Clinical Ophthalmology

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ORIGINAL RESEARCH

# Analysis of Asphericity and Corneal Longitudinal Spherical Aberration of 915 Chinese Myopic Adult Eyes

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**Purpose:** To analyze the corneal asphericity, longitudinal spherical aberration (LSA), and related factors in Chinese myopic adult eyes.

**Methods:** This was a retrospective study of myopic adult patients. The corneal asphericity and LSA were measured at 3.0, 4.0, 5.0, 6.0, and 7.0 mm diameter apertures using corneal tomography. Age and refractive power were recorded for correlation analysis.

**Results:** In total, 531 females and 384 males were included. At the above five diameter settings the corneal asphericity values (Q) of the anterior surface were −0.09±0.21, −0.14±0.16, −0.15±0.13, −0.17±0.11, and −0.20±0.11, and those of the posterior surface were 0.23±0.49, 0.06±0.29, −0.01±0.22, −0.07±0.16, and −0.08±0.15, respectively. The anterior corneal LSA values at these diameters were 0.39±0.19, 0.63±0.27, 0.97±0.36, 0.90±0.30, and 0.83±0.29 D, respectively and the whole corneal values were 0.26±0.20, 0.44±0.27, 0.70±0.36, 0.66±0.30, and 0.59±0.28 D, respectively. Corneal asphericity and peripheral LSA showed no or weak correlation with age or spherical equivalent (all $r < 0.2$).

**Conclusion:** Corneal anterior and posterior Q values in myopia patients are negatively correlated with corneal diameter. Corneal anterior and whole corneal LSA increased significantly with diameter up to 5 mm, then decreased slightly with diameter. Corneal asphericity and peripheral LSA showed very weak or no correlation with age or spherical equivalent.

**Clinical Trial Registration Number:** ChiCTR1800015985.

**Keywords:** wavefront aberration, asphericity, longitudinal spherical aberration, myopia

## Introduction

In human eyes, the aspherical shape of the cornea and crystalline lens work together to optimize focus on the macula. Due to refractive index differences between the cornea and its surrounding refractive media, slight changes in corneal asphericity can modulate the focus of peripheral light significantly, while having little effect on focus of paraxial light. Changes in the spread of focal points may optimize visual quality or depth of field according to clinical needs.[1–3] The Q value is a quantitative indicator of asphericity and is defined as the radius of curvature change from the apex to the periphery.[4,5] Spherical-like aberration, which belongs to the category of transverse aberration, refers to the root mean square (RMS) of the zero-frequency Zernike coefficients above fourth-order.[6] Longitudinal spherical aberration (LSA), which belongs to the category of longitudinal aberration, is a result of peripheral light rays being refracted more or less than those close to the axis, and may be measured as the difference between the points at which peripheral and more axial rays intersect with the axis, in diopter.[4] Therefore, when the corneal Q value changes, the corneal spherical-like aberration and LSA will change accordingly, and the Q value can be used to modulate spherical-like aberration or LSA. Although both spherical-like aberration and LSA are characterized by the refraction of peripheral rays.[1,7] LSA, the focal distance on the optical axis, is more closely associated with refractive error and may have implications for corneal refractive surgery strategies in presbyopia. In addition, few studies have been conducted on corneal LSA.

Received: 11 January 2023
Accepted: 9 February 2023
Published: 15 February 2023

Presently, spherical-like aberration but no LSA can be obtained directly using standard ophthalmic equipment. The results of relevant studies between spherical-like aberrations with multifactor appear contradictory.[8–10] With increasing attention on corneal refractive surgery for presbyopia, the potential for LSA-based estimation of near refractive error has attracted interest. For example, 1.00 D LSA allows peripheral light to provide 1.00 D near addition, while a similar effect can be achieved by 0.12 μm spherical-like aberration, but seems harder to understand. The main objective of the present study was to determine amplitude and range of corneal LSA in the Chinese myopic population, as a step toward a more accurate model of the Chinese eye.

# Materials and Methods

## Study Design and Patients

This was a retrospective study of patients planning to undergo therapeutic refractive surgery at Hangzhou MSK Eye Hospital between October 2018 and December 2018. The study was approved by the institutional review board at each participating site and by the ethics committee of Hangzhou MSK Eye Hospital. Since the data are anonymous, were stored confidentially and the study was compliant with the Declaration of Helsinki, the requirement for informed consent was waived.

The inclusion criteria were: (1) diagnosis of myopia; and (2) 18–40 years of age. Those with any history of ocular surgery (such as corneal refractive surgery, corneal traumatic repair, corneal transplantation, anterior chamber puncture, iris repair, and others), history of contact lens use within six months, or using any ocular medication were excluded from the study.

## Ophthalmic Examination

Data from detailed ophthalmic assessments were extracted from the medical charts. These examinations were carried out before corneal refractive surgery and included a complete medical and ophthalmic history and a thorough ocular examination, including measurements of uncorrected visual acuity, refractive error (in diopters), best corrected visual acuity (BCVA), cycloplegic refraction, slit-lamp examination (to assess corneal status, any scarring, history of corneal transplantation, anterior chamber puncture, iris repair), axial length, gonioscopy (to look for peripheral retinal tears), fundoscopy (central retinal examination to screen for fundus diseases such as macular diseases and vasculopathy), and intraocular pressure. In addition, corneal topography, including parameters such as corneal central thickness (CCT) and Sim-K of anterior and posterior corneal surface, was conducted using a tomography system (CSO, Sirius, Florence, Italy). Spherical equivalent (SE) was obtained as spherical refractive error + 1/2 cylindrical refractive error based on manifest refraction.

## Measurement of Vertex Curvature and the Q Value of Anterior and Posterior Corneal Surfaces

In the corneal tangential curvature map, the origin of the coordinate system is the corneal vertex curvature. The Q values of the anterior and posterior corneal surface at 3.0, 4.0, 5.0, 6.0, and 7.0 mm aperture diameters were obtained using tomography. All measurements were performed three times, and the mean was used for statistical analysis.

## Calculation of LSA of the Anterior Corneal Surface and Whole Cornea

The LSAs of the anterior corneal surface and the whole cornea were calculated at 3.0, 4.0, 5.0, 6.0, and 7.0 mm aperture diameters.[7] For the convenience of data collation, the LSA calculation process can be transformed as follows.

Corneal asphericity was calculated as follows[11]

$$x^2+y^2+(1+Q)z^2-2zR=0 \quad (1)$$

Where x and y are the radii from the corneal apex, z is the distance from cornea to the XY plane, R is the radius of the curvature at corneal apex, and Q is the asphericity of the cornea.

A cross section of the corneal surface in the XOZ plane is shown in Figure 1. A single meridian on the corneal surface can be expressed as part of a conic curve.

Because the corneal surface is only the front part of the quadric surface, the quadratic equation may be expressed as

$$z = f(x) = \frac{R - \sqrt{R^2 - (1 + Q)x^2}}{1 + Q} \tag{2}$$

Figures 2 and 3 show schematic diagrams of reflection by the anterior and posterior corneal surfaces.

By calculating the first and second derivative of z to x, the angle of motion α, angle of motion β (posterior surface), speed v, and the acceleration in the direction of the z axis at the edge of the optical zone can be obtained.

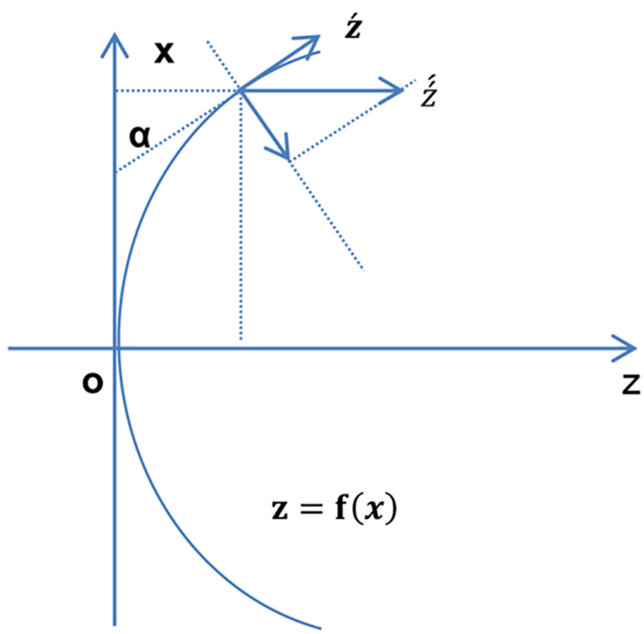


**Figure 1** Corneal surface coordinate system. For a point moving along the curve, z is its velocity, α the angle of motion, and z is its acceleration parallel to the z axis.

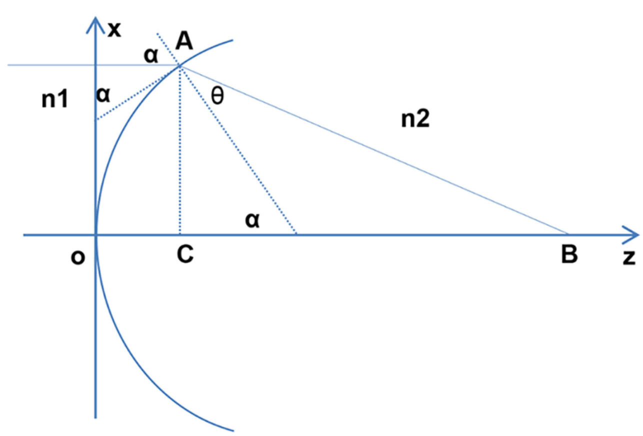


**Figure 2** Refractive trajectory of light passing through the anterior surface of the cornea. The angle of motion α is also the angle of incidence, θ the angle of reflection; and n1 and n2 are the refractive indices of air and cornea respectively.

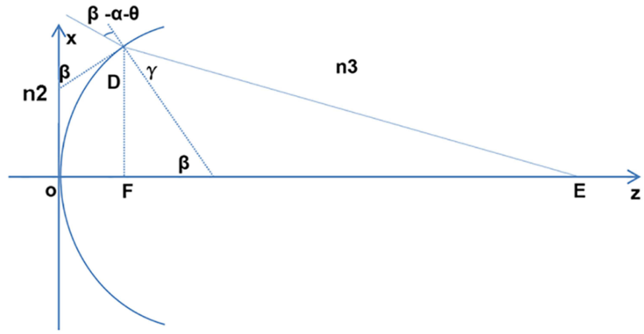


**Figure 3** Refractive trajectory of light passing through the posterior surface of the cornea. β is the angle of motion; γ the angle of reflection; and n2 and n3 are the refractive indices of the cornea and aqueous humor, respectively.

$$z' = f'(x) = tan\alpha = v = \frac{x}{\sqrt{R^2-(1+Q)x^2}} \tag{3}$$

$$z'' = f''(x) = \frac{\sqrt{R^2-(1+Q)x^2} + (1+Q)x^2\left[R^2-(1+Q)x^2\right]^{-\frac{1}{2}}}{R^2-(1+Q)x^2} \tag{4}$$

According to the formula of centripetal acceleration in circular motion, the radius r of curvature at the edge of the optical zone can be obtained.

$$\mathrm{r} = \frac{\left[1+f'(x)2\right]^{\frac{3}{2}}}{f''(x)} \tag{5}$$

According to Figure 2, the LSA of the anterior corneal surface of the target optical zone can be calculated.

$$\text{LSA of the anterior corneal surface} = \frac{\mathrm{n_2}1000}{\mathrm{OB}} - \frac{\mathrm{n_2}1000}{\lim\limits_{\mathrm{x0}}\mathrm{AB}} = \frac{\mathrm{n_2}1000}{\frac{\mathrm{x}}{\tan\left[\alpha-\arcsin\left(\frac{\mathrm{n_1}}{\mathrm{n_2}}\sin\alpha\right)\right]} + \frac{\mathrm{R}-\sqrt{\mathrm{R}^2-(1+\mathrm{Q})\mathrm{x}^2}}{1+\mathrm{Q}}} - \frac{\mathrm{n_2}1000}{\frac{\mathrm{n_2R}}{\mathrm{n_2-n_1}}} \tag{6}$$

According to Figure 3, the LSA of the whole cornea at the target optical zone can be calculated.

$$LSAofthewholecornea = \frac{n_2 1000}{OE} - \frac{n_2 1000}{\lim\limits_{x\to0}DE} = \frac{n_2 1000}{\frac{x}{tan\left[\beta-\arcsin\left(\frac{n_2}{n_3}sin\alpha\beta\right)\right]} + \frac{R(b)-\sqrt{R(b)^2-(1+Q)x^2}}{1+Q}} - \frac{n_2 1000}{\frac{n_3}{\frac{n_3-n_2}{R(b)}+\frac{n_2}{\lim\limits_{x\to0}AB}}} \tag{7}$$

## Statistical Analysis

Continuous variables are expressed as means ± standard deviation (SD). Correlations between parameters were examined using the Pearson correlation. All statistical analyses were performed using SPSS 19.0 (IBM, SPSS, Armonk, NY, USA). Two-sided *P* values <0.05 were considered statistically significant.

# Results

## Characteristics of the Patients

This study included 915 eyes from 915 myopic patients, including 531 females with a mean age of 28.3±6.8 years and 384 males with a mean age of 24.1±6.9 years. In the total cohort, SE ranged from −13.00 to −0.50 D (mean: −6.5±2.2 D). The mean CCT and Sim-K of the anterior and posterior corneal surfaces were 536.0±91.2 µm, 43.0±1.4 D, and −6.0±0.2 D, respectively (Table 1). Slit-lamp examination, gonioscopy, and fundoscopy showed no significant lesions in these patients.

**Table 1** Characteristics of the Patients

| Characteristics | Patients (n=915) |
|---|---|
| Age, years | 26.52±7.16 |
| Sex, female, n (%) | 531 (58.0%) |
| Ocular examination | |
| Uncorrected visual acuity (LogMAR) | 1.31±0.27 |
| Manifest refraction (D) | −6.48±2.16 |
| Best corrected visual acuity (LogMAR) | −0.05±0.05 |
| Cycloplegic refraction (D) | −6.37±1.92 |
| Axial length (mm) | 25.8±1.0 |
| Intraocular pressure (mmHg) | 15.6±2.8 |
| Corneal topography | |
| Corneal central thickness (μm) | 543.69±29.98 |
| Sim-K of anterior surface (D) | 43.04±1.41 |
| Sim-K of posterior surface (D) | −5.95±0.24 |

**Abbreviation**: D, dioptor.

## Corneal Q Values

The anterior surface corneal Q values were −0.09±0.21, −0.14±0.16, −0.15±0.13, −0.17±0.11, and −0.20±0.11 at 3.0, 4.0, 5.0, 6.0, and 7.0 mm diameters, respectively; those of the posterior surface were 0.23±0.49, 0.06±0.29, −0.01±0.22, −0.07±0.16, and −0.08±0.15, respectively. The distribution of corneal Q value at these aperture diameters is shown in Figure 4.

## Corneal LSA Values

The corneal LSA values of the anterior surface at these diameters were 0.39±0.19 D, 0.63±0.27 D, 0.97±0.36 D, 0.90 ±0.30 D, and 0.83±0.29 D, respectively; values for the whole cornea were 0.26±0.20 D, 0.44±0.27 D, 0.70±0.36 D, 0.66 ±0.30 D, and 0.59±0.28 D, respectively. Therefore, the corneal LSA values of the posterior surface were: −0.13±0.07 D, −0.19±0.09 D, −0.27±0.12 D, −0.24±0.10 D, and −0.24±0.09 D, respectively. The distribution of corneal LSA values at the range of aperture diameters is shown in Figure 5.

## Correlations

Both corneal Q values and LSA at each of the aperture diameters showed very weak or no correlation with age and spherical equivalent (all $r < 0.2$) (Table 2).

# Discussion

Understanding of the human ocular refractive system is constantly improving with the rapid development of physical optics. In particular, higher order aberration (HOA) has enhanced the study of visual quality[12–14] and has become an important index in research on refractive surgery. Spherical-like aberration or LSA is a higher order aberration with significant impact on visual quality.[15] Previous studies have focused on its elimination[16–18] or reduction to a level sufficient to meet clinical needs. However, as mentioned above, LSA has unique advantages. Understanding the distribution of corneal LSA in myopia may help to more accurately model the Chinese eye and provide guidance for custom corneal ablation treatment. In the case of extended focus presbyopia correction, LSA may enhance estimation of the near correction, a strategy which has attracted increasing attention.[19–21] In addition, it is known that matching corneal asphericity with optical elements helps to establish an aberration balance or reduce spherical-like aberration,[22,23] demonstrating that corneal asphericity Q value plays an important role in visual function.[24] Therefore, the aim of this study was to report the distribution of corneal Q-value and LSA in patients with myopia.

We investigated the distribution of Q values in multiple regions on the myopic cornea, and the results are supported by previous studies. While those studies report different Q values (for example −0.08 for Horner,[25] −0.20 for Fuller,[2]

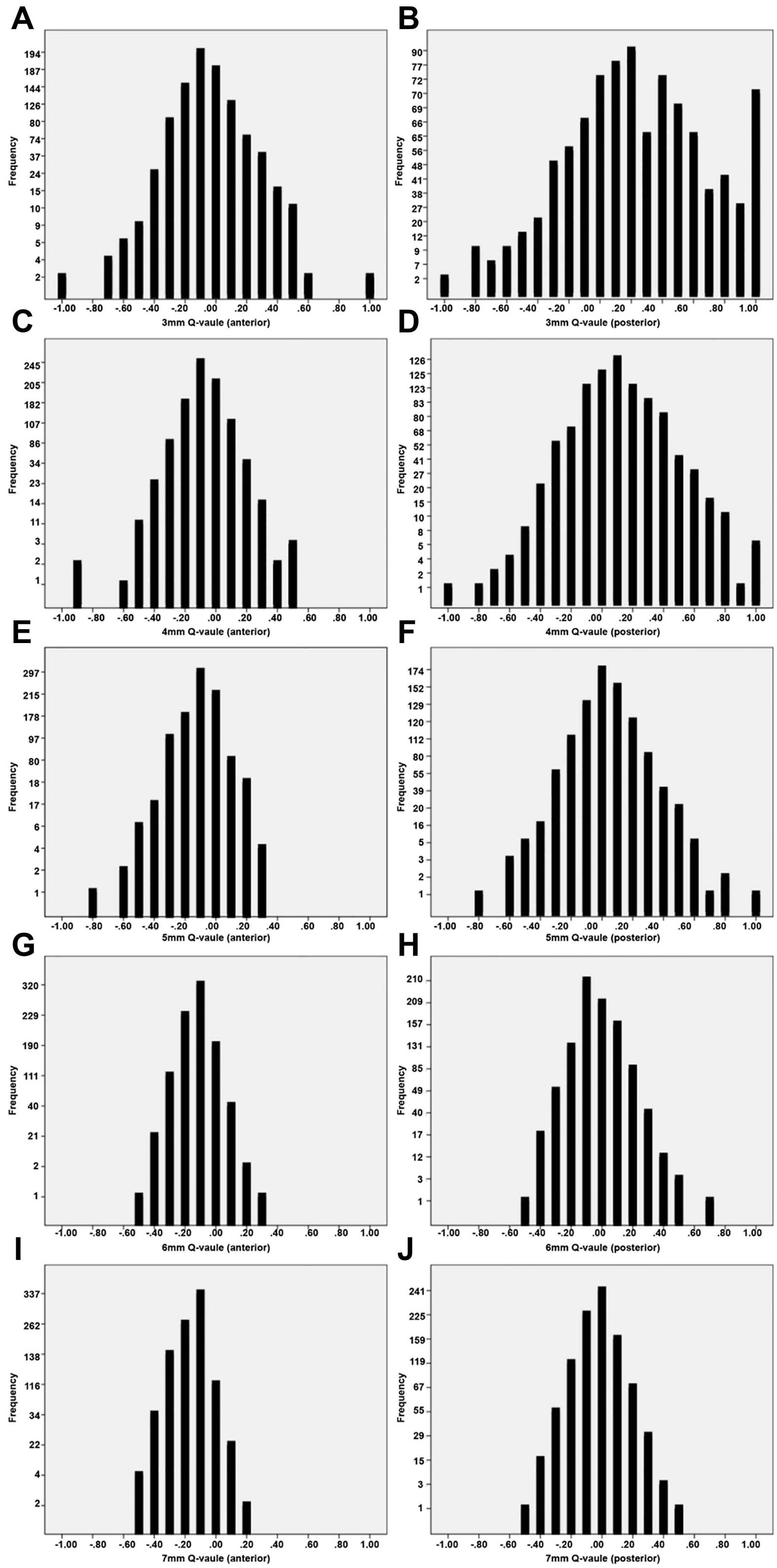


**Figure 4** Distribution of corneal Q value at 3.0, 4.0, 5.0, 6.0, and 7.0 mm aperture diameters, anteriorly and posteriorly, in 915 individuals. The corneal Q values of the anterior surface were: −0.09±0.21, −0.14±0.16, −0.15±0.13, −0.17±0.11, and −0.20±0.11, respectively, and those of posterior surface were 0.23±0.49, 0.06±0.29, −0.01 ±0.22, −0.07±0.16, and −0.08±0.15, respectively.

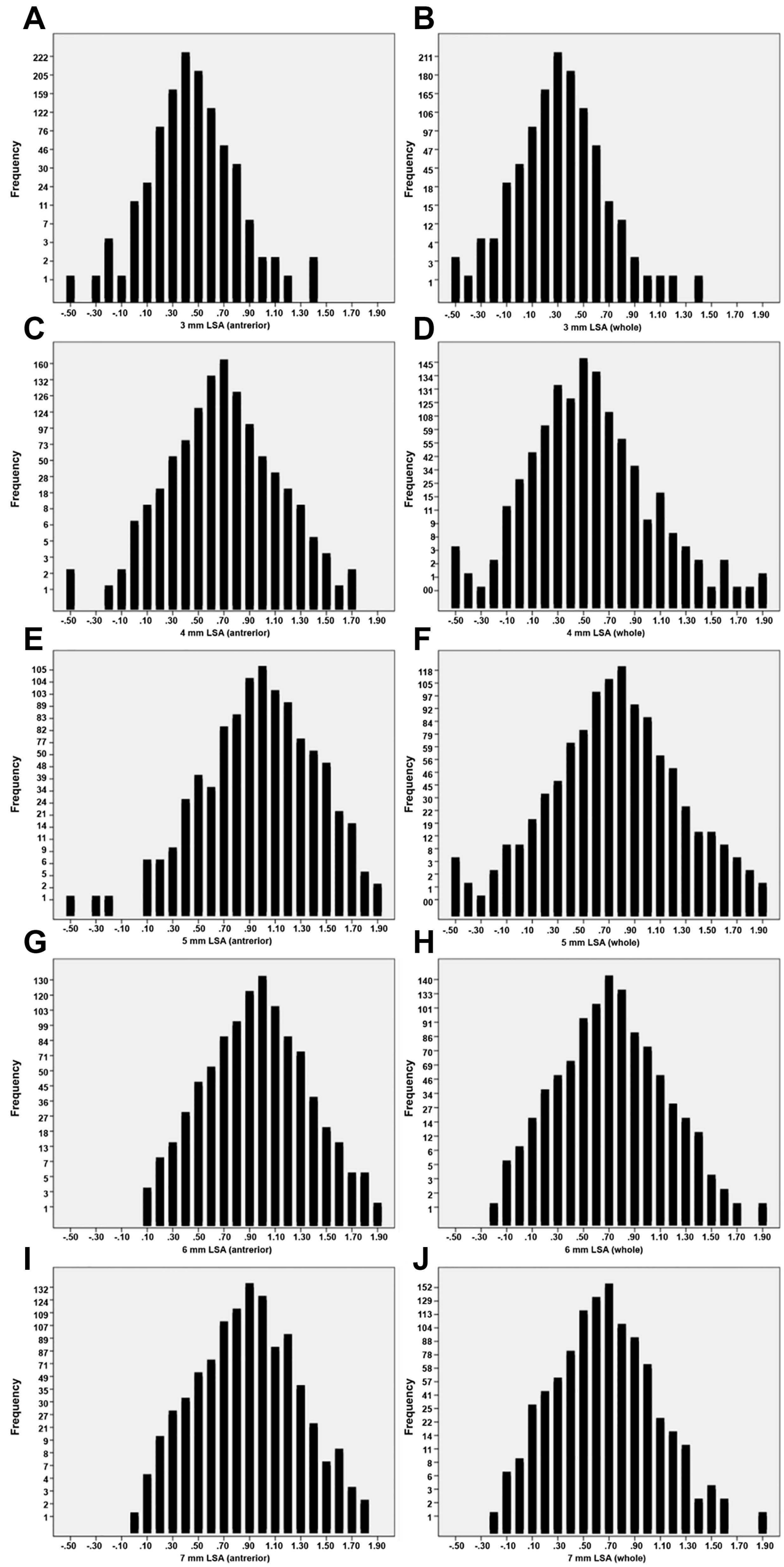


**Figure 5** Distribution of corneal longitudinal spherical aberration (LSA) values at 3.0, 4.0, 5.0, 6.0, and 7.0 mm aperture diameters, anteriorly and wholly, in 915 individuals. The corneal LSA values of the anterior surface were: 0.39±0.19 D, 0.63±0.27 D, 0.97±0.36 D, 0.90±0.30 D, and 0.83±0.29 D, respectively, and the mean whole corneal LSA values were 0.26±0.20 D, 0.44±0.27 D, 0.70±0.36 D, 0.66±0.30 D, and 0.59±0.28 D respectively.

**Table 2** Results of Correlation Analyses

| Parameters | Age | | SE | |
|---|---|---|---|---|
| | *r* | *P* | *r* | *P* |
| Q value of anterior cornea | | | | |
| 3 mm | −0.083 | 0.012 | <0.001 | 0.999 |
| 4 mm | −0.102 | 0.002 | 0.052 | 0.118 |
| 5 mm | −0.089 | 0.007 | 0.054 | 0.102 |
| 6mm | −0.069 | 0.036 | 0.114 | 0.001 |
| 7 mm | −0.055 | 0.096 | 0.120 | <0.001 |
| Q value of posterior cornea | | | | |
| 3 mm | 0.176 | <0.001 | 0.029 | 0.379 |
| 4 mm | 0.181 | <0.001 | 0.029 | 0.374 |
| 5 mm | 0.175 | <0.001 | 0.019 | 0.572 |
| 6 mm | 0.155 | <0.001 | 0.009 | 0.775 |
| 7 mm | 0.155 | <0.001 | −0.015 | 0.649 |
| LSA of anterior cornea | | | | |
| 3 mm | −0.050 | 0.134 | −0.009 | 0.793 |
| 4 mm | −0.055 | 0.097 | 0.034 | 0.304 |
| 5 mm | −0.036 | 0.280 | 0.037 | 0.266 |
| 6 mm | −0.009 | 0.794 | 0.092 | 0.005 |
| 7 mm | 0.004 | 0.899 | 0.100 | 0.002 |
| LSA of whole cornea | | | | |
| 3 mm | −0.103 | 0.002 | −0.014 | 0.668 |
| 4 mm | −0.100 | 0.003 | 0.028 | 0.405 |
| 5 mm | −0.076 | 0.022 | 0.035 | 0.284 |
| 6 mm | −0.037 | 0.263 | 0.097 | 0.003 |
| 7 mm | −0.021 | 0.527 | 0.113 | 0.001 |
| LSA of posterior cornea | | | | |
| 3 mm | −0.152 | <0.001 | −0.018 | 0.577 |
| 4 mm | −0.145 | <0.001 | −0.016 | 0.618 |
| 5 mm | −0.120 | <0.001 | −0.002 | 0.944 |
| 6 mm | −0.083 | 0.012 | 0.01 | 0.761 |
| 7 mm | −0.076 | 0.022 | 0.032 | 0.333 |

**Abbreviations**: SE, spherical equivalent; LSA, longitudinal spherical aberration.

−0.22 for Cheung[14] and Scholz,[26] −0.24 for Dubbelman,[27] −0.30 for Zhang,[1] −0.33 for Carney,[24] and −0.35 for Davis)[28] all are in the lower negative range, indicating that the corneal profile is prolate. Furthermore, we found that both anterior and posterior corneal Q values decreased with increasing diameter. From the apex of the cornea to the periphery of the cornea, the profile of the anterior corneal surface changes from spherical to prolate and the posterior surface from oblate to prolate. We also investigated the distribution of LSA at multiple corneal regions in myopia. Both corneal anterior and whole corneal LSA increased significantly up to 5 mm diameter, but beyond 5 mm they decreased slightly with increasing diameter. This may be related to eyelid compression and is not consistent with the previous assumption that all HOAs increases significantly with diameter. Both corneal Q values and LSA at all apertures showed very weak or no correlation with age or spherical equivalent. Similar conclusions were obtained by Fuller,[2] Zhang,[1] and Llorente.[29]

The present study has limitations. First, this was a single-center study with a relatively small sample size. Second, only myopic patients were included.

## Conclusions

To summarize, the anterior and posterior corneal surface Q values in myopic patients were similar to those of previous studies, with Q values decreasing as diameter increased. From corneal apex to periphery, the profile of the anterior corneal surface changes from spherical to prolate, and that of the posterior surface changes from oblate to prolate. Both corneal anterior and whole corneal LSA increased significantly at diameters up to 5 mm, while beyond 5 mm both anterior and whole corneal LSA decreased slightly with diameter. Both corneal asphericity and LSA showed very weak or no correlation with age or spherical equivalent. These results may provide a useful reference for designing aspheric keratorefractive surgery, visual optical products, and future study of the optical properties of the human eye.

## Abbreviations

LSA, longitudinal spherical aberration; ZZ IOL, Zhang & Zheng IOL; RMS, root mean square; BCVA, best corrected visual acuity; CCT, corneal central thickness; SE, spherical equivalent; HOA, higher order aberration.

## Ethics Approval and Informed Consent

The study was approved by the institutional review board at each participating site and by the ethics committee of Hangzhou MSK Eye Hospital. The data are anonymous, confidential and the study was in compliance with the Declaration of Helsinki, so the requirement for informed consent was waived.

## Acknowledgments

This work was supported by the Zhejiang Province Medical and Health Science and Technology Project (2018267858).

## Disclosure

All authors declare that they have no conflicts of interest in this work.

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