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Characterization of anterior corneal high-order wavefront aberrations and correlations with astigmatism in Chinese elderly subjects

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ABSTRACT

This study aimed to investigate the distribution of total high-order aberrations (HOAs) $Z_3^{\pm1}$, Z_4^0, and $Z_3^{\pm3}$ of anterior cornea and their correlations to astigmatism. In addition, the relationship between different axes of astigmatism and Z_3^{-1} or Z_3^1 was analyzed. The HOAs in the central 6-mm zone of the cornea were measured with an iTrace wavefront analyzer in 556 cataractous eyes at the Tianjin Eye Hospital in China. Simulated keratoscope readings (Sim k) were also measured with the analyzer. The corneal total HOAs $Z_3^{\pm1}$, Z_4^0 and $Z_3^{\pm3}$ exhibited a non-normal distribution. Significant correlations were found between the topographic-simulated keratometric power (ΔSim k) with the axis at $180^\circ \pm 5^\circ$ and absolute value of Z_3^{-1} ($P = 0.008$), the ΔSim k with the axis at $90^\circ \pm 5^\circ$ and absolute value of Z_3^1 ($P < 0.001$), and the ΔSim k and total HOAs ($P < 0.001$), $Z_3^{\pm1}$ ($P < 0.001$), and $Z_3^{\pm3}$ ($P < 0.001$). No significant correlation was found between ΔSim k and Z_4^0 ($P = 0.404$). In conclusion, corneal astigmatism with the axis near the horizontal position was mainly associated with the value of Z_3^{-1}. Corneal astigmatism with the axis near the vertical position was mainly related to the value of Z_3^1. HOAs except Z_4^0 are correlated with astigmatism.

1. Introduction

The optical characteristics of the human eye are still being characterized [1]. High-order wavefront aberrations (HOAs), such as spherical aberration and coma, limit the optical quality of the image that ultimately reaches the retina [2]. With the use of wavefront aberration analyzers, clinicians have obtained more accurate parameters of HOAs of the anterior cornea [3,4]. In the normal eye, approximately 90% of HOAs are caused by the cornea [5]; therefore, corneal wavefront analysis is an important tool for evaluating ocular optical quality. However, aberrations are rarely present alone, and the complex relations between aberrations still require further studies, particularly the relations between coma aberration ($Z_3^{\pm1}$), spherical aberration (Z_4^0), trefoil aberration ($Z_3^{\pm3}$) of the anterior cornea and astigmatism, as well as the relationship between astigmatism with different axes and vertical coma (Z_3^{-1}) or horizontal coma (Z_3^1).

Individually selected intraocular lens (IOL) asphericities based on corneal spherical aberration (SA) have been shown to reduce the final ocular spherical aberration while improving visual quality [6]. Wavefront-customized IOLs are a promising mean to restore near-perfect visual acuity [7]. However, HOAs of the anterior cornea still impair vision despite IOLs, and a better characterization of these aberrations could lead to the design of IOLs tailored to each patient. The inclusion of HOAs is important to design appropriate IOLs [8]. In addition, Lim et al. [9] reported that corneal aberrations in Chinese patients were significantly greater than that observed for other patient populations. However, HOAs need to be better defined before an eventual clinical application might be undertaken.

We aimed to observe if total HOAs, coma aberration ($Z_3^{\pm1}$), spherical aberration (Z_4^0) and trefoil aberration ($Z_3^{\pm3}$) of the anterior cornea are correlated with astigmatism in Chinese patients. Therefore, we investigated the distribution of total HOAs, coma aberration, spherical aberration, trefoil aberration and their correlations with astigmatism in Chinese patients. We also analyzed the relationship between astigmatism with different axes and both vertical and horizontal coma.

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2. Patients and methods

2.1. Patients

Between January 2012 and February 2013, the eyes analyzed in the present study were randomly selected (right or left) in 556 elderly Chinese patients (247 men, 309 women; 68.4 ± 10.4 years, range: 41–95 years) enrolled at the Tianjin Eye Hospital. They were scheduled for cataract surgery at the Tianjin Eye Hospital. The eyes in which data for the central 6-mm zone could not be obtained were excluded from the study. Patients with a history of keratopathy, previous ocular surgery, high myopia, high hypermetropia, amblyopia, strabismus or xerophthalmia were also excluded. Patients wearing contact lenses were asked to discontinue their use for 1 month before examination.

This study was approved by the Tianjin Eye Hospital Ethics Committee and conducted according to the tenets of the Declaration of Helsinki. All patients provided written informed consent.

2.2. Wavefront aberration analysis

Wavefront aberration data and simulated keratoscope readings (Sim *k*) were obtained using an iTrace wavefront analyzer (Tracey Technologies, Houston, TX, USA). The calibration of the iTrace was checked routinely. Patients were positioned in the same manner as for a wavefront exam, forehead against the headrest, and chin in the chinrest. During corneal wavefront aberration measurements, patients were asked to watch the red spot light in the center of the Tracey Eyesys' Placido plate. Immediately before measurement, subjects were instructed to blink and hold their eyes wide open thereafter. A video image appeared on the monitor, showing the eye, the rings and the central target. The corneal reflection ring was clear and complete without rupture of tear film or deposition of tear and secretion. Using a joystick, the middle ring in the target was centered and the data acquisition unit was moved in and out until the white spot crossed the center of the middle ring and target. The iTrace automatically acquired data in these conditions. A CT verification display appeared after acquisition and the image was reviewed to determine whether the edges of the rings were correctly detected. If there were no errors, the exam was saved. Otherwise, the exam was run anew (Fig. 1). To minimize variations in measurement conditions, we took repeated measurements in a short period and instructed subjects to blink immediately before each measurement. Three consecutive good-quality images were obtained per eye by the same expert at the same period of the day and the averages of each corneal HOAs in the central 6 mm area was calculated. Head positioning and eye alignment were carefully checked before every measurement.

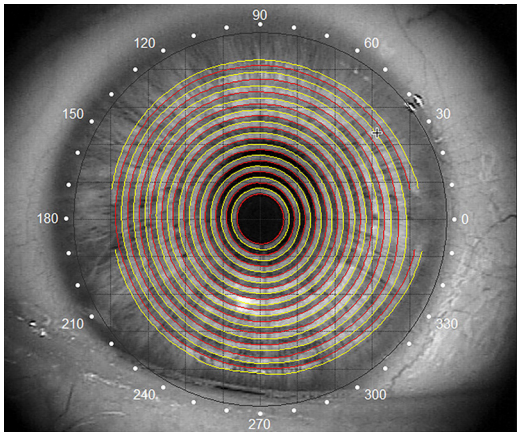

Fig. 1. The *CT Verification Display* (Rings) view. The edge detection analysis was automatically performed by the software (red and yellow dots along alternating edges of the rings) to be certain that no gross errors occurred (cross over of one color to the other side of the ring, missing ring edge detection, detection of non-ring edges, etc.). There was no option to edit this information; instead the operator could just repeat the exam. When errors occurred, the exam was repeated. (For interpretation of the references to color in figure legend, the reader is referred to the web version of the article.)

Sim *k* readings represent the mean maximum refractive power readings for rings 6, 7 and 8. It has been demonstrated that before refractive surgery, the keratometer has a similar clinical value as the corneal topography, and the ΔSim *k* value is related to the graphic pattern of corneal topography. However, the keratometer is limited in measuring mild changes in corneal curvature after refractive surgery, while the astigmatism expressed by ΔSim *k* in corneal topography is more accurate [10].

Corneal aberrations represent the majority of eye aberrations and are mainly composed of aberrations at corneal anterior surface and at corneal posterior surface.

The images were revised to pupil-center images, and total HOA, coma aberration ($Z_3^{\pm 1}$), spherical aberration (Z_4^{0}) and trefoil aberration ($Z_3^{\pm 3}$) from the anterior cornea were calculated for the central 6-mm zone. Root-mean-square (RMS) was used to describe the value of HOA, helping to avoid potential errors due to mirror symmetry since right and left eyes were both included. The absolute values of coma show the sizes, while plus and minus indicate directions. Zernike orders 3–6 for the central 6-mm zone of the anterior cornea of each patient were recorded as well. The difference between steep Sim *k* and flat Sim *k*, denoted as ΔSim *k*, was used to estimate corneal astigmatism. All measurements were performed by an experienced technician using the same instrument and procedures.

2.3. Statistical analysis

SPSS 16.0 for Windows (SPSS Inc., Chicago, IL, USA) was used for statistical analyses. Continuous data were first analyzed to determine if they fitted a normal distribution. Then, descriptive statistics and correlation analyses were conducted. In order to eliminate the interference of age and refractive error among variables, a partial correlation analysis was used. After patients were divided according to their astigmatism status, measurement data in various groups were compared by the Mann–Whitney test. The measurement data in multiple groups were compared by the Kruskal–Wallis *H* test. Two-sided *P*-values <0.05 were considered statistically significant.

3. Results

The total HOA, total coma aberration, spherical aberration, trefoil aberration, and Zernike orders 3–6 were skewed parameters and are therefore presented as median and interquartile range (all $P < 0.001$) (Table 1 and Fig. 2). Median total HOA was 0.570 (interquartile range: 0.464, 0.721) μm for the central 6-mm zone (Table 1).

3.1. Correlations between astigmatism and coma

The correlation between astigmatism with different axes and both vertical (Z_3^{-1}) and horizontal coma (Z_3^{1}) aberrations were investigated. To eliminate the interference of age and refractive error among variables, a partial correlation analysis was used to determine the relationship between astigmatism with different axes and vertical coma (Z_3^{-1}), and astigmatism with different axes and horizontal coma (Z_3^{1}). A significant positive correlation was found between ΔSim *k* with the axes at 180° ± 5° (i.e. 0°–5° and 175°–180°) and the absolute vertical coma values ($n = 117$, $r = 0.248$,