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Tissue Birefringence Characterization by use of Fiber-Based Polarization-Sensitive Optical Coherence Tomography

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ABSTRACT

A fiber-based polarization-sensitive optical coherence tomography system was described. The polarization modulator in this system was introduced in the reference arm rather than in the source arm, providing an increased power delivered from light source to sample. Based on angle preservation of Stokes vectors in the PS-OCT system, Stokes parameters of backscattered light measured at the detection arm were used to determine the phase retardation of birefringence samples as a function of depth. With the developed PS-OCT system, investigation on birefringence alternation of ligament under different physical condition was carried out.

Keywords: Polarization-sensitive optical coherence tomography, tissue birefringence, noninvasive imaging

I. INTRODUCTION

Optical coherence tomography (OCT) [1] is a noninvasive, noncontact imaging modality, which functions as a type of "optical biopsy" promising for real time in situ visualization of tissue structure with resolutions approaching to that of conventional histopathology. Since OCT is optically based, it can be interfaced with a wide range of clinical instruments such as catheters, hand-held probes, endoscopes, and laparoscopes for internal body imaging. Currently, OCT has been developed not only for morphological imaging, but also for functional imaging. Optical Doppler tomography (ODT) implements Doppler principle in OCT to visualize blood flow in small vessels, [2-4] serving as an example of functional imaging in OCT. Spectroscopic OCT combines spectroscopic analysis with OCT to obtain depth resolved tissue absorption spectra. [5] Polarization sensitive OCT (PS-OCT) combines polarimetry with OCT to determine depth resolved tissue birefringence. [6-9] PS-OCT is emerging as an attractive branch of functional OCT, in which the transverse wave character of light are fully exploited to fetch additional information beyond structure.

The key in instrumentation of PS-OCT is to add the capabilities of controlling the polarization state of light incident upon the sample and measuring the reflectivities of light returning in particular polarization states. Due to difficulty in maintenance of predictable polarization in single mode (SM) fibers, most prior reported PS-OCT systems were implemented in bulk optics, therefore not convenient for clinic studies. The present work introduces a fiber-based PS-OCT system that allows for spatially resolved birefringence imaging of tissue. In contrast to previous system, [8,9] polarization modulation is realized in the reference arm, providing increased power delivered from source to sample. The capability of the developed system for tissue birefringence characterization was demonstrated in experiment.

II. METHOD

The fiber-based PS-OCT system as illustrated in Figure 1 detects the backscattered light coherently in orthogonal polarization states at the PBS. The amplitude and relative phase of the interference fringes in each orthogonal channel are then used to derive the depth-resolved Stokes vectors. However, due to birefringence of the SM fiber, Stokes

parameters of the backscattered light measure at the PBS are most likely not equal to that at the sample space. Fortunately, as the source in the fiber-based PS-OCT system is only partially polarized, the light delivered to the sample thus has components of any polarization states. Due to coherence detection intrinsic to OCT, backscattered light that originates from incident light at different polarization states can be picked out by controlling polarization states at the reference arm. Modulating the reference light at four orthogonal polarization states allows coherent detections of backscattered light from the sample under equivalent illumination at four different polarization states. For a sample with an assumed linear birefringence, there exist two eigenwaves that are polarized along the projected fast and slow axes of the sample normal to the propagation direction of incident light. Stokes vectors of these eigenwaves determine a rotation axis in the equator plane of a Poincaré sphere, and the effect of birefringence is to rotate the Stokes vector about this axis through an angle that is equal to the phase retardation of the sample. [10] Conversely, the rotation axis can be determined from the known polarization states of incident and backscattered light at the sample space. As the rotation axis must reside on the bisectional plane of the two Stokes vectors representing polarization states of incident and backscattered light, intersection of two such planes yields the rotation axis. Rotation angle about this axis representing the phase retardation of sample is then calculated. [8] At the PBS, the Stokes vectors measured will be different from that at the sample space, producing an overall rotation axis that might be not constrained to the equator plane of the Poincaré sphere. However, due to angle preservation of Stokes vectors in the fiber-based PS-OCT system, rotation angle of Stokes vectors is preserved. This guarantees the rotation angle calculated from the measured Stokes vectors at the PBS is same as the phase retardation of the sample to be determined. The phase retardation, gray-scale coded from 0 to 180 degree, composites the phase retardation image characterizing tissue birefringence.
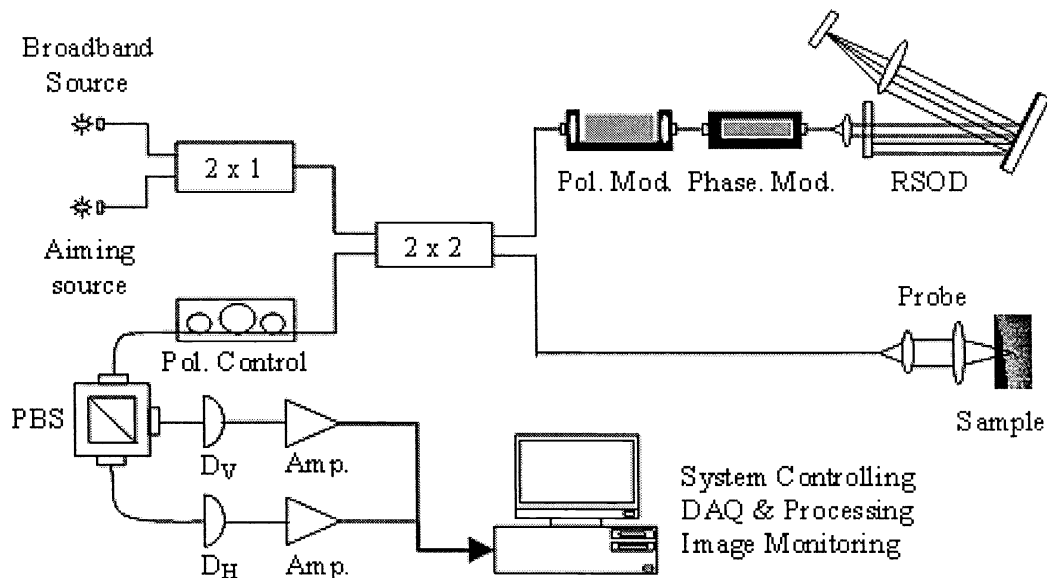

Figure 1 Schematic fiber-based PS-OCT system. Pol. Control, static polarization controller; PBS, polarization beam splitter; D_V and D_H, detectors for vertical and horizontal polarization components; Amp., low noise preamplifier; Pol. Mod., polarization modulator; Phase Mod., phase modulator; RSOD, rapid scanning optical delay line.

III. RESULTS

Investigation on birefringence alternation of ligament from a pig under different physical condition was carried out. During sample preparation and PS-OCT measurements, samples were kept fresh by covering a moisturized pledget carrying normal saline. The first sample was a fresh ligament at its original state with either end attached to bone. The calculated phase retardation image and typical depth profile are shown in Figure 2 (left). The depth profile is fetched along the line where an arrow is labeled in the phase image and starts from the air-sample interface. The

second sample was a relaxed ligament cut from attaching bones at both ends. The reduced number of banded structures and increased cycling period, as shown in Figure 2 (middle), reveal a significant loss of birefringence due to relaxation. To investigate the residual effect of prolonged tension on ligament birefringence, the first sample was measured again after been experienced a prolonged tension with fifty ponds weight on either attaching bone for over six hours. As exhibited in Figure 2 (right), the alteration of birefringence due to residual effect of pronged tension is not as evident as in the relaxation case. The residual effect of prolonged tension on birefringence is not evident to be noticed from phase retardation images, but still can be recognized from the quantified results of index difference. Based on the averaged phase cycling periods, the index differences characterizing ligament birefringence under three conditions are estimated to be 4.54×10^{-3}, 3.26×10^{-3} and 4.70×10^{-3}, respectively.
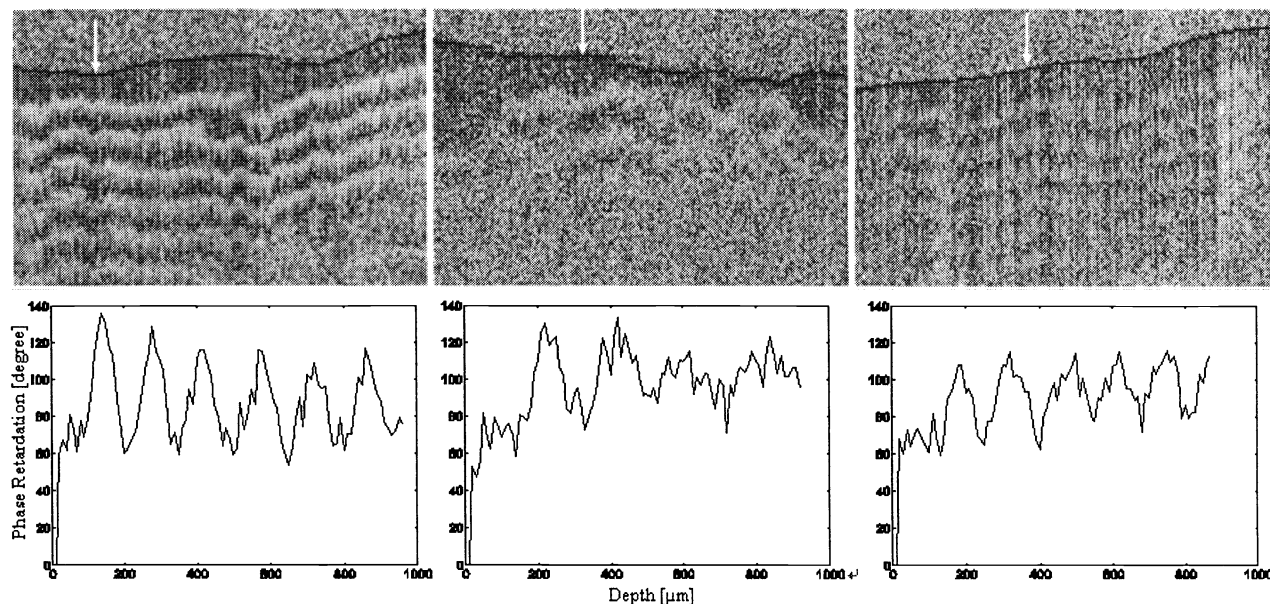

Figure 2 Phase retardation images (2 mm × 1.28 mm) and corresponding profiles along the pointed arrow on fresh ligament (left), relaxed ligament (middle) and tension experienced ligament (right).

There are fast phase jumps around the air-sample interface in the phase retardation images shown in Figure 2, one possible explanation could be the phase abrupt change due to Snell reflections. To clarify this phenomenon further investigations are required.

Although several periods of phase cycling are demonstrated in the phase retardation images, the minimum of zero and the maximum of π phase retardations are never reached. Noises in detected signal, numerical errors in phase calculation, multiple scattering light detection and limited axial resolution are the possible reasons that account for this reduced amplitude in phase cycling. Despite of limitation in accuracy for phase retardation determination, the distance of phase cycling period should be still correct, which allows for the estimation of the birefringence at reasonable precision.

Caution must be taken in measurement of birefringence sample with depth dependence orientation of optic axis. In general, combination of linear birefringence retarders with different orientations could not be modeled as one equivalent linear birefringence retarder. The rotation axis of such combined retarders determined might be no longer constrained to the equator plane and has no connection with optic axis. The phase retardation about this rotation axis calculated may be misleading.

IV. CONCLUSION

In conclusion, we have developed a fiber-based PS-OCT system that allows for imaging and quantification of birefringence in biological tissue. Alignment of elastic fibers in ligament influences tissue birefringence. When ligament is under tension with either end attached to bone, the fibers are aligned, while under relaxation this alignment of fibers is decreased. However, the residual effect of stretching is not eminent, probably due to restoring process of elastic fibers. The capability to detect residual effect of stress instead of the effect under stress directly is more meaningful in view point of clinic diagnosis.

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