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Wavefront aberrations in the accommodated human eye based on individual eye model

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Abstract

In this research, we firstly construct individual eye models based on the wavefront and the measured cornea structure of the eyes. Then we analyze the influence of accommodation on the wavefront aberrations based on individual eye model. The individual eye model has the same wavefront aberration as that measured from Hartmann–Shack wavefront sensor. The optical design software ZEMAX is used to construct the individual eye models for 20 normal eyes. Accommodative conditions are from 0 to –4 diopter in steps of one diopter. The variations of the total, the spherical, the coma and the higher-order root-mean-square wavefront aberrations, as accommodations, are illustrated. Influence of accommodation on wavefront aberration varies from individual to individual, and the variation magnitude is independent of the magnitude of the wavefront aberration of the eye.

Keywords: Accommodation; Individual eye model; Wavefront aberration; ZEMAX

1. Introduction

Wavefront aberrations of human eyes are expected to change when eyes are forced to see objects at various distances clearly. Accommodation that includes changes of refractive power and position of crystalline lens is thought to have an effect on wavefront aberrations of the human eyes [1] and then on the retinal image quality. So it is significant to analyze the wavefront aberrations in the accommodated normal human eye.

Impact of accommodation on wavefront aberrations has been reported in some previous researches. Atchison et al. [2] made the first attempt to characterize the wavefront aberrations of eyes for 15 subjects in detail by using the aberroscope technique. They found no clear trend, on the wavefront aberrations, up to the forth order in amount or direction of change with 0D, -1.5D and –3D accommodative conditions. Lopez-Gil et al. [3] studied the change in retinal image quality with accommodation by using near-infrared double-pass technique and reported that the double-pass image for the accommodated eye tended to be more symmetric than that of the unaccommodated eye. He et al. [4] found a consistent trend in the change of aberrations over the accommodative range by subjective ray-tracing technique [4], and only one eye from the eight eyes studied changed very little. With regard to the particular aberrations, authors in previous studies suggested that the amount of spherical aberration decreases with

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accommodation, although most of those results were subject dependent. The change in coma in He et al. did not show a variation trend, and the average over eight eyes gave almost no change with accommodation.

Influence of accommodation in previous studies was all based on actual measurements of normal human eyes. In this article, we analyze the influence of accommodation based on an individual eye model in principle. Some early work has been done on the eye model for optical performance. Gullstrand–Le Grand scheme eye model offered a powerful tool in the early 20th century. Many later researchers paid more interests on it and continued to modify this model. Those eye models in previous researches [5–7] were all based on anatomy and were summarized from the average results by statistics. However, actually, each eye corresponds to its own individual physiological characteristics and eye models should reflect the individual ocular aberrations. To better describe the optical performance of human eye, we firstly 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 by Harmann–Shack wavefront sensor. We then investigate the influence of the accommodation on the ocular aberrations with the constructed individual eye model.

The data from 20 eyes are reported in this study. For all subjects whose ages range from 18 to 32, the pupil sizes are greater than 5 mm for cornea and aberration measurements. No cyclopentolate hydrochloride, for dilating pupils, is adopted in this study because of its influence on aberrations measurements. There are emmetropes, myopes and hyperopias in these subjects whose defocus range from –6D to +3D. No subject in this experiment has a record of ocular disease.

2. Construction of individual eye model

Hartmann–Shack is used to measure the wavefront aberrations of the whole eye. The principle of the Hartmann–Shack wavefront sensor is as follows [8]. A narrow near-infrared beam projects onto the subject's retina acts as a beacon source. On the way out, the light propagates through the eye's optics, suffering local phase shifts in the wavefront, before reaching a lenslet that samples the local average of the wavefront tilt over the eye pupil. This sampling generates a distribution of spots that is captured by a CCD camera in the focal plane of the lenslet. When a perfect plane wave is measured, the lenslet array forms a regular array of focus spots. If a deformed wavefront is measured, the image spot focused by each lenslet is displaced in proportion to the local wavefront slopes in x and y-directions. In the Hartmann–Shack image, the relative displacement of each sample spot is proportional to the wavefront slope within the corresponding sub-aperture. The wavefront aberration is expressed as Zernike polynomial expansion.

The corneal topographic system used to measure the corneal surfaces is Orbscan II. With a Placido-based videokeratographic device, the discrete set of corneal elevation data in radial distribution over the pupil plane can be obtained for the anterior and the posterior corneal surface. The elevation data of the corneal surfaces in vertical distribution that is defined as along the optical axis are calculated from the elevation data in radial distribution. Differences in path length between the ray passing the pupil center and the rays traveling through the other pupil area are calculated with software MatLab. Then, the corneal surfaces including the anterior and posterior surfaces are established. The least-square procedure is used to decompose the corneal surfaces to 35 terms of Zernike polynomials [9]. Zernike coefficients of the cornea with the unit of micrometers are all calculated. The detailed corneal structural parameters of 20 eyes are listed in Table 1, which are input into optical design software ZEMAX. Only three Zernike coefficients have been showed because of the limited space. The accuracy of this procedure was previously evaluated with the use of reference surfaces. It can be seen from the table that different eye carries different radius and thickness of cornea. Radius of anterior cornea is larger than that of posterior cornea for all eyes. The seventh eye has the largest anterior and posterior corneal radii. While the 12th eye has the smallest anterior corneal radius, the 14th eye has the smallest posterior corneal radius.

We use the medical BMF-200 A/B Ultrasonic Diagnostic Instrument to measure the eye's axial lengths, including the depth of cornea, anterior chamber, crystalline lens and vitreous body. According to ultrasonic spreading, at different times in different types of medium, we can get the depth of the very part of the eye by measuring the spread time accurately. Each eye is measured ten times to get an average.

The parameters of the crystalline lens are difficult to be measured. To do this, we choose Gullstrand–Le Grand eye model as the initial configuration with the individual corneal and eye's axial length parameters. In order to make the total aberrations of eye model correspond to the aberrations of actual eye, the operands ZERN in ZEMAX is added to the merit function with the coefficients defining the aberrations of the actual eye. Zernike Fringe Sag surface helps to optimize the lens surface for getting the Zernike coefficients, which can fit the lens well. After optimizing, the eye model shows similar characters with the actual