Quantitative adjustment of spherical aberration for aspheric refractive surgery: A Pilot Study

Running title: Quantitative adjustment of spherical aberration

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ABSTRACT

Background: The aim of the study is to introduce the acquisition of target diameter spherical aberration in term of diopter (SA-D), and to report the distribution of SA-D in patients with myopia.
**Methods:** This was a retrospective study of patients who underwent therapeutic refractive surgery at Hangzhou MSK Eye Hospital between 10/2018 and 12/2018. The corneal Q values and apex curvature of the anterior and posterior surfaces were measured at 3.0, 4.0, 5.0, 6.0, and 7.0 mm of aperture diameters using corneal tomography.

**Results:** In total, 531 females and 384 males were included. The anterior corneal SA-D values were: 0.39±0.19, 0.63±0.27, 0.97±0.36, 0.90±0.30, and 0.83±0.29 D at 3.0, 4.0, 5.0, 6.0, and 7.0 mm; 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. SE was positively correlated with anterior corneal peripheral Q-value and SA-D and whole ocular peripheral SA-D.

**Conclusions:** Both corneal anterior and posterior Q values of myopia patients decreased while diameter increased. Both anterior and whole corneal SA-D increases significantly while diameter increases within 5mm, and both anterior and whole corneal SA-D outside 5mm decreases slightly while diameter increases. SE was positively correlated with anterior corneal peripheral Q-value and SA-D and whole ocular peripheral SA-D.

**Keywords:** cornea; corneal wavefront aberration; myopia.

**Background**

In human eyes, the special aspheric shape of cornea and crystalline lens work together to focus light on the macula better, so as to obtain higher visual quality. Due
to the characteristic of high refractive index of cornea and crystalline lens, slight changes in corneal or crystalline lens morphology can impair this delicate system. Such as the halo phenomenon after traditional corneal refractive surgery. However, if we can change the aspheric shape purposefully and effectively, we can also improve the visual quality or extend the depth of field to assist near vision, based on previous research[1-3]. And the related basic theory has been applied to contact lens fitting, ocular aberration measurement, refractive surgeries, and design of intraocular lens (IOL)[4, 5].

In order to better understand asphericity, we need to introduce the concept of Q value, which is a quantitative indicator of the aspherical degree, and is defined as the radius of the curvature change from the corneal apex to the periphery of the morphology. Therefore, as one of the key parameters of mathematical modal, Q value can be used to describe the surface morphology and optical properties of cornea or lens[6, 7].

**Methods**

**Study design and patients**

This was a retrospective study of patients planned for therapeutic refractive surgery at Hangzhou MSK Eye Hospital between October 2018 and December 2018. The study was approved by the ethics committee of Hangzhou MSK Eye Hospital. Informed consent was waived because of the retrospective nature of the study.

The inclusion criteria were: 1) patient with 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, etc.), history of contact lens use within 6 months, and 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, refraction (to measure diopter), best corrected visual acuity (BCVA), cycloplegic refraction, slit-lamp examination (to assess corneal status, presence of scar, history of corneal transplantation, anterior chamber puncture, iris repair, etc.), axial length, gonioscopy (peripheral retinal examination to assess retinal tears, etc.), funduscopy (central retinal examination to screen for fundus diseases such as macular and vasculopathy), and intraocular pressure. In addition, corneal topography, including parameters like corneal central thickness (CCT) and Sim-K of anterior and posterior corneal surface, was obtained using a tomography instrument (Sirius; CSO, Florence, Italy). SE was obtained as “the spherical diopter + 1/2 cylindrical diopter”, based on BCVA data.

**Measurement of vertex curvature of anterior and posterior corneal surfaces**

In the corneal tangential curvature map, the origin of the coordinate system is the
corneal vertex curvature. All measurements were performed thrice, and the mean was used for statistical analysis.

**Measurement of Q value of the anterior and posterior corneal surfaces**

The Q values of different areas, including the anterior and posterior corneal surface at 3.0, 4.0, 5.0, 6.0, and 7.0 mm aperture diameters, were obtained using the tomography results. All measurements were performed thrice, and the mean was used for statistical analysis.

**Calculation of SA-D of the anterior corneal surface and whole cornea**

The SA-D of different areas, including the anterior corneal surface and whole cornea at 3.0, 4.0, 5.0, 6.0, and 7.0 mm aperture diameters, were calculated by follows:

The equation describing the asphericity of the cornea is [8]

\[
x^2 + y^2 + (1 + Q)z^2 - 2zR = 0
\]

(1)

Where x and y are the radius 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.

In the XOZ plane, the cross section of the corneal surface 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 can be expressed as
\[ z = f(x) = \frac{R - \sqrt{R^2 - (1+Q)x^2}}{1+Q} \]  

(2)

By calculating the first and second derivative of \( z \) to \( x \), the motion angle \( \alpha \), motion angle \( \beta \) (back surface), speed \( v \), and the acceleration in the direction of the \( z \) axis of the target diameter can be obtained.

\[ \dot{z} = f'(x) = \tan\alpha = v = \frac{x}{\sqrt{R^2 - (1+Q)x^2}} \]  

(3)

\[ \ddot{z} = f''(x) = \frac{\sqrt{R^2 - (1+Q)x^2} + (1+Q)x^2[R^2 - (1+Q)x^2]^{-\frac{1}{2}}}{R^2 - (1+Q)x^2} \]  

(4)

According to the formula of centripetal acceleration of a circular motion, the target diameter curvature can be obtained.

\[ r = \frac{[1+f(x)]^{\frac{3}{2}}}{f'(x)} \]  

(5)

Reflection from the anterior corneal surface is shown in Figure 2.

According to Figure 2, the SA-D of the anterior corneal surface of the target diameter can be calculated.

\[ \text{SA-D of the anterior corneal surface} = \frac{n_2^{1000}}{OB} - \frac{n_2^{1000}}{\lim_{x \to 0} AB} = \frac{n_2^{1000} x}{\tan[\alpha - \arcsin\left(\frac{n_1^{1000} \sin \alpha}{n_2^{1000}}\right)]} - \frac{n_2^{1000} n_2 R}{n_2 - n_1} \]  

(6)

The reflection from the posterior corneal surface is shown in Figure 3.

According to Figure 3, the SA-D of the whole cornea of the target diameter can be calculated.
SA - D of the whole cornea = \frac{n_2 1000}{OE} - \frac{n_2 1000}{\lim_{x \to 0} D'E} = \frac{n_2 1000}{x} \left[ \frac{R(b) - \sqrt{R(b)^2 - (1 + Q)x^2}}{1 + Q} \right] \frac{\pi n_3}{\lim_{x \to 0} A'B} \tan(\beta - \arcsin\left(\frac{n_2}{n_3} \sin \alpha \beta \right)} + R(b) - \sqrt{R(b)^2 - (1 + Q)x^2} + n_2 1000 \lim_{x \to 0} AB \tag{7}

The SA-D value of anterior and whole corneal surface at 3.0, 4.0, 5.0, 6.0 and 7.0 mm of aperture diameters were recorded and analyzed.

**Statistical analysis**

Continuous variables are expressed as means ± standard deviation (SD). Correlations among parameters were examined using the Pearson correlation. All statistical analyses were performed using SPSS 19.0 (IBM, 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. The SE range of -13.00 to -0.50 D (mean: -6.5±2.2 D). The corneal central thickness (CCT) and Sim-K of the anterior and posterior corneal surfaces were 536.0±91.2 μm, 43.5±12.7 D, and -5.9±0.4 D, respectively (see Additional file 1). Slit-lamp examination, gonioscopy, and funduscopy showed no significant lesions in these patients.
**Corneal Q values**

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 at 3.0, 4.0, 5.0, 6.0, and 7.0 mm of aperture diameters, respectively. The corneal Q values 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 at 3.0, 4.0, 5.0, 6.0, and 7.0 mm of aperture diameters, respectively. The distribution of corneal Q value at different aperture diameters is shown in Figure 4.

**Corneal SA-D values**

The corneal SA-D 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 at 3.0, 4.0, 5.0, 6.0, and 7.0 mm of aperture diameters, respectively. The whole corneal SA-D 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 at 3.0, 4.0, 5.0, 6.0, and 7.0 mm of aperture diameters, respectively. Therefore, the corneal SA-D 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 at 3.0, 4.0, 5.0, 6.0, and 7.0 mm of aperture diameters, respectively. The distribution of corneal SA-D values at different aperture diameters is shown in Figure 5.

**Correlations**

Age was correlated with Q values in multiple areas of the cornea, including at anterior 3 mm, 4 mm, 5 mm, and 6 mm, and posterior 3 mm, 4 mm, 5 mm, 6 mm, and
Age was correlated with SA-D in multiple areas of the cornea, including whole 3 mm, 4 mm, and 5 mm, and posterior 3 mm, 4 mm, 5 mm, 6 mm, and 7 mm. SE was correlated with 6-mm and 7-mm anterior Q values, anterior SA-D, and whole corneal SA-D (see Additional file 1).

Discussion

The understanding of the refractive system of human eyes is constantly improving with the rapid development of physical optics. Especially, the introduction of HOAs has brought the study of visual quality to a higher level. HOAs has become an important research index in refractive surgery. SA, as an aberration item with lower order and lower frequency, has a great impact on visual quality[9]. Almost all previous studies on SA are directly referenced from physical optics, which is more difficult to understand and apply in ophthalmology compare to SA-D. Therefore, the calculation method of SA-D in this paper should be able to assist corneal refractive surgery.

Previous studies have confirmed that aspheric keratorefractive surgery is safe and effective. And compared with the traditional operative strategy, Q-value-guided can better maintain the anterior corneal surface morphology, reduce the introduction of SA and better obtain the visual quality[10, 11]. At present, the aspheric operative strategy usually is achieved by adjusting anterior corneal Q-value, and cannot be achieved by adjusting SA-D. As mentioned above, this will limit the significance of clinical guidance. Although thought the theoretical calculation Manns et al. show that adjust
anterior corneal Q value to -0.45 ~ -0.47 can make ocular SA to zero [12], there will be errors for patients, especially when the corneal curvature deviates from the normal data due to ametropia correction.

Therefore, it is not difficult to know that quantitative adjustment of SA-D can provide better guidance for surgical strategy, compare to adjustment of Q-value or SA-μm. Limited by the software system of current equipment, such as Alcon EX500 excimer equipment, aspheric treatment can only be achieved by quantitative adjustment of Q value or e value. In order to adjust SA-D quantitatively, it is necessary to convert Q-value adjustment through a calculator, which is open access on www.zzcal.com, according to the above formula while ametropia correction.

This method might be helpful for keratorefractive surgery. For example, for young patients who want to achieve high visual quality, we may wish to set ocular SA-D to zero or do not change ocular SA-D. So according to the value of pre-operative ocular SA-D, the adjustment amount of SA-D (ΔSA-D) can be calculated. Then combined with pre-operative corneal curvature and planned corrected diopter, the adjustment amount of Q-value (ΔQ) can be calculated. For another example, for elder patients who want to achieve EDOF quantitatively, such as set ocular SA-D to -1.50D, which can compensate for the decrease of accommodation of presbyopia and improve the near-term vision of the eye with decreased accommodation capacity [13-15]. ΔQ can still be calculated by the above method.

Besides, we have known that corneal asphericity matches with optical elements to establish an aberration balance and reduces SA[16]. Increase in corneal asphericity is
associated with an increase in SA. Indirectly, asphericity correlates with SA, one of the most effective factors in degrading image quality[17]. It is necessary to measure the corneal asphericity in order to correct corneal aberration. Corneal asphericity plays an important role in visual function[18]. Therefore, another aim of this study is to report the distribution of corneal Q-value and SA-D in patients with myopia.

First, in the present study, the distribution of corneal Q values in multiple regions in myopia patients was determined, and the results are supported by previous studies. Although different studies have different Q values (for example -0.08 for Horner [19], -0.20 for Fuller[2], -0.22 for Cheung [8] and Scholz[20], -0.24 for Dubbelman[21], -0.30 for Zhang[1], -0.33 for Carney[18], and -0.35 for Davis [22]) all of them are in the lower negative range, which means that the corneal profile is prolate. Furthermore, the trend of both anterior and posterior corneal Q value was found to decrease with increasing diameter. From the apex of the cornea to the periphery of the cornea, the profile of the anterior corneal surface changes from circle to prolate and posterior surface from oblate to prolate. Second, the phenomenon of distribution of corneal SA-D in multiple regions in myopia patients was very interesting. Both anterior and whole corneal SA-D increases significantly while diameter increases only within 5mm, but both anterior and whole corneal SA-D outside 5mm decreases slightly while diameter increases. This is not consistent with the previous assumption that all HOA items increases significantly with the increase of diameter.

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

Target diameter corneal SA-D can be obtained using the method presented in this paper. Corneal Q values of anterior and posterior surfaces of myopia patients were similar with those of previous studies. Q values decrease with increasing diameter. From the apex of cornea to the periphery of cornea, the profile of the anterior corneal surface changes from circle to prolate, and that of the posterior surface changes from oblate to prolate. Both anterior and whole corneal SA-D increases significantly while diameter increases within 5mm, and both anterior and whole corneal SA-D outside 5mm decreases slightly while diameter increases. SE was positively correlated with anterior corneal peripheral Q-value and SA-D and whole ocular peripheral SA-D. 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.

List of abbreviations

SA-D, spherical aberration in term of diopter

IOL, intraocular lens

HOAs, high-order aberrations

SA, spherical aberration
EDOF, expected extend depth of field

SE, spherical equivalent

BCVA, best corrected visual acuity

CCT, corneal central thickness

**Declarations**

**Ethics approval and consent to participate**

The study was approved by the ethics committee of Hangzhou MSK Eye Hospital (APPROVAL NO.MSKLL20190310). Hangzhou MSK Eye Hospital (3301034128970) has waived the need of informed consent because of the retrospective nature of the study. And all methods were carried out in accordance with relevant guidelines and regulations.

**Consent for publication**

Not applicable

**Availability of data and materials**

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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**Competing interests**

The authors declare that they have no competing interests

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**Authors' contributions**

ZJ and ZL conceived and supervised the study; ZX designed experiments; GJD and ZYX performed experiments; WK analysed data; XX, XX and XX wrote the manuscript; ZL made manuscript revisions. All authors reviewed the results and approved the final version of the manuscript.

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Not applicable

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Additional file 1
Characteristics of the patients
Correlation analyses

Figure legends

**Figure 1:** Corneal surface coordinate system. Suppose that a point moves along the curve, \( \dot{z} \) is the velocity of this point, \( \alpha \) is the motion angle of this point, and \( \ddot{z} \) is the acceleration of this point parallel to the \( z \) axis.

**Figure 2:** Refractive trajectory of light passing through the anterior surface of the cornea. The motion angle \( \alpha \) is also the incidence angle; \( \theta \) is the reflection angle; and \( n_1 \) and \( n_2 \) are the refractive index of the air and cornea.

**Figure 3:** Refractive trajectory of light passing through the posterior surface of the cornea. \( \beta \) is the motion angle; \( \gamma \) is the reflection angle; and \( n_2 \) and \( n_3 \) are the refractive index of the cornea and aqueous.

**Figure 4:** Distribution of corneal Q value at 3.0, 4.0, 5.0, 6.0, and 7.0 mm of aperture diameters, anteriorly and posteriorly, in 915 individuals. The corneal Q values of the anterior surface were: \(-0.09\pm0.21\), \(-0.14\pm0.16\), \(-0.15\pm0.13\), \(-0.17\pm0.11\), and \(-0.20\pm0.11\),
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, at 3.0, 4.0, 5.0, 6.0, and 7.0 mm of aperture diameters, respectively.

**Figure 5:** Distribution of corneal LSA values at 3.0, 4.0, 5.0, 6.0, and 7.0 mm of 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, 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, at 3.0, 4.0, 5.0, 6.0, and 7.0 mm of aperture diameters, respectively. LSA: longitudinal spherical aberration.