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Single-camera sequential-scan-based polarization-sensitive SDOCT for retinal imaging

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Abstract

A single-camera, high-speed, polarization-sensitive, spectral-domain optical-coherence-tomography system was developed to measure the polarization properties of the *in vivo* human retina. A novel phase-unwrapping method in birefringent media is described to extract the total reflectivity, accumulative retardance, and fast-axis orientation from a specially designed sequence of polarization states incident on the sample. A quarter-wave plate was employed to test the performance of the system. The average error and standard deviation of retardance measurements were 3.2° and 2.3° , respectively, and of the fast-axis orientation 1.2° and 0.7° over the range of 0° - 180° . The depolarization properties of the retinal pigment epithelium were clearly observed in both retardance and fast-axis orientation image. A normalized standard deviation of the retardance and of the fast-axis orientation is introduced to segment the polarization-scrambling layer of the retinal pigment epithelium.

Spectral-domain optical-coherence tomography (SDOCT) has recently emerged as a powerful new tool for noninvasive human retinal imaging. Polarization-sensitive optical-coherence tomography (PSOCT) was first proposed in 1992 to quantify sample birefringence [1] then further developed by several groups to measure the birefringence effects of skin [2-4], the cornea [5], the retina [6-8], and other biological tissues [9,10]. PSOCT provides additional contrast, such as retardance and fast-axis orientation, for retinal imaging and has been shown to be sensitive to the orientation and density of the ganglion cell axons, microtubules, and fibers in the retinal nerve fiber layer and Henle's fiber layer [11,12]. In addition, PSOCT can be potentially used to aid in the diagnosis of age-related macular degeneration (AMD), which is characterized by the formation of lipoproteinaceous deposits (drusen) between the retinal pigment epithelium (RPE) and underlying structures [13]. For example, recently researchers proposed to segment the RPE using the retardance scrambling properties of RPE [14]. A few preliminary spectral domain PSOCT systems have recently been reported; however, they have included multiple expensive spectrometers or difficult alignments using a Wollaston prism inside a single spectrometer [7,10,12]. In this Letter we report on a compact, high-speed, polarization-sensitive SDOCT (PS-SDOCT) system for retinal imaging that is a simple modification of a state-of-the-art SDOCT system and operates at 17,000 A scans/s (integration time, 50 μ s). This PS-SDOCT system is able to perform imaging of the birefringent properties of the human retina without significant motion artifact. In addition, we introduce the combination of the standard deviation of the fast-axis orientation and retardance to extract the RPE layer from the retina.

Our high-speed retinal PS-SDOCT system is shown in Fig. 1. The system employs a superluminescent diode (SLD) emitting at 840 nm (Super SLD-371-HP), and an electro-optic modulator (EOM). Modified commercial software (Bioptigen, Inc.) was used to collect repeated A scans from a 2048 pixel line scan camera at a readout rate of up to 17 kHz. Jones matrices are used to model the tissue birefringent characteristics [9,15]. The optical power detected from the sample arm is given by [9]

$$P(r) = P_s \left\{ \frac{1}{2} + \frac{1}{2} \cos^2(r) \left[\cos^2(2\theta) + \sin^2(2\theta) \cos(\delta) \right] - \cos(r) \sin(r) \sin(2\theta) \sin(\delta) - \frac{1}{2} \sin^2(r) \cos(\delta) \right\}, \quad (1)$$

where P_s is the power incident on the sample arm, r is the retardance of the EOM, δ is the accumulated net sample retardance, and θ is the accumulated net sample fast-axis orientation. The E_y component of the Jones vector of the sample-scattering electric field is

$$E_y = \sin(\delta) \exp(i(\pi - \delta - 2\theta)), \quad \varphi_{y1} = \pi - \delta - 2\theta. \quad (2)$$

Here, φ_{y1} is the phase of the E_y component. Since $P(r) \propto E_y^2$ introduces phase wrapping in Eq. (2), which limits the encoded fast-axis orientation range to 90° , one more polarization state of $r = -90^\circ$ is utilized, and a novel phase-unwrapping algorithm in birefringent media is proposed to extend the unambiguous range of the optic axis. The E_y of the sample scattering field when $r = -90^\circ$ is

$$E_y = \sin(\delta) \exp(i(-\delta + 2\theta)), \quad \varphi_{y2} = -\delta + 2\theta, \quad (3)$$

where φ_{y2} is the phase of E_y when the setting of EOM $r = -90^\circ$. If sample motion is ignored, the resulting expressions for retardance, fast-axis orientation, and reflectivity are then

$$\begin{aligned} A_{is}^2 &= \frac{1}{2} (A_{45}^2 + A_{-45}^2) + \frac{1}{2} \left[(A_{45}^2 + A_{-45}^2 - 2A_{+90}^2)^2 + (A_{45}^2 - A_{-45}^2)^2 \right]^{1/2}, \\ \delta &= \cos^{-1} \left(1 - 2A_{+90}^2 / A_{is}^2 \right), \\ \theta &= \begin{cases} \frac{\pi - (\varphi_{y1} - \varphi_{y2})}{4} & \text{if } A_{-45}^2 > A_{45}^2 \\ \frac{\pi - (\varphi_{y1} - \varphi_{y2})}{4} + \frac{\pi}{2} & \text{if } A_{-45}^2 < A_{45}^2 \end{cases} \text{phase unwrapping} \end{aligned} \quad (4)$$

In the above expressions, A_{is}^2 represents the total reflectivity [9]. A_r represents the amplitude of envelope of the interferogram at a given depth measured with an EOM retardance of r . A quarter-wave plate was employed to calibrate the performance of the PS-SDOCT system. The new unambiguous range of optic-axis orientation is from -90° to 90° , which is twice as large as that described in [9], as illustrated in Fig. 2B. The standard deviation of the retardance measurement (2.3°) is comparable to recently reported PS-SDOCT systems; however, the measured standard deviation of the fast-axis orientation (0.7°) is much more accurate than for other reported PS-SDOCT systems [7,10] since the single-channel configuration will reduce common mode noises. We further tested the system's depth resolving capability of retardance detection by cascading a Berek variable wave plate with a quarter-wave plate [9]. The combined retardation measurements were taken when the variable Berek settings were 0° , -24.2° , and -57.8° separately. The average retardation measurement error was 2.6° and the standard deviation was 2.1° , which agree very well with the purely quarter-wave-plate calibration results.

A healthy volunteer's retina (Asian, male) was imaged using this system under Investigational Review Board approval. Figure 3 illustrates the reflectivity (Fig. 3A), retardance (Fig. 3B), and fast-axis orientation images (Fig. 3C) in the foveal area. The retardance of the top layer of the retina was 24.6° , which we attribute to birefringence of the cornea. According to recent research [13], the appearance of drusen between the choroid and RPE is an indicator of early AMD. Hence the RPE layer plays a critical role in diagnosing the integrity [14] and function of the surrounding photoreceptors and Bruch's membrane. Both the retardance and the fast-axis orientation images show the polarization scrambling properties at the RPE layer, which is viewed as a blue, light blue, green, and red interleaving band. To further quantify the depolarization property of the RPE layer, the normalized standard deviation images of both retardance and fast-axis orientation were computed to quantitatively describe the degree of depolarization. A previous report employed a histogram method to segment RPE from the retardance image using a $20\text{ (H)} \times 8\text{ (V)}$ size floating window [14]. A floating square window [$5\text{ (V)} \times 9\text{ (H)} = 45\text{ pixels}$] was adopted to sweep over the entire retardance and fast axis orientation images. A smaller floating window will give a better spatial resolution. The standard deviation calculation was limited to window positions where the average intensity was higher than a threshold set at 68 db. Then the standard deviation was normalized by a factor of effective pixels/45. To further detect the most depolarized locations, the standard deviation of the retardance and the fast-axis orientation were multiplied together, and the resulting image is shown in Fig. 3D in the $20\log_{10}$ scale in units of decibels. The standard deviation multiplication image is less sensitive to speckle noise, bulk motion, and illumination conditions. Clearly, the higher standard deviation areas are only centered on the RPE. A fixed threshold 65 db was chosen to extract the RPE layer, and the segmented RPE was overlaid with reflectivity image of Fig. 3A. Blue stands for light depolarization (65-70 db), green for middle depolarization (70-75 db), and red for strong depolarization ($>75\text{ db}$), respectively. Despite these encouraging observations, it is important to note that our use of the Jones matrix approach intrinsically assumes polarization-maintaining media; any postprocessing algorithms such as the standard deviation analysis are purely heuristic.

In conclusion, a single-channel polarization-sensitive SDOCT system using a single spectrometer has been developed for high-speed characterization of total reflectivity, accumulative birefringence, and fast-axis orientation. This is a novel, simple, and relatively easy alignment single-camera spectral-domain PSOCT system. A unique phase-unwrapping algorithm in birefringent media was implemented to precisely detect the fast-axis orientation with a standard deviation of less than 0.7° , which is much more accurate than in contemporary PSOCT systems [7,10]. A plausible approach for segmentation of the RPE relying on the combination of the standard deviation of the fast-axis orientation and that of retardance is suggested, allowing for quantitative measure of the degree of depolarization of the RPE layer.

Acknowledgments

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References

1. Hee MR, Huang D, Swanson EA, Fujimoto JG. J. Opt. Soc. Am. B 1992;9:903.
2. de Boer JF, Milner TE, van Gemert MJC, Nelson JS. Opt. Lett 1997;22:934. [PubMed: 18185711]
3. de Boer JF, Srinivas SM, Malekafzali A, Chen Z, Nelson JS. Opt. Express 1998;3:212. [PubMed: 19384363]
4. Jiao S, Yu W, Stoica G, Wang LV. Opt. Lett 2003;28:1206. [PubMed: 12885022]
5. Pircher M, Goetzinger E, Leitgeb R, Hitzenberger CK. Med. Biol 2004;49:4.

6. Pircher M, Göttinger E, Leitgeb R, Sattmann H, Findl O, Hitzenberger C. Opt. Express 2004;12:5940. [PubMed: 19488235]
7. Göttinger E, Pircher M, Hitzenberger CK. Opt. Express 2005;13:10217. [PubMed: 19503236]
8. Kemp NJ, Park J, Zaatari HN, Rylander HG, Milner TE. J. Opt. Soc. Am. A 2005;22:552.
9. Roth JE, Kozak JA, Yazdanfar S, Rollins AM, Izatt JA. Opt. Lett 2001;26:1069. [PubMed: 18049522]
10. Yamanari M, Makita S, Madjarova VD, Yatagai T, Yasuno Y. Opt. Express 2006;14:6502. [PubMed: 19516828]
11. Huang X, Knighton RW. Invest. Ophthalmol. Visual Sci 2005;46:4588. [PubMed: 16303953]
12. Cense B, Mujat M, Chen TC, Park BH, de Boer JF. Opt. Express 2007;15:11.
13. Nordgaard CL, Berg KM, Kapphahn RJ, Reilly C, Feng X, Olsen TW, Ferrington DA. Invest. Ophthalmol. Visual Sci 2006;47:8.
14. Göttinger E, Pircher M, Geitzenauer W, Ahlers C, Baumann B, Michels S, Schmidt-Erfurth U, Hitzenberger CK. Opt. Express 2008;16:13. [PubMed: 18521128]
15. Hitzenberger CK, Göttinger E, Sticker M, Pircher M, Fercher AF. Opt. Express 2001;9:780. [PubMed: 19424315]

Fig. 1. (Color online) Schematic of the PS-OCT system: SP, spectrometer; PC, polarization controller; FC, fiber collimator; VP, vertical polarizer; M, mirror; BS, nonpolarization beam splitter.

Fig. 2.

(Color online) Quarter-wave-plate calibration: A, double pass phase retardance calibration. The mean absolute error was 3.2° , and the standard deviation was 2.3° ; B, fast-axis orientation calibration. The mean absolute error was 1.2° , and the standard deviation was 0.7° .

Fig. 3.

(Color online) *In vivo* human retinal imaging results. A, reflectivity image; image size: ~ 2.5 mm (x) $\times$ 2.5 mm (y), 500 lines. The unit of the gray color bar is decibels. Blue, light depolarization (65-70 db); green, middle depolarization (70-75 db); red, strong depolarization (>75 db). B, single-pass retardance; the depolarization scrambling RPE layer is viewed as a blue, green, and red interleaving band (bright white layer in black/white version). C, fast-axis orientation. D, the multiplication image of the standard deviation of retardance and the fast-axis orientation. The color bar is in units of decibels.