improved patient outcomes. [Orthopedics. 2015; 38(9):e836-e843.]

The authors are from L. A. Shoulder & Sports Medicine (TH), Los Angeles; the California Institute of Technology (JR), Pasadena; and the Department of Orthopedic Surgery (CTV), University of Southern California Keck School of Medicine, Los Angeles, California.

The authors have no relevant financial relationships to disclose.

Correspondence should be addressed to: C. Thomas Vangsness Jr, MD, Department of Orthopedic Surgery, University of Southern California Keck School of Medicine, Healthcare Consultation Center II, 1520 San Pablo St, Ste 2000, Los Angeles, CA 90033 (vangsnes@usc.edu).

Received: March 4, 2014; Accepted: December 10, 2014.
Optical coherence tomography (OCT) is a rapidly developing, noninvasive diagnostic imaging modality that enables in vivo cross-sectional visualization of the internal microstructure in biological tissues. It is analogous to ultrasound, generating cross-sectional or 3-dimensional images by measuring the echo time delay and magnitude of backscattered or back-reflected infrared light rather than sound waves.

The high speed of light propagation makes it difficult to measure electronically, so OCT uses a technique in which the light wave is split evenly, with half of the light directed toward the sample and half toward a reference mirror. The light reflected back from the sample is combined with light reflected from the mirror, and OCT measures the intensity of interference of these 2 waves (Figure 1). It functions as a type of optical biopsy, providing information in situ and in real-time, with high-resolution images (<10-μm axial resolution) approaching that of excisional biopsy and histopathology. The attenuation of light through tissue is influenced by the properties of the tissue and is an exponential function of its thickness.

The majority of the initial literature was published in the field of ophthalmology, where OCT was first used in vivo to image the retina in 1993. In 2006, 75% of the publications on OCT were published in optics or ophthalmic journals. However, during the past decade, OCT has had tremendous growth due to improved technological parameters, and its use has spread to the fields of orthopedic surgery, cardiology, dermatology, and gastroenterology.

The first orthopedic application of OCT involved the evaluation of animal and human articular cartilage. In 1999, Herrmann et al trialed normal and arthritic cartilage and described fibrillations, fibrosis, cartilage thickness, and abnormalities in the subchondral plate using OCT. In 2001, Drexler et al examined the relationship between the polarization sensitivity of cartilage as detected by polarization-sensitive OCT (PS-OCT) and the changes seen in collagen organization, as determined by polarized light microscopy of human osteochondral explants. They determined that collagen disorganization found in arthritic articular cartilage is detectable by PS-OCT as a loss of normal form birefringence. This specific finding was described in subsequent studies as well.

Optical coherence tomography birefringence is seen as an echogenic banding pattern parallel to the tissue surface, with alternating dark and light areas. Chu et al showed that arthroscopic OCT was substantially more sensitive than conventional arthroscopic surface imaging in identifying microstructural breakdown of the articular surface. In addition, OCT was able to detect areas of acute cartilage changes after impact injury that were not detectable by visible inspection. Use of OCT in orthopedic surgery continues to expand, and in 2012 OCT was used to precisely localize vertebral growth plates ex vivo in hopes of developing a minimally invasive fusion procedure for adolescent idiopathic scoliosis.

Arthroscopic evaluation of the rotator cuff is the current gold standard for the assessment of rotator cuff pathology. During the past 10 years, a paradigm shift has occurred from open repair to reliable, procedure-specific arthroscopic instrumentation based on established biomechanical principles. Although arthroscopy may offer some advantages over open repair, they are similar in that tissue quality is determined by gross inspection and probing. To that end, these techniques fall short of the mechanical, biochemical, and histopathological evaluations that are possible in the laboratory. Tissue biopsy can detect collagen microarchitecture and determine the presence and extent of tissue disease, but it is not a practical means for routine clinical detection of early cuff changes because histology requires the removal and destruction of the tissue being examined. Radiographs are able to detect end-stage bone-related changes and are inadequate for accurate determination of soft tissue injury.

Magnetic resonance imaging (MRI) and ultrasound are the current noninvasive standards for imaging of the rotator cuff prior to surgical intervention. Magnetic resonance imaging, although a noninvasive cross-sectional imaging technology, has a lower resolution and is unable to accurately discern collagen matrix changes leading to cuff degeneration. Ultrasound has been shown to have comparable accuracy to MRI for identifying and measuring the size of full- and partial-thickness tears with a low level of interobserver variability. Unfortunately, ultrasound has poor resolution (roughly 80-90 μm) and cannot assess early degenerative changes prior to gross failure or tendon integrity after a tear has occurred.

The hypothesis of this research study is that OCT will provide a near-microscopic assessment of the RTC tissue in real-time, allowing the assessor to qualitatively evaluate the tissue and potential clinical pathology, including calcific tendonitis, cuff tears, and concealed interstitial delamination (CID) lesions. Concealed interstitial delamination lesions are tears within the substance of the tendon tissue and cannot be visualized with intra-articular or subacromial arthroscopic assessment. A secondary objective is to evaluate the correlation...
Figure 2: Human specimens were obtained in 6-mm wide sections that included the entire supraspinatus tendon enthesis (A) as well as 2 cm of tendon medial to the enthesis (B). The removed section was centered on the area approximately 13 to 17 mm posterior to the biceps tendon as viewed from anterior (C) and posterior (D).

between the OCT images and their respective histologic sections.

**MATERIALS AND METHODS**

**Specimen Collection**

There were 4 parts to this study: (1) porcine tissue analysis using OCT; (2) human tissue analysis using OCT; (3) evaluation of fabricated pathology in human specimens using OCT; and (4) histological evaluation of all specimens. Twelve embalmed shoulder specimens with known medical history but unknown rotator cuff pathology were harvested from 7 human cadavers and 6 fresh porcine shoulder specimens harvested at approximately 6 months of age were used for evaluation.

Average age for the human specimens was 75 years (range, 29-93 years). In 4 cadavers, a specimen was obtained from each shoulder. In 1 cadaver, 2 adjacent specimens were taken from the same shoulder; 1 section contained a full-thickness, U-shaped supraspinatus tear and the other section contained an articular-sided portion of the tear with the lateral-most fibers of the supraspinatus still attached. A 6-mm wide section of humerus was removed from the coronal oblique plane that included the enthesis of the supraspinatus tendon and joint capsule (Figure 2). Kim et al.\(^4\) showed that degenerative rotator cuff tears initiate in a region 13- to 17-mm posterior to the biceps tendon, and the removed section was centered on this area. Thickness of the supraspinatus tendon ranged from 0 (full-thickness tear) to 7 mm.

**Optical Coherence Tomography Evaluation**

Optical coherence tomography collection was performed using the Swept Source Frequency-Domain OCT (FD-OCT) Imaging System (Thorlabs, Newton, New Jersey) with a 1310-nm center wavelength and an imaging depth of approximately 3 mm (Figure 3). This wavelength value has been used effectively in previous studies.\(^10\) Frequency-domain OCT simply means the axial scanning is achieved by detecting changes in tissue composition based on changes in the frequency of the light reflected back off of the tissue. This OCT system has a lateral resolution of 25 µm and an axial resolution of 12 µm. Image acquisition is 5 frames per second, and each frame contains 1024x512 pixels. The scanner was applied in noncontact mode perpendicular to the tissue while the light source was swept parallel to the tendon fiber orientation. Images were digitally recorded in real-time along the entire length of each specimen.

**Simulated Pathology**

After the initial OCT evaluation, 2 human specimens were selected and used to replicate a rotator cuff with calcific tendonitis and CID lesion, respectively. Each specimen was without evidence of gross degeneration and had been obtained from a cadaver in which a contralateral shoulder specimen had also been obtained harvested. Calcific tendonitis was replicated by placing a 15-blade knife completely through the mid-substance of the tendon in-line with the tendon fibers 5 mm from the insertion and then turning the knife 90° to create a space. Calcium carbonate was then packed into this space. A CID lesion was created in a similar way, but the longitudinal incision was extended a length of 5 mm and 3 mm of the tendon tissue was removed from the central portion of the tendon along that length.

**Histologic Evaluation**

After the OCT evaluation, all porcine and human specimens were fixed in buffered formalin, decalcified, and sectioned at a thickness of 11 µm in a plane longitudinal with the tendon fibers and stained with hematoxylin-eosin. These specimens where then analyzed with a high-resolution digital slide scanner (Leica SCN400; Leica Microsystems, Wetzlar, Germany) at 20x magnification and compared to the OCT images.

**RESULTS**

The algorithm of macroscopic inspection, OCT evaluation, and histologic correlation were completed on all 18 specimens. Analysis of all 6 porcine specimens revealed healthy, robust tendons with no gross evidence of pathology. Of the 12 human specimens, 6 were found to have an obvious tendon tear of the supraspinatus tendon: 1 full-thickness tear with a U-shaped pattern, 2 bursal-sided tears, 2 partial articular-sided tendon avulsions (PASTA lesions), and 1 bursal-sided tear at the myotendinous junction. The fact that half of the human specimens were found to have rotator cuff pathology is not surprising given the average specimen age of 75 years. Of note, 2 healthy human
specimens were from the same 26-year-old female donor.

Using the FD-OCT system, the current authors determined that healthy-appearing human and porcine rotator cuff tissue without gross evidence of degeneration had an easily discernible banding pattern, consistent with previous studies describing OCT birefringence in articular cartilage. Although similar, the pattern produced by the collagen in the rotator cuff tissue had subtle differences, including more numerous bands and a more obvious difference in the size of the larger white band and the smaller dark band (Figure 4).

These observations were not quantitatively recorded but may be due to the increased collagen density or thickness of the tendon tissue relative to cartilage. This recognizable banding pattern was consistently visualized in normal tissue, with fewer bands seen more laterally on the enthesis of the rotator cuff insertion and an increasing number of bands seen as the OCT scanner was moved medially on the specimen. This is consistent with established histologic analysis of tendon insertion to bone. Small blood vessels present in the superficial layers were not visualized directly on OCT but could occasionally be identified by the long, thin shadows they cast on the deeper structures.

In the human specimens with gross evidence of pathology, the most remarkable finding was the loss of OCT birefringence, or banding pattern. In 1 sample, gross inspection and histologic analysis both showed a slight bursal-sided irregularity of the normally smooth superficial layer of the supraspinatus. When this specific area was compared with the correlating OCT image, the current authors identified a loss of birefringence that was present throughout the entire sample (Figure 5). There were 3 samples with complete rotator cuff tears, and all of these specimens showed complete loss of the OCT form birefringence at the edge of the tear (Figure 6).

The bursal-sided tears were easily identified because the depth of penetration of the OCT scanner was approximately 3 mm. The PASTA lesions were more difficult to identify at the time of OCT evaluation but retrospective analysis shows a signal change underneath the superficial layer at a distance different than that of normal cuff tissue (Figure 7). Interestingly, a different OCT birefringence pattern was seen in the specimen with the superficial tear just distal (or lateral) to the myotendinous junction. Close inspection of this specimen showed loss of the superficial layers of the supraspinatus tendon with exposed collagen fascicles running at approximately 45° to each other (Figure 8). No
Other objectives of the current study were to create a specimen with calcific tendonitis and another with a CID lesion and to evaluate the ability of the OCT device to accurately reflect the underlying pathology. These specific pathologic processes were chosen because both occur within the substance of the tendon and can be difficult to visualize during either open or arthroscopic shoulder surgery.

A small defect (8 mm³) was created approximately 2 to 3 mm below the surface of tendon at the enthesis and filled with calcium carbonate. When the OCT scanner was placed over this area, a unique type of birefringent pattern was observed immediately deep to the calcium carbonate. The lighter bands showed equivalent width to that of the calcium deposit but had greater depth and separation (Figure 9). There was an obvious difference in the banding pattern in the area with calcium carbonate in comparison to the adjacent tissue that was used as the control area. A CID lesion was then created on a different specimen as described above, leaving both the articular and bursal-sided tendon connections intact. Overall, it was difficult to appreciate the area of intratendinous delamination using OCT. There was light attenuation beneath the superficial layer of cuff tissue, but this area was ill defined and inconsistently visualized during repeated examination (Figure 10).

Although not a direct objective of this study, 2 lesions involving the cartilage were encountered. In 1 sample, there was gross osteoarthritis in the superior humeral head where the cartilage was thinned and transitioned to subchondral bone. The OCT probe was placed in this area and discovered that it was easy to delineate this area and discriminate between the cartilaginous layer and the subchondral bone. The OCT probe was placed in this area and discovered that it was easy to delineate this area and discriminate between the cartilaginous layer and the subchondral bone. In another sample, a small, full-thickness crack was observed but the cartilage layer was nondisplaced.

Although not a direct objective of this study, 2 lesions involving the cartilage were encountered. In 1 sample, there was gross osteoarthritis in the superior humeral head where the cartilage was thinned and transitioned to subchondral bone. The OCT probe was placed in this area and discovered that it was easy to delineate this area and discriminate between the cartilaginous layer and the subchondral bone. In another sample, a small, full-thickness crack was observed but the cartilage layer was nondisplaced. It was difficult to visualize grossly and required close inspection. However,
when the OCT probe was placed in this area, the defect was easily identified.

**Discussion**

In 1992, Clark and Harryman described 5 histologic layers of the rotator cuff, showing the majority of blood vessels to be present in layers 1 and 2, the most superficial 4 to 6 mm of the rotator cuff. Previous research has hypothesized that degeneration of the rotator cuff may be initiated by impingement and damage to these layers against the undersurface of the acromion, compromising blood flow and leading to degeneration of the collagen architecture. Tears of the rotator cuff typically occur near the insertion of tendon.

The causes of tears are often multifactorial but include etiologies such as diminished blood supply, mechanical impingement, subject age, and potential predisposing anatomical factors. Microstructural changes occurring prior to gross structural failure of the rotator cuff are not easily visualized intraoperatively. These include factors such as vulnerability to tearing and degeneration related to the avascularity of the tendon, age-related changes in the collagen, and concealed mechanical trauma. However, assessment of these variables is difficult during arthroscopic assessment, and preoperative evaluation with MRI or ultrasound is the most common imaging modality currently used to help better elucidate the tendon architecture and quality.

During the past decade, ultrasonography has gained increased popularity and exposure in the assessment of rotator cuff tears. Although the majority of evaluations occur in the clinical setting, an increasing number of surgeons are using ultrasound as an intraoperative tool. When comparing ultrasound to OCT, a hand-held OCT probe would have an advantage because it has a much higher resolution than ultrasound. Both would be able to provide real-time evaluation, but OCT would allow the surgeon to appreciate the quality of the collagen tissue microstructure, follow healing, evaluate blood flow, and allow for potential biologic evaluation and treatments.

Optical coherence tomography also has an advantage over ultrasound in a few specific clinical scenarios. The first includes the localization of a CID lesion. The resolution provided by ultrasound may be too low to identify these lesions, and the surgeon may be forced to make multiple incisions into the tendon to evaluate for intrasubstance pathology. Optical coherence tomography could identify these lesions by scanning the rotator cuff tissue in real-time, allowing...
Figure 10: Evaluation of a concealed interstitial delamination (CID) lesion. Optical coherence tomography (OCT) evaluation shows an area of attenuated signal (yellow bracket in A) in the area of the tear, but the layer of collagen deep to the tear is difficult to appreciate. A photograph of the created CID lesion is shown in B (yellow box is area evaluated with OCT). Histologic evaluation (hematoxylin-eosin, original magnification ×20) clearly shows the interstitial tear. All depictions are perpendicular to the longitudinal axis of the section (C).

for appropriate repair without tissue destruction.

This approach is also appropriate for calcific tendonitis. Occasionally, it is difficult to identify the calcific deposit within the tendon tissue, and the surgeon may incise the tendon tissue multiple times in an attempt to localize the deposit. Optical coherence tomography would allow for noninvasive localization and precise excision of the deposit.

The PASTA lesion is another scenario that may benefit from OCT evaluation. Intraoperatively, it is difficult to appreciate the thickness of the tendon remaining attached to the lateral footprint, and controversy currently exists as to what percentage of tendon attachment is required to proceed with a debridement vs completion of the tear and repair. A hand-held OCT probe could assist in determining the thickness of the tendon remaining and aid in decision making.

Treatment options available for rotator cuff tears continue to improve and expand, with a recent interest in adjuvant biological treatments such as platelet-rich plasma, basic fibroblast growth factors, bone morphogenic proteins, cartilage oligomeric matrix protein, and connective tissue growth factors. One study showed that growth factor expression increased in the mid-substance of the tendon during the remodeling phase of rotator cuff repair.17

Through previous studies, it is known that partial and complete tears are predisposed by resorption of damaged collagen fibers, and that signs of degeneration of the cuff include the following: hyaline necrosis of collagen, microscopic tears in fibers, calcific deposits, and intimal changes in the arterioles.16 Uthhoff et al16 studied a group of shoulders that had partial tears or no tears of the tendons of the cuff and reported that fibrillation, necrosis, and so-called microtears were common on histological examination. The advantage of OCT is that the resolution is comparable with low power microscopy and could be used to identify focal areas of pathology within the tendon and could allow for accurate placement of the aforementioned biologic factors.

Limitations

The primary limitation of OCT for clinical assessment of rotator cuff lesions is the shallow imaging depth of approximately 3 to 4 mm. This permits evaluation of only the superficial layers of cuff tissue, which typically measures 8 to 10 mm in total thickness in healthy subjects.16 Swiontkowski et al1 showed that the depth of penetration (defined as 1/e or approximately 37% attenuation) of his laser light source was 1.5 mm.

Although the penetration depth is largely determined by the scattering properties of the tissues themselves, laser sources with longer coherence length and various design changes in the engineering of the laser are underway and are likely to increase the imaging window and depth of focus respectively.18,19 Another weakness of this study was that the specimens were examined ex vivo, and OCT images obtained within the subacromial space in vivo could potentially have signal attenuation caused by fluid within this space if used arthroscopically. However, placing the probe directly on the tissue should mitigate this issue.

Conclusion

This study provided the first qualitative analysis of rotator cuff tissue using OCT. Optical coherence tomography was able to detect articular-sided, bursal-sided, and full-thickness rotator cuff tears. Digital histologic evaluation was also found to correlate well with both the gross specimens and OCT images. The banding pattern, also referred to as OCT form birefringence, seen in previous OCT studies on healthy cartilage was seen in the current specimens as well, although the pattern seen in cartilage and tendon were themselves unique.

The current authors recognize that the clinical applicability of this technology in its current form is limited. These probes are difficult to obtain and require technical instruction and experience for accurate use. The hardware itself also requires calibration and consistent quality assessments. Optical coherence tomography will not replace the
gold standards of tissue biopsy or surgery to assess histopathology or the presence of rotator cuff tears, respectively, but this study supports the use of OCT as an important translational clinical research tool in rotator cuff evaluation and treatment. Although advancements in OCT technology are needed to provide more practical utility for the surgeon, this adjunctive tool can aid in monitoring and validating novel therapeutic approaches and promises to play a more influential role with the advancement of stem cell transfer, biological matrices, or pharmaceuticals.2

REFERENCES


