Introduction: With increasing focus on the detection, study and treatment of early stage osteoarthritis (OA), there is increasing interest in novel imaging modalities capable of detecting changes in various joint tissues during early stages of the disease. The surface of the meniscus consists of a relatively thin layer of randomly oriented collagen fibers that overlies the circumferential collagen fibers surrounded by a secondary network of tie fiber sheets [1]. This surface layer appears to be functionally distinct from the underlying tissue [2], and degenerative changes to the surface may be functionally significant. Optical coherence tomography (OCT) [3], based on the scattering of near-infrared light, is used clinically and experimentally to evaluate a variety of tissues. In this study we investigated the use of OCT to nondestructively measure the thickness of the meniscal surface layer as a potential diagnostic tool.

Methods: OCT Imaging: Three pairs of fresh medial and lateral menisci were isolated from mature (2 years) bovine stifles. A clinical OCT system (Imalux, Co.) was used to examine the femoral (proximal) and tibial (distal) surfaces of each meniscus in the (radially) outer and middle (OM) portion of the anterior, central, and posterior thirds (A/C/P, 12 sites total per meniscus). The OCT probe produced cross-sectional images perpendicular to the surface with a 2mm penetration depth, 2.6mm lateral scanning range and 8µm resolution. OCT images displayed a characteristic banding/birefringence pattern (Fig 1a) with a visually distinct region near the surface of meniscal tissues. A custom image processing protocol involving a fast Fourier transform (FFT) and thresholding was developed to consistently identify the surface region (Fig. 1b-d). The mean thickness of the region over the image width was taken as the OCT-based measurement. Histology: After OCT imaging, blocks of tissue corresponding to imaged tissue sections were fixed in 10% neutral buffered formalin, paraffin embedded, sectioned at 10µm and stained with Masson’s trichrome to highlight the collagen structure near the surface. The surface layer thickness was then measured from 11 histological images using ImageJ (NIH). Analysis: Linear regression analysis was used to examine the relationship between the OCT birefringence-based measurement and the histological thickness. The regression equation was used as a calibration curve to predict surface layer thickness from OCT measurements. General linear models were used to assess differences in surface thickness between surfaces and among regions, with Tukey’s test for pairwise comparisons (p<0.05).

Results: A distinct surface layer was observed in most trichrome stained histological images captured from different regions of the meniscus (Fig. 2a). A surface region was also apparent in the corresponding OCT images (Fig. 2b). The depth of the region identified from OCT images was consistently larger than the histologically measured thickness, but the two measurements had a strong positive correlation (r=0.82, Fig. 2c). Using least squares linear regression, the OCT measurement (δ_{OCT}) can be converted to an estimated histological thickness (δ_{Hist}) via the formula:

\[ δ_{Hist} = 0.4426 \times δ_{OCT} + 2.7273 \]  

Based on Eq. (1), all OCT measurements were converted to estimated histological thicknesses (Fig. 3). Across all meniscal regions, the estimated surface thickness ranged from 75.8 to 145 µm. No significant differences in surface thickness were found between lateral and medial menisci, between femoral and tibial surfaces, or with circumferential position. Interestingly, the surface thickness from the middle section was significantly greater than that of the outer section (p<0.006).

Discussion: While histology is the gold standard for assessing tissue composition and microstructure for pathology or animal studies, there is a clear need for viable clinical strategies for assessing the health of articular tissues in early disease stages. OCT is an emerging imaging tool enabling rapid, nondestructive, qualitative, and quantitative observations of meniscus and cartilage features in vivo [4, 5], and is suitable for, arthroscopic inspection of the meniscus. This is the first validation of the use of OCT to obtain quantitative measurements of meniscal structural features, providing estimates of regional patterns of meniscal surface thickness. The approach taken does not directly visualize the surface layer, but relies on quantification of birefringence patterns related to the optical transmission properties of the tissue (presumably influenced by a mismatch in properties between the surface and deeper meniscal tissue). This indirect measurement was strongly correlated with the histologically measured thickness in mature bovine meniscus, providing evidence for the feasibility of this approach. As surface properties may change during early disease processes, the extent to which this OCT measurement can characterize the surface thickness or surface degradation in early OA needs to be directly examined. Nevertheless, these preliminary studies demonstrate the potential of OCT as a novel imaging methodology for evaluating meniscal structure.

Significance: Change in surface thickness of meniscus may be the biomarker of early knee osteoarthritis (OA). A novel non-destructive optical coherence tomography (OCT) imaging probe may enable the early diagnosis of OA by detecting changes to the meniscal surface.

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