2075

Optical-digital procedure for the determination of white-light retinal images of a point test

Pablo Artal
Javier Santamaría
Julian Bescós
Consejo Superior de Investigaciones Cientificas
Instituto de Optica
Serrano 121
28006 Madrid, Spain

Abstract. The white-light point spread function (PSF) of the human eye is computed from monochromatic results obtained by a hybrid optical-digital procedure. The method is based on the linear recording of monochromatic aerial short-term retinal images of a point test. From these data, the monochromatic PSF is computed, and the wave aberration of the human eye is retrieved from the actual PSF by means of a phase retrieval method. The white-light PSF is generated by a digital image processing system from the monochromatic wave aberrations corresponding to three different wavelengths. The procedure proposed here allows a more complete evaluation of the optical image quality in the human eye and can be used in a variety of practical applications. As an example, the methodology is used to obtain objectively information on the reflecting layers in the retina for different incident wavelengths.

Subject terms: image processing; physiological optics; vision.

Optical Engineering 28(6), 687-690 (June 1989).

CONTENTS

1. INTRODUCTION

The optical image quality of the dioptrics of the human eye generally has been described in terms of the unidimensional modulation transfer function (MTF). This function usually has been obtained from measurements of aerial retinal images of line or grating tests formed by double pass through the optical media of the eye.[1-3] However, taking into account the asymmetries of the wave aberration of the eye and the irregularities of the retina, it is more appropriate to use a point as the object test to obtain complete bidimensional information.

Previously, we developed a method for the dynamic recording of the monocular and binocular aerial retinal images of a point source.[4] This method allowed us to visualize the aerial retinal images and to study their temporal variations, the binocular interaction effects, and the microfluctuations of the accommodation. However, owing to limitations in the incident energy, a nonlinear light intensifier was used in the recording step. The method proved to be useful for comparative and qualitative studies, but quantitative analysis was not possible because of the nonlinearity in the recording. To overcome this difficulty, we recently presented a hybrid optical-digital method for determining the monochromatic point spread function (PSF) of the human eye.[5]

Paper 2593 received June 20, 1988; revised manuscript received Dec. 3, 1988; accepted for publication Jan. 26, 1989.

In spite of the interest in white-light image quality determinations in the human eye, the polychromatic PSF has not yet been obtained, owing mainly to experimental limitations. A. van Meeteren[6] calculated the unidimensional MTF for white light using aberration data previously presented in the literature. Bour[7] computed the white-light MTF from monochromatic measurements obtained by psychophysical methods. His unidimensional white-light MTF results were approximately similar to the monochromatic MTF previously measured.

In this paper, we present a digital generation of the bidimensional white-light PSF computed directly from three monochromatic aerial retinal images obtained by the hybrid optical-digital procedure.[5] Finally, the complete methodology is used to determine differences in the relative positions of the retinal layers responsible for the reflection of different wavelengths.

2. OPTICAL-DIGITAL PROCEDURE FOR MONOCHROMATIC PSF AND WAVE ABERRATION DETERMINATIONS

In this section, we briefly describe the procedure for determining the monochromatic PSF and wave aberration. The method[5] is based on a double-pass setup characterized by the use of a spatial filter pinhole as the point object test and a He-Ne laser beam ($\lambda = 632$ nm) as the light source. The beam enters the eye and forms the image of the point test on the retina. The light reflected from the retina leaves the eye, and a lens forms the aerial retinal image on the photocathode of a calibrated TV camera, which introduces the image into a digital image processing system. To record linearly and with the incident energy below the safety standards, only instantaneous images (1/15 s exposure) are obtained. The corneal irradiance is always lower than 0.2 mW/cm^2, which is more than one order below U.S. safety standards.[8] The aerial image is computed by averaging a number of short-term images to

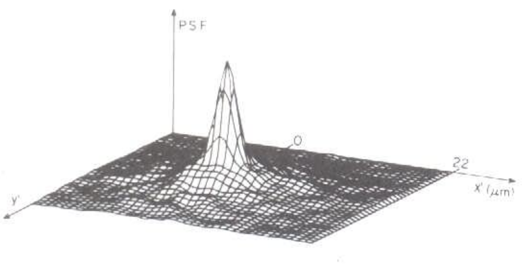


Fig. 1. Isometric plot of the bidimensional monochromatic (632 nm) retinal image of a point test (PSF) for an emmetropized subject.

get the image that would be obtained with a long recording time. This is equivalent to considering the second pass as an incoherent imaging process. If we assume incoherent image formation in the second pass, the PSF can be calculated directly by deconvolution of the averaged aerial retinal image. By a subsequent Fourier transformation, the bidimensional optical transfer function is also obtained. The isometric plot of the bidimensional PSF for an emmetropic subject having a 6 mm pupil diameter is shown in Fig. 1. The results were obtained in normal sight conditions and in foveal vision. The wave aberration function contains complete information on the image quality and allows one to predict the evolution of the image quality (PSF) under different conditions. Taking this characteristic into account, the optical-digital procedure has been completed by developing a phase retrieval method to compute the wave aberration.[9] This function is retrieved from the actual PSF data and the modulus of the complex pupil function. The retrieval is done by application of a bidimensional Gerchberg-Saxton algorithm[10] joined to an iterative phase-unwrapping procedure.[11]

To improve the convergence, the initial wave aberration for starting the algorithm was estimated using an iterative nonlinear least squares phase retrieval method.[12] In all cases, the retrieved wavefront aberrations for emmetropic subjects show irregularities superimposed on the regular components and important regular asymmetric aberrations.[9] Figure 2 shows the contour plot at $\lambda/2$ intervals of the regular components of the wave aberration retrieved from the actual PSF shown in Fig. 1. The results in all subjects considered show an important contribution of the asymmetric aberrations. The OTF is always a complex function. Its phase, the PTF, plays an important role in image quality determinations. Its influence on PSF and wave aberration also has been evaluated recently.[13]

3. COMPUTATION OF THE WHITE-LIGHT PSF

The polychromatic PSF can be computed as a weighted superposition of the monochromatic components.[14] In this work, the monochromatic results are obtained by the procedure outlined above. However, additional experimental difficulties appear when wavelengths shorter than red are used. The two main reasons that explain this point are the lower retinal reflection factor[15] corresponding to shorter wavelengths and the higher spectral sensitivity of the central region of the visible spectrum. Owing to these, the recording of retinal images of a point test in green and blue light is not as comfortable for the subjects as in red light. In spite of this, the PSF and subsequently the wave aberration are obtained using an ion Ar laser beam with wavelengths of 476 nm (blue) and

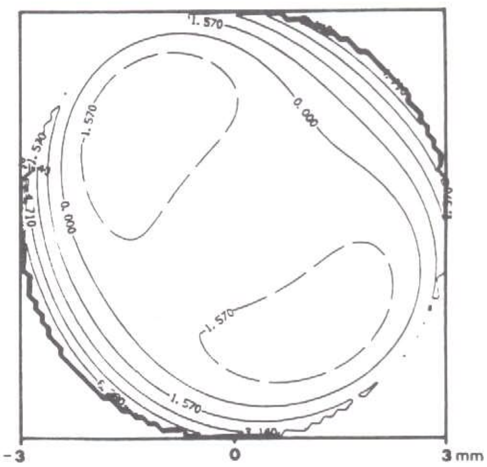


Fig. 2. Contour plot at $\lambda/2$ intervals of a polynomial expansion of the wave aberration function retrieved from the PSF.

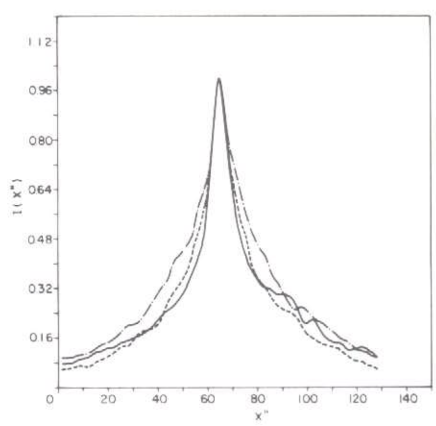


Fig. 3. Sections of the experimental results of the aerial retinal images obtained by using the hybrid optical-digital method with different wavelengths. Dashed line—$\lambda = 476$ nm; solid line—$\lambda = 514$ nm; dashed/dotted line—$\lambda = 632$ nm.

514 nm (green) and a He-Ne laser beam at 632 nm (red). The subjects used in the study had normal vision and a pupil diameter between 5 and 6 mm.

Due to the energy limitation in the recording, only when the subject is in the best state of accommodation are the aerial retinal images brilliant enough to be digitized. Moreover, the pinhole constitutes both an accommodation test and a point test.[5] The measurements were performed with the subject in the best state of accommodation for the three wavelengths used. Under this condition, the longitudinal chromatic aberration is minimized by the accommodation of the subject. Information on only monochromatic aberration is then obtained for each wavelength.

Sections of the experimental results of the aerial retinal images for the three different wavelengths used in the experiment are shown in Fig. 3.

The procedure to compute the white-light PSF from these monochromatic aerial retinal images is as follows: Each monochromatic PSF is computed from the aerial image by direct deconvolution. Subsequently, by use of the phase retrieval method,[9] the monochromatic wave aberrations are determined from the PSFs. At this point, we introduce in the

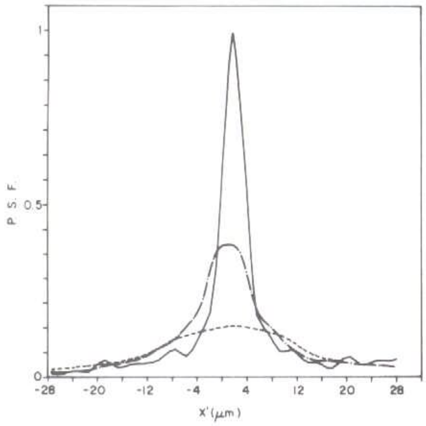


Fig. 4. Sections of the actual monochromatic PSF computed by considering the chromatic aberration data. Dashed/dotted line—λ = 476 nm; solid line—λ = 514 nm; dashed line—λ = 632 nm.

computations the longitudinal chromatic aberration data present in the literature.[16] To do this, we add the defocusing coefficient to the wave aberration functions and compute the actual monochromatic PSF $[P_\lambda(x',y')]$ by means of the expression

$$P_\lambda(x',y') = \left| \iint_{\alpha^2+\beta^2\leq 1} \exp\left\{ i\,\frac{2\pi}{\lambda}\,[W_\lambda(\alpha,\beta) + W_{c\lambda}(\alpha^2+\beta^2)] \right\} \times \exp\left[i\,\frac{2\pi}{\lambda f'}(\alpha x' + \beta y') \right] d\alpha d\beta \right|^2 , \qquad (1)$$

where x′ and y′ are retinal image plane coordinates, α and β are normalized pupil coordinates, $W_\lambda(\alpha,\beta)$ is the wave aberration, $W_{c\lambda}$ is the chromatic aberration coefficient, λ is the corresponding wavelength, and f′ is the mean focal length of the human eye.

Sections of the bidimensional PSF results computed by Eq. (1) and containing the chromatic aberration information for each wavelength are shown in Fig. 4. The last step in the procedure is the generation in a digital image processing system of the white-light PSF from these monochromatic PSF data $[P_\lambda(x',y')]$. The computer generation is performed as a weighted superposition of the monochromatic components present in Fig. 4. The result is shown in Fig. 5. The computer-generated polychromatic results show an image quality similar to the monochromatic results. Other significant facts present in the results are the irregularities and the differences in the results for individual emmetropized subjects.

4. APPLICATION OF THE METHOD FOR RETINAL REFLECTION EVALUATION

The methodology presented here can be used in a variety of applied studies to determine physical parameters of the eye's optical system. As an example, we report here an evaluation of the retinal reflection for incident light of different wavelengths. On this point, Charman and Jennings[16] found discrepancies between measurements of longitudinal chromatic aberration performed by two different methods, objective and subjective, for the same eye. Glickstein and Millodot[17] also

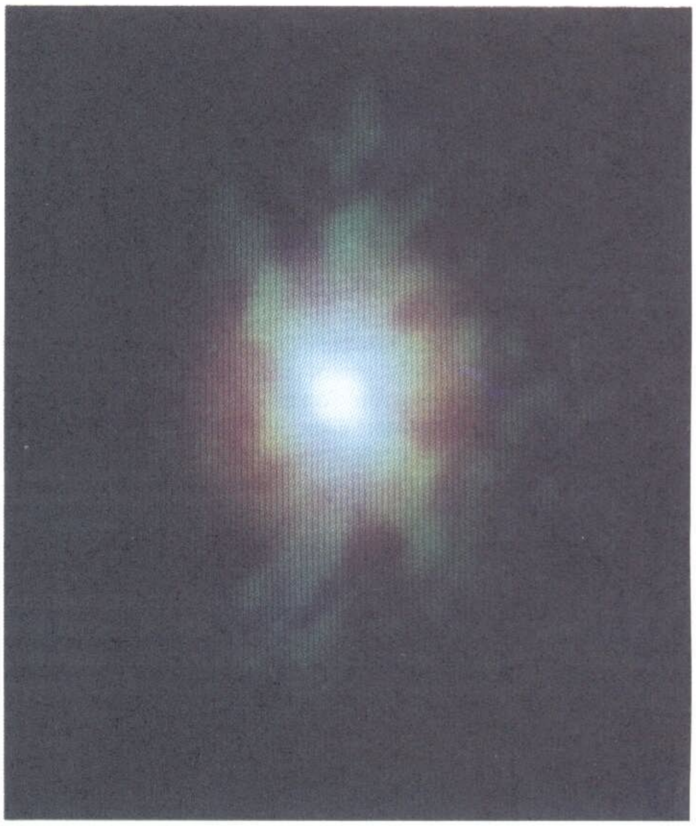


Fig. 5. White-light PSF of an individualized human eye generated in an image processing system from monochromatic experimental retinal images.

found discrepancies in retinoscopy measurements. These discrepancies could be explained by assuming that light of different wavelengths is reflected from different layers in the retina. However, as far as we know there are no data obtained in a completely objective way on the relative positions of such reflecting retinal layers.

We have used a part of the method just described to obtain additional information on this point based exclusively on objective experimental measurements of retinal images. The methodology consists of analyzing defocusing coefficients present in the monochromatic wave aberrations that have been retrieved from the PSF data obtained with three wavelengths. From these defocusing factors we are able to correlate differences in the relative positions of reflecting layers in the retina for different wavelengths. The procedure is as follows: An incident beam with wavelength λ enters the eye and is reflected in a retinal layer separated by a distance Δz from the photoreceptor image plane. After the double pass through the eye, an additional defocusing factor W_λ^o is introduced in the wavefront, given by

$$W_\lambda^o = \frac{n'}{2}\sin^2\gamma\Delta z , \qquad (2)$$

where n′ is the mean index of refraction and γ is the numerical aperture of the eye. By using the phase retrieval method,[9] we compute the wave aberration $W_\lambda(\alpha,\beta)$ from the aerial retinal images. Each of these wave aberrations contains information about the defocusing factor introduced in the retinal reflection W^o_λ. The wave aberration is then fit to a polynomial expansion to separate the defocusing factor:

$$W_\lambda(\alpha,\beta) = W'_\lambda(\alpha,\beta) + W^o_\lambda(\alpha^2 + \beta^2) \ . \qquad (3)$$

By comparison of the factors W^o_λ obtained for different wavelengths, we can correlate the differences between the relative positions in the retinal reflection. The method has two limitations: the noise present in the experimental retinal images and convergence errors in the phase retrieval algorithm. However, we have been able to obtain repetitively significant differences between the defocusing factors obtained in several wavelengths. The results show mean values for the distance between the layers responsible for greeen (514 nm) and red (632 nm) light reflection of the order of 30 μm, with slight dependence on the subjects. These are the first data obtained by means of a completely objective procedure that can confirm the explanation of the discrepancies in chromatic aberration and retinoscopy measurements found in previous works.

5. CONCLUSIONS

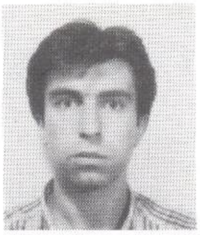
An optical-digital procedure that allows the computer generation of the white-light point spread function (PSF) of the human eye has been presented. The method is based on the recording of monochromatic aerial retinal images of a point test for different wavelengths. The white-light PSF is computed in a digital image processing system by using the wave aberrations retrieved from the monochromatic PSF. The results allow us to describe more completely the optical image quality of the living human eye in foveal vision. Using this method, we have obtained the first objective results corresponding to the differences in the relative positions of retinal layers responsible for the reflection of green and red incident light.

6. ACKNOWLEDGMENTS

The authors thank Ana Plaza and Manuel Pérez for their helpful collaboration and technical assistance. This research was supported by Comisión Asesora de Investigación Científica y Técnica grant 2520/83, Ministerio de Educación y Ciencia, Spain.

7. REFERENCES

1. M. F. Flamant, "Etude de la repartition de lumière dans l'image retinienne d'une fente," Rev. Opt. 34, 433–459 (1955).
2. J. Krauskopf, "Light distribution in human retinal images," J. Opt. Soc. Am. 52, 1046–1050 (1962).
3. F. W. Campbell and R. W. Gubisch, "Optical performance of the human eye," J. Physiol. 186, 558–579 (1966).
4. A. Arnulf, J. Santamaría, and J. Bescós, "A cinematographic method for the dynamic study of the image formation by the human eye. Microfluctuations of the accommodation," J. Opt. 12, 123–128 (1981).
5. J. Santamaría, P. Artal, and J. Bescós, "Determination of the point-spread function of human eyes using a hybrid optical-digital method," J. Opt. Soc. Am. A 4, 1109–1114 (1987).
6. A. van Meeteren, "Calculations on the optical modulation transfer function of the human eye for white light," Opt. Acta 21, 395–412 (1972).
7. Lo. J. Bour, "MTF of the defocused optical system of the human eye for incoherent monochromatic light," J. Opt. Soc. Am 70, 321–328 (1980).
8. D. Sliney and M. Wolbarsht, *Safety with Lasers and Other Optical Sources*, Plenum, New York (1980).
9. P. Artal, J. Santamaría, and J. Bescós, "Retrieval of the wave aberration of human eyes from actual P.S.F data," J. Opt. Soc. Am. A 5, 1201–1206 (1988).
10. R. W. Gerchberg and W. O. Saxton, "A practical algorithm for the determination of phase from image and diffraction plane pictures," Optik 35, 237–246 (1972).
11. A. V. Oppenheim and R. W. Schafer, *Digital Signal Processing*, Prentice-Hall, Englewood Cliffs, N.J. (1975).
12. W. H. Southwell, "Wave-front analyzer using a maximum likelihood algorithm," J. Opt. Soc. Am. 67, 396–399 (1977).
13. P. Artal, J. Santamaría, and J. Bescós, "Phase-transfer function of the human eye and its influence on point spread function and wave aberration," J. Opt. Soc. Am. A 5, 1791–1795 (1988).
14. M. J. Yzuel and J. Santamaría, "Polychromatic optical image. Diffraction limited system and influence of the longitudinal chromatic aberration," Opt. Acta 22, 673–690 (1975).
15. D. Van Norren and L. F. Tiemeijer, "Spectral reflectance of the human eye," Vision Res. 26, 313–320 (1986).
16. W. N. Charman and J. A. M. Jennings, "Objective measurement of the longitudinal chromatic aberration of the human eye," Vision Res. 16, 999–1005 (1975).
17. M. Glickstein and M. Millodot, "Retinoscopy and eye size," Science 168, 605–606 (1970).



Pablo Artal was born in Zaragoza, Spain, in 1961 and received the MS degree in physics from the University of Zaragoza in 1984 and the Ph.D. degree in physics from the University Complutense, Madrid, in 1988. He is now a postdoctoral fellow at the Instituto de Optica, Madrid. His major research interests are vision, image processing, and image understanding.

Javier Santamaría received his MS and Ph.D. degrees in physics from the University of Zaragoza, Spain, in 1969 and 1973, respectively. Then he joined the Instituto de Optica, Madrid, where he has been working as a research scientist in the fields of image evaluation, image processing, and vision. Now he is working in optical engineering at Sener Ingenieria y Sistemas, Madrid.

Julian Bescós received the Ph.D. degree in physics in 1973 from the University of Zaragoza, Spain, where he worked as an assistant professor from 1969 to 1972. Then he joined the Instituto de Optica, Madrid, where he has been involved in the fields of optical evaluation, image processing, and vision. He has held several positions on the boards of optical societies in Europe. Now he is working at the Fundacion Ramon Areces, Madrid.