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Three dimensional structural and local birefringence imaging of the bovine meniscus by use of OCT and PSOCT

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Abstract

Menisci are frequently injured. A small meniscus tear may progress to a deeper tear if not treated. We will present the capability of diagnosis of meniscus injuries with OCT and PSOCT and the performance improvement of OCT that benefits from both local birefringence imaging and 3-dimensional reconstructions.

Key words: optical coherence tomography, polarization, birefringence, noninvasive, biomedical optical imaging, meniscus, 3-D imaging

Introduction

Menisci act as surfaces for articulation and are responsible for shock absorption, load transmission, and stability within the knee joint. The fibrocartilaginous C-shaped menisci are frequently injured, usually by a twisting trauma to the knee. Tears may occur in either meniscus or in both menisci at the same time. Horizontal tears of the meniscus appear to be a delamination of the substance of the meniscus. Neglected horizontal tears frequently result in an unstable flap of meniscal tissue, which can also cause mechanical signs in the injured knee such as recurrent effusions, giving way, and a catching sensation. A small meniscus tear may progress to a deeper tear if not treated [1]. Moreover, Injuries to the knee menisci can cause significant discomfort and can lead to cartilage injury on the articular surfaces of the femur and the tibia, leading to the later development of the degenerative joint disease. Before the importance of this tissue was appreciated, treatments for meniscal injuries often involved the complete removal of the meniscus. By removing the meniscus, the average stress in the joint can be increased nearly threefold, while peak stresses can be increased to an even greater magnitude.

The arthroscope, which can provide surface imaging, is the normal medical diagnosis device for meniscus damage. However, small subsurface damage cannot be detected with an arthroscope. Optical coherence tomography (OCT) is a recently developed imaging modality based on the coherence-domain optical technology[2,3]. OCT takes advantage of the short coherence length of broadband light sources to perform micrometer-scale, cross-sectional imaging of biological tissues. OCT can be easily integrated with conventional arthroscopy for *in vivo* diagnosis. [4] Polarization-sensitive OCT (PSOCT) combines polarization sensitive detection with OCT to provide additional information of the sample under study. [5-12] OCT and PSOCT can provide near-immediate assessment of not only surface but also subsurface structures, thus have capabilities to diagnose injuries of menisci. Moreover, in many cases, 2-dimensional OCT images are not sufficient to fully describe and explain morphological changes. In this paper, we will demonstrate the performance improvement of OCT that benefits from both local

Fig. 1. Fiber-based PS-OCT system. Pol. Mod., polarization modulator; Pol. Control, polarization controllers; Phase Mod., phase modulator; PBS, polarization beam splitter; RSOD, rapid scanning optical delay line; and D_1 & D_2 , detectors.

birefringence imaging and 3-dimensional reconstructions.

Method

In our previous study, we demonstrated capabilities of local birefringence imaging by use of PS-OCT with the specimens modeled as multiple layered retarders with arbitrary optical axes. [12] Fig.1 shows the fiber-based PS-OCT system. [8,12] Light from the broadband light source (AFC Technologies, central wavelength $\lambda_0 = 1310$ nm, FWHM $\Delta\lambda = 80$ nm) enters a 2x2 fiber coupler. In the reference arm, a rapid scanning optical delay line (RSOD) provides A-scans at 500 Hz without phase modulation. A phase modulator generates 500 kHz phase modulation for heterodyne detection. A four-step driving function is applied to the polarization modulator and each step introduces a $\pi/4$ phase shift. Since only vertical linear polarized light can pass the phase modulator, four reference polarization states are selected. The four corresponding polarization states scattered from the sample arm are obtained by phase-resolved processing of the interference fringe signals obtained from two perpendicular polarization detection channels. Local birefringence and differential optical axis are calculated with the method described in Ref. [12]. Both axial and lateral resolutions are about 10 microns.

Results

Subsequent study has revealed three layers of meniscal organization [13]: a superficial layer of mesh-like fibers with a primarily radial orientation, a surface layer just beneath the superficial layer with irregularly aligned collagen bundles, and a middle layer or deep zone of larger fibers oriented in a parallel, circumferential direction. Therefore, unlike the articular cartilage that has a vertical optical axis [14], the optical axis of the meniscus is horizontal thus much stronger birefringence can be detected with PS-OCT. We imaged a health bovine meniscus with a volume 6 mm x 2.5 mm x 2.5 mm. 100 section images were obtained with an interval of 25 microns. Fig. 2 shows typical 2-D PS-OCT images of a bovine meniscus. Fig. 2(a) shows 16 Stokes parameter images. The left 4 images show the tissue structure while the right 12 images indicate changes in polarization states within the tissue. Fig. 2 (b) is the average of the left 4 images of Fig. 2(a). Figs. 2(c) and 2(d) are the local birefringence and differential optical axis images,

respectively. A boundary between the superficial layer and the surface layer can be clearly identified in Figs. 2(c) and 2(d) while not in Fig 2(b). Boundaries between neighboring irregularly aligned collagen bundles in the surface layer can be identified in all of Figs. 2(b), 2(c) and 2(d) while Figs. 2(c) and 2(d) provide clear ones. Fig. 2(e) is the roundtrip phase retardation image which is calculated based on the assumption of a constant optical axis.

Fig. 2 2-D PSOCT images of a bovine meniscus. (a) Stokes parameter images; (b) structural image; (c) birefringence image; (d) differential optical axis image; (e) phase retardation image.

Fig. 3 The constructed 3-D OCT and PSOCT images of bovine meniscus. (a) and (c) are 3-D OCT structural images. (b) and (d) are 3-D local birefringence images.

Fig. 3 shows some of 3-D OCT and PSOCT images of the bovine meniscus using 2-D image sets. Videos of 3-D volume images are obtained. A section image with any arbitrary angle can also be displayed. In the 3-D OCT video, the structure of the superficial layer shifts much faster than the surface layer does, which not only improves the image contrast to show the boundary, but also indicates different fiber orientations in different layers. This is confirmed in both the 3-D birefringence and differential optical axis videos, in which a clear boundary interface can be identified.

In summary, we present the performance improvement of OCT that benefits from both local birefringence imaging and 3-dimensional reconstructions. To our best knowledge, this is the first demonstration of 3-dimensional local birefringence imaging by use of PSOCT.

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