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Depolarization effects in the human eye

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Abstract

We have studied the effects of depolarization in the living human eye by using a spatially resolved Mueller-matrix polarimeter [Opt. Lett. 24 (1999) 64]. Results show that the degree of polarization for the central part of double-pass images is about 0.85 and 0.70 for 2 mm and 5 mm of pupil, respectively. This parameter decreases towards the tails of the image. In the plane of the pupil, the degree of polarization also depends on the analyzed area, and it has been related to the different components of the light coming back from the retina. Values of polarizance suggest that the eye presents a slight polarizing power mainly due to the existence of both circular birefringence and dichroic properties. Polarizance is also larger at the central part of double-pass images (about 0.25 on average) and decreases along the radius. In addition, it has been shown that the major retinal layer where the light is reflected does not depend on the state of polarization of the incident light. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Depolarization; Polarizance; Imaging polarimetry

1. Introduction

Depolarization is a natural property intrinsically associated with the scattering and loss of coherence in the polarization state (Chipman, 1995). This is a process that couples polarized light into unpolarized light and characterizes averaged and random polarizations generated by reflection, transmission or scattering of light by a medium or optical components (Nee, 1999). Scientific-grade optical components are usually made with smooth surfaces whose depolarization is negligible in conventional polarimetry. However, real-world objects are mostly rough and induce depolarization in reflection and scattering. The case of the human eye is a paradigmatic example of interest where effects of depolarization occur.

The ocular media and the retina have rather complicated polarization properties (van Blokland, 1986a; Bour, 1991). Therefore, defining the change in the polarization state by the relative position of a polarizer–analyzer system is not necessarily complete or even correct. Scattering could change the polarization in a complicated way, and this configuration would erroneously identify completely polarized states as partially depolarized. These polarizing properties should be taken into account, particularly in such applications as fundus reflectometry or in measurements of the retinal image quality by using double-pass techniques (van Blokland & van Norren, 1986; Bueno & Artal, 2001).

Concerning the depolarization of the light in the ocular media, there is a large variety of results in the previous literature. Several studies found a complete depolarization of the light reflected at the retina (Brindley & Willmer, 1952; Alpern & Campbell, 1962; Vos, Munnik, & Boogaard, 1965). Other authors showed that the polarization was substantially preserved (Weale, 1966; Röhler, Miller, & Aberl, 1969; Charman, 1980; van Blokland, 1985). Even a polarizing effect when non-polarized light was incident on the retina was found (Röhler & Schmielau, 1976).

Röhler and collaborators (1969) reported that the part of the returning light retaining polarization was reflected by the outer segments of the photoreceptors, whereas the depolarized fraction came from an anterior layer. O'Leary and Millodot (1978) also agreed with that idea. Previously, Weale (1966) located the reflection of the light retaining polarization on the Bruch

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membrane. Charman (1980) placed the retinal reflection on the internal limiting membrane.

In general, the degree of polarization (DOP) of light scattered at the retinal fundus is largely preserved in almost all conditions studied (pupil position, bleaching level, location on the retina,…) with the notable exception of red light (van Blokland & van Norren, 1986). Due to this invariance, polarization is not a useful entity to distinguish scattered components. Van Blokland (1986a) showed the existence of a directional (guided through photoreceptors) and a diffuse component (due to the scattering of light not passing through the photoreceptors) in the reflected light. Burns and co-workers (1995) obtained similar results. The directional component is generally propagated through the outer segments but not always oriented to the center of the pupil. The diffuse component is observable with all positions of the entrance pupil.

This study concentrates on both the depolarizing properties and the polarizing power of the human eye, affecting the light after a double-pass through the ocular media and reflection in the retina. These effects have been studied by using spatially resolved Mueller matrices obtained by means of a double-pass imaging polarimeter (Bueno & Artal, 1999). We also determine whether incident light with different states of polarization suffers reflection in a different retinal layer.

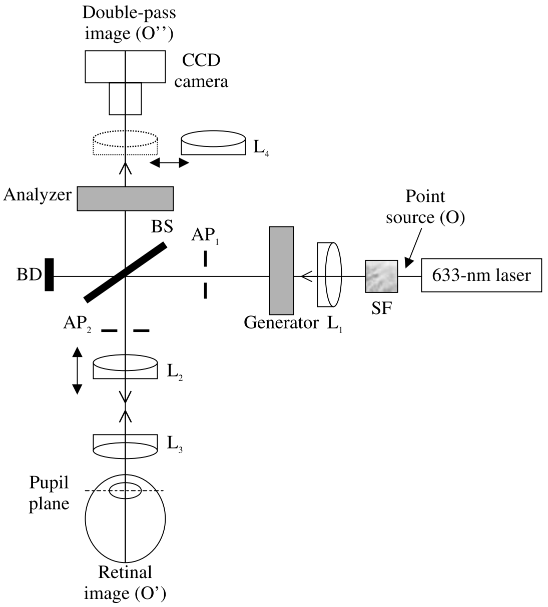


Fig. 1. Simplified configuration of the double-pass imaging polarimeter. SF, spatial filter (composed of a pinhole, O, and a microscope objective not shown in figure); L$_1$, collimation lens; L$_2$, L$_3$ and L$_4$, achromatic lenses; AP$_1$ and AP$_2$, artificial pupils; BS, pellicle beam splitter; BD, black diffuser.

2. Methods

2.1. Theory

While the Jones formalism cannot describe partial polarization, Mueller matrices describe all the polarization effects of a sample including depolarization (Shurcliff, 1962; Azzam & Bashara, 1992). A system presents depolarizing effects if the DOP of the emergent beam is smaller than the DOP corresponding to the incident light. The DOP of a system represented by the Mueller matrix M_{ij} $(i, j = 0, 1, 2, 3)$ is given by (Gil & Bernabeu, 1986; Chipman, 1995):

$$\mathrm{DOP} = \frac{\sqrt{\left(\sum_{i,j=0}^{3} M_{ij}^2\right) - M_{00}^2}}{\sqrt{3}M_{00}} \quad (0 \le \mathrm{DOP} \le 1). \tag{1}$$

On the other hand, the DOP of the transmitted light when unpolarized light is incident is known as polarizance (P) (Shurcliff, 1962). In other words, P describes the possibility of increasing the DOP of the non-polarized incident light on the system (polarizing power) and is defined as:

$$P = \frac{\sqrt{M_{10}^2 + M_{20}^2 + M_{30}^2}}{M_{00}} = \sqrt{P_1^2 + P_2^2 + P_3^2} \quad (0 \le P \le 1). \tag{2}$$

This concept can be further generalized into the polarizance vector $\vec{P}$ expressed as (Lu & Chipman, 1996):

$$\vec{P} = \begin{pmatrix} P_1 \\ P_2 \\ P_3 \end{pmatrix} = \frac{1}{M_{00}} \begin{pmatrix} M_{10} \\ M_{20} \\ M_{30} \end{pmatrix}. \tag{3}$$

When having a spatially resolved Mueller matrix, DOP and P can be directly computed from the numerical values of each pixel of the elements of the matrix. In this paper, both spatially resolved parameters will be treated and discussed in a similar way.

2.2. Apparatus and experimental procedure

The experimental system used to obtain spatially resolved Mueller matrices of the living human eye has been described in detail elsewhere (Bueno & Artal, 1999). The apparatus is a double-pass configuration (Santamaría, Artal, & Bescós, 1987) incorporating two electronically controlled liquid-crystal variable retarders acting as generator and analyzer units in the in-coming and out-coming pathways respectively (Fig. 1). Briefly, a point source (O) generated by a 633 nm He–Ne laser is imaged on the retina (retinal image, O′), and the light reflected back is imaged a second time on a recording stage (aerial or double-pass image, O″). The size of the beam entering the eye (either 2 mm or 5 mm in

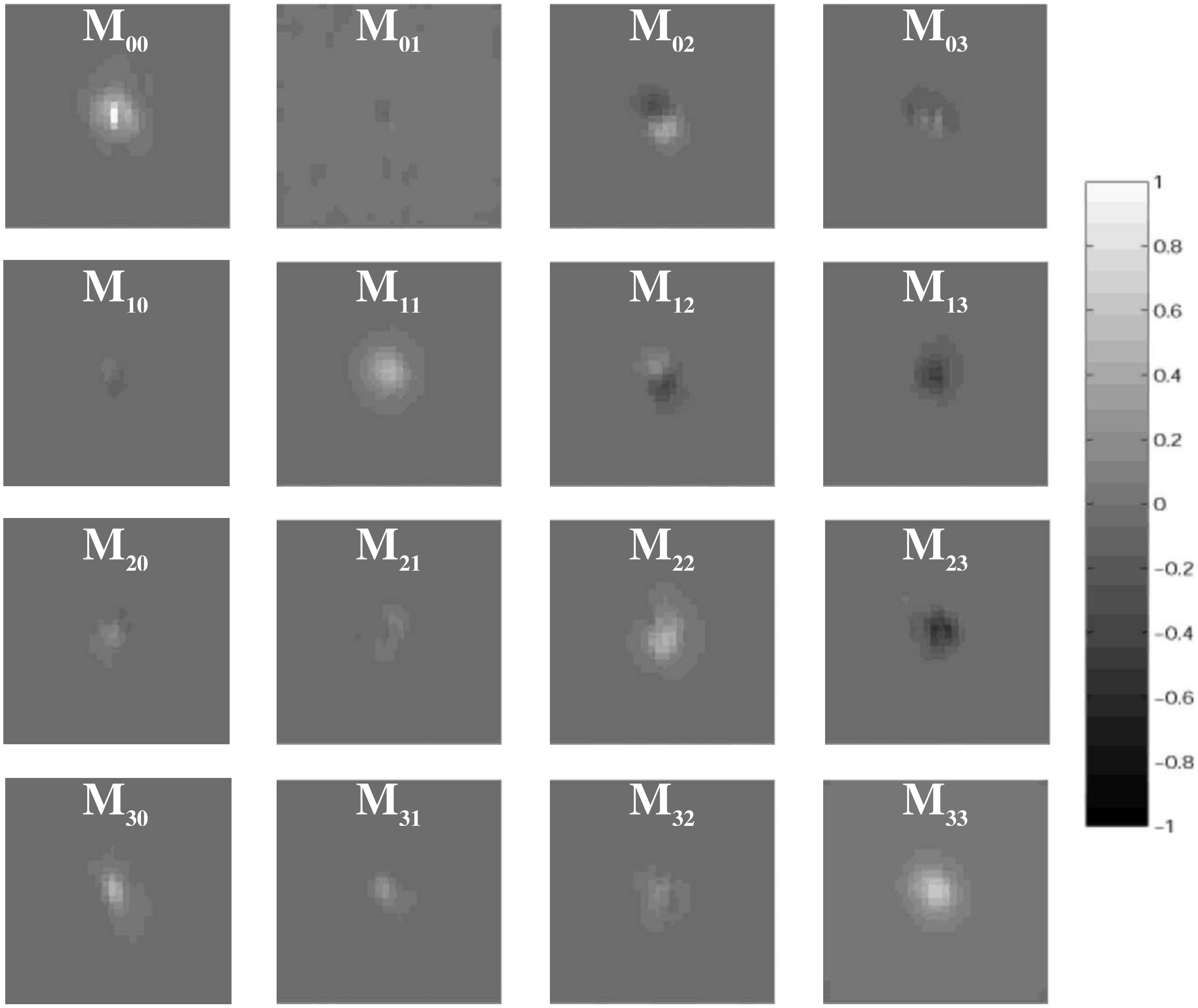


Fig. 2. Spatially resolved Mueller matrix for observer JB and 2 mm pupil size. Each image subtends 29 min of arc and corresponds to an element of the Mueller matrix as indicated.

diameter) is controlled by aperture AP_1 (entrance pupil). An afocal system (lenses L_2 and L_3) in front of the eye allows the correction and generation of defocus.

Series of 16 double-pass retinal images (4 s exposure) corresponding to independent combinations of generator-analyzer polarization states (horizontal, vertical, 45 deg linear and right circular) were recorded. These combinations were obtained by driving the liquid crystals with appropriate voltages and placing a pair of quarter-wave plates when necessary (Bueno, 2000a). When registering images of the pupil plane, a 2 mm diameter beam illuminated the eye, and an additional lens (L_4 in Fig. 1) was introduced in the second passage in order to conjugate the pupil of the observer with the CCD plane. Spatially resolved Mueller matrices for both retinal and pupil planes were calculated by using a matrix-inversion method previously reported (Bueno & Artal, 1999; Bueno 2000b). From the Mueller matrix, DOP and P are computed using the equations presented above.

Three well-experimented subjects (AG, JB and PA) with normal vision were tested. Accommodation was paralyzed with two drops of tropicamide (1%). The best refractive state for each subject was determined. Subjects looked for the best focus moving L_2 (Fig. 1) while staring at the point source directly (the intensity was conveniently attenuated) until they saw the smallest and the brightest point source. By recording double-pass images for different focus positions around this best subjective focus, the focus setting was confirmed. Images for the pupil plane were recorded before dilation.

3. Results

3.1. Spatially resolved Mueller matrix

As indicated above, the spatially resolved Mueller matrix was obtained from each set of 16 double-pass images. Fig. 2 shows the matrix for JB's eye for a 2 mm pupil diameter. Each image corresponds to one element of the matrix and subtends 29 min of arc. This matrix contains information on the retinal reflection and the double-pass through the ocular media. It is easy to note that element M_{00} is positive (it represents the emergent intensity when non-polarized light in incident), but all other elements can have positive or negative values.

3.2. Spatially resolved degree of polarization

The spatially resolved DOP corresponding to double-pass images was derived from the Mueller matrices using Eq. (1). Fig. 3 shows maps of the DOP for the retinal plane and two different pupil sizes (2 mm and 5 mm) in subject JB. The parameter is larger for the central part of the retinal images for both pupil sizes.

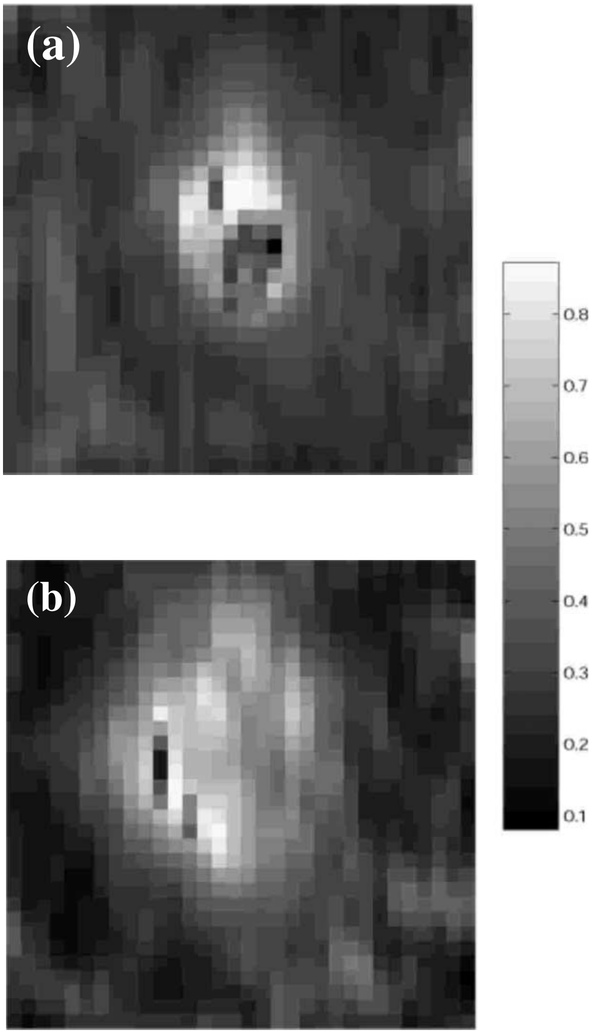
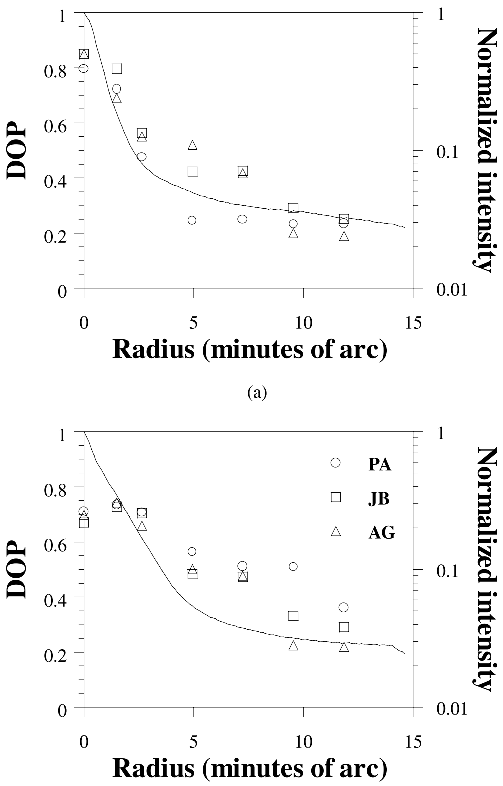


Fig. 3. Spatially resolved DOP for double-pass images in subject JB for 2 (a) and 5 mm (b) pupil diameter. Each image subtends 29 min of arc of visual field.



(a)

(b)

Fig. 4. DOP radial profile for three subjects and averaged intensity radial profile (gray line) of retinal double-pass images obtained with 2 (a) and 5 mm (b) pupil diameters.

For a better discrimination, Fig. 4 presents the DOP radial profile for the three subjects and both pupil sizes. In the same plot the averaged intensity radial profile of the retinal image (log scale) for the two different pupil diameters is also presented. For the central area of the 2 mm pupil retinal images the averaged DOP (for all subjects) was 0.83 ± 0.04 (mean ± standard deviation) and it decreased to 0.25 ± 0.04 in the skirts. For a 5 mm pupil diameter values were 0.69 ± 0.03 and 0.29 ± 0.07 respectively. The averaged DOP for the whole image (subtending about half a degree of visual field) was 0.47 ± 0.05 and 0.54 ± 0.03 for 2 mm and 5 mm of pupil diameter, respectively.

Using the Mueller matrices for the pupil plane, the spatially resolved DOP for that plane was also computed. Fig. 5 shows the map of the DOP in JB's pupil. Fig. 6 presents the DOP radial profile from the center of the pupil for the two subjects involved in this experiment. Although the maximum for this parameter does not exactly correspond to the center of the pupil, it decreases towards the margins of the pupil (values ranged from 0.70 to 0.51). This parameter reduces around 25% in a radius of approximately 2 mm. The

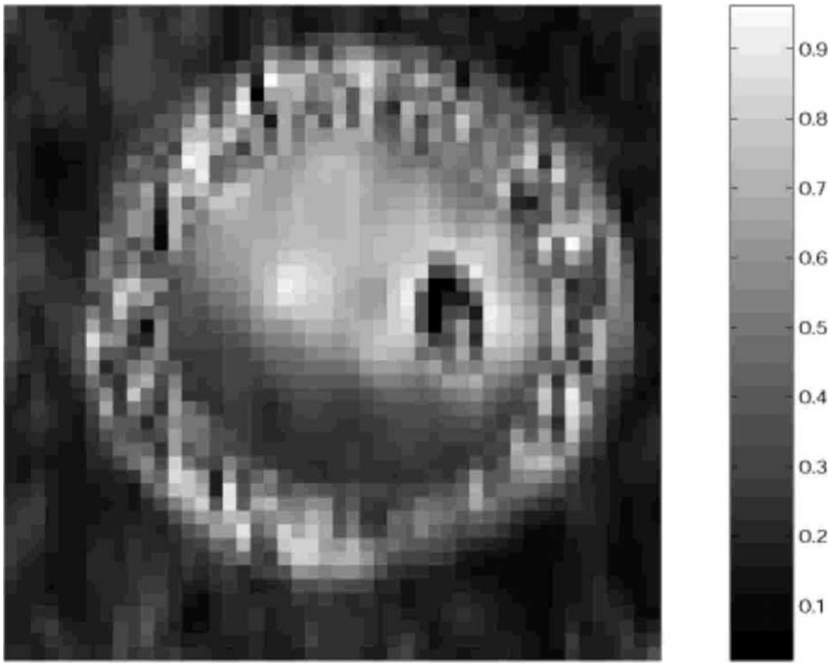


Fig. 5. Spatially resolved DOP for JB's pupil plane. The size of the image is 7.7 mm.

averaged parameter (just at the effective area of the pupil) has been 0.57. Due to slight changes in the size of the natural pupil of the observers during the image recording (they were not dilated for this experiment—see Section 4.1), a noisy area just at the edge of the pupil appears.

Previous experiments reported two contributions in the light reflected back in the retina: a portion of the light guided by the photoreceptors that keeps the polarization and the diffuse component corresponding to depolarized light (van Blokland, 1986a). In this sense, the location of the intensity peak or maximum of the guided component (Gorrand & Delori, 1990; Burns, Wu, Delori, & Elsner, 1995) and the maximum of the DOP at the pupil plane are presented in Fig. 7 for the two subjects.

3.3. Spatially resolved polarizance

The first column of the Mueller matrix (Fig. 2) contains information on the polarizance of the system (Eqs. (2) and (3)). The values of the three elements of the spatially resolved polarizance vector (P_1, P_2 and P_3) along a horizontal meridian are plotted in Fig. 8 for three subjects.

Fig. 9(a) shows the distribution of polarizance (Eq. (2)) for subject JB. The polarizance radial profiles for the three subjects are presented in Fig. 9(b). This parameter is also larger for the central part and decreases along the radius. For the central area and the skirts of the images, the averaged polarizance values (all subjects) were 0.243 ± 0.030 and 0.011 ± 0.002, respectively. The mean polarizance for the whole images and all subjects was 0.055 ± 0.007.

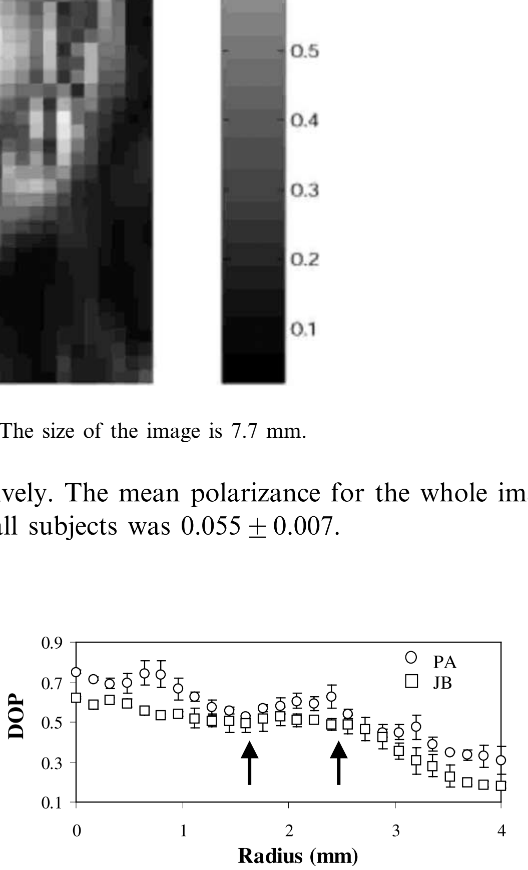


Fig. 6. DOP radial profile for the pupil plane of two subjects (PA, circles; JB, squares). Arrows indicate the edge of the pupil.

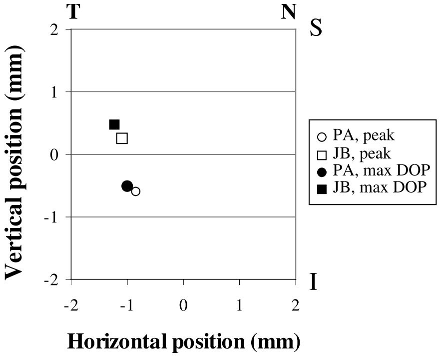


Fig. 7. Locations of the peak of the guided component (white symbols) and the maximum of the DOP (black symbols) in the plane of the pupil for subjects PA (circles) and JB (squares). N, T, S and I mean nasal, temporal, superior and inferior directions respectively. Point (0,0) represents the center of the pupil.

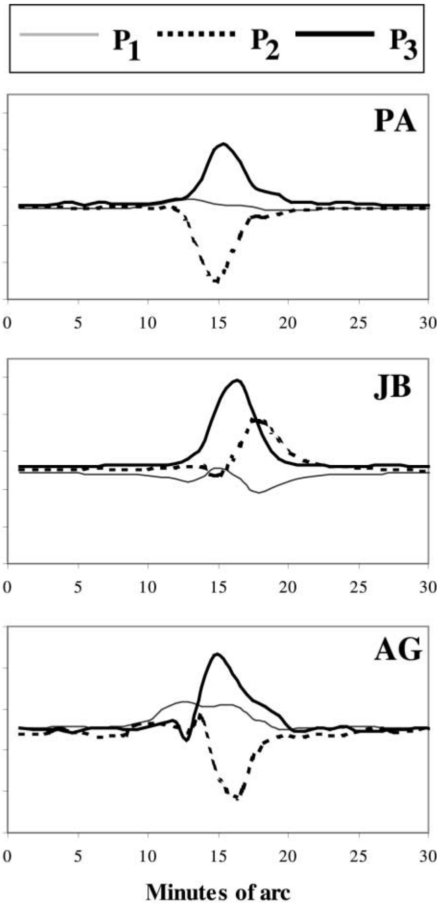


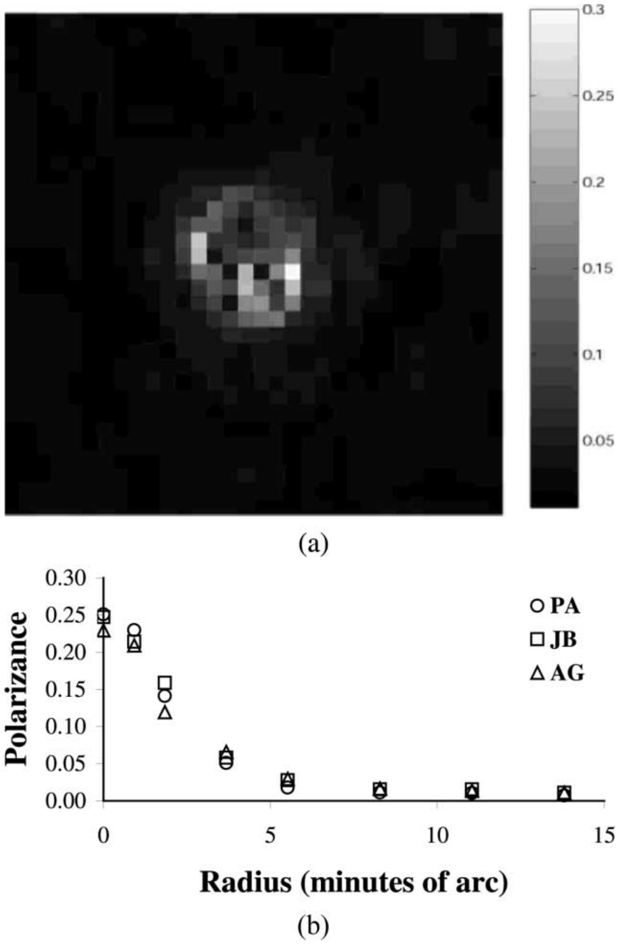
Fig. 8. Profiles corresponding to the elements of the spatially resolved polarizance vector in three different subjects for a 2 mm pupil size.

By direct inspection of Fig. 8, it can be observed that the contribution of the central part of the element P_1 in subject PA, corresponding to horizontal (if positive) or vertical (if negative) linear polarizations was very small (about 2%). However, 45 deg linear and circular components (P_2 and P_3, respectively) contributed with approximately 20% and 18% (negative values indicate the tendency to be -45 deg linear or left circular polarized). For subject JB, the horizontal component was near the 8%, and central parts of P_2 and P_3 ranged from 13% to 24%. In subject AG, whereas the contribution of P_1 was about 5%, 15% was found for both P_2 and P_3.

3.4. Retinal reflection plane and polarization

If the light is reflected in the retina at different layers depending on its polarization state, the setting for the best focus measured using different polarization states should be different. If this is true, the image quality for different polarization states should also be different. Therefore, it would be possible to improve the measured retinal image quality by selecting the appropriate focus. To test this hypothesis, series of double-pass retinal images for two different combinations of generator-analyzer polarization states and different positions of focus around the best objective focus were recorded. The different positions of focus were generated by moving lens L_2 (Fig. 1). One diopter of defocus produced by the afocal system placed in front of the eye corresponds to a displacement in the retinal image of 375 μm (Bennett & Rabbetts, 1989).

Subsequently, MTFs and Strehl ratios were calculated for each image (see Artal, Iglesias, López-Gil, & Green, 1995 for details on how the MTF and the Strehl ratio were computed). Fig. 10(a) shows double-pass retinal images for different focus locations with two independent combinations of generator-analyzer polarization states (vertical–vertical and horizontal–vertical). In Fig. 10(b), Strehl ratios computed for two different subjects have been represented as a function of the location of the image in the retina. Although, for the two subjects, the image quality for every focus is worse for the case of crossed polarizations (horizontal–vertical), the best focus (maximum Strehl ratio) is located at approximately the same place.



(a)

(b)

Fig. 9. (a) Spatially resolved polarizance for subject JB (2 mm pupil diameter). The image subtends 29 min of arc. (b) Polarizance radial profile for the three subjects.

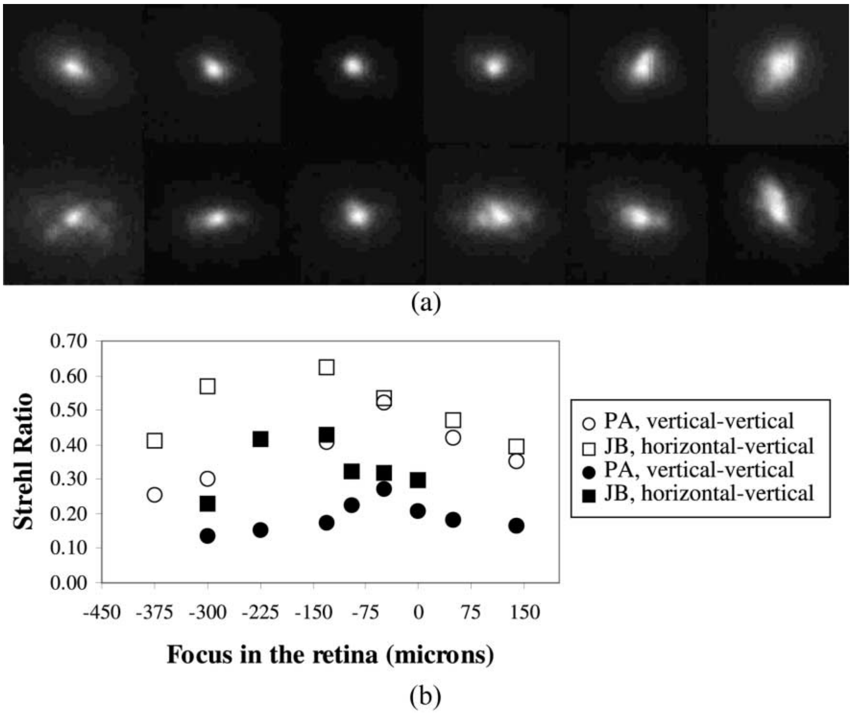

(a)
(b)

Fig. 10. (a) Double-pass retinal images in subject JB for different focus positions around the best objective focus, with 2 mm pupil diameter and combinations vertical–vertical (upper row) and horizontal–vertical (lower row). Each image subtends 14.75 min of arc. (b) Strehl ratios for subjects JB (squares) and PA (circles) as a function of retinal focus: vertical–vertical (white symbols) and horizontal–vertical (black symbols). Position 0 in the horizontal scale is associated with an emmetropic eye, and negative and positive values correspond to myopic and hyperopic locations respectively.

4. Discussion and conclusions

4.1. Degree of polarization

Figs. 3 and 4 confirm that in double-pass images, the DOP of the light forming the central part is higher than the corresponding to the skirts of the image. For the central part of the images with a 5 mm pupil diameter, the parameter is lower, although it also reduces towards the skirts. For the pupil plane, the DOP decreases along the radius towards the margins. In this sense, if totally polarized light enters the eye, it will change its state of polarization due to the corneal and retinal birefringence and the retinal dichroism. In addition, the DOP of the light will decrease because of the depolarizing effects. In general, any incident totally polarized state will turn into an elliptical partially polarized state. This suggests that every technique based on collecting the light scattered back in the retina will be potentially affected by the ocular polarization.

Most of the previous studies involving polarization used a polarizer–analyzer configuration: a fixed linear polarizer in the illumination channel and a second linear rotating polarizer (analyzer) in the detection channel. Those experiments recording images only with linear polarizers are not completely appropriate to understand the depolarization effects of an optical system. Many authors have claimed that the light registered when the axes of the polarizer and the analyzer are parallel remains polarized, whereas that corresponding to crossed polarizers has been depolarized. As stated, that is not a valid hypothesis. In fact, when this kind of configuration is used, there is a possibility of identifying elliptical polarization as partially depolarized light. Circular and depolarized light cannot be distinguished either. All those disadvantages can be avoided using Mueller-matrix polarimetry, because the polarization state of the light emerging from a system is completely determined.

Using Mueller-matrix polarimetry for wide areas in the retina (not imaging polarimetry), van Blokland and van Norren (1986) measured the DOP along a horizontal meridian of the pupil plane (3 mm in radius) for the light double-passing the ocular media. In general, they found that near the margins of the pupil, the parameter is 10% lower than in the central part (0.75). However, for light of 647 nm, they measured a DOP of 0.40, which was associated with a probably larger ocular scattering. According to those results, a lower DOP was expected for the wavelength used in this work. However, those previous studies used detectors covering a relatively large area (at least 1 deg). In the present case, the averaged parameter obtained for the pupil's area is close to those earlier results. The DOP corresponding to the whole retinal image (for both 2 mm and 5 mm pupil diameter) is also close to that proposed by those authors. In addition, larger DOPs for both red (Dreher, Reiter, & Weinred, 1992) and infrared lights (Pelz, 1997) were also found in spite of the scattering expected for those wavelengths.

The area of the pupil with a larger DOP and the location of a maximum in the detected intensity are close to each other (Fig. 7), confirming that the DOP corresponding to directional component returning from the photoreceptors is higher than the DOP associated with the diffuse component. Neither the directional component is totally polarized nor the diffuse component totally depolarized. Present results for the pupil plane also agree with those found by Burns and colleagues (1995) when using a configuration polarizer–analyzer.

The maxima for both the detected intensity and the Stiles–Crawford effect have been usually found to be the same (van Blokland, 1986b). The Stiles–Crawford effect cannot be measured with the present experimental system; however, since the guided portion of the light coming back from the ocular fundus fills only a portion of the pupil, whereas the other component fills the entire pupil (Burns et al., 1995), the spatially resolved DOP represents a useful tool to measure directional properties of human photoreceptors.

As explained above, measurements referred to the DOP at the pupil plane were made without dilation. There is no special reason for that experimental condition. Slight variations on the pupil size were found afterwards, when analyzing the images. For our purpose, this fact does not change the results because directionality of photoreceptors is a physiological property, and it does not depend on the size of the pupil. However, dilation probably could have been better.

4.2. Polarizance

When non-polarized light is incident, the polarization state of the emergent light depends on the elements of the first column of the Mueller matrix of the system. If those elements are zero, the emergent light is depolarized. When using spatially resolved matrices, elements M_{10}, M_{20} and M_{30} must be zero at every point. The distribution of polarizance (Figs. 8 and 9) indicates that the light forming the central part of the double-pass image registered when depolarized light is incident on the eye will increase its DOP (values of P are clearly different from zero). However, light corresponding to the skirts of the image will remain depolarized.

The increase in the DOP of the light of that central part is mainly due to two contributions: ± 45 deg linear and circular polarizations. These contributions seem to indicate the existence of a slight polarizing power in the human eye due to both dichroism and circular birefringence. The dichroism has been broadly studied (see, for instance, Bour, 1991 as a general review) and it has always been attributed to the retina. In addition, the presence of circular birefringence is also proposed here. Although recent studies for both in vitro corneas and lenses (Bueno & Campbell, 2001; Bueno & Jaronski, 2001) have reported a non-significant polarizing power due to those elements of the eye, previous experiments using Purkinje images showed that cornea and lens exhibit circular birefringence (Pierscionek & Weale, 1988). As Bueno and Jaronski (2001) suggest, probably the circular birefringence reported by Pierscionek and Weale is a result of using wide angles for illumination and recording pathways instead of perpendicular incidence. Since some media exhibit circular birefringence along the optics axis but are linearly birefringent in other directions (Jenkins & White, 1976), the circular birefringence should appear when calculating the Mueller matrices associated with Purkinje images. Because the experimental configuration proposed in this paper uses perpendicular incidence, the polarizing power (directly extracted from the Mueller matrices) reported here will be associated with the retinal structure, which agrees with the early work by Röhler and Schmielau (1976).

4.3. Retinal structure and polarization

The problem of the localization of the retinal reflection has been analyzed by several authors (see Section 1), but different conclusions have been reported. In general, it has been suggested that the origin of the two components of the light reflected back in the retina is a different retinal layer (Röhler et al., 1969; O'Leary & Millodot, 1978; Charman, 1980; van Blokland, 1986a).

Bueno and Artal (2001) have shown that the retinal image quality obtained with the double-pass method depends strongly on the combinations of independent polarization states generator-analyzer. In particular, present results (Fig. 10) show that the image quality associated with a parallel configuration (vertical–vertical) is better than that associated with a crossed configuration (horizontal–vertical). Moreover, this dependence is present not only at the position of the best focus, but also out of focus. Even for the parallel configuration, positions out of focus are comparable with, or much better than, those best foci corresponding to the crossed configuration.

Previous experiments also reported that the ocular MTF for crossed polarizers is worse than that corresponding to a parallel configuration (Röhler et al., 1969; Charman, 1980; Gorrand, Alfieri, & Boire, 1984; Williams, Brainard, McMahon, & Navarro, 1994). The results of this work agree with this, but the image quality associated with crossed polarizers could not be improved by focusing the light onto a different retinal layer as some authors stated (Röhler et al., 1969; Gorrand et al., 1984). Data presented here show that there is a common focus for those combinations, which gives a better image quality.

O'Leary and Millodot (1978) studied the discrepancy between retinoscopy and subjective refraction using parallel and crossed polarizers in a large group of people as a funtion of the age. They determined the relationship between polarization and retinoscopic refraction to confirm the existence of two fundus reflecting layers. Whereas, for crossed polarizers, they did not find a significant difference with age (discrepancy around −0.085 D), for the parallel configuration, a gradual decrease in discrepancy with age was found (from 0.4 to −0.04 D).

In our experiment, since the best image quality is associated with the same focus with independence of the different polarization states of the incoming light, for this wavelength and at the fovea there is a major layer responsible for the retinal reflection. This means that for these experimental conditions, there is no relationship between the state of polarization and the location of the reflection in the retina.

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