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ELSEVIER
Optik 119 (2008) 383–387
Optik Optics
www.elsevier.de/ijleo

The study of wavelength-dependent wavefront aberrations based on individual eye model

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Received 28 July 2006; accepted 6 January 2007

Abstract

Theoretical calculations of the wavelength dependence of the ocular wavefront aberrations are performed with individual eye model. Individual eye model, based on the traditional Gullstrand–Le Grand eye model, has been established with measured individual cornea data, eyeball depth and wavefront aberrations. We analyze the wavelength-dependent wavefront aberrations at 12 different visible wavelengths (between 400 and 750 nm) for eight eyes. The change of defocus with wavelength (longitudinal chromatic aberration, LCA) is noticeable, and in good agreement with the results from references. In most cases, the primary spherical aberration changes significantly with wavelength. In comparison with the primary spherical aberration, the other higher-order wavefront aberrations have a smaller change with wavelength. These results have potential applications in those situations where defocus or higher-order wavefront aberrations information in arbitrary wavelength is required.

Keywords: Chromatic wavefront aberration; Visible spectrum; Individual eye model; ZEMAX

1. Introduction

The human eye exhibits a diverse range of wavefront aberrations, which significantly limit the retinal image quality. The two main contributors to the overall wavefront aberrations are cornea and crystalline lens. Their surfaces and their internal refractive index distribution are mainly responsible for the ocular wavefront aberrations. The refractive indices are wavelength dependent and, as a consequence, the wavefront aberrations of the human eye vary over the visible spectrum.

Longitudinal chromatic aberration (LCA), chromatic focus shift, causing shorter wavelengths to focus closer to the lens than longer wavelengths, has been measured in the human eyes [1–4]. It has been found to be about two diopters (D) across the visible spectrum, with some differences across studies. Because the higher-order aberrations are small compared to the defocus, the change of higher-order aberrations with wavelength is expected to be modest in comparison with defocus. The change of the wavefront aberrations across the visible spectrum was directly measured, using a spatially resolved refractometer [5]. Measured LCA was in good agreement with that of the references, and the higher-order wavefront aberrations increased slightly with wavelength.

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0030-4026/$ - see front matter
doi:10.1016/j.ijleo.2007.01.002

Eye models that can reproduce optical properties of the human eye are especially useful to simulate experiments. Since the beginning of 20th century, many models have been proposed, progressively developed and improved. The famous Gullstrand eye, later revised by Le Grand, has been highly successful and widely used for first-order aberration calculations. The ocular chromatic aberration has been modeled using the Le Grand's theoretical eye model [7] and the Indiana chromatic reduced eye model [11]. The predictions of these models were in good agreement with the average values of experimental results over the visible range. However, the prediction on the ocular aberrations was basically limited to the LCA. Higher-order aberrations, even if astigmatism, could not be predicted with these models.

To obtain the predictions of higher-order aberrations, individual eye model has been established based on Gullstrand–Le Grand eye model using optical design software ZEMAX, which has the same wavefront aberrations as that of real eye [6]. In this paper, we investigate the wavelength-dependent wavefront aberrations, especially the higher-order aberrations, at different visible wavelengths with the constructed individual eye model.

2. Individual eye model

Individual optical elements, including cornea, anterior chamber, crystalline lens and vitreous body, are incorporated into the traditional Gullstrand–Le Grand eye model to construct the individual eye model by optical design software ZEMAX. As a result, the wavefront aberrations calculated from the individual eye model are equal to those measured from the real eye. Theoretical calculations of the wavelength dependence of wavefront aberrations are performed with the individual eye model.

The wavefront aberrations of the human eyes are measured with a Hartmann–Shack wavefront sensor with a natural pupil [8]. No cyclopentolate hydrochloride for dilating pupils is adopted in this study because of the influence on aberrations measurements. The measured wavefront aberrations are expressed as Zernike polynomial expansion, and the coefficient ordering and normalization follow the Optical Society of America standardization committee recommendations [9].

Corneal elevation maps are obtained using a Bausch & Lomb ORBSCAN II corneal topographer. The analysis of corneal topography involves fitting the raw data to a parametric geometric model that includes a regular basis surface plus irregular residual component. The regular basis surface accounts for the overall shape of the cornea, which is spherical model in this paper. The irregular residual component is fitted with Zernike polynomial expansion using a least-squares procedure.

The medical BMF-200 A/B Ultrasonic Diagnostic Instrument is used to measure the eye's axial lengths, including the depth of cornea, anterior chamber, crystalline lens and vitreous body. Each eye is measured 10 times for average.

To obtain the geometric parameters of the crystalline lens, including a regular basis surface and irregular residual component, we firstly modify the traditional Gullstrand–Le Grand eye model with the measured individual elements about the geometric parameters of the cornea, and the depth of cornea, anterior chamber, crystalline lens and vitreous body in the software ZEMAX. We then make optimization with the geometric parameters of the crystalline lens as variables and the measured wavefront aberrations as the target of the merit function [6]. After optimizing, the individual eye model has the similar character with actual eye.

The refractive indices of the cornea, the aqueous humor, the crystalline lens and the vitreous humor all depend on the wavelength being used. The refractive indices ($n(\lambda)$) as a function of wavelength (λ) are obtained by reference [7], with λ expressed in nanometers. For the limited space, we only list the refractive indices of the cornea and the crystalline lens:

Refractive index for the cornea:

$$n(\lambda) = 1.51167 - 0.000636054\lambda + 1.17 \times 10^{-6}\lambda^2 - 1.01 \times 10^{-9}\lambda^3 + 3.31 \times 10^{-13}\lambda^4, \quad (1)$$

Refractive index for the crystalline lens:

$$n(\lambda) = 1.53808 - 0.000448268\lambda + 5.74 \times 10^{-7}\lambda^2 - 2.61 \times 10^{-10}\lambda^3. \quad (2)$$

3. Results

We have established eight individual eye models, and analyzed the wavefront aberrations of the eight eye models at 12 different wavelengths in the visible range, which are 400, 450, 490, 500, 530, 555, 570, 600, 620, 650, 700 and 750 nm.

The change of defocus of all the eight eyes over the visible spectrum is studied separately. Data from each of the eight individual eye models are shown in Fig. 1. The abscissa is the wavelength studied with, and the ordinate indicates the defocus in diopters, which is estimated directly from the Zernike polynomial expansion of the wavefront aberrations [10]. Due to the individual level of refractive error of each eye, there is a bodily shift of the curves up or down the dioptric axis. Nonetheless, the evolution of defocus with wavelength among eyes is very similar. In order to compare eyes, we first need to factor out any overall refractive error that an individual eye