Study of wavefront aberrations on the corneal anterior surface and related factors in patients after corneal refractive surgery

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Abstract

Background To investigate the characteristics and distribution of anterior and posterior surface wavefront aberrations in patients suitable for corneal refractive surgery. Methods Sixty myopic patients (120 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) values from 3 to 6 (RMS 3 to 6) of the whole eye higher-order wave surface aberrations at a 6.0 mm pupil diameter showed a decreasing trend in patients with corneal refractive surgery, and an RMS value of 3 accounted for 62.92% of the total HOAs. The coma ratio increased with increasing diopter, while the spherical aberration ratio 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), which showed a normal distribution. There were significant differences in coma aberrations (3, 1) in the low, middle and high myopia groups ($P=0.013$). The spherical equivalent was positively correlated with corneal coma ($R = -0.241$, $P = 0.009$), and the Q value was positively correlated with total higher-order as well as spherical aberrations ($R = 0.326$, $P <0.001$; $R = 0.675$, $P <0.001$). 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

A 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 high-stage aberrations. Myopia, hypermetropia and astigmatism are included in low-stage wavefrontaberrations. Geometric astigmatisms, such as spherical and coma aberrations, are included in high-stage wavefront aberrations. Conventional corneal laser refractive surgery significantly improves high-stage aberrations and corrects low-stage 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 surface of the cornea, 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 to guide individualized corneal refractive surgery.

Materials And Methods

Patients

From June 2015 to October 2015, 60 patients underwent FS-LASIK surgery (Department of Ophthalmology, Affiliated Hospital of Yanbian University)to correct myopia, including 32 males and 28 females, aged 17-45 years with an average of 25.58 ± 5.90 years old. The patients had equivalent sphere diameters ranging from -025~-9.63 D; astigmatisms ≤1.50 D; intraocular pressure ranging from 8.5~20.1 mmHg, average 12.49 ± 2.85 mmHg; and corneal thinnest point thickness ranging from 463▯603 μm, average 524.96±26.67 μm. The patients were required to wear mirrored corneal contacts for more than 2 weeks. None of the patients had obvious eye diseases, such as glaucoma, cataract or other systemic diseases. The institutional review board at 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 was used to measure the high-stage aberrations on the corneal anterior surface with a 6.0 mm area at the center of the pupil. 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 oculist skilled in the operation of the system using a joystick according to the instructions on the screening and 180° scanning of Scheimpflug 3D imaging was performed within 2s. Each patient was tested by the same oculist.The measurement was taken 3 times continuouslyfor trefoil, spherical, coma aberrations and clover aberrations. The average values were calculated for trefoil, spherical, and coma aberrations. The average of the root-mean-square higher-order aberrations (RMS HOAs)for clover aberrations were calculateded.

Operation groups

The patients were divided into 3 groups by myopic degree: the low group included 16 patients with 32 eyes, the middle group included 23 patients with 46 eyes, and the high group contained 21 patients with 42 eyes.

Statistics

The continuous variables were summarized by mean ± standard deviation (SD) and range. The categorical variables were summarized by frequencies and proportions. The the analysis of variance (ANOVA) along with Duncan’s multiple range test was used to compare wavefront variables among the three groups. Simple linear regression model and the 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 60 patients (32 men and 28 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 lengths (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) values from 3 to 6 (RMS 3 to 6) of the whole eye higher-order wave surface aberrations at a 6.0 mm pupil diameter in different myopia groups are shown in Table 2. As shown in Table 2, the Zernike coefficients progressively decreasedat RMS values from 3 to 6, and the total of higher-order aberrations at an RMS value of 3 was approximately 62.96%. 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 diameter, the total corneal higher-order aberration was 0.351 ± 0.152μm and the spherical aberration was 0.203 ± 0.082μm (range was 0.061-0.503μm), 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, forming a normal distribution. In addition, the coma and trifolium aberrations were 0.134 ±0.052μm and 0.157 ±0.094μm, respectively. The corneal higher-order aberrations in different myopia groups withcoma aberrations (3, 1) were significantly decreased (P=0.013 at 3, 1, Figure 1). Moreover, as the diopter increased, the coma aberration ratio increased, but the spherical aberration decreased in the ocular, while the spherical aberration did not change in the cornea (Figure 2).

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

Refractive error	n	Total HOA	Coma	SA	Trefoil
High myopes(-10 to -6 DS)	35	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)	32	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 6.0mm pupil diameter of the anterior corneal surface suitable for excimer laser surgery in patients was -0.19 ± 0.03 (range: -0.58 to 0.31) and showed a normal distribution. The number 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 number 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 equivalent spherical mirror was positively correlated with the corneal coma aberration (R = -0.241, P = 0.009), but there were no correlations 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 and spherical aberrations (R = 0.326, P <0.001 and R = 0.675, P <0.001, respectively) but not 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 an operation with high safety, predictability and rapid recovery. This type of surgery is also the most active and fastest growing discipline in the current ophthalmology. Approximately 10 million patients undergo corneal refractive surgery every year worldwide, of which approximately 1.35 million receive operations in the United States.

China is one of the countries with the highest incidence of myopia in the world, and more than 1 million patients with myopia undergo surgery every year to get rid of their glasses [5].

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 wavefronts in physical optics is the wavefront aberration [7], which is an effective strategy for clinically diagnosing and evaluating the retinal imaging quality in humans. The 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 atherectomy technology has become a hot topic and is regarded as a milestone in the development of corneal refractive surgery [13]. Individualized atherectomy 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, custom-made femtosecond laser combined with excimer laser in situ keratomileusis tailored to the optical properties of an individual is a complex process [14].

In the present study, the wavefront aberrations in the anterior corneal surface of the patients were investigated to correct high-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, middle and high myopia groups. The frequency of spherical aberration was maintained at approximately 70% and did not change by the diopter. Moreover, the changes in diopter and Q values showed a positive relationship between the low and middle myopia groups, but there were no significant differences in Q values between the middle 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, there was divergence in studies of the relationship among Q values, refractive status and diopter in patients. Sheridan et al found no differences in Q values between face, myopia and hyperopia groups [15]. However, Dubbelman et al. reported that corneal Q values were positively correlated with the increment of myopia degree [16]. The results of the present study showed that the spherical aberrations on the corneal anterior surface increase 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. The results suggest that wave-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, the wavefront aberration combined with the excimer laser system for individualized atherectomy has an upstanding theoretical basis. However, there were significant differences in patients who experience higher-order aberrations after corneal refractive surgery. It shows that there is still a gap between the actual and ideal visual quality. Therefore, further study is needed on the relationship between the components of the wavefront aberration and the visual quality and the digital correspondence with the personalized cutting mode.

Abbreviations

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

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

ANOVA: analysis of variance; SE: spherical equivalent; SA, spherical aberration.

Declarations

Ethics approval and consent to participate

The institutional review board at 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.

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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 analysis and interpretation of data and revising manuscript; CLL and HYJ was involved in collecting data and analysing 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.

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Figures

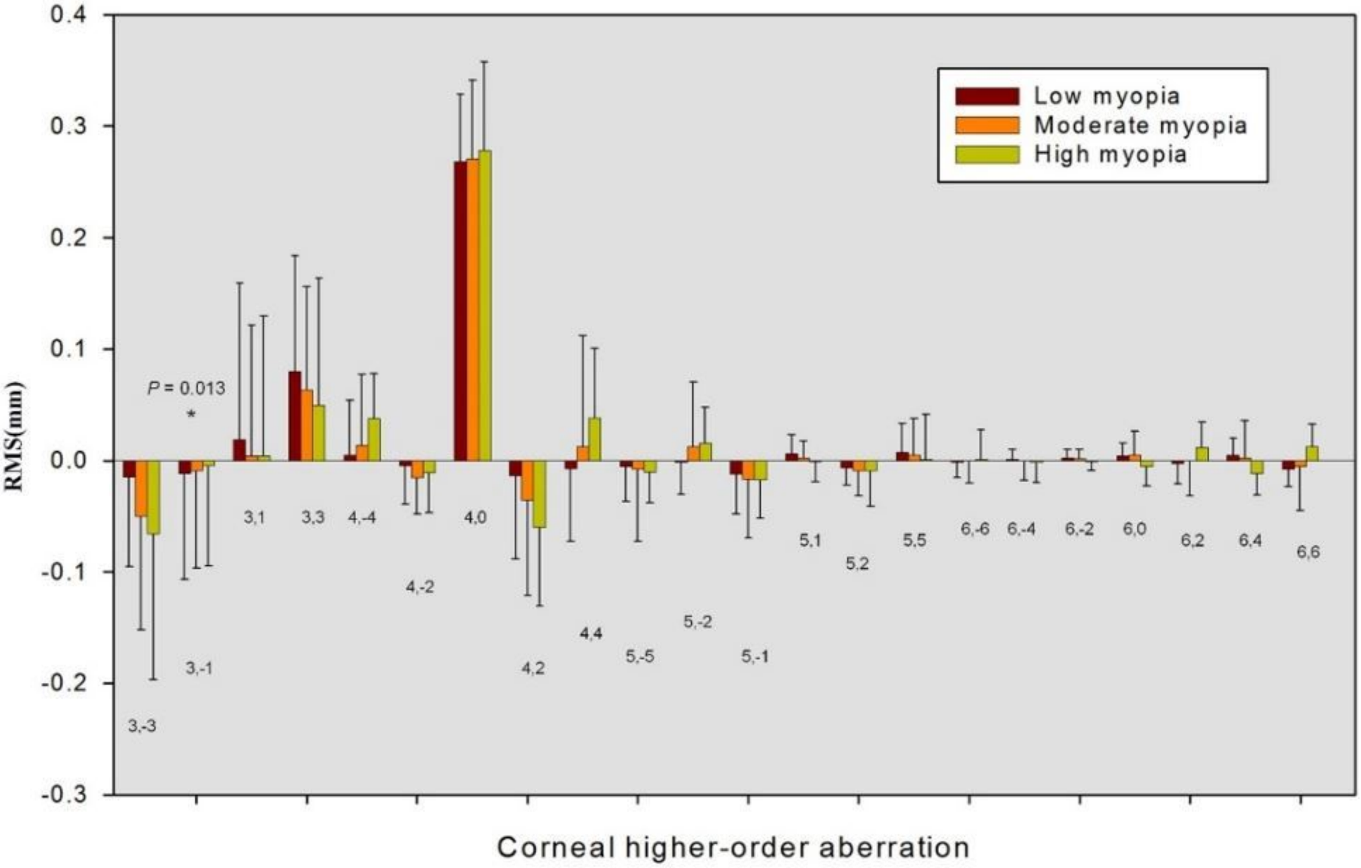

Figure 1

The corneal aberrations of different myopia groups were compared.

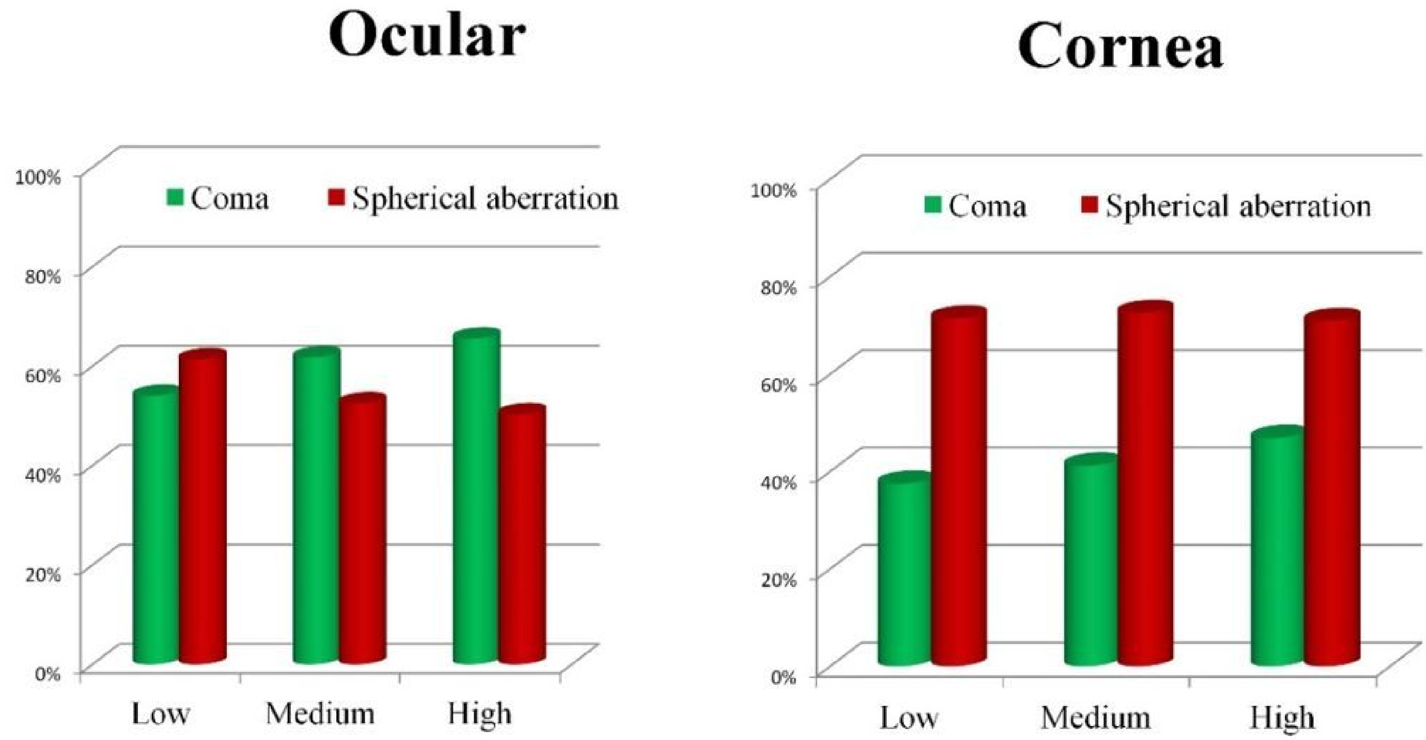

Figure 2

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

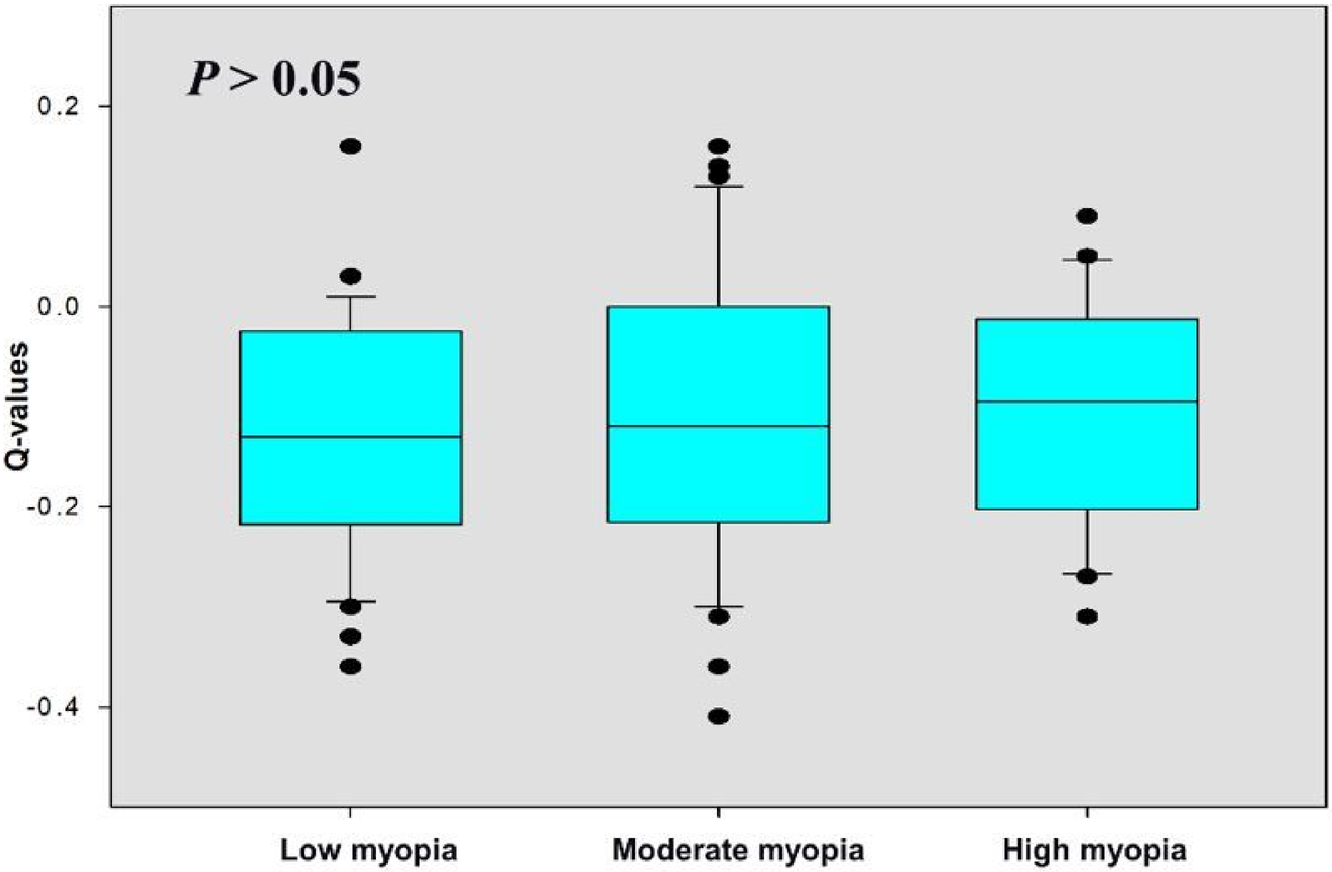

Figure 3

The Q values of different myopia groups were compared

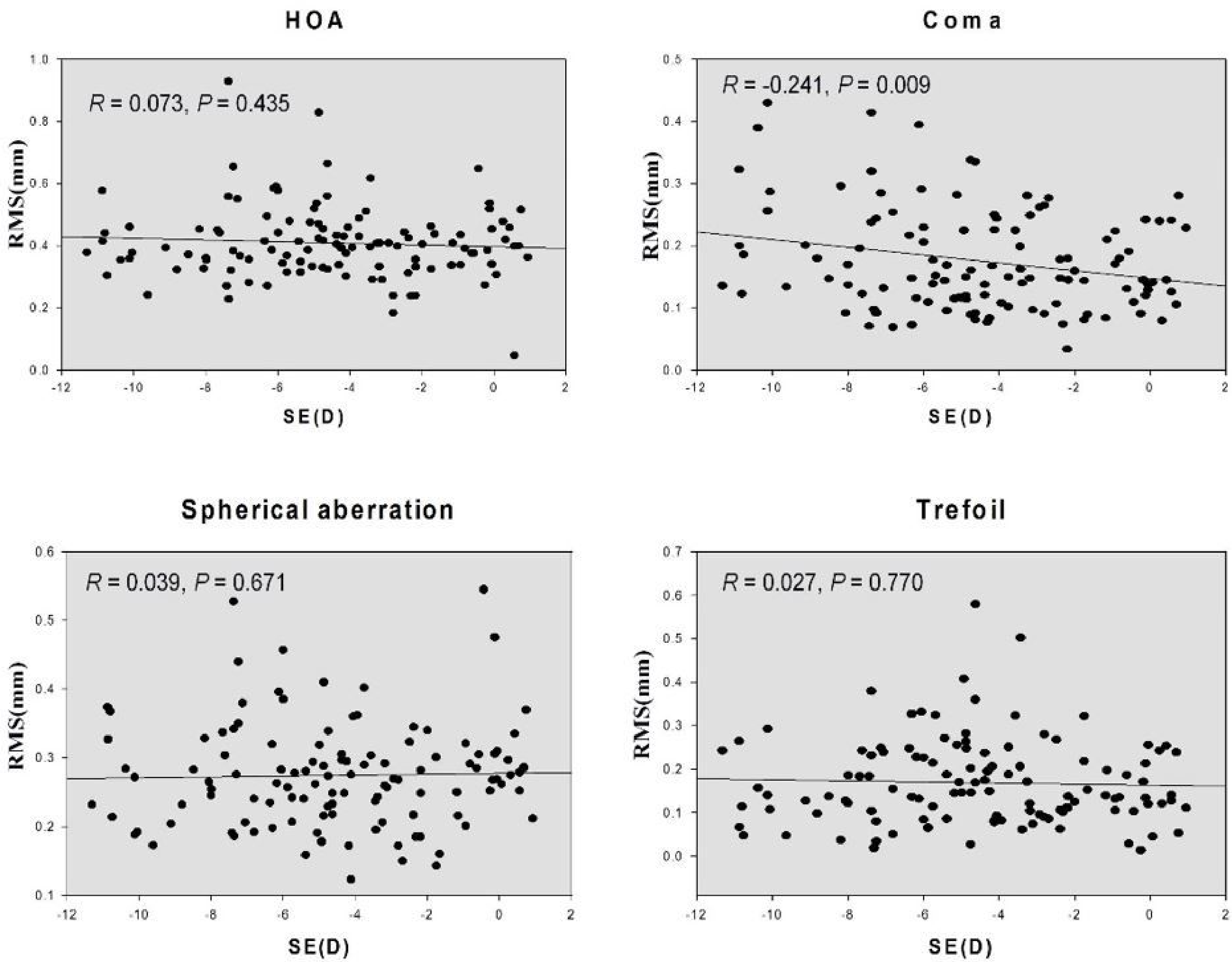

Figure 4

Correlations between spherical equivalents and anterior corneal aberrations.

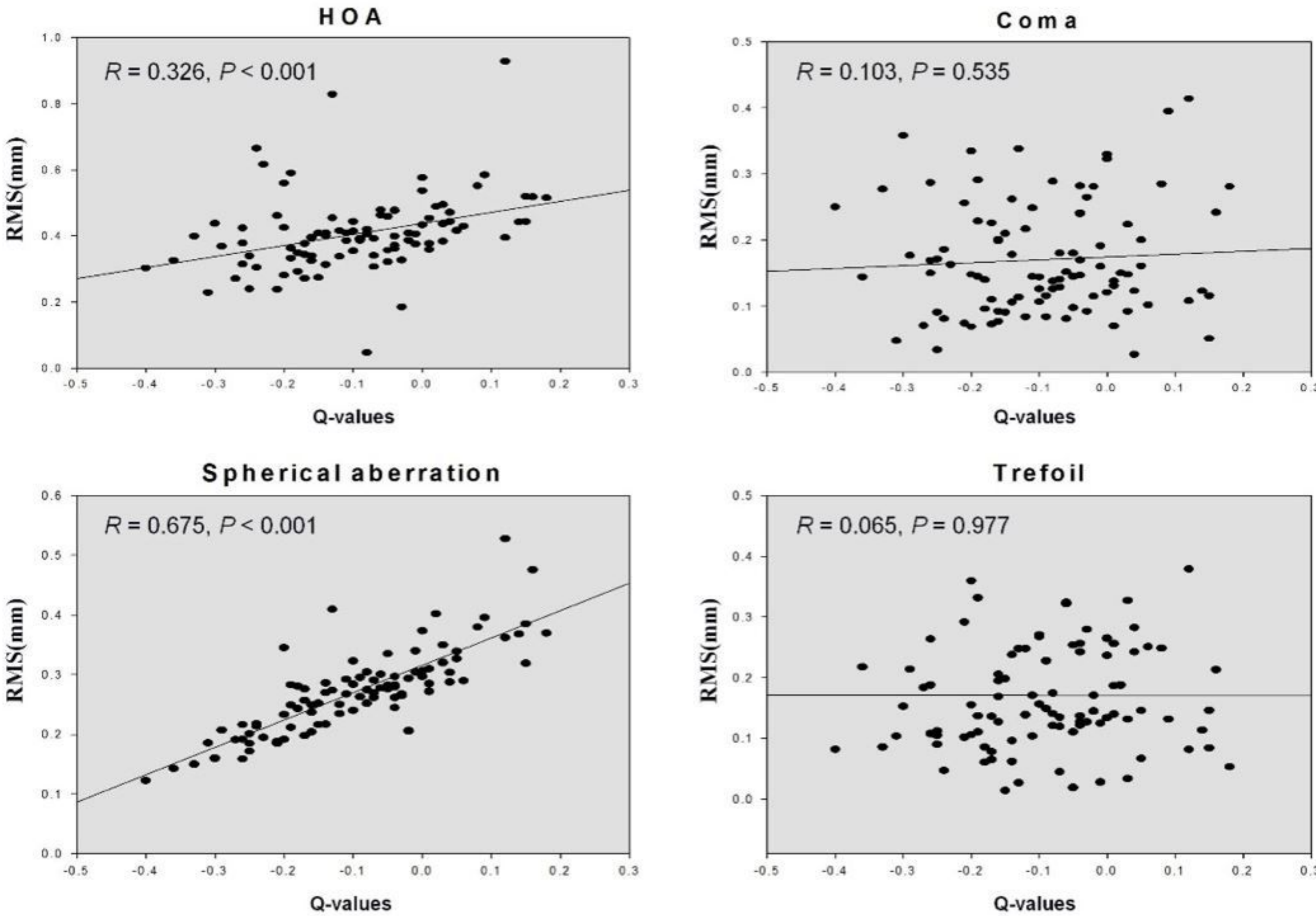

Figure 5

Correlations between the Q value and anterior corneal aberrations.