

# Based on polarisation mode delay, intravascular polarization-sensitive optical coherence tomography

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Nichols C. Based on polarisation mode delay, intravascular polarization-sensitive optical coherence tomography. *Clin Cardiol J.* 2022; 6(3):26-27.

## ABSTRACT

IV-PSOCT (intravascular polarization-sensitive optical coherence tomography) delivers depth-resolved tissue birefringence, which can be utilised to assess a plaque's mechanical stability. A new technique for constructing polarization-sensitive optical coherence tomography in a microscope platform was described in a prior paper. We showed how this technology may be used in an endoscopic platform, which has a wide

has a wide range of therapeutic uses. A 12-m polarization-maintaining fiber-based imaging probe can be added to a standard intravascular OCT system to enable IV-PSOCT. Its two polarisation modes provide OCT images of polarisation detection channels that are spatially separated by a 2.7 mm image separation. With chicken tendon, chicken breast, and coronary artery as image examples, we experimentally validated our IV-PSOCT. Our IV-PSOCT was able to successfully visualise the birefringent characteristics.

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## INTRODUCTION

Plaque buildup (i.e., fatty deposits) occurs within the lining of an artery in atherosclerosis, which is a degenerative illness. 86% of heart attacks and 45% of brain aneurysms are caused by rupturing plaques. These high-risk, susceptible plaques can be undetected for a long time, and their early appearance can be fatal. Detection approaches that aim for early detection of susceptible plaques are crucial first and foremost for avoiding fatal effects. There is a link between plaque vulnerability and its form, chemical content, and biomechanical qualities, according to research: (1) The thickness of a fibrous cap is a valid morphological indication of plaque vulnerability. (2) Chemically, intra-lesion lipid density and cholesterol concentration are linked to susceptibility and; (3) Collagen is the extracellular matrix protein that provides mechanical stability to a plaque and is secreted by smooth muscle cells that include myosin and actin. For the early detection of susceptible plaque, a range of optical and non-optical imaging approaches have been developed. To visualise the stratified structure of the vascular tissue, intravascular ultrasonography (IVUS) and intravascular optical coherence tomography (IVOCT) are routinely employed in clinical practice. IVUS allows for a full-depth vision of the coronary lumen, blood vessel wall, and atherosclerotic plaque formation because of its deep penetration depth. IVOCT can measure fibrous cap thickness thanks to its micron-scale resolution. Optical methods such as intravascular near-infrared fluorescence and spectroscopy (NIRF and NIRS), which are capable of characterising the

intra-lesion lipid contents but lack depth resolvability, have been investigated to determine the plaque's molecular composition. While maintaining the better imaging depth of ultrasound-based imaging, intravascular photoacoustic imaging can give good molecular contrast in depth-resolved pictures. None of these, however, can directly offer the mechanical properties of the fibrous cap, which are critical for determining the vulnerability. The stress in a fibrous cap is altered by its thickness and macrophage infiltration, so shifting in local tissue elasticity is one of the key indicators biomechanically; more importantly, tissue elasticity can be used to identify plaque-type based on the composition-dependent biomechanical property of the plaque. PSOCT, or polarization-sensitive optical coherence tomography, can detect depth-resolved sample birefringence. PSOCT has been built in a microscope platform using a variety of approaches. However, integrating PSOCT into an endoscope platform remains difficult. Recent research has presented an advanced endoscopic IVOCT scheme based on PSOCT, in which the polarisation state was dynamically controlled while using a specific photodetector that can sense the polarization state of the sample light field. They discovered that birefringence data may be used to assess the mechanical integrity and vulnerability of atherosclerotic plaques, which is a significant step toward a more comprehensive diagnosis of atherosclerosis. However, restoration of tissue birefringence necessitates a complex algorithm, which reduces the system's axial resolution. Further development of a cost-effective and easy PSOCT imaging technology combined with a downsized endoscopic catheter is necessary to ensure the technique's

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Received: 10-May-2022, Manuscript No. PULCJ-22-5011; Editor assigned: 12-May-2022, PreQC No. PULCJ-22-5011(PQ); Reviewed: 17-May-2022, QC No. PULCJ-22-5011(Q); Revised: 19-May-2022, Manuscript No. PULCJ-22-5011(R); Published: 30-May-2022, DOI: 10.37532/pulcj.22.6(3).26-27.

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clinical feasibility. In 2019, our team demonstrated a straightforward technique for building PSOCT that uses a piece of polarization-maintain fibre (PMF) for polarisation detection channels without the requirement for active polarisation modulation or costly calculation while keeping the original resolution.

## RESULTS

**Microscopic PSOCT imaging test:** The suggested method's imaging capabilities were initially tested *ex vivo* using a tissue sample of chicken tendon and chicken breast utilising a microscopic PSOCT. In the pseudo-colour map, the effect of sample birefringence is seen. Furthermore, the levels of birefringence in tendon and chicken breast differ.

**Experiments with IV-PSOCT:** Following the feasibility test, the intravascular imaging probe was connected to the PSOCT system in place of the microscopic scanner for additional verification. For intravascular imaging, a cut chicken breast was first folded into a cylinder. Then a cadaver's atherosclerotic plaque was scanned. Fresh human coronary artery samples were taken from cadavers and frozen at 19° Celsius. The tissue was decalcified, embedded, and sectioned onto 6 m-thick slides after imaging. After that, H&E was used to stain the slides.

## DISCUSSION

We demonstrated a straightforward way of building an IV-PSOCT system in this work. This was achieved by using a long section of PMF to split two polarisation modes spatially due to their distinct propagation speeds. For IV-PSOCT validation, images of the chicken tendon, chicken breast, and atherosclerotic plaque were taken. The imaging results revealed a distinct birefringence effect as well as various levels of birefringence. There are a few design enhancements that can be made to improve the clinical translation. First, the sweeping light source contains a 400 MHz k-clock signal, allowing for an imaging range of 11 mm in normal OCT or 3.7 mm for each image [FF image, FS image, and slow-slow (SS) image in one Frame] using the proposed approach. In large arteries, such as the aorta, this imaging range may not be sufficient. There is also a picture overlap marked by a white arrow. The imaging range can be improved by doubling the k-clock frequency or using dual edge sampling to overcome this issue. To boost penetration depth, even more, a swept-source laser with a longer centre wavelength, such as 1.7  $\mu\text{m}$ , can be used. For the sheath in our experiment, we used an extruded plastic tube. It was birefringent, like most plastic tubes, due to the production process. The inhomogeneous residual tension non the plastic tube induced varied degrees of retardation in the sheath image (the inner circle). The orientation of the birefringence is assumed to be parallel to the axis due to its origin. It affected the retardation we got in our PSOCT photos, but it didn't stop us from seeing local birefringence. A birefringent-free sheath will be researched, or a calibration technique will be implemented, for further improvement. The present intravascular probe size is 1.6 mm, which is constrained by the size of QWP (1 mm), preventing *in vivo* intravascular imaging. This problem can be remedied by using a more precise fabrication method. Furthermore, the artefacts created by interfaces in a probe will be replicated as a result of replicated OCT images, lowering OCT image quality. As a result, a fused connection between the PMF and the GRIN lens will be used to reduce image artefacts even more. *Ex vivo* imaging of tissues containing atherosclerotic plaques from cadavers and animal models will be performed in the future, and the results will be correlated with histological analysis. More quantitative studies, such as breakdown and collagen density, will also be examined to provide a comprehensive assessment of plaque. Finally, to translate this technology into an *in vivo* application, the pr-

-obe must be further miniaturised. Using chicken tendon, chicken breast, and atherosclerotic plaque, we tested and confirmed the feasibility and performance of our IV-PSOCT. The birefringence effect was visible. We feel that, with further development, the suggested IV-PSOCT has considerable promise in intravascular imaging to establish a new road for evaluating plaque biomechanical features. Clinicians will be better equipped to detect susceptible lesions, tailor interventional therapy, and track disease progression as a result of this.

## METHODS

### Principle

With two linearly polarised (LP) eigenmodes, the PMF used in our system is strongly birefringent. In the PMF, light propagates quicker along the fast axis than it does along the slow axis. As a result, three OCT pictures can be obtained. The OCT signal is transmitted through the fast axis on the roundtrip, resulting in the FF image. In the roundtrip, the SS image is created by using the slow axis. The FS image is created by delivering the OCT signal through the fast axis in one direction and the slow axis in the other. The group delay of PMF determines the axial separation  $z$  between the FF, FS, and SS pictures.

### System Setup

A standard OCT system based on a swept-source was changed by putting a 12-m long PMF in the sample arm to combine PSOCT with the minimalistic system setup. Due to the difference in group delay, this long section of fibre delay can temporally split the signals into the two polarisation states in the returning routes. In addition, the reference arm now has a 12-m single-mode optical fibre. The signal from the reference arm was then interfered with by the two temporally separated polarization states, resulting in two sets of intensity pictures, I1 (FF) and I2 (FF) (FS). For our device, we prepared two microscopic scanner objective pieces and an intravascular probe. The intravascular probe is attached to the distal end of the sample arm to create an IV-PSOCT. Microscopic and intravascular PSOCT have lateral resolutions of 35  $\mu\text{m}$  and 30  $\mu\text{m}$ , respectively. Axial resolution is 9  $\mu\text{m}$ . To compensate for the delay induced by the 12 m optical fibres, a 30 m coaxial cable is employed to delay both the clock signal and the trigger signal output from the swept-source laser. In addition, data postprocessing was used to address wavelength dispersion. The OCT light was delivered to the probe through a PMF. The PMF employed in the sample arm is 12 m long in total. For high-resolution imaging, a gradient-index (GRIN) lens was used to focus the OCT light on the sample. A custom-made quarter-wave plate (QWP) was fitted to the GRIN lens for polarisation state conversion. The QWP was rotated 45° clockwise in relation to the PMF's fast axis. A mirror mounted to the shaft of a micromotor reflected the illumination light. For circumferential beam scanning, the micromotor turns the mirror. When compared to the method based on a fibre rotary joint, the micromotor-based beam scanning method has an advantage in terms of imaging speed and quality (non-uniform rotation distortion-free). Procedure for microscopic PSOCT pre-operational setup

The polarisation controller in the sample arm was changed during the setup procedure before the operation of our system so that the illumination light is linearly polarised along the fast axis of the PMF at the distal end of the PMF. The linear polarisation state is subsequently converted to a circular polarisation state by the quarter-wave plate, resulting in an equal distribution of the two linear polarisation states in the sample. For equal intensities of interference with the two polarisation detection channels of I1 and I2, the polarisation controller was employed in the reference arm.