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Wide-field direct ocular straylight meter

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Abstract: The impact of the intraocular straylight (IOS) on the visual performance and retinal imaging is still a challenging topic. Direct optical methods to measure IOS avoid psychophysical approaches and interaction with the patient. In this work, we developed an optical instrument providing direct imaging measurement of IOS based on the double-pass technology. The system was tested in an artificial eye IOS model constructed with holographic diffusers and validated with theoretical simulations.

1. Introduction

When the eye is exposed to an intense glare source, the contrast sensitivity decreases limiting the ability to discriminate details due to the scattering effects that spreads the light out of the desire focus. If the intensity of the light is high enough, the eye experiences a temporal loss of visibility due to a veiling effect covering the whole retina. This phenomenon is known as disability glare [1] or intra-ocular straylight (IOS). The main contributions to IOS in the eye correspond to the cornea [2], iris, crystalline lens [3] and the retina [4]. Those contributions increase significantly with age [5] due to physiological changes in the crystalline lens [6], iris pigmentation or loss of optical transparency [7]. IOS is also associated to pathological processes such as corneal edema, keratoconus [7], cataracts [8], retinal diseases and high myopia [9]. Other factors including refractive surgery have been reported to increase the IOS due to the alteration of the stromal morphology and corneal density [10].

At the beginning of the 20th century, Percy Cobb [11] studied for the first time the effect of an intense light source on the visual acuity introducing the concept of "disability glare". Since then, psychophysical and optical techniques have been developed to estimate the IOS. The contrast sensitivity function has the potential of assessing the visual system over a spatial frequency distribution, in this sense some clinical instruments have been proposed to test the disability glare based on the relationship between straylight and glare perception [12,13]. Other methods based on the equivalent luminance assume that the effect of projecting a bright source at a given retinal eccentricity is equivalent to superimpose a veiling with the same illuminance over the observed object [14,15]. The need of expanding the angular field of the illumination tests brought the development of the direct compensation method which consists of the estimation of the veiling that produces a glare source using the retina as the detector itself [16,17].

However, the main disadvantage of those psychophysics methods is the indirect nature of the measurement as require the participation of the patient. On the other hand, the optical methods based on objective measurements are wide in technology and converging into the double-pass (DP) technique. DP technology was first introduced by Flamant in 1955 [18] and consist of acquiring the image of a punctual source after retinal reflection [19]. The acquired image contains integrated information about aberrations, diffraction and scattering. The DP commercial systems (*HD Analyzer*, Visiometrics, CO) have been successfully employed to assess the retinal image quality or the optical quality of the eye, however its capabilities to measure IOS are scarce due to the limitation of angular range of analysis to a few tens of arc minutes [20], considering that the angular domain of the retinal straylight ranges between 1° and 90°. This limitation was overpassed

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by Ginis and collaborators [21] with the development of a new optical method to reconstruct the wide-angle point spread function (*PSF*) of the eye up to 8° of eccentricity. Employing DP technology, the punctual illumination was replaced by an extended source projecting uniform disks on the retina.

To date, there are no reported optical methods providing objective measurements of the IOS at large peripheral eccentricities and direct visualization of the generated veiling effect. This is particularly relevant due to the significant differences between the central and peripheral retina at both embryologic, anatomic and functional levels. In addition, some retinal injuries have its origin at the periphery which signs and manifestations are quite different from the central retina.

In this work, a new methodology based on the DP technique is proposed to provide direct measurement of the IOS at a maximum eccentricity of 22°, visualization of the fundus and the veiling produced by scattering effects. Increasing the measurement range for scattering it is a step further in a more complete description of the image quality of the eye. For this purpose, a new instrument incorporating a wide-field circular pattern illumination will be designed and tested with holographic diffusers in an artificial eye.

2. Methods

2.1. Optical layout and operating principle of the instrument

This section describes the optical instrument developed for the measurement of the IOS and the operating procedure. The illumination source is composed of a high-power green LED followed by a plastic diffuser (aperture angle of 20°) and limited by a field-stop mask composed of an annulus and a central occluder as shown in Fig. 1. The source is collimated and conjugated with the pupil plane by means of a relay telescope (composed of a couple of achromatic doublets). To ensure diffraction-limited illumination, the entrance pupil diameter was chosen to be 2 mm.

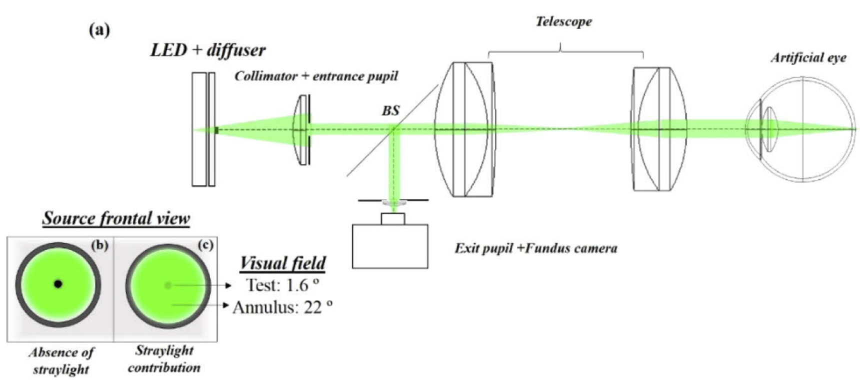

Fig. 1. Optical layout of the direct straylight meter.

After reflection at the retinal plane of an artificial eye (see Section 2.2), the light pass-through the same optical pathway and is deflected by a 50:50 beam splitter (BS) to a CMOS camera (DMK 42BUC03, the Imaging Source). The exit pupil (4-mm diameter) is conjugated in the double-pass with the pupil plane trough the relay telescope. A camera objective ensures conjugation of the retinal plane with the CMOS sensor.

The optical layout was design to project a circular annular pattern of 22° of angular field on the retina. This pattern also includes a central occluder to avoid illuminating the central 1.6° of visual field that acts as the testing area.

If the eye has no straylight contributions, the measured intensity at the occluder of acquired DP image must be zero (or equivalently the offset minimum gray level of the camera). Conversely, the presence of scattering particles or straylight contributions produce a veil of light spread throughout the retina [22] as illustrated in Figs. 1(b) and 1(c).

2.2. Artificial eye and straylight model

The artificial eye employed in the experimental set up was composed of a 22-mm focal-length meniscus and a white screen static diffuser. A straylight eye model was constructed by incorporating light shaping diffusers (Luminit, LLC) at the retinal plane. The diffusers are based on holographic patterns imbedded in acrylic sheets that change the direction of the light energy according to a symmetric radial distribution. To generate different levels of straylight, different aperture angles of the diffusers were chosen: 0° (control), 5°, 20°, 30°, 60° and 80°. The proximity of the light diffusers to the image plane was chosen in order to obtain a reliable retinal image for all the elements of this particular set of light shaping diffusers.

To simulate the performance of the IOS effects, Zemax optical design software (Zemax OpticStudio, LCC) was used to model the diffusers incorporating the Luminit´s optical model to Zemax Dynamic Link Library (DLL) provided by the manufacturer. Figure 2 shows the simulation of the diffusers performed in non-sequential component (NSC). The left panels depict a uniform disk projected onto the retinal plane without [Fig. 2(a)] and with different angle apertures of the diffuser [Figs. 2(b) and 2(c)]. The right panels show the cross-sectional intensity profiles: The higher the aperture angle the lower the peak intensity and wider the angular distribution.

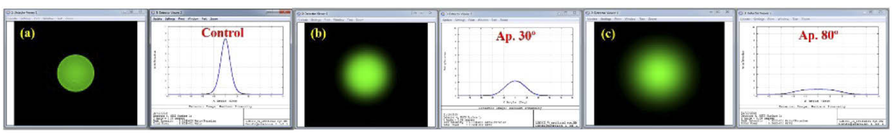

Fig. 2. Simulation of the diffusers in Zemax OpticStudio for different aperture angles (Ap.); control (a); 30° (b); and 80° (c), respectively. Right panels show the cross-sectional intensity profiles.

Once the diffusers were modeled, the optical layout shown in Fig. 1 was incorporated to a NSC Zemax file including the diffusers at the retinal plane of the eye model. To generate a realistic simulation of the illumination pattern, both LED source and fundus camera specifications were incorporated into the Zemax file.

2.3. Straylight index calculation

The aim of this work is to provide a direct measurement of the intraocular straylight by projecting a wide-field circular pattern on the retinal fundus using DP technology. The proposed algorithm is applied directly on the DP acquired image since the testing area corresponding to the central occluder contain the straylight information. The sequential algorithm is depicted in Fig. 3. After image acquisition, the angular field and the centroid of the occluder are detected (step 1), where $\boldsymbol{a}$, is the radius of the occluder in degrees and $\boldsymbol{\theta}$, the maximum visual angle (22°). Once "$\boldsymbol{a}$" and "$\boldsymbol{\theta}$" are stablished, a radial profile is computed to obtain the spatial intensity distribution corresponding to both the testing area and the annulus (step 3). Finally, the straylight index (SI) is calculated (step 4) by means of Eq. (1). To avoid undesired signal background and spurious reflections, a reference image was acquired before the imaging session and then every final image was the result of subtracting the reference from the original. A set of DP images were acquired for every aperture angle of the light diffusers placed at the retinal plane of an artificial eye (described in Sec. 2.2). Image processing was performed using MATLAB (The Mathworks Inc., Natick,

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MA).

$$\boldsymbol{SI(\theta)} = \frac{\left[\int_0^{a} \boldsymbol{I_{Dp}(\theta)d\theta}\right] / (Л \cdot \boldsymbol{a}^2)}{\left[\int_0^{\vartheta} \boldsymbol{I_{Dp}(\theta).d\theta}\right] / (Л \cdot \boldsymbol{\theta}^2)} \tag{1}$$

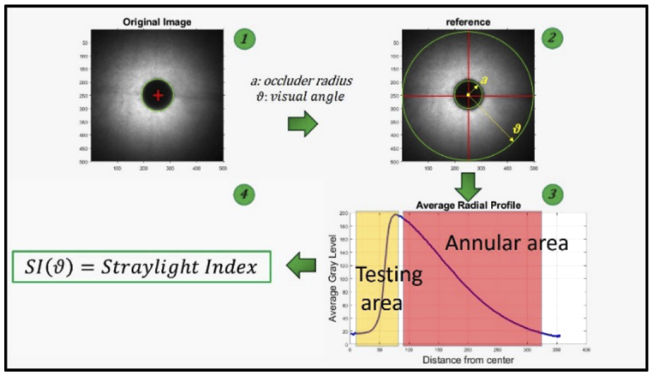

Fig. 3. Algorithm to compute the straylight index from wide-field DP circular patterns.

3. Results

Figure 4 compares the simulated and experimental DP images of the projected circular pattern for a straylight-free artificial eye and for different angles of aperture of the diffusers placed at the retinal plane. Clearly evident is the veiling effect induced by the diffusers and the scattered light contribution at the testing area. A visual inspection reveals that the higher the aperture of the diffuser, the stronger the straylight contribution at the testing area.

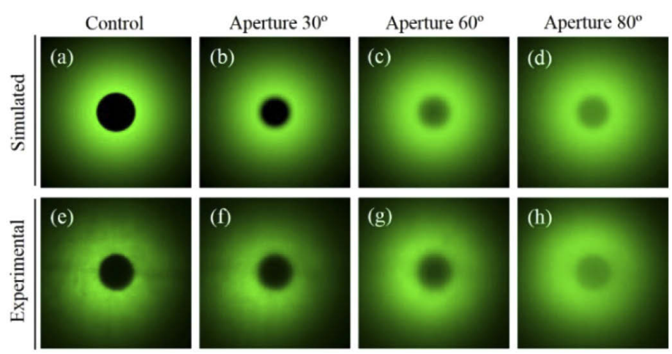

Fig. 4. DP images of the circular pattern (described in Fig. 1) as a function of the aperture angle of the retinal diffuser. For a better visualization of the central testing area, images have been cropped to a visual field of 6°. Images are shown at the same gray-scale level without normalization.

To quantify the straylight contribution shown in the DP images of Fig. 4, the algorithm described in Sec. 2.3 was applied to both simulated and experimental DP images. Figure 5 shows the average radial profiles obtained from the images corresponding to 30° [Fig. 4(b)], 60° [Fig. 4(c)] and 80° [Fig. 4(d)] aperture angles of the diffusers. No significant differences were found between experimental and simulated profiles.

Finally, the SI parameter was computed for the maximum visual field of 22° through the application of Eq. (1) in both experimental and simulated DP images. Figure 5(d) compares

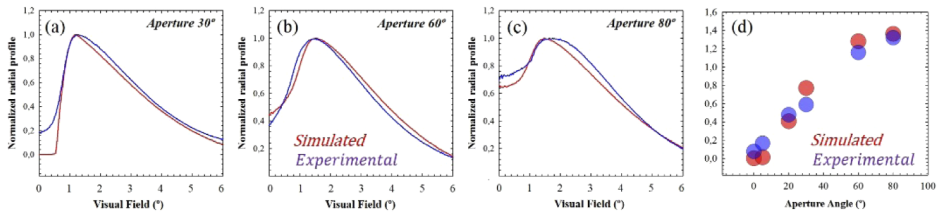

Fig. 5. DP images of the circular pattern (described in Fig. 1) as a function of the aperture angle of the retinal diffuser. For a better visualization of the central testing area, images have been cropped to a visual field of 6°.

the experimental and theoretical SI values as a function of the increasing aperture angle of the retinal diffusers. No significant differences were found between the theoretical and experimental values (Student´s t-test, p=0.981). These results allow to assume the capacity of the proposed methodology to directly quantify the IOS due to retinal diffusion.

4. Discussion and conclusions

In the present work, a new instrument to measure the IOS based on direct imaging measurement methodology has been presented. The performance of the optical instrument has been evaluated in an artificial eye and tested with holographic diffusers and compared with optical simulation carried out with Zemax optical design software.

IOS has been measured in the clinical practice through psychophysical methods over the past years [12,16,23,24]. According to the Commission of International de L'Eclairage (CIE), the disability glare due to straylight must be assessed by measuring the *PSF* of the eye [25], in particular paying attention to larger radial visual angles. There is a wide battery of optical methods that provide direct measurement of the central part of the *PSF* (see for instance Ref. [13]), however only an optical method exploring the peripheral areas of the PSF (up to 8° of visual field) providing objective IOS assessment of weak scattering media has been reported [26] so far. Increasing the field range of measurement, the proposed device opens the possibility to measure the IOS generated by clinically relevant scattering conditions, such as cataracts for instance.

In conclusions, we have implemented a DP-based instrument to measure intra-ocular scattering at large eccentricities (22° of visual field). The measurement methodology allows computing the IOS directly from the acquired image avoiding complex imaging post-processing or Fourier analysis [26], visualizing the fundus and the veiling effect at the testing area. The implementation of the instrument in a clinical prototype will allow the potential of exploring the wide-field IOS in the living human eye up to 22° of visual field by direct measurement of the DP images.

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Disclosures

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