Published in final edited form as:

Appl Opt. 2009 March 20; 48(9): 1663–1667.

Snapshot polarimeter fundus camera

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Abstract

A snapshot imaging polarimeter utilizing Savart plates is integrated into a fundus camera for retinal imaging. Acquired retinal images can be processed to reconstruct Stokes vector images, giving insight into the polarization properties of the retina. Results for images from a normal healthy retina and retinas with pathology are examined and compared.

1. Introduction

Imaging polarimeters such as the Savart plate polarimeter (SPP) allow for snapshot polarization-sensitive imaging. A SPP operates by generating multiple interference fringes that spatially modulate the image proportional to the polarization properties of the sample. The spatial modulation of the image can be decoded using Fourier methods to determine the polarization components. These polarization components are represented as two-dimensional distributions of the image's Stokes vector composition. This particular device shows great potential in the areas of remote sensing, biological imaging, and other fields where gathering information about polarization structure is advantageous [1,2].

Application of polarization-sensitive imaging to ophthalmology has proved to be beneficial in the diagnosis and monitoring of certain retinal pathologies. The retinal nerve fiber layer (RNFL) exhibits birefringent properties that can be measured to assess vision loss due to certain eye diseases, especially glaucoma. Polarization-sensitive imaging of the retina has also shown the ability to assess damage to the retina not visible by conventional retinal photography. The emergence of such imaging modalities has led to the early detection and prevention of retinal disease. Current methods of polarization-sensitive imaging in the eye, scanning laser ophthalmoscopy (SLO) and optical coherence tomography (OCT), rely on laser scanning of the retina. SLO and OCT systems make use of ellipsometry to detect the change in polarization between the input and the output scan beams. By acquiring a series of laser scanned images,

polarization changes in the output beam can be detected and the birefringent properties of the retina can be measured [3–6].

We have successfully integrated a SPP into a fundus camera to develop what is to our knowledge the first snapshot polarimeter fundus camera (SPFC) capable of measuring the polarization structure of the retina from a single image. Unlike current systems, the SPFC measures the two-dimensional Stokes vector distributions of the retina rather than birefringence, which measures only the magnitude of the change in incident polarization state. Two-dimensional Stokes vector images give a spatial distribution of the magnitude and state of polarization of the retina, thereby allowing the nature of how retinal structure affects the incident polarization to be determined. This has the potential to provide more information about the polarization structure of the retina, specifically the RFNL, the optic disk, and the macula. The elimination of scanning optics allows for a more robust optical system, faster image acquisition, reduced effects from eye motion, and simplistic image processing. We demonstrate the ability of the SPFC to measure the polarization structure of several retinas from healthy subjects and subjects with pathology. Resulting Stokes vector images show the differences in the polarization structure of healthy retinas and retinas with pathology.

2. Methods

A. Principle of Operation

A schematic of a SPP is shown in Fig. 1. The SPP consists of a pair of Savart plates, a half-wave plate, and an analyzer placed in a collimated beam between two lenses responsible for imaging a sample onto a CCD. The principle of operation of a SPP is similar to a lateral shearing interferometer. An incoming beam is sheared into four beams based on its polarization components. The imaging lens combines the four beams to create interference, resulting in spatial modulation on the CCD. The spatial modulation of the image, $I(x, y)$, is described by Eq. (1) and Eq. (2) [1,2]:

$$I(x, y) = \frac{1}{2}S_0 + \frac{1}{2}\cos(2\pi\Omega(x+y))S_1 + \frac{1}{4}|S_{23}|\cos(4\pi\Omega x - \arg(S_{23})) - j\frac{1}{4}|S_{23}|\cos(4\pi\Omega y + \arg(S_{23})), \quad (1)$$

$$S_{23} = S_2 + jS_3, \quad \Omega = \frac{\Delta}{\lambda f_2}. \quad (2)$$

In these equations $I(x, y)$ is the spatial modulated image irradiance; $S_0(x, y)$, $S_1(x, y)$, $S_2(x, y)$, and $S_3(x, y)$ are Stokes vector images representing depolarized, linearly polarized oriented at 0° , linearly polarized oriented at 45° , and circularly polarized states, respectively; Δ is the shear distance of the crystal, which is proportional to the crystal thickness; Ω is the frequency of the spatial modulation; λ is the wavelength; and f_1 and f_2 are the focal lengths of the front and back lenses, respectively [1].

B. Instrumentation

A schematic of the SPFC is shown in Fig. 2. A SPFC is designed using stock optics to meet the following specifications: 633nm wavelength, 2mm entrance pupil diameter, 20° field of view, $3.6\text{mm} \times 4.8\text{mm}$ CCD camera, Savart Plate system with a shear distance of $113\text{ }\mu\text{m}$, and an illumination annulus at the pupil of 2mm inner diameter and 6mm outer diameter. The SPFC imaging system consists of an objective responsible for forming an intermediate image of the retina in front of the holed mirror. The SPP reimages the intermediate image of the retina onto

the CCD and spatially modulates the image. The illumination system consists of a holed mirror placed conjugate to the pupil of the eye. A $4f$ system relays the tungsten halogen illumination source to the holed mirror. The holed mirror is responsible for limiting the entrance pupil diameter of the imaging system, providing annular illumination at the pupil of the eye and coupling the illumination and imaging systems. A narrowband filter at 633 nm, black dot, linear polarizer, and quarter-wave plate are placed between the $4f$ illumination optics to provide polarized monochromatic illumination. The location of the black dot is adjusted to minimize back-reflections from the surfaces of the objective lens. Polarization optics can be adjusted to change the state of polarization incident on the retina, and they allow for the ability to compensate for the birefringence of the cornea. This is accomplished by adjusting the polarization optics to achieve maximum contrast fringes in all directions while imaging the macula [6].

The SPFC system is extremely sensitive to the aberrations in the imaging system. Increased aberrations not only reduce image quality but also reduce fringe contrast, making the recovery of polarization information difficult if not impossible. The design and instrumentation phases of the SPFC showed that the distance between the final lens and the CCD is a critical factor. A small deviation of 250 μm from the focal plane results in the loss of fringes despite maintaining image quality. Image quality for the final system is shown in the form of spot diagrams and modulation transfer function (Fig. 3). Using stock optics we are able to maintain excellent image quality and fringe contrast as demonstrated by the overlapping sheared beams.

C. Retinal Imaging Procedure

Patients were recruited with the help of practicing ophthalmologists of the Department of Ophthalmology and Vision Science at the University of Arizona. Ophthalmologists were asked to refer patients with healthy retinas, glaucoma, and other retina diseases that met the following criteria: free of cataracts, clear ocular media, and refractive error between 0 to -3 D. To facilitate the process of imaging the retina the SPFC is mounted on the base of a slit lamp position frame, allowing the patient's head to be supported by a head and chin rest while the SPFC could be positioned using the swivel arm. A drop of 1% tropicamide was administered to the patient to dilate the pupil and minimize accommodation. During the examination process, patients' retinas were continuously exposed to 250 $\mu\text{W}/\text{cm}^2$ for no more than 2 min intervals to ensure patient comfort. Images were acquired by the CCD camera at 15 Hz. A total of 9 patients with the following conditions were imaged: 4 healthy retinas, 3 glaucoma suspects with increased cup to disk ratios but no peripheral vision loss, 1 Morning Glory Syndrome, and 1 advanced glaucoma.

3. Results

A. Normal Retina

In a normal healthy retina, Fig. 4(a), the polarization properties are associated with the polarization preservation properties of the rods and cones and the birefringence of the RNFL. The absence of the rods and cones in the optic disk results in the depolarization of the light being reflected from the optic disk [7,8]. The birefringence-associated RNFL exhibits a bowtie pattern centered on the optic disk [6]. Examination of the Stokes vector images, Fig. 4(b), shows the depolarization of the optic disk and a polarization signal above and below that resembles part of a bowtie pattern. As previously mentioned, we would expect a depolarized signal from the optic disk and a polarized signal from the optic disk where the RNFL is thickest. It is also interesting to observe the strong polarization signal from the blood vessels. These results are consistent with the other healthy retinas. The subjects with slightly increased cup to disk ratios did not show any significant deviations from the healthy retinas.

B. Retina with Morning Glory Syndrome

Morning Glory Syndrome, Fig. 5(a), is a congenital birth defect that consists of a funnel-shaped excavated disk and a surrounding annulus of discoloration. This particular pathology results in vision loss due to the malformation of the optic disk and RNFL [9]. We would expect to see little polarization signal surrounding the optic disk due to the malformation of the RNFL. The Stokes vector images, Fig. 5(b), show a strong depolarization surrounding the malformed optic disk. The malformed disk seems to exhibit a strong polarized signal unlike the healthy retina. A faint annulus can be seen in Fig 5, due to backreflection caused by imaging the patient outside of the 0 to $-3D$ range (patient refractive error is around $-6 D$). To ensure the backreflection does not add to the polarization structure of the retina, an image of backreflection is processed and the background polarization information is subtracted from the polarization information of the retina.

C. Retina with Glaucoma

Glaucoma is a disease characterized by increased intraocular pressure. Visual diagnosis of glaucoma can be made by the assessment of the optic disk. Increased cup to disk ratios and excavated disks are indicators of glaucoma [4,10]. Progression of this disease results in vision loss due to the thinning of the RNFL [4–6]. Figure 6(a) shows the optic disk of a patient with advanced glaucoma as indicated by the excavated disk. Stokes vector images, Fig. 6(b), show the rim of the disk is depolarized. The S1 image indicates a strong depolarization in the periphery unlike the healthy retina in Fig. 4(b). The S2 and S3 images show a strong polarization signal from the optic disk much like the subject with Morning Glory Syndrome. These images show a clear distinction between a glaucomatous and a healthy retina.

4. Conclusions

The ability of the SPFC to identify features of the polarization structure of the retina is demonstrated. Using the SPFC we have shown a difference in the SOP of certain retinal pathologies and normal healthy retinas. Images of the healthy retinas demonstrate polarization properties that appear similar to the bowtie pattern associated with the RNFL birefringence measured with current technologies. From our results, it is unclear as to why the damaged optic disks in Fig. 5 and Fig. 6 exhibit a strong polarized signal unlike healthy retina; see Fig. 3. Even though this insight is left unanswered, this study shows that SPFC has the potential to be used as a clinical instrument for the assessment of retinal health. The SPFC offers more information about the polarization structure of the retina and more robust design over current retinal polarization imaging modalities. Further testing of the SPFC on retinas with and without pathology will be conducted by the University of Arizona Ophthalmology and Vision Science to determine how the retinal SOP information provided by the SPFC can be used to effectively determine retinal health.

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Fig. 1.
(Color online) Savart plate polarimeter.

Fig. 2.
(Color online) Fundus camera with an integrated SPP.

Fig. 3.

(Color online) (a) Spot diagrams of the SPFC showing the shear pattern of the input polarized beam focused at the CCD for fields 0, 7, and 10° corresponding to fields 1, 2, and 3, respectively. Each of the sheared beams is represented by a different color. The black circle shows the diffraction limited Airy disk size. The spot size at the focal plane is given by rms and geometric radius. (b) Image quality of the SPFC given by modulation transfer function for fields 0, 7, 10°.

Fig. 4.
(Color online) (a) Normal retina with no pathology and (b) associated Stokes vector images.

Fig. 5.
(Color online) (a) Retina with Morning Glory Syndrome and (b) associated Stokes vector images.

Fig. 6.
(Color online) (a) Retina with advanced glaucoma and (b) associated Stokes vector images