Study on the corneal higher-order aberrations and correlation in patients with different degrees of myopia suitable for wavefront-guided FS-LASIK

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Research article

Keywords: Corneal refractive surgery, Anterior and posterior corneal surface, Higher-order aberration, Spherical aberration

Posted Date: May 1st, 2019

DOI: https://doi.org/10.21203/rs.2.433/v2

Version of Record: A version of this preprint was published at Journal of Biosciences and Medicines on January 1st, 2020. See the published version at https://doi.org/10.4236/jbm.2020.81003.

Abstract

Background: To investigate the characteristics and distribution of anterior and posterior surface wavefront aberrations in patients suitable for corneal refractive surgery. Methods: A total of 121 myopic patients (121 eyes, 14-46 years old) who underwent corneal refractive surgery were randomly selected by the Pentacam anterior segment analysis system with a spherical equivalent (SE) of -1.50 to -12.00 D. The corneal anterior and posterior aberrations (higher-order aberration, HOA; spherical aberration, SA; Coma; Trefoil) and Q and K values were detected, and a correlation analysis of the relevant parameters was carried out. Results: The root-mean-square (RMS) of the third to sixth order aberrations of the ocular and corneal wave surface aberrations at a 6.0-mm pupil showed a decreasing trend in patients suitable for the corneal refractive surgery, and the RMS of the third order aberrations accounted for 62.92% of the total HOAs. The coma ratio (coma ratio: coma/total cornea higher-order aberrations) was increased with the increasing diopters, while the spherical aberration ratio (spherical aberration/ total cornea higher-order aberrations) was not changed. In addition, the spherical aberration was 0.203± 0.082 μm (range: 0.061 to 0.503 μm), and the Q30 was -0.19±0.03 (range: -0.58 to 0.31). There were significant differences in the coma aberrations of preoperative corneal anterior surface (3, 1) between the low, middle and high myopia groups (P=0.013). The spherical equivalent was positively correlated with the corneal coma of the preoperative anterior corneal surfaces (R=-0.241, P=0.009), and the Q value was positively correlated with the total higher-order aberrations (R=0.326, P<0.001). Conclusions: Individual wavefront aberrations on the anterior and posterior surfaces of the cornea are comparatively different, and the Zernike coefficients are related to the degree of myopia. Spherical aberrations are the most overriding aberrations of the cornea.

Background

Wavefront aberration is the deviation between the actual and the ideal wavefront, including wavefront aberrations of the cornea and inner eye, which are the main factors affecting visual quality. The connotation of wavefront aberrations can be expressed by the Zernike polynomial periodic table [1]. The wavefront is divided into low and higher-order aberrations. Myopia, hypermetropia and astigmatism are low order wavefront aberrations, while spherical and coma aberrations are higher-order wavefront aberrations. Conventional corneal laser refractive surgery significantly improves higher-order aberrations and corrects low order aberrations, and consequently significantly improves visual quality [2-4].

Although there have been numerous studies on wavefront aberrations in the integral eye, there are few studies on wavefront aberrations of the cornea. Corneal refractive surgery is performed on the anterior surface of the cornea. The increase in wavefront aberrations after femtosecond laser-assisted laser in situ keratomileusis (FS-LASIK) is mainly due to changes in wavefront aberrations on the anterior corneal surface because changes on the posterior surface of the cornea are smaller [4]. The aim of our study is to investigate the wavefront aberrations on the anterior surface of the cornea in a myopic population and to provide a clinical basis for designing a more reasonable wavefront-guided individualized corneal refractive surgery.

Methods

Patients

From January 2016 to May 2016, 121 patients underwent FS-LASIK surgery (Department of Ophthalmology, the Affiliated Hospital of Yanbian University) to correct myopia, including 59 males and 62 females, aged 17-45 years with an average of 25.58±5.90 years old. The patients had spherical equivalent power ranging from -025 to -9.63 diopters (D); astigmatisms≤1.50 D; intraocular pressure ranging from 8.5 to 20.1 mmHg, average 12.49±2.85 mmHg; and corneal thinnest point thickness ranging from 463 to 603 μm, average 524.96±26.67 μm. The patients were required to wear corneal contact lenses for more than 2 weeks. None of the patients had obvious eye diseases, such as glaucoma, cataract or other systemic diseases. Each patient was enrolled in only the right eye for study. The institutional review board at the Affiliated Hospital of Yanbian University approved this study, which followed the tenets of the Declaration of Helsinki. Written informed consent was obtained from all patients after the nature and possible consequences of the study were explained.

Wavefront aberration measurement

The Pentacam system (Oculus, Inc, USA) was used to measure the higher-order aberrations on the corneal anterior surface with a 6.0-mm area at the center of the pupil. The iTrace aberrometer (Tracey, Inc, USA) was used to measure ocular aberration. During the test, the patients were required to take a seat and stare at the fixation target, a blue band at the center of the rotation axis in the Pentacam system. Aiming and focusing in the system were achieved by an ophthalmologist skilled in the operation of the system using a joystick according to the instructions on the screen and 180° scanning of Scheimpflug 3D imaging performed within 2s. Each patient was tested by the same ophthalmologist. The measurement was taken 3 times consecutively for trefoil, spherical, and coma aberrations and trefoil aberrations. The average values were calculated for trefoil, spherical, and coma aberrations. The average values of the root-mean-square higher-order aberrations (RMS HOAs) for trefoil aberration were calculated. All surgeries were performed by the same ophthalmologist using the FS200 femtosecond laser (Alcon Laboratories, Inc, Fort Worth, TX) to make a 110-μm thickness and a pedicle on the top corneal flap. Then, after opening and stacking the flap, the EX500 excimer (Alcon Laboratories, Inc, Fort Worth, TX) laser systems was used to cut a 6.5-mm optical zone under the wavefront-guided customized ablations system. After cutting the optical zone, the stromal bed was rinsed with balanced salt solution, and the flap was recovered.

Operation groups

The patients were divided into 3 groups by myopic degree: the low group included 42 patients with 42 eyes, the moderate group included 40 patients with 40 eyes, and the high group contained 39 patients with 39 eyes.

Statistics

The continuous variables were summarized by means ± standard deviations (SDs) and ranges. The categorical variables were summarized by frequencies and proportions. Analysis of variance (ANOVA) along with Duncan's multiple range test was used to compare wavefront variables among the three groups. A simple linear regression model and Spearman's rank correlation coefficient were used to assess the relationship between nuclear lens density and internal optics aberration. A *P* value of less than 0.05 was considered statistically significant. All data analysis was performed using SPSS version 12 (SPSS, Inc., Chicago, IL, USA).

Results

A total of 121 patients (59 men and 62 women) were evaluated. The mean age of the patients was 29.3 ± 7.5 years (range 18 to 48 years). The average corneal curvature was 42.62 ± 1.23 D (range 39.32 to 48.91 D). In addition, the mean values for the spherical equivalent (SE), axial length (mm), sphere (D) and cylinder (D) are shown in Table 1. Differences in the binocular sphere degree were ≤ 2.50 D.

Table 1. Characteristics of patients and surgical data.

	Mean ± SD	Range
Age (years)	29.3 ± 7.5	18 to 45
SE (D)	-5.74 ± 1.91	0 to -10.50
· Axial length (mm)	26.51 ± 1.49	23.09 to 31.85
Sphere(D)	-4.93 ± 1.75	-0.25 to -9.63
Cylinder (D)	-0.79 ±0.81	0 to -2.00

The root-mean-square (RMS) of (the third to the sixth order) aberrations of the ocular and corneal higher-order wave surface aberrations at a 6.0-mm pupil in different myopia groups are shown in Table 2. As shown in Table 2, the Zernike coefficients progressively decrease the RMS values from the third to the sixth order, and the total of the higher-order aberrations at an RMS of the third order aberrations was approximately 62.96%. There were some changes in spherical aberrations and coma aberrations before corneal refractive surgery: the spherical aberrations accounted for 53.3%, 52.1% and 42.5%, in the low, moderate and high myopia groups, respectively, and the coma aberrations were 42.2%, 56.4% and 62.3%, respectively. At a 6.0-mm pupil, the total corneal higher-order aberration was 0.351±0.152μm, and the spherical aberration was 0.203±0.082μm (range from 0.061 to 0.503μm), in which 71.6%, 19.2% and 32.7% of the patient eyes were at 0.15 - 0.30μm, 0.25 - 0.30μm and 0.20 - 0.25μm, respectively. In addition, the coma and trefoil aberrations were 0.134±0.052μm and 0.157±0.094μm, respectively. The aberrations of the corneal anterior surface between the low, moderate and high myopia groups (3, 1) were significantly decreased (*P*=0.013 at 3, 1, Figure 1). Moreover, as the diopter increased, the coma aberration ratio (coma aberration ratio: spherical aberration/ total cornea higher-order aberrations) increased, but the spherical aberration decreased in the ocular, while the spherical aberration not changed in the cornea (Figure 2).

Table 2. Mean levels of RMS (μm) in different myopic groups for a 6-mm pupil

Refractive error	n	Total HOA	Coma	SA	Trefoil
High myopes(-10 to -6 DS)	39	0.47 ± 0.12	0.23 ± 0.11	0.10 ± 0.06	0.24 ± 0.12
Moderate myopes (-6 to -3 DS)	40	0.43 ± 0.15	0.23 ± 0.12	0.11 ± 0.07	0.22 ± 0.13
Low myopes (-3 to -0.75 DS)	42	0.45 ± 0.11	0.19 ± 0.08	0.14 ± 0.10	0.17 ± 0.08
P		0.154	0.016	0.203	0.541

RMS HOAs, root –mean-square of higher-order aberrations; SA, spherical aberration.

The Q30 value at the 6.0-mm pupil of the anterior corneal surface suitable for excimer laser surgery in patients was -0.19 ± 0.03 (range: -0.58 to 0.31). The numbers of eyes with negative Q20, Q25, Q30, Q35 and Q40 values accounted for 81.21%, 87.31%, 90.14%, 100% and 93.24% of the total eyes, respectively. The Q value of the posterior corneal surface was relatively large. The numbers of eyes with positive Q20, Q25, Q30, Q35 and Q40 values accounted for 72.56%, 80.31%, 32.26%, 15.23% and 3.58% of the total eyes, respectively. The Q30 value of the posterior corneal surface was 0.02 ± 0.03 (range: -0.21 to 0.26). There were no significant differences in Q values among the low, moderate and high myopia groups (Figure 3).

In addition, the results of the correlation analysis showed that the spherical equivalent power was positively correlated with the coma of the anterior

corneal surfaces (R = -0.241, P = 0.009), but there was no correlation with the total higher-order, spherical or trefoil aberrations (R = 0.073, P = 0.435; R = 0.039, P = 0.671; R = 0.027, P = 0.770, respectively, Figure 4). Furthermore, the Q value was positively correlated with the total higher-order aberrations (R = 0.326, P <0.001), but was not correlate with coma or trefoil aberrations (R = 0.103, P = 0.535 and R = 0.065, P = 0.977, respectively, Figure5).

Discussion

With the continuous development of corneal refractive surgery and the further updating of related equipment, excimer laser corneal refractive surgery has become a procedure with high safety, predictability and rapid recovery. This type of surgery is also the most active and fastest growing discipline in current ophthalmology. Based on the worldwide prevalence of myopia, it can be estimated that over 22% of the current world population, that is, 1.5 billion people, are myopic. LASIK has emerged as the refractive corneal surgical procedure of choice for the correction of myopia, with approximately 620,000 to 720,000 procedures performed annually in the last 5 years in the US to correct refractive error.

China is one of the countries with the highest incidence of myopia in the world, and increasingly many surgeries will be needed every year to allow people to get rid of their glasses [5, 6, 7].
In conventional optics, the image is differentiated into chromatic and monochromatic aberrations[6]. Monochromatic aberrations can be divided into spherical aberration, coma, astigmatism, curvature of field and distortion. The difference between actual and ideal wavefront in physical optics is the wavefront aberration[7], which is an effective strategy for clinically diagnosing and evaluating retinal imaging quality in humans. Retinal imaging quality is affected by various factors, such as pupil size [8], tear film [9] and age [10].

Traditional corneal refractive surgery may correct low order aberrations, such as myopia, hyperopia and astigmatism, but higher-order aberrations, which cause adverse symptoms, including night vision decline, glare, halos, and visual discoloration, are not corrected in some patients with surgery [11, 12]. For this reason, individualized corneal refractive surgery guided by wavefront has been performed, and the adverse symptoms mentioned above have been improved. Wavefront-guided individualized corneal refractive surgery has become a hot topic and is regarded as a milestone in the development of corneal refractive surgery [13]. Individualized corneal refractive surgery requires an understanding of the basis of higher-order aberrations before surgery, an examination of the changes in anterior and posterior corneal surface and intraocular aberrations and an analysis of their effects on the entire eye system in humans. Therefore, customization of femtosecond laser corneal refractive surgery tailored to the optical properties of an individual is a complex process [14].

In the present study, wavefront aberrations in the anterior corneal surface of the patients were investigated to correct higher-order aberrations with corneal refractive surgery. Our study showed that sphere and coma were the main aberrations in corneal refractive surgery patients. The ratio of coma aberration was increased in the high myopia group, and the sphere was the most dominant type of aberration in the low, moderate and high myopia groups. The frequency of spherical aberration was maintained at approximately 70% and did not change with the diopter. Moreover, the changes in diopter and Q values showed a positive relationship between the low and moderate myopia groups, but there were no significant differences in Q values between the moderate and high myopia groups. These results indicate that the relationship may not be linear and that the correlation was no longer close when the progress reached a certain degree of myopia. Nevertheless, studies of the relationship among Q values, refractive status and diopter in patients have shown divergent results. Sheridan et al found no difference in Q values between the face, myopia and hyperopia groups[15]. However, Dubbelman et al. reported that corneal Q values were positively correlated with the increase in myopia degree [16]. The results of the present study showed that the spherical aberrations on the corneal anterior surface increased with increasing myopia degree; however, there was no significance between the aberration types, although the coma aberration was negatively correlated with the degree of myopia. These results suggest that wavefront-guided individualized refractive surgery in a high myopia population can reduce postoperative coma aberrations without an obvious advantage in reducing spherical aberrations. This idea requires further verification to remediate the large spherical aberration after corneal refractive surgery in high myopia.

Conclusions

Overall, wavefront aberration combined with the excimer laser system for individualized corneal refractive surgery has an upstanding theoretical basis. However, there were significant differences in patients who experienced higher-order aberrations after corneal refractive surgery. These findings indicate that there is still a gap between actual and ideal visual quality. Therefore, further study is needed on the relationship between the components of wavefront aberrations and visual quality and digital correspondence with individualized cutting modes.

Abbreviations

SE: spherical equivalent; RMS: root-mean-square; SD: standard deviation;

FS-LASIK: femtosecond laser-assisted laser in situ keratomileusis;

ANOVA: analysis of variance; SA: spherical aberration.

HOAs: higher-order aberrations.

Declarations

Ethics approval and consent to participate

The institutional review board at the Affiliated Hospital of Yanbian University approved this study, which followed the tenets of the Declaration of Helsinki. Written informed consent was obtained from all patients after the nature and possible consequences of the study were explained.

Consent to publish

Not applicable.

Availability of data and materials

The datasets and materials used during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

Funding

This study was supported by the National Natural Science Foundation of China (81560167).

Authors’ contributions

CZW took part in the design of the study, and revised the manuscript; XC participated in collecting the data and writing the manuscript; ZRL, HC and HJ was involved in the analysis and interpretation of the data and revising the manuscript; CLL and HYJ was involved in collecting data and analyzing the data. YJL participated in the design of the study and gave final approval of the version to be published. All authors read and approved the final manuscript.

Acknowledgments

Not applicable.

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Figures

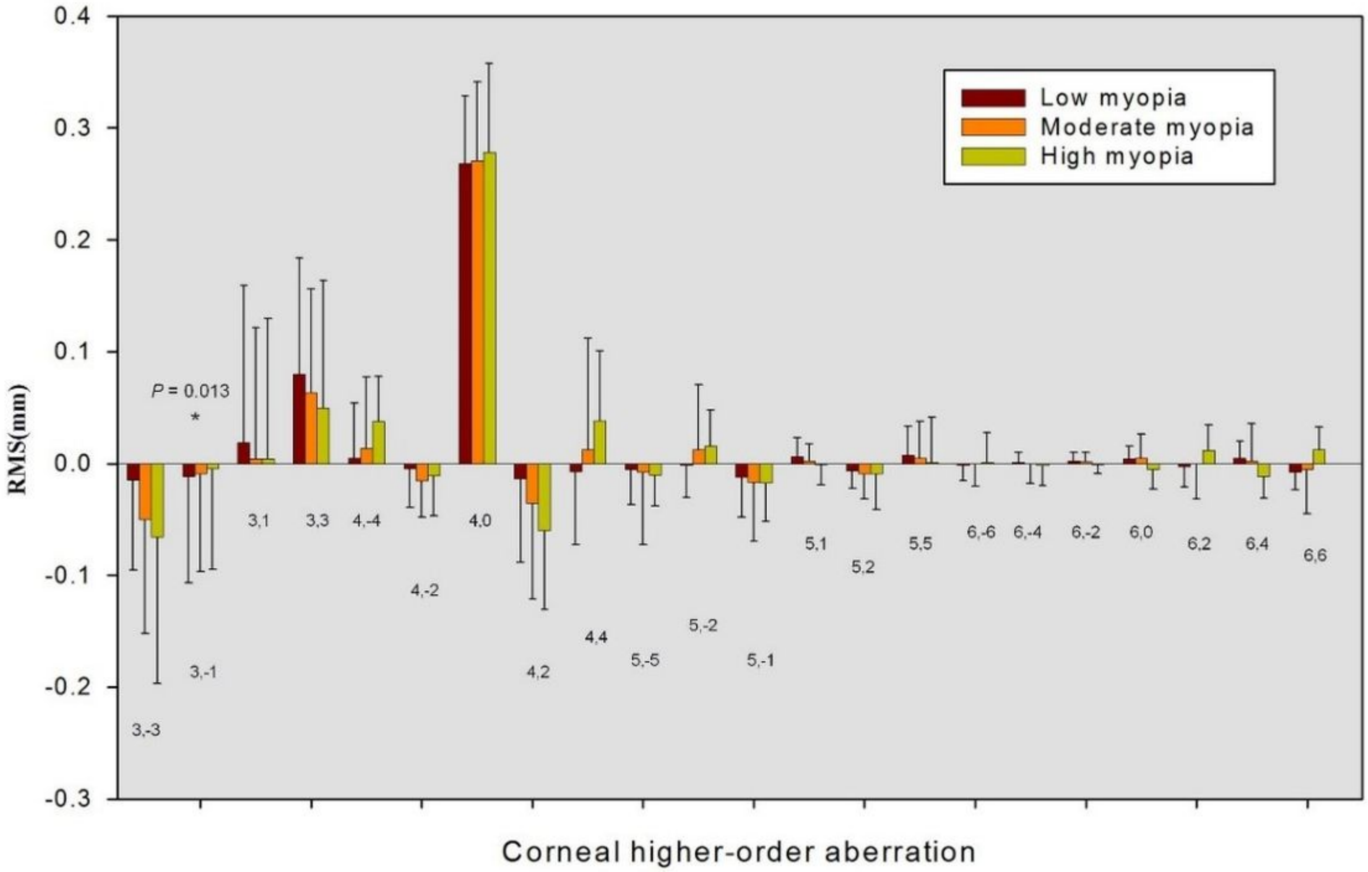

图 2. 不同近视组的角膜高阶像差

Figure 1

The anterior corneal aberrations of different myopia groups were compared.

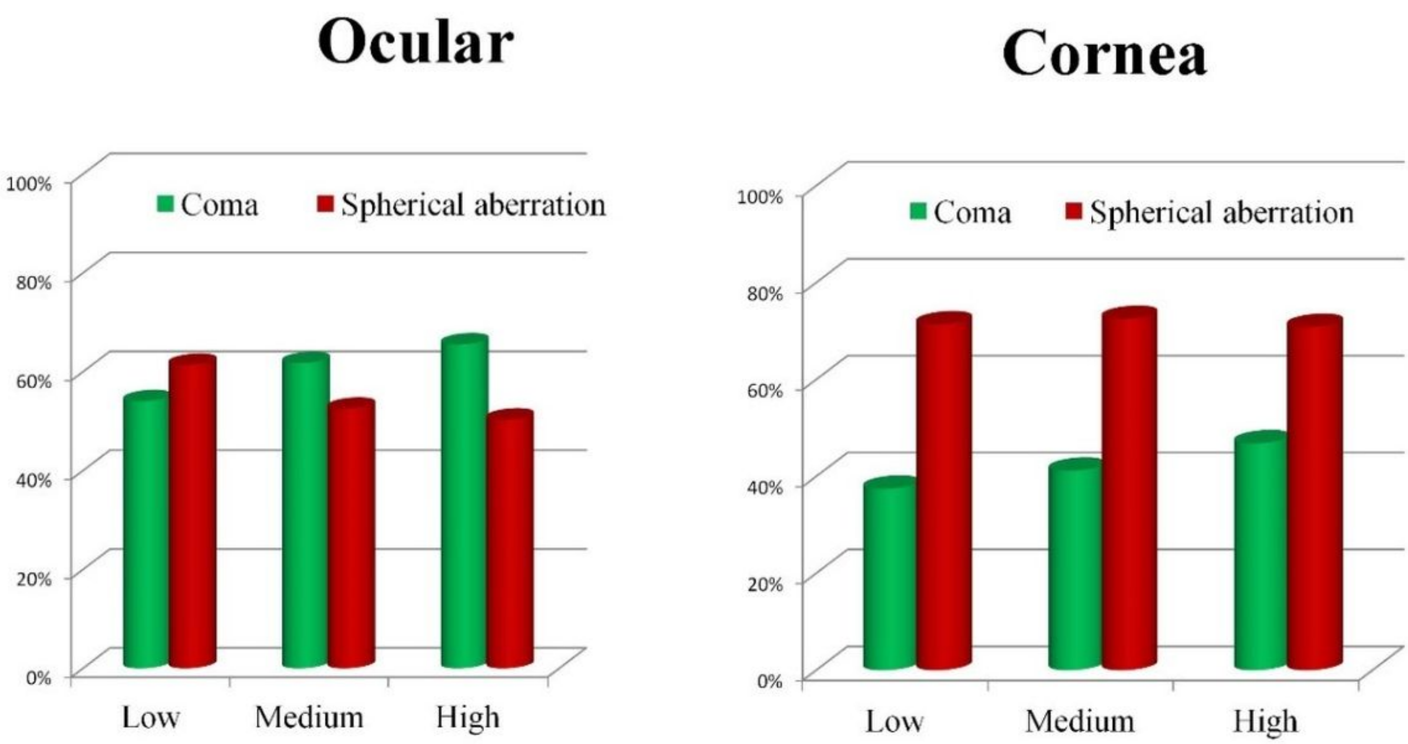

图3. 不同近视组与慧差及球差比率的关系

Figure 2

The ratios of coma and spherical aberration in different myopia groups.

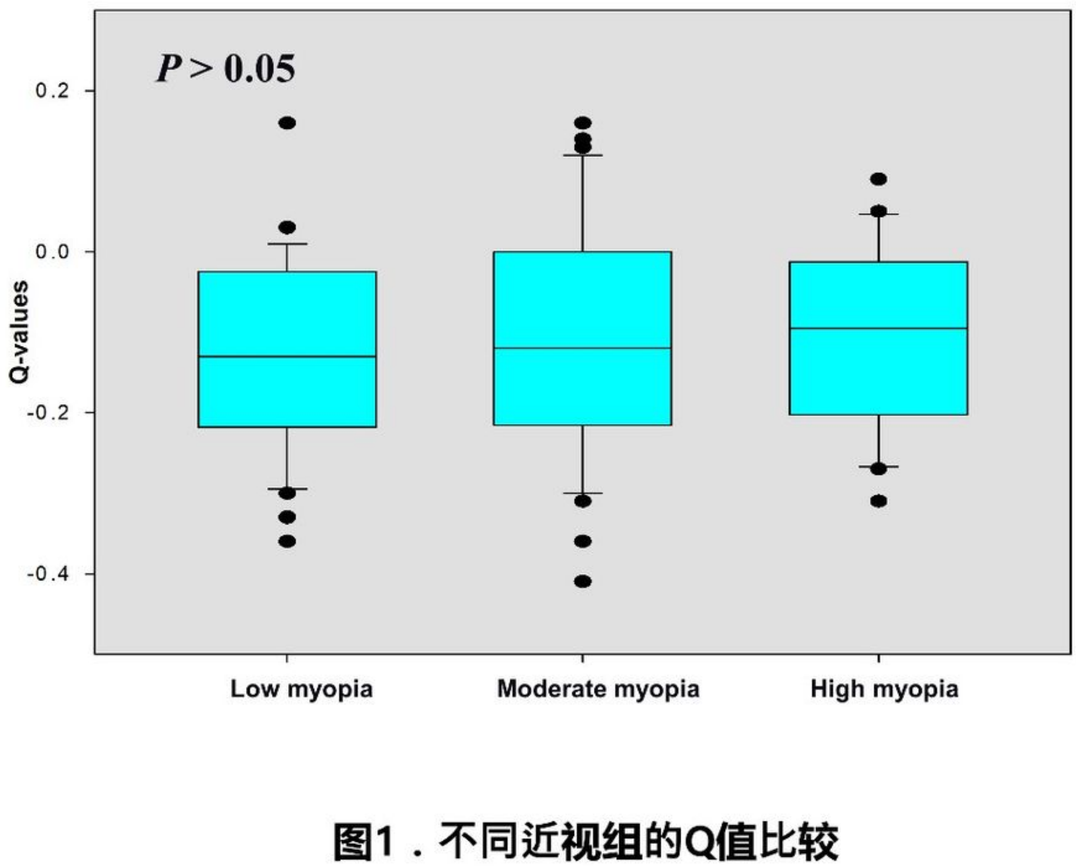

Figure 3

The Q values of different myopia groups were compared.

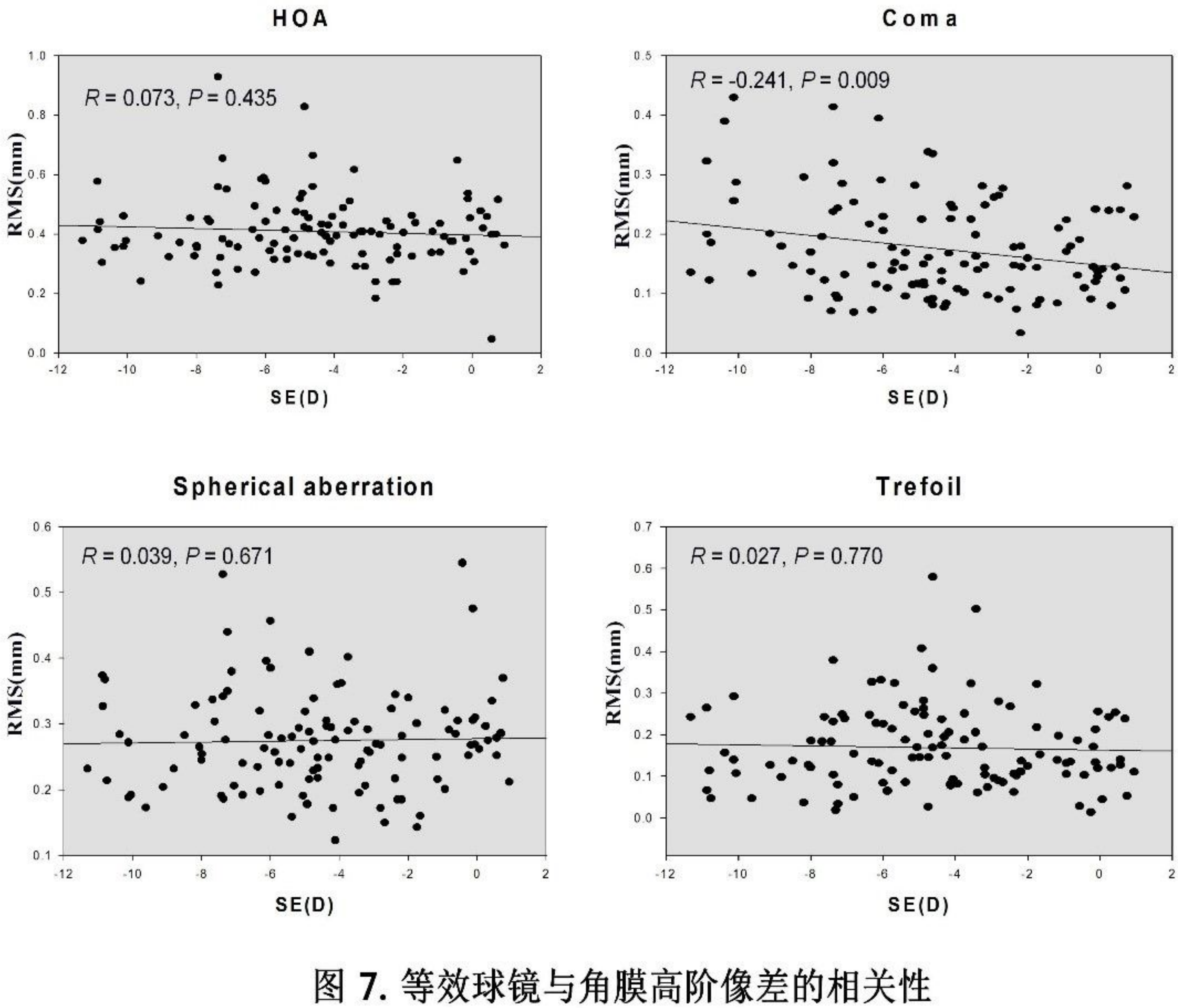

Figure 4

Correlations between spherical equivalents and anterior corneal aberrations.

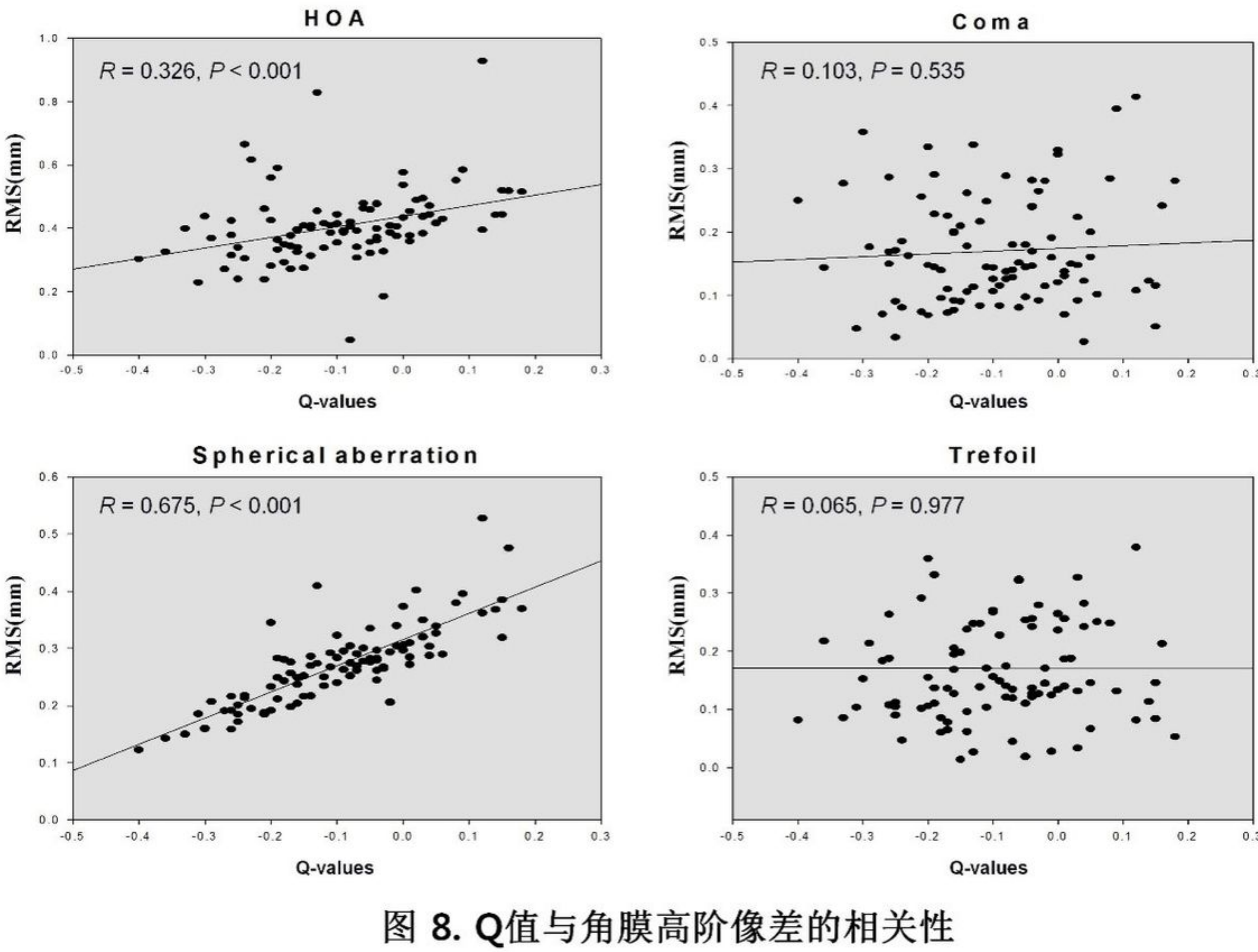

Figure 5

Correlations between the Q value and anterior corneal aberrations.