Method to estimate the human pupil size from the bandwidth of coherent retinal images

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A new technique for extracting information on the size of the pupil of the human eye is presented. It is based on the recording of coherent short-exposure retinal images of a point source after double pass through the ocular media. The eye's pupil size is then estimated by computing the cutoff frequency in the power spectrum of these coherent images, which is related with the average width of the speckle. First the validity of the technique is established by use of an artificial eye, and then results are obtained in the living human eye. This method has the potential of determining the eye's pupil diameter with a standard error of the order of 0.1 mm and can be used in different visual optics experiments, although with its present components it is especially appropriate for experiments based on the recording of coherent retinal images.

Introduction

The size of the pupil in the human eye is continuously varying and depends both on the luminance of the visual field and on many other factors, such as accommodation, convergence, fatigue, attention, and spatial structure of object tests. Variations in pupil size affect both the intensity and the optical quality of the retinal image. Since the measurement of the pupil size is important in basic vision research and also in clinical applications, several different systems have been developed to measure the area (or width) of the pupil. Most of them use an infrared light as an illuminating source to avoid any influence on the examination conditions.

Typical pupillometer systems were based on scanning a small infrared spot across the eye and detecting the reflected flux.¹ More recently, closed-circuit TV pupillometers^{2,3} were proposed. In these systems the eye is illuminated by an infrared source, and an objective forms an image of the pupil on a TV camera that introduces the image into a computer for processing, detecting the diameter or area of the pupil. Several improvements of this method have been proposed, specifically in the illumination procedure and computer processing.⁴ Nowadays, pupillometers based on this principle are readily available and widely used.

The size of the pupil plays a major role both in retinal image quality and in visual performance. For this reason the pupil size is often precisely controlled in experiments on visual optics and spatial vision. Artificial pupils have been used extensively to maintain a constant pupil size during these experiments. However, the retinal image quality depends on the artificial pupil position,⁵ and it is not always easy to achieve an accurate centering. On the other hand, sometimes the use of artificial pupils is undesirable, for instance, when one is performing experiments under natural viewing conditions. The eye's image quality with natural pupil in the fovea; a double-pass method was used to record and process coherent retinal images of a point source after a double pass through the optical media. The point-spread function, the optical transfer function, and the wave aberration⁶⁻⁸ were computed by deconvolution and decorrelation of the averaged aerial retinal image. More recently the method has also been applied to determination of the eye's image quality in the peripheral retina⁹ and to the study of retinal reflection characteristics.¹⁰ Since these experiments were carried out under natural viewing conditions, the determination of the pupil size during the measurements was a major issue. The pupil size during each exposure was measured with a new, inexpensive infrared TV pupillometer. This system yields pupil size results with an accuracy of the order of 0.2 mm. In the course of these measurements of the eye's image quality, I developed the method reported in this paper to measure the pupil size.

This new technique takes advantage of the spatial

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characteristics of the coherent retinal images (speckle structure and limited bandwidth), and it is based on the recording of coherent retinal images of a point source and computing the eye's pupil size from the cutoff frequency of the power spectrum of speckle retinal images. The relation between the spatial structure of a speckle pattern and the pupil size of the image-forming optical system, a well-known phenomenon in optical physics,^{11,12} is applied here to determine the human pupil size from the bandwidth of coherent retinal images. Because of the nature of the method, it is especially appropriate to measure the pupil size during experiments in which coherent retinal images are recorded, as in several systems already proposed.^{6,13} Nevertheless, further improvements in the components of this system, mainly by use of an infrared laser for illumination and intensified camera in the recording, would permit more general applications.

In what follows, a description of the experimental system and of the image-processing techniques, along with typical experimental results and conclusions, is presented.

Methods

Description of the Apparatus

The experimental system used to record the coherent retinal images of a point source in the fovea is depicted in Fig. 1. It is a modification of a double-pass optical-digital system used to assess the image quality of the eye.⁶ A He-Ne laser ($\lambda = 632$ nm), with nominal power 10 mW, is used as the light source. First the beam passes through an optional neutral low-density filter used to match the beam intensity to the optimum CCD camera sensitivity range for each particular experimental condition (pupil size, image quality, etc.). A second, high-density filter, with $D = 4$, attached to a rotary solenoid (R) attenuates the intensity of the beam, allowing the subject to comfortably look at the point source. During the short exposure time, this filter is removed, synchronized with the camera, acting as a flash shutter. The beam is expanded by a $20\times$ microscope objective (M) and filtered by a $10\text{-}\mu\text{m}$ pinhole (P), which acts as the test object (O). The diverging beam is collimated by lens L_1 ($f' = 200$ mm). After reflecting in a pellicle beam splitter, the beam passes through a two-lens system (L_3 and L_4), both lenses having the same focal length (f), and the eye forms the image of O on the retina O' .

A small fraction of the incident light is reflected in the fundus, passing again through the ocular media, lenses L_3 and L_4 , and the beam splitter. Lens L_2 ($f'_2 = 500$ or 1000 nm) forms the aerial image O'' of the retinal O' on the CCD camera (Pulnix TM-745). The lens permits the magnification of the system to be approximately $30\times$ or $60\times$ (ratio between the eye and lens L_2 foci). The aerial retinal image is digitized and stored on an AT computer by means of a frame grabber-image processing board (Matrox MVP-AT). This system was calibrated previously to have

Fig. 1: Experimental setup of the proposed technique to measure the eye's pupil diameter. System for recording the coherent retinal image of a point test (O''). ODF, optical density filter; DF, high-density filter; R, rotary solenoid; M, objective microscope; P, pinhole; O, point object test; D, stop; L_3 , L_4 , lenses, both with the same focal length (f); IPC, infrared TV-camera pupillometer system; IS, infrared source.

a horizontal pixel size of $12.5\text{ }\mu\text{m}$ and a vertical size of $11.1\text{ }\mu\text{m}$. Since the aspect ratio is not equal to 1, it must be corrected during the later image-processing procedure. The aerial coherent image O'' is oversampled more than twice the Nyquist frequency to prevent aliasing, since the interlaced scan of the camera causes the real vertical resolution to be half of the theoretical value.

The setup is designed in such a way that the eye's pupil is imaged on L_2 by the two-lens system (L_3 and L_4): the pupil of the eye is placed a distance f from L_4 , and L_2 is a distance f from L_3 . This system configuration ensures that the mean speckle size and the bandwidth of the images in the recording plane are determined by the eye pupil diameter, when this is smaller than the illuminating beam width. The high-density filter is removed from the beam at the same time that the short-exposure images are grabbed. The exposure time affects the speckle contrast that is due to the eye movements. The contrast in the images is sufficiently good up to exposure times of close to 1 s. However, in this particular experiment

carried out to validate the technique the exposure time was 2 ms (controlled by the electronic shutter of the CCD camera). With respect to eye safety, the longest laser exposure time used in these experiments was ~ 100 ms, with a maximum laser power irradiance in the eye pupil plane of 0.1 mW/cm^2 . Taking into account the area of the retinal image and the duration of the snapshot, I found that the laser exposure is at least 1 order of magnitude below the American National Standards Institute laser safety standards,¹⁴ (for direct viewing into a He-Ne laser beam, the American National Standards Institute value is above 1 mW/cm^2 for the exposure time 0.1 s).

When the experiment is carried out in natural viewing conditions an additional pupillometer system (IPC in Fig. 1) is used to obtain another pupil size measurement as a reference. That system is a version of an infrared TV camera pupillometer. An infrared source (IS) illuminates the front of the eye, and a CCD camera introduces the image of the pupil, with a given magnification, in a computer. The pupil size is then determined either by an operator using a calibrated reticle on a TV monitor or by subsequent computer processing with an accuracy of around 0.2 mm.

Experimental Procedure and Image Processing

We record the desired number of short exposure images of the point test during the particular experiment. First we correct each frame (512×512 pixel image with 8 bits/pixel) for both bias and pixel sensitivity differences, subtracting the dark current image and dividing by a flat field white image. A background image is also subtracted from each retinal image. We obtain these images by taking a snapshot when a black diffuser is placed in the position of the eye's pupil. We correct the pixel aspect ratio by computing new samples by interpolation in the y axis. Then the Fourier transform of the processed coherent image is performed by a fast Fourier transform algorithm, and the logarithm of the magnitude of the spectrum, $\{\log[1 + F(u, v)]\}$, is calculated. The exit pupil size (in our setup the same as the eye pupil) is directly related to the cutoff frequency (ν_N) in the power spectrum of the coherent retinal image by¹²

$$D = \lambda f_2' \nu_N, \quad (1)$$

where λ is the wavelength of the light (in this case 632 nm), f_2' is the focal length of lens L_2 , and D is the diameter of the eye's pupil for this particular setup.

Calibration of the Apparatus

First I calibrated by placing an artificial eye, consisting of a lens with a diffuser in its focal plane, in place of the eye. Images of a point source with 0.5-ms exposure time were obtained for different pupil diameters from 3 to 7 mm. Figure 2 shows how pupil size affects the appearance of the speckle images (Figs. 2a and 2b: 3- and 6-mm pupil diameter, respectively). The corresponding two-dimensional logarithm of the

Fig. 2. Contour plots of the speckle images obtained in the calibration process with an artificial eye and pupil diameters of a, 3 mm and b, 6 mm.

power spectrum of these two images are also presented in Fig. 3, in a saturated scale in intensity to permit a better visual discrimination of the location of the cutoff frequency (ν_N). To determine this value in the cases of foveal coherent images, I computed the radial projection of the logarithm of the spectrum, averaging the two-dimensional function over all orientations. A typical example of these results is shown in Fig. 4 (solid curve). The procedure to determine the zero value (cutoff frequency) in the power spectrum is based in the idea that the higher spatial frequency part in this logarithm representation follows a straight line quite well. This function is fitted to the high spatial frequency part of the spectrum (see Fig. 4), and then it is subtracted from the original radial projection curve, yielding the processed one-dimensional spectrum (dashed curve in Fig. 4).

(a)

(b)

Fig. 3. Power spectra of the speckle images of Fig. 2. They are presented in a saturated intensity logarithm scale to permit a better discrimination of the cutoff frequency location.

Fig. 4. Radial projection of the logarithm of the spectrum of a speckle image obtained with the artificial eye with 3-mm pupil diameter (solid curve). The dashed curve corresponds to the same data after subtraction of the fitted straight line to the high spatial frequency part.

Fig. 5. Radial projections of the logarithm of the spectra of images (after subtraction of the straight line) obtained with the artificial eye for different pupil diameters.

Finally, the smaller spatial frequency giving a value of the processed logarithm of the spectrum lower than 0.01 is taken as the cutoff limit (ν_N). Figure 5 shows the resulting curves obtained for the artificial eye after this processing for four different pupil sizes. The arrows in the figure indicate the expected actual locations of the cutoff frequencies for the four pupil sizes considered in this calibration procedure. Table 1 presents the measured pupil diameters results compared with the actual values of the pupils. These estimations of the pupil diameters give the correct values with an approximate mean standard error of $\sim 1\%$. In principle, that would permit the determination of the pupil size with an accuracy better than 0.1 mm.

In the cases of coherent retinal images recorded for locations in the peripheral retina instead of the fovea, the method could also be used to determine both the shape (related with the eccentricity) and the size of the pupil. However, in these cases we cannot compute the radial projection averaging because the elliptical shape of the power spectrum. We simply perform the same procedure as that indicated above but to linear sections in the horizontal and vertical directions of the power spectrum. This slightly reduces the accuracy of the technique because the larger amount of remaining noise in the sections of the spectrum.

Table 1. Results of the Calibration Process Using an Artificial Eye

Artificial Eye Pupil Diameter (mm)	Results Obtained with the Technique (mm)	Error (%)
3	2.97	0.7
4.3	4.2	2.2
5	4.96	0.8
6	5.95	0.7

After this calibration with an artificial eye, measurements were also carried out with the living eye, first with an artificial pupil of known diameter. The mean standard errors of these results were quite similar to those previously obtained with the artificial eye. An even lower standard error can be obtained by averaging several independent coherent image spectra before computing the pupil diameter. Nevertheless, even when the less favorable situation is considered, as in the previous calibration process (no averaging, considering only one image), the accuracy of this method seems good enough for most practical cases.

Results

In this section, pupil size measurements in the human eye, obtained by using the method described above, are presented. To permit a comparison of the results, I also measured the pupil diameter simultaneously, using an infrared TV-camera pupillometer (IPC in Fig. 1), for which an operator determines the pupil size during the recording of the retinal images. Figure 6 shows the logarithm of the power spectrum of a coherent retinal image for the emmetropized subject PA, which has been presented in a saturated intensity scale to permit an easier discrimination of the location of the cutoff frequency. As a comparison with the results obtained in the calibration with the artificial eye, Fig. 7 shows the radial projection of two spectra, one corresponding to the retinal images for subject PA (solid curve) and the other to the artificial eye (dashed curve). In the case of the artificial eye, the curve is steeper for values around the cutoff frequency. The reason is that larger optical aberrations in the human eye produce lower values of the spectrum for spatial frequencies below the cutoff limit. Nevertheless, the method is robust enough to problems of defocus, for instance, when the eye's

Fig. 6. Power spectrum of the coherent retinal image for the subject PA for 3-mm pupil diameter presented in a saturated intensity scale to permit a better discrimination of the cutoff frequency location.

Fig. 7. Comparison of radial projection of the logarithm of power spectra when either the artificial eye (dashed curve) or the human eye (solid curve) is used.

subject is not in the best refractive state or well accommodated, the method still works properly, although the procedure to compute the cutoff frequency yields a larger standard error.

Figure 8 shows the radial projection of the logarithm of the power spectra for two different pupil sizes along with the expected location of cutoff frequency, obtained from simultaneous measurements with the infrared TV-camera pupillometer. For pupils of 4- and 5.8-mm diameters, respectively the technique yields values of 4.03 and 5.87 mm. Also, note the steeper decay of the 4-mm case radial projection that is due to a smaller contribution of the aberrations for that smaller pupil diameter. For larger pupils (more than 6 mm diameter) it is necessary to change the focal length of L_2 from 500 to 1000 mm to maintain a similar accuracy.

The technique does not require special alignment of the subject. In the present setup configuration the illuminating beam is of the order of 8 to 10 mm in diameter, and in consequence the subject's head can be moved several millimeters without changing the results.

Conclusions

In the course of the recording of coherent retinal images I have discovered an indirect way to measure the size of the eye pupil from the cutoff frequency of its power-spectrum value related to the average size of the speckle in those images. This new technique for measuring the human pupil diameter is in principle especially designed to be used in experiments in which coherent retinal images are recorded. However, future improvement of the components in the system, by using infrared laser for illumination and image-intensified camera in the recording together with appropriate real-time image processing, would

Fig. 8. Radial projections of the logarithm of power spectra for the subject PA after (solid curve) and before (dashed curve) processing for a, 4-mm and b, 5.8-mm pupil diameter.

permit a more general use of pupillometer systems based on this principle. The calibration with an artificial eye and typical experimental results in the living human eye indicate that the technique can have an accuracy of ~ 0.1 mm. This precision is

similar to that of infrared TV-camera pupillometers, and consequently it may already be used in experiments where coherent retinal images have to be recorded under natural viewing conditions.

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