Available online at www.sciencedirect.com
ScienceDirect
Optik 121 (2010) 101–106
Optik Optics
www.elsevier.de/ijleo

Measurements of retinal aerial image modulation (AIM) for white light based on wave-front aberration of human eye

Tao Liu[a], Zhao-Qi Wang[a,*], Yan Wang[b], Guo-Guang Mu[a], Kan-Xing Zhao[b]

[a]*Key Laboratory of Opto-Electronic Information Science and Technology, Ministry of Education, Institute of Modern Optics, Nankai University, Tianjin 300071, PR China*
[b]*Tianjin Eye Hospital, Refractive Surgery Center, Tianjin 300020, PR China*

Received 25 January 2008; accepted 24 May 2008

Abstract

The aerial image modulation (AIM) curve of retina under the condition of white light is obtained based on the wave-front aberration of human eye. According to the relationship between the wavelength and defocus, we modify the monochromatic wave-front aberration data to calculate the modulation transfer function (MTF) of human eye in the white-light illumination. Combined with the measurement of contrast sensitivity function (CSF) for complete eye and visual acuity (VA) under the same luminance condition, we deduce the AIM curve in natural light. We find that AIM varies slightly at lower and intermediate spatial frequencies among different eyes; at higher frequencies AIM is the predominant factor for VA when the wave-front aberration is not significant. In addition, retinal AIM is expressed in terms of neural contrast sensitivity function (NCSF) which is the clinical valuable for ophthalmologists. Considering the real illumination circumstance, it is of practical significance to obtain the AIM curve and NCSF curve under white-light condition.

Keywords: Wave-front aberration of eye; Contrast sensitivity function; Modulation transfer function; Aerial image modulation

1. Introduction

The visual function of human eye can be broken down into two cascading processes. One is the optics of the eye which forms an image on the retina, the other is the retina–brain course which consists of perception by the photoreceptor, neural interactions in the retina and subsequent visual pathways [1]. When degeneration of visual performance occurs, it is imperative to locate the problem so that the ophthalmologist can readily diagnose the disease and improve clinical eye care practice.

Presently, visual acuity (VA) and contrast sensitivity function (CSF) are the main parameters for the ophthalmologist to evaluate the performance of visual system. Compared with the VA, CSF can provide more information for some ocular disease including glaucoma, lens opacity and diseases of the retina and optic nerve [2]. However, both VA and CSF reflect the visual performance of complete eye. Once CSF curve fluctuates abnormally, it is difficult to determine whether the dioptrics or the retina–brain process should account for the peculiarity. Retinal aerial image modulation (AIM) represents the contrast threshold that the photoreceptor

*Corresponding author.
E-mail address: wangzq@nankai.edu.cn (Z.-Q. Wang).

0030-4026/$ - see front matter
doi:10.1016/j.ijleo.2008.05.021

of retina can detect at different spatial frequencies which, starting from the retina, circumvents the optics of the eye and reveals the character of retina, neural system and visual center. Measurement of the AIM of human retina has been made by the well-known interference fringe technique [3] which formed a sinusoidal pattern with tunable spatial frequency and contrast level directly on the retina. In consequence, the AIM acquired with the method mentioned above corresponds to monochromatic light. For real-world vision, human eye perceive white light rather than monochromatic, so it is meaningful to attain retinal AIM in natural light. To the best of our best knowledge, there has been no white-light AIM reported yet.

Adapted for measuring wave-front aberration of human eye by Liang and colleagues [4] in 1994, Hartmann–Shack sensor technique has been employed extensively in research laboratories and available as a commercial instrument in related clinical disciplines. Since the measurement of wave-front aberration of human eye provides relatively accurate and rich information of the eye's optical system, it is of convenience to reveal the contribution of dioptrics to the overall visual performance. On account of separating the optical component from the entire process, the features of the neural factors can be brought to light.

In this paper, wave-front aberration measurements of 10 normal eyes are made, using a Hartmann–Shack wave-front aberrometer. Given dependence of the wavelength and wave-front aberration, we calculate monochromatic optical transfer function (OTF) at different wavelengths and deduce the OTF of white light by summing the weighed OTF at each individual wavelength. The modulation transfer function (MTF) of white light is then obtained. On the other hand, the characteristics of complete eye can be acquired with the traditional CSF test. According to the relationship between CSF and MTF, the retinal AIM of white light is obtained.

2. Methods

2.1. Calculation of MTF in white light

The wave-front aberration of human eye obtained by a Hartmann–Shack sensor can be decomposed into a set of Zernike polynomials. Formally, it has the form [5]

$$W(x,y)=\sum_k C_k Z_k(x,y) \tag{1}$$

with $W(x,y)$ being a Cartesian representation of the wave aberration on exit pupil, $Z_k(x,y)$ the kth Zernike polynomial function and C_k the coefficient of the Zernike polynomial.

The pupil function can be given by

$$P(x,y)=p(x,y)\exp\left[-\mathrm{i}\frac{2\pi}{\lambda}W(x,y)\right] \tag{2}$$

where

$$p(x,y)=\begin{cases}1 & \text{in pupil}\\ 0 & \text{out pupil}\end{cases}$$

and λ is the measuring wavelength of the aberrometer. The optical performance of the human eye, as the first step in visual processing, is described by OTF, which is the autocorrelation of the pupil function $P(x,y)$ [6] given by

$$\mathrm{OTF}(f_x,f_y)=\frac{\iint_{S_{\text{pupil}}} P\left(\xi-\frac{\lambda d_i f_x}{2},\eta-\frac{\lambda d_i f_y}{2}\right)P^*\left(\xi+\frac{\lambda d_i f_x}{2},\eta+\frac{\lambda d_i f_y}{2}\right)\mathrm{d}\xi\,\mathrm{d}\eta}{\iint_{S_{\text{pupil}}} P(\xi,\eta)P^*(\xi,\eta)\mathrm{d}\xi\,\mathrm{d}\eta} \tag{3}$$

with d_i being the distance from the retina to the nodal point, and $P^*(\xi,\eta)$ the conjugate of $P(\xi,\eta)$. MTF is defined as the modulus of OTF.

In our previous research [7], the change of defocus of human eye with wavelength is noticeable, nearly 2.15 D within visible spectrum, while the variation of astigmatism and other high-order aberration is so slight that it can be ignored. The wavelength-dependent defocus [7] is described by

$$D(\lambda)=-12.27+0.04590\lambda-5.74\times10^{-5}\lambda^2+2.57\times10^{-8}\lambda^3 \tag{4}$$

where D is defocus in diopters and λ is wavelength in nanometers. Defocus is related to the Zernike coefficient by [8]

$$D=\frac{4\sqrt{3}C_4}{R^2} \tag{5}$$

where C_4 is the second-order Zernike Coefficient representing defocus, and R is the pupil semi-diameter. Using Eqs. (1), (4) and (5), the wave-front aberration $W(x,y)$ at arbitrary wavelength λ_k in the range of visible spectrum can be calculated with C_4 modified and other Zernike coefficients unchanged. In addition, OTF_k for wavelength λ_k other than the measuring wavelength is available by auto-correlating its own pupil function given by Eqs. (2) and (3).

Taking the spectral power distribution of light source and the spectral sensitivity of the photoreceptor on the retina into account [9], the OTF in natural light is given by

$$\mathrm{OTF}_{\text{white}}=\frac{\sum_{k=1}^{N}\omega_{\lambda_k}\mathrm{OTF}_{\lambda_k}}{\sum_{k=1}^{N}\omega_{\lambda_k}} \tag{6}$$