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Design of eye models used in quantitative analysis of interaction between chromatic and higher-order aberrations of eye

Yi Zhai [a,b], Yan Wang [c,*], Zhaoqi Wang [a,b], Yongji Liu [a,b], Lin Zhang [c], Yuanqing He [a,b], Shengjiang Chang [a,b]

[a] Institute of Modern Optics, Nankai University, Tianjin 300071, China
[b] Key Laboratory of Optical Information Science and Technology, Ministry of Education, Tianjin 300071, China
[c] Tianjin Eye Hospital & Eye Institute, Tianjin Key Lab of Ophthalmology and Visual Science, Tianjin Medical University, Tianjin 300020, China

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ABSTRACT

Special kinds of eye models are constructed by means of optical system design to quantitatively investigate impacts of longitudinal chromatic aberration (LCA), transverse chromatic aberration (TCA) and LCA+TCA on retina image quality and on depth of focus (DOF), as well as interaction between chromatic and higher-order aberrations. Results show that LCA plays a main role in enhancement of DOF and higher-order aberrations further increase DOF. For most of the eyes the impact of higher-order aberrations on vision is much smaller than that of LCA+TCA and the presence of LCA+TCA further reduces the impact of higher-order aberrations. The impact of LCA approximates to that of LCA+TCA, and the impact of TCA approximates to that of normal level of higher-order aberrations and is negligible.

1. Introduction

Modern studies have shown that the human eyeball suffers from many higher-order monochromatic aberrations, and correction of the aberrations can make improvements in visual quality. The eyeball as an optical system also possesses substantial amounts of chromatic aberrations, which the longitudinal chromatic aberration (LCA) is about 0.8 D over the visible spectrum from 474 nm to 653 nm measured with psychophysical experiments on seven subjects [1], without significant change across different individuals. Transverse chromatic aberration (TCA) is subject to certain individual differences, with typical value of approximately 0.6 arcmin [2–4]. The impact of interaction between chromatic aberration and monochromatic aberration that simultaneously exist in eyeball system on vision has become the focus of researchers' attention. Yoon and Williams [5] investigated two types of aberrations with the help of adaptive optics technology. Ravikumar et al. [6] evaluated the impacts of differing levels of monochromatic aberrations on the quality of polychromatic retinal images by means of polychromatic computational optics. Atchison et al. [7–9] used an adaptive optics system to study subjective blur limits of higher-order aberrations in white light or in monochromatic light. Employing Thibos and Bradley eye model, Autrusseau et al. [10] studied the influence of monochromatic aberration on chromatic aberration on the basis of stimulations of three kinds of cones S, M, and L by retina image. In 2008, Ravikumar et al. [11] computed the polychromatic retinal image quality, and then evaluated the impacts of higher-order aberration, LCA and TCA using a metric called visual Strehl ratio (VSOTF). Zhang et al. [12] and He et al. [13] constructed two kinds of individual eye models to investigate the properties of TCA and LCA over the visible spectrum, and then evaluated their impacts on visual quality.

Visual performance of the eyeball not only includes the retina image clarity, but also contains the depth of focus (DOF). Campbell [14] used subjective method to measure the DOFs for 7 subjects and indicated that chromatic aberration was beneficial to increasing the depth of focus. Nio et al. [15] thought that higher-order aberrations played an important role in the balance between visual acuity and depth of focus to obtain the optimal visual quality. Ravikumar et al. [11] examined the impacts of higher-order aberration and chromatic aberration on depth of focus, employing a criterion of VSOTF lowered by 0.08 from its peak.

In this paper, we firstly construct three kinds of special eye models which various amounts of high-order aberrations can be added along visual axis by means of optical system design. The first is the model with visual axis accordant to optical axis, the second is the model involving the angle formed by visual and optical axes and the third is the model with a LCA corrector in the second kind of model. To our best knowledge, the last two models

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* Corresponding author. Tel.: +86 22 27305083.
E-mail address: wangyan7143@vip.sina.com (Y. Wang).

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proposed here have never been reported yet. We then employ the eye models to quantitatively investigate the impacts of LCA-only, LCA+TCA and TCA-only on vision, as well as the interaction between chromatic and higher-order aberrations according to the statistics of actual data of human eyes' higher-order aberrations. With the criterion in Ref. [11], we further investigate the effects of chromatic and higher-order aberrations on depth of focus, and demonstrate the significant contribution of chromatic aberration in this matter.

2. Methods

2.1. *Measurement and statistics of ocular wavefront aberration*

A group of 127 eyes (74 OD and 53 OS) of 79 subjects is selected. Among them 96 eyes are from 48 subjects. All of these eyes are normal without ocular disease and corneal surgery. The study followed the tenets of the Declaration of Helsinki. The study protocol was approved by Tianjin Eye Hospital Institutional Review Board. All participants provided written informed consent. Wavefront aberrations are measured with Hartmann–Shack wavefront aberrometer, Wavescan (VISX, Santa Clara, CA, USA) in the case of darkroom with natural pupils of the diameter range from 5.5 mm to 7.5 mm. In order to investigate visual characteristic under the photopic condition, a conversion of wavefront aberrations from the actual pupil diameter to the fixed pupil diameter of 3 mm is carried out by programming in MATLAB [16]. Fig. 1 is the statistical histogram of root-mean-square of higher-order aberrations (RMS_H) of 127 eyes where the abscissa represents the value of RMS_H with unit of μm and the ordinate indicates the quantity of eyes. The RMS_H values of 127 eyes (third-order to sixth-order Zernike polynomials) vary in the range from 0.009 μm to 0.097 μm, with 37 eyes in the peak range of histogram from 0.018 μm to 0.027 μm.

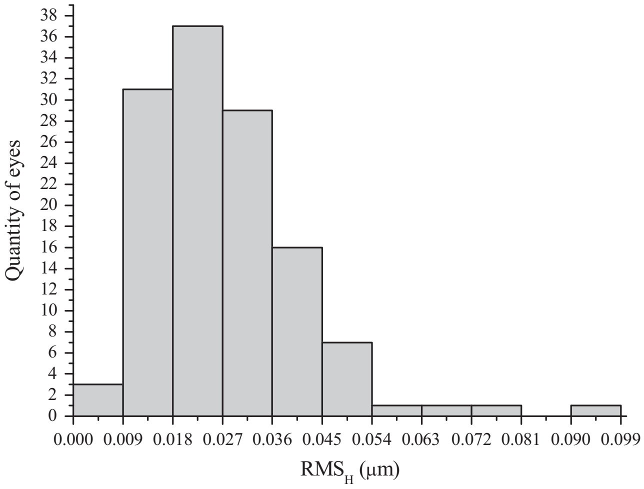

Fig. 1. Statistical histogram of RMS_H values of 127 eyes.

2.2. *Construction of three kinds of eye models*

Three kinds of eye models are constructed by means of optical design software ZEMAX, that are then used for the investigation of visual performance of eyeball of LCA-only, LCA+TCA and TCA-only, respectively. The first kind of eye model, used to estimate the impact of LCA-only on vision, is with visual axis accordant to optical axis. Using the improved Gullstrand–Le Grand eye model [13] as initial structure, we set the pupil diameter to be 3 mm and the primary wavelength to be 555 nm. Executing optimization with the quadratic surface coefficient (conic) of the posterior surface of crystalline lens and the thickness of vitreous as variables, the optical modulation transfer function (MTF) is close to diffraction limit. Table 1 shows the structural parameters of this eye model. Five wavelengths of 470 nm, 510 nm, 555 nm, 610 nm and 650 nm, weighted by the luminosity function curve under the photopic condition, are set to estimate the effect of LCA on vision.

To investigate the effect of LCA+TCA on vision, we construct the second kind of eye model involving the angle formed by visual and optical axes based on the structural parameters of the eye model shown in Table 1. The angle formed by visual and optical axes is typically 5° in temporal side and 1.5° in down side [17] which corresponds to the field of view (FOV) of θ of 4° in the *X*-direction (horizontal) and 1.2° in the *Y*-direction. We add the value of field of view to the first kind of eye model and then execute two-step optimization.

(1) Set the type of the anterior corneal surface to be 'Zernike Fringe Sag' with 4–15 Zernike coefficients as variables and carry out the first step optimization.
(2) Set the type of the posterior surface of crystalline lens to be 'Even Asphere' with 4th-order, 6th-order and 8th-order polynomial coefficients as variables and complete the second step optimization.

After optimization, the MTFs at FOV of zero and θ degrees are both close to diffraction limit. The optical axis is the line connecting all centers of curvature of surfaces and is along horizontal direction. The visual axis is along the direction of FOV of θ degree. Finally we complete the construction by rotating the entire eye model with the center of posterior surface of crystalline lens as rotation center to make the visual axis in the horizontal direction, as shown in Fig. 2. For the second kind of model, LCA is about 1.33 D and TCA is approximately 4.94 μm in the wavelength range from 470 nm to 650 nm.

To investigate the impact of TCA-only on vision, we construct the third kind of eye model by inserting a LCA corrector in the second kind of eye model before rotation. From a point of view of optical design, the performance of the achromatic element strongly depends on its location in optical system. For example, if the achromatic element is in the object space of a system, the LCA can be well eliminated but the TCA increases. Correcting LCA while maintaining TCA can be guaranteed only if when the achromatic element is in the vicinity of aperture diaphragm of the system. Diffractive optical element is with excellent achromatic

Table 1
Structural parameters of the first kind of eye model.

Surface	Radius (mm)	Thickness (mm)	Refractive index (555 nm)	Abbe number	Diameter (mm)	Conic
Anterior cornea	7.8	0.55	1.38	55.8	3.38	0
Posterior cornea	6.5	3.05	1.34	52.8	3.34	0
Pupil	Infinity	0	1.34	52.8	3	0
Anterior lens	10.2	4	1.42	49.8	2.98	0
Posterior lens	−6.0	16.55	1.34	52.8	2.54	−6.74
Retina	−12.5	–	–	–	12	0