

Higher-Order Aberrations of Anterior and Posterior Corneal Surfaces in Patients With Keratectasia After LASIK

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PURPOSE. We investigated higher-order aberrations (HOAs) of the anterior and posterior corneal surfaces in patients with keratectasia after LASIK.

METHODS. The subjects comprised four groups: 12 eyes with keratectasia after LASIK, 30 eyes following LASIK without keratectasia, 30 keratoconic eyes, and 30 normal eyes. Corneal HOAs due to the anterior and posterior corneal surfaces for 6-mm pupils (root mean square [μm]) were obtained using a Scheimpflug-based corneal tomographer and compared among the four groups.

RESULTS. There were significant differences in total HOAs of the anterior and posterior corneal surfaces (mean \pm SD) in the keratectasia (2.49 ± 1.37 and 0.83 ± 0.57), keratoconus (4.50 ± 2.57 and 1.18 ± 0.65), LASIK (0.84 ± 0.25 and 0.14 ± 0.04), and normal (0.52 ± 0.15 and 0.17 ± 0.06) groups except for between keratoconus and keratectasia at the posterior surface. Keratectasia and keratoconus showed similar coma-dominant patterns at both surfaces, and there were no significant differences in the Zernike terms between both groups except for the total HOAs and coma aberration at the anterior surface.

CONCLUSIONS. Although flap creation and laser ablation were supposed to center on the primary line of sight in LASIK, keratectasia after LASIK showed coma-dominant HOAs at both corneal surfaces. This suggests that the cornea in keratectasia has optical properties similar to those in keratoconus.

Keywords: keratectasia, LASIK, keratoconus, aberration, cornea

LASIK has been the primary type of corneal refractive surgery for mild-to-moderate myopia and myopic astigmatism for many years. The efficacy and safety of LASIK have been excellent, and have been improved with the aid of wavefront technology and the femtosecond laser.¹⁻³ However, there still may be some intraoperative and postoperative complications following LASIK.

Keratectasia or post-LASIK corneal ectasia, is a serious complication after LASIK.⁴⁻⁸ Keratectasia can be defined as a progressive anterior protrusion of the central cornea after corneal refractive surgery with steepening and irregularity of the corneal shape inside the optical zone. This condition induces the progression of myopic astigmatism and irregular astigmatism that can lead to the loss of uncorrected distance visual acuity and corrected distance visual acuity (CDVA).

Although the mechanism of keratectasia still is unknown, there are at least two pathogenesis for keratectasia; that is, a thin stromal bed with normal stroma^{4,6} or a sufficient stromal bed with undetected or mild keratoconus.⁵ Histopathologic studies have revealed the consistent or discrepant results for the similarities between keratoconus and keratectasia.⁹⁻¹¹

We investigated the higher-order aberrations (HOAs) of the anterior and posterior corneal surfaces in eyes with keratectasia after LASIK using a rotating Scheimpflug corneal tomographer, and we compared those measurements with those in the eyes in the normal, LASIK, and keratoconus groups.

METHODS

This retrospective, observational case series included 12 eyes of 7 cases that had LASIK in other clinics and were referred to the Osaka University Hospital as having keratectasia after LASIK (Table 1). We included as the subjects 30 eyes without keratectasia after LASIK, 30 keratoconic eyes, and 30 normal eyes (Table 1).

Keratectasia was defined as the progressive anterior protrusion of the central cornea after LASIK with the loss of CDVA. Normal eyes (control) had no ocular disorders except for refractive errors. The criteria for diagnosing keratoconus were the presence of central thinning of the cornea with a Fleischer ring and/or Vogt's striae by slit-lamp examination.¹² Eyes that were keratoconus suspect or had forme fruste keratoconus were not included. Keratoconic eyes with corneal scarring and a history of acute hydrops or other disorders that affected the topographic findings also were excluded. All eyes were diagnosed by one experienced ophthalmologist (NM).

The research followed the tenets of the Declaration of Helsinki. Informed consent was obtained from the subjects after explanation of the nature and possible consequences of the study. The research was approved by the Institutional Review Board of Osaka University.

The subjects were examined using a rotating Scheimpflug camera (PentacamHR; Oculus Optikgeräte, GmbH, Wetzlar,

TABLE 1. Subject Data

	Cases/Eyes	Male/Female	R/L	Age
Control	30/30	16/14	16/14	38.9 ± 12.8
LASIK	15/30	6/9	15/15	38.9 ± 10.7
Keratoconus	30/30	15/15	15/15	33.6 ± 9.0
Kerectasia	7/12	4/3	6/6	39.1 ± 9.7

Germany). A total of 25 pictures was taken during one scan to reconstruct a three-dimensional model of the entire corneal configuration. All subjects were examined at least twice to confirm the reproducibility of the obtained data. The quality of the data from examination was assessed with a built-in program, and the results with serious errors were excluded.

To maintain the consistency of the methodology in our study, HOAs of 6-mm pupils were calculated by an original program for the anterior and posterior corneal surfaces as published previously.^{13,14} The wavefront aberration was expanded with the normalized Zernike polynomials. For each pair of the standard Zernike terms for trefoil, coma, tetrafoil, and secondary astigmatism, a combined value for the magnitude and axis was calculated for the anterior and posterior corneal aberrations. Total HOAs were defined as the root mean square of the magnitudes of the third- and fourth-order aberrations. The magnitude of the spherical aberration was expressed as either a positive or negative value and not as an absolute value. The axes of left eyes were transposed about the vertical axis to correct for enantiomorphism.¹⁵

The data were analyzed using statistical analysis software JMP version 9 (SAS, Inc., Cary, NC, USA). The Kruskal-Wallis test was used to compare the total HOAs, trefoil, coma, tetrafoil, secondary astigmatism, and spherical aberration of the anterior and posterior corneal surfaces among the four groups. The Kruskal-Wallis test also was used to compare the ratios of the anterior corneal HOAs to the posterior corneal HOAs (A/P ratio) for total HOAs and each Zernike term except for spherical aberration among the four groups. The Steel-Dwass method was used for pair comparisons. *P* values of <0.05 were considered statistically significant.

RESULTS

Figure 1 shows the characteristic examples of elevation and HOA maps for the anterior and posterior surfaces in the normal eye, post-LASIK eye, kerectasia eye, and keratoconic eye.

The HOA maps caused by anterior/posterior corneal surfaces in the normal eye (column 1) showed a flat wavefront. The HOA map of the anterior surface in the post-LASIK eye (column 2) revealed a slightly decentered fast wavefront that was associated with the central depression pattern in the anterior elevation map. Kerectasia (column 3) and keratoconic (column 4) eyes showed a vertical coma pattern in the anterior and posterior HOA maps. The HOAs from the posterior surface were smaller, and the pattern was in the opposite direction than HOAs from the anterior surface. The means and the standard deviations of the total HOAs and each Zernike term for the anterior and posterior corneal surfaces inside the 6-mm diameter are shown in Figures 2 and 3, respectively.

The Kruskal-Wallis test showed that the total HOAs and each Zernike term for the anterior and posterior corneal surfaces were significantly different among the four groups (*P* < 0.0001), and there were significant differences in the A/P ratio of the total HOAs (*P* < 0.0001), coma (*P* = 0.0005), trefoil

(*P* = 0.0215), and secondary astigmatism (*P* < 0.0001), but no significant difference in tetrafoil (*P* = 0.90084).

The results of statistical significances between two groups with the Steel-Dwass method are shown in Table 2. There were significant differences in the total HOAs of the anterior and posterior corneal surfaces (mean ± SD) among the kerectasia (2.49 ± 1.37 and 0.83 ± 0.57), keratoconus (4.50 ± 2.57 and 1.18 ± 0.65), LASIK (0.84 ± 0.25 and 0.14 ± 0.04), and normal (0.52 ± 0.15 and 0.17 ± 0.06) groups except between keratoconus and kerectasia at the posterior surface.

Kerectasia and keratoconus showed a similar coma-dominant pattern in the Zernike terms of both surfaces. No significant differences in the total HOAs and all Zernike terms for the anterior and posterior surfaces were found between keratoconus and kerectasia except for the total HOAs and coma at the anterior surface.

In the comparison between normal and post-LASIK eyes, the total HOAs, coma, and spherical aberration at the anterior surface in the LASIK group were significantly higher than those in the normal controls, and the total HOAs and secondary astigmatism at the posterior surface in the LASIK group were significantly lower than those in normal eyes. There were no significant differences between both groups except these parameters.

There were significant differences in the total HOAs and all Zernike terms of the anterior and posterior surfaces between keratoconic and normal eyes, and between keratoconic and post-LASIK eyes except tetrafoil at both surfaces. There also were significant differences in the total HOA, trefoil, coma, and secondary astigmatism of the anterior and posterior surfaces between kerectasia and normal eyes, and between kerectasia and post-LASIK eyes.

Figure 4 shows the A/P ratios for the total HOAs and each Zernike term. The total HOAs of the anterior surfaces were approximately 3 to 4 times greater than those of the posterior surfaces in control eyes. The A/P ratio for the total HOAs in LASIK eyes was significantly higher than that in normal, keratoconic, and kerectasia eyes. The A/P ratio of coma in LASIK eyes also was significantly higher than that in normal eyes.

Figure 5 indicates the coma due to the anterior and posterior surfaces on the polar coordinates. The scatter patterns in kerectasia and keratoconus were similar for the anterior and posterior surfaces. The axes in most of kerectasia and keratoconic eyes were distributed from 45° to 90° for the anterior surface, but the axes were distributed from 180° to 270° in the opposite direction for the posterior surface. In contrast, the axis of the coma of the anterior and posterior surfaces in normal and post-LASIK eyes was small, and no such trend was seen for the axis of coma of the anterior and posterior surfaces.

DISCUSSION

It will be important to understand the characteristics of the optical properties of the anterior and posterior corneal surfaces in kerectasia to improve the results of treatments for kerectasia, such as prescribing rigid gas permeable (RGP) contact lenses,^{16,17} intracorneal rings,¹⁸ corneal crosslinking,¹⁹ and corneal transplantation. Only few studies have been conducted for the evaluation of HOAs in kerectasia.^{20,21} Kerectasia and post-LASIK eyes were compared in one study; the coma-like aberrations and spherical-like aberrations that were calculated based on the anterior corneal shape were significantly higher in kerectasia eyes than in post-LASIK eyes.²¹ Another study showed an increase in ocular HOAs and

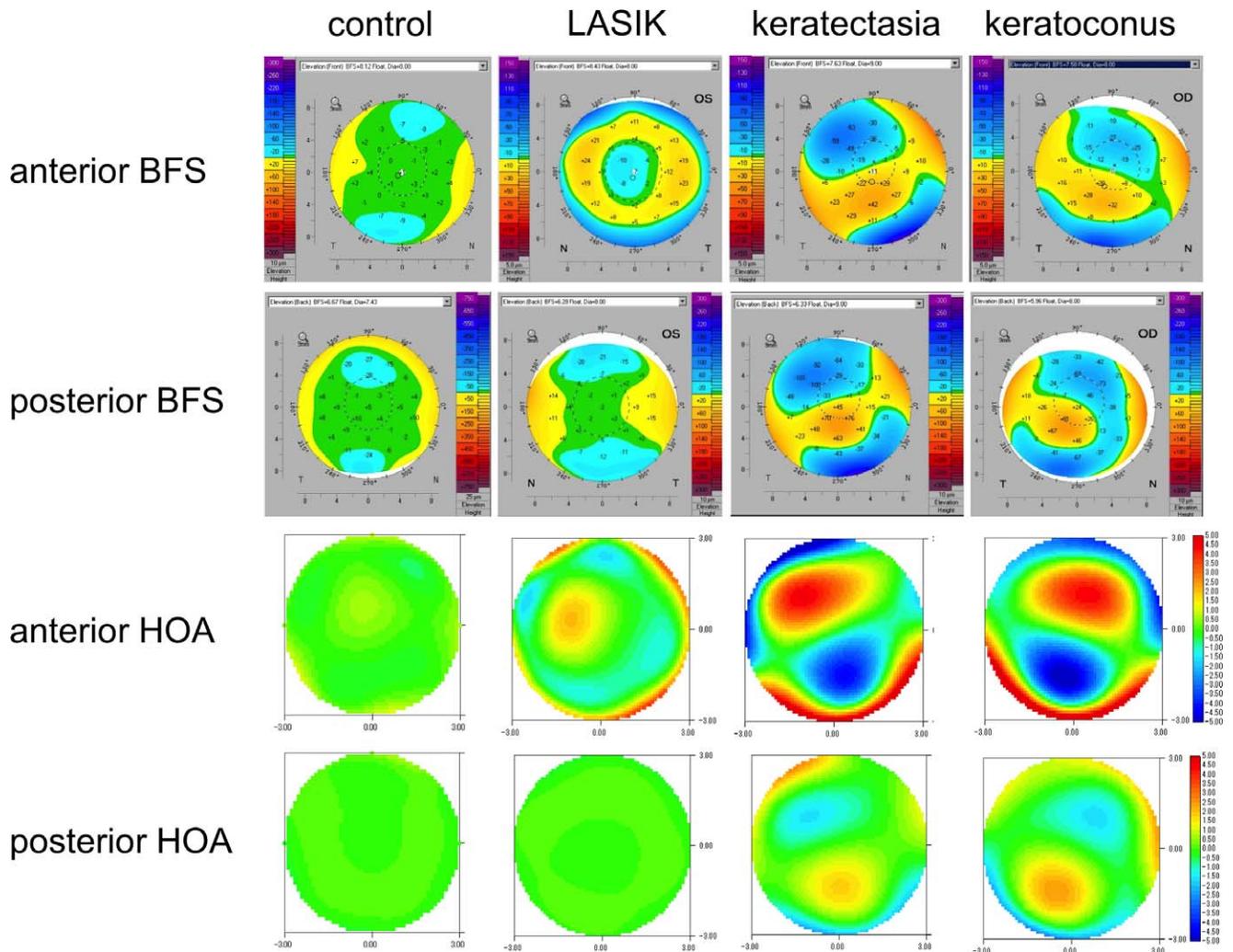


FIGURE 1. The characteristic examples of elevation and HOA maps of the anterior and posterior surfaces in normal, post-LASIK, keratectasia, and keratoconic eyes. No clinically relevant HOAs were detected for the anterior and posterior surfaces in control eyes (*column 1*). The HOA map of the anterior surface in post-LASIK eyes (*column 2*) revealed a slightly decentered fast wavefront pattern (*warmer colors*) that was associated with the central depression pattern in the anterior elevation map associated with laser ablation. Keratectasia (*column 3*) and keratoconic (*column 4*) eyes showed an anterior protrusion at the paracentral zone in the anterior and posterior elevation maps. These changes yielded the vertical coma pattern in the anterior and posterior HOA maps. The amplitude of HOAs from the posterior surface was smaller, and the pattern of the maps was in the opposite direction than those from the anterior surface in keratoconus and keratectasia. An inferior slow pattern; that is, a pattern in which the slow wavefront area (*cooler colors*) was located at the inferior area, was seen for the HOA maps of the anterior surface. The HOA maps from the posterior surface were in the opposite direction; that is, a superior slow pattern, compared to the anterior surface in keratoconic and keratectasia eyes. BFS, best-fit-sphere.

an increase in higher order irregularity for the elevations of the anterior and posterior surfaces.²⁰

The results of the present study confirmed the same trend for an increase in HOAs at the anterior corneal surface. In addition, the increase in HOAs at the posterior corneal surface and the details of the Zernike terms for both surfaces were described.

It is believed that these HOAs in keratectasia may be caused by the combination of laser ablation to the stromal bed and the protrusions of the anterior and posterior corneal surfaces associated with the biomechanical weakness of the cornea.

Post-LASIK eyes had slightly higher HOAs at the anterior corneal surface and normal HOAs at the posterior surface, resulting in the increase of the A/P ratio in the total HOAs and coma. This possibly was caused after LASIK by a shape change in the anterior corneal surface because of laser ablation.

Although no detailed information was available for the LASIK procedures in keratectasia eyes, these should have laser ablation aligned to the primary line of sight. If keratectasia was induced mainly by stromal instability due to laser ablation, a symmetrical protrusion of the anterior and posterior corneal surfaces can be expected. However, the distribution pattern of the Zernike terms in keratectasia indicated coma dominance (Figs. 2, 3), and the axis of coma had a specific distribution (Fig. 5). The characteristics of the corneal HOAs in keratectasia were similar to those in keratoconus for both corneal surfaces.^{12,13,22}

These results confirmed that the basic strategy for the treatment of keratectasia should be similar to that for keratoconus. To maintain a good quality of vision with spectacles or contact lenses, it will be important to inhibit the progression of keratectasia when the corneal HOAs are still within the acceptable range. For moderate to advanced

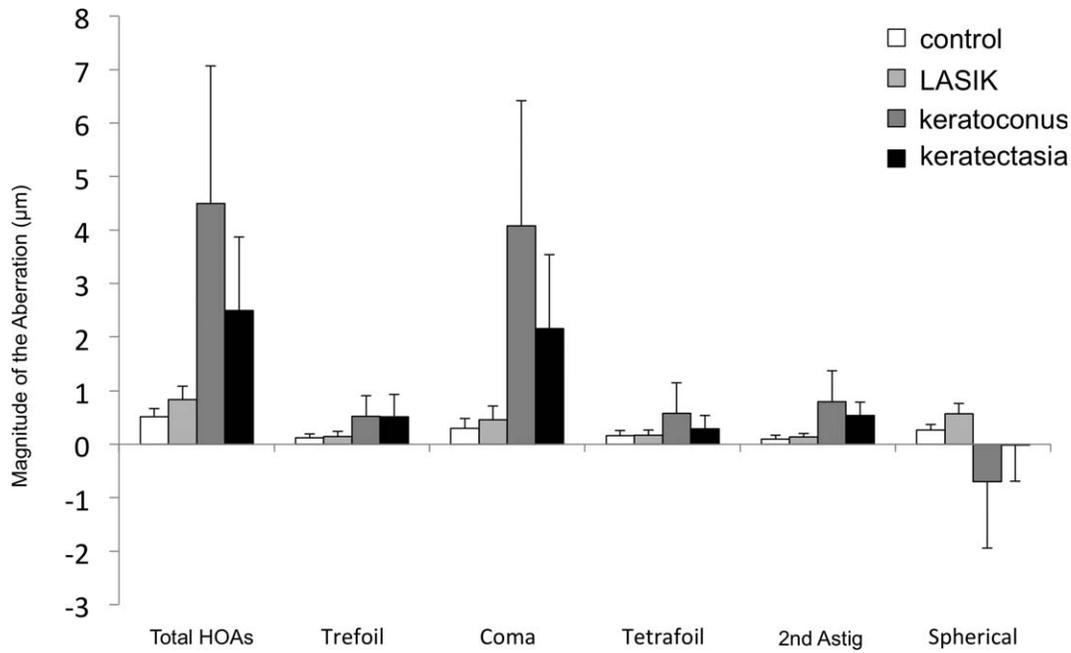


FIGURE 2. The means and standard deviations of the total HOAs and each Zernike term of the anterior corneal surface for the 6-mm diameter. The graph shows the simple averages and standard deviations of the magnitudes of the total HOAs (RMS) and each Zernike term. Keratectasia and keratoconus showed similar coma-dominant patterns in the Zernike terms for the anterior corneal surface. 2nd Astig, secondary astigmatism; spherical, spherical aberration.

keratectasia with the increase in HOAs at the posterior corneal surface, CDVA with RGP contact lens will be limited by the residual HOAs because of the posterior surface.^{13,22}

Radlema et al.²³ reported that preoperative topographic abnormality, low residual stromal bed thickness, young age,

thin corneas, and high myopia were factors that increased the risk for developing post-LASIK corneal ectasia. Among them, the most significant factor was abnormal topography.

The preoperative abnormal topographic findings seen in keratectasia may have a very early sign of keratoconus. The

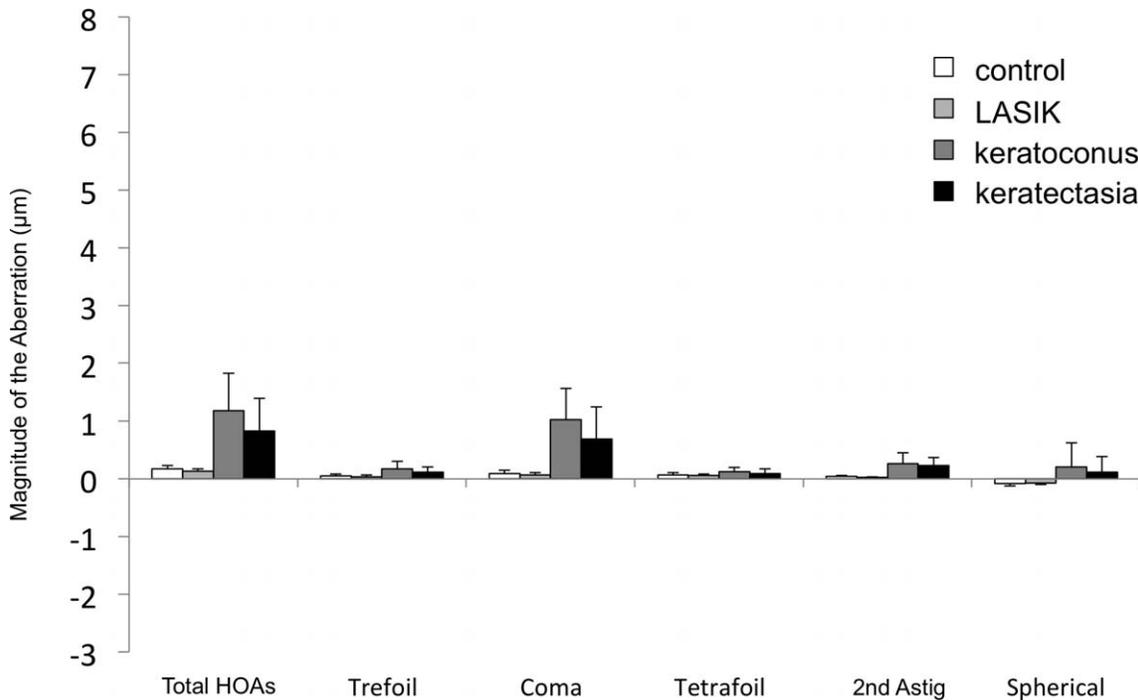


FIGURE 3. The averages and standard deviations of the total HOAs and each Zernike term of the posterior corneal surface for the 6-mm diameter. The graph shows the simple averages and standard deviations of the magnitudes of the total HOAs (RMS) and each Zernike term. Keratectasia and keratoconus showed similar coma-dominant patterns in the Zernike terms also for the posterior corneal surface.

TABLE 2. Statistical Significance (P Values) of HOAs by the Steel-Dwass Test

	Total HOAs	Trefoil	Coma	Tetrafoil	Second Astig	Spherical
Anterior surface						
Control vs. LASIK	<0.001*	0.5433	0.0337*	0.9180	0.0613	<0.001*
Control vs. KC	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
Control vs. ectasia	<0.001*	<0.001*	<0.001*	0.2249	<0.001*	0.9987
LASIK vs. KC	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
LASIK vs. ectasia	0.0002*	0.0003*	<0.001*	0.4781	<0.001*	0.0206*
KC vs. ectasia	0.0310*	1.0000	0.0492*	0.0924	0.7235	0.3319
Posterior surface						
Control vs. LASIK	0.0113*	0.2442	0.3274	0.8586	0.0001*	0.5104
Control vs. KC	<0.001*	<0.001*	<0.001*	0.0007*	<0.001*	0.0002*
Control vs. ectasia	<0.001*	0.0423*	<0.001*	0.6982	0.0001*	0.0286*
LASIK vs. KC	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	0.0003*
LASIK vs. ectasia	<0.001*	0.0059*	<0.001*	0.2686	<0.001*	0.0264*
KC vs. ectasia	0.4608	0.6724	0.4955	0.3172	0.9997	0.8993
A/P ratio						
Control vs. LASIK	<0.001*	0.1204	0.0024*	n. s.	<0.001*	n/a
Control vs. KC	0.0262*	0.9958	0.4193	n. s.	0.1089	n/a
Control vs. ectasia	0.9855	0.2133	0.9236	n. s.	0.9236	n/a
LASIK vs. KC	<0.001*	0.1204	0.0184*	n. s.	0.0018*	n/a
LASIK vs. ectasia	0.0012*	0.9913	0.0657	n. s.	0.0206*	n/a
KC vs. ectasia	0.4438	0.2249	0.7719	n. s.	0.8574	n/a

* Statistically significant.

present study also indicated that in kerectasia, the cornea had optical properties similar to those in keratoconus. It will be very important for the prevention of kerectasia after LASIK to discern these specific abnormal findings of the corneal shape in those cases who might be quantitatively predisposed to keratoconus.²⁴

The present study had some limitations. Because of the rareness of this disease, the number of kerectasia cases was small. Mild cases of kerectasia were not included, and the changes in HOAs during the course of progression in kerectasia were unknown. The groups of post-LASIK eyes with or without kerectasia included the information of both eyes. The

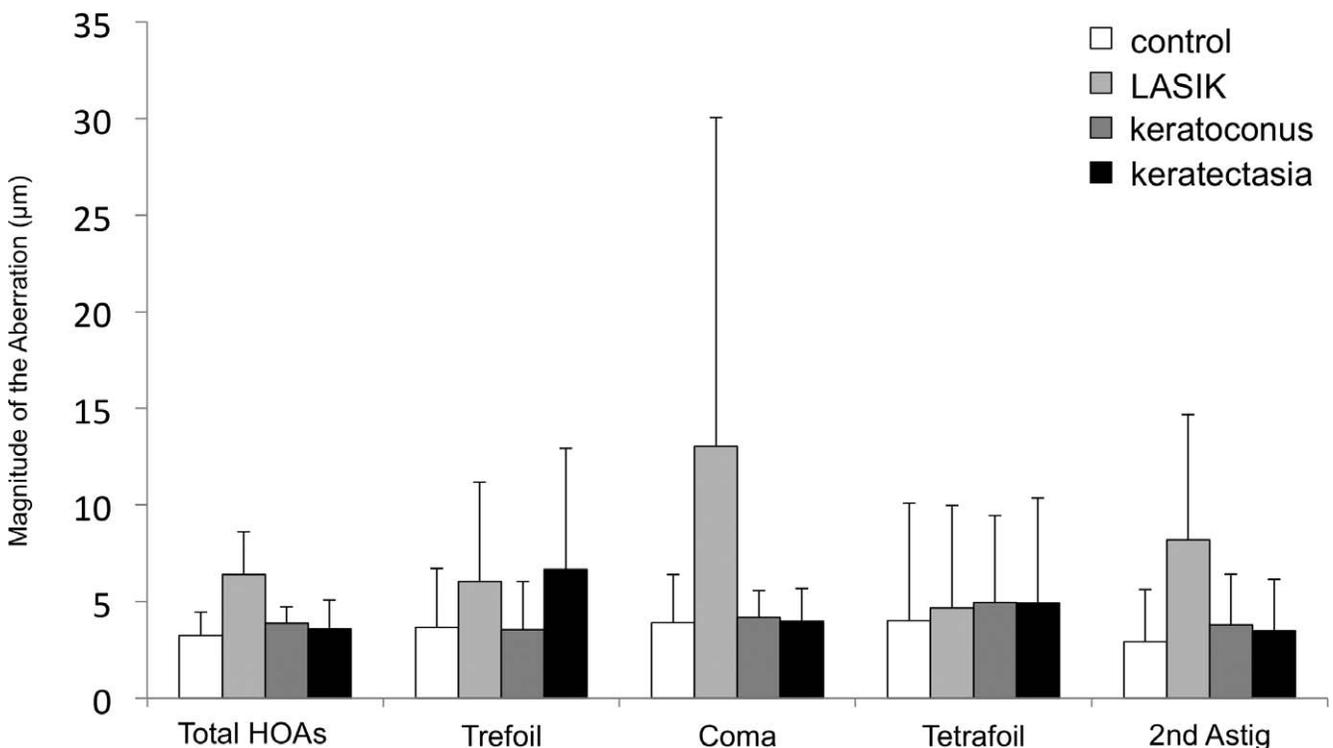


FIGURE 4. The averages and standard deviations of the anterior/posterior ratio of the total HOAs and each Zernike term for the 6-mm diameter. The A/P ratios of total HOAs and coma in LASIK eyes were significantly higher than those in normal eyes.

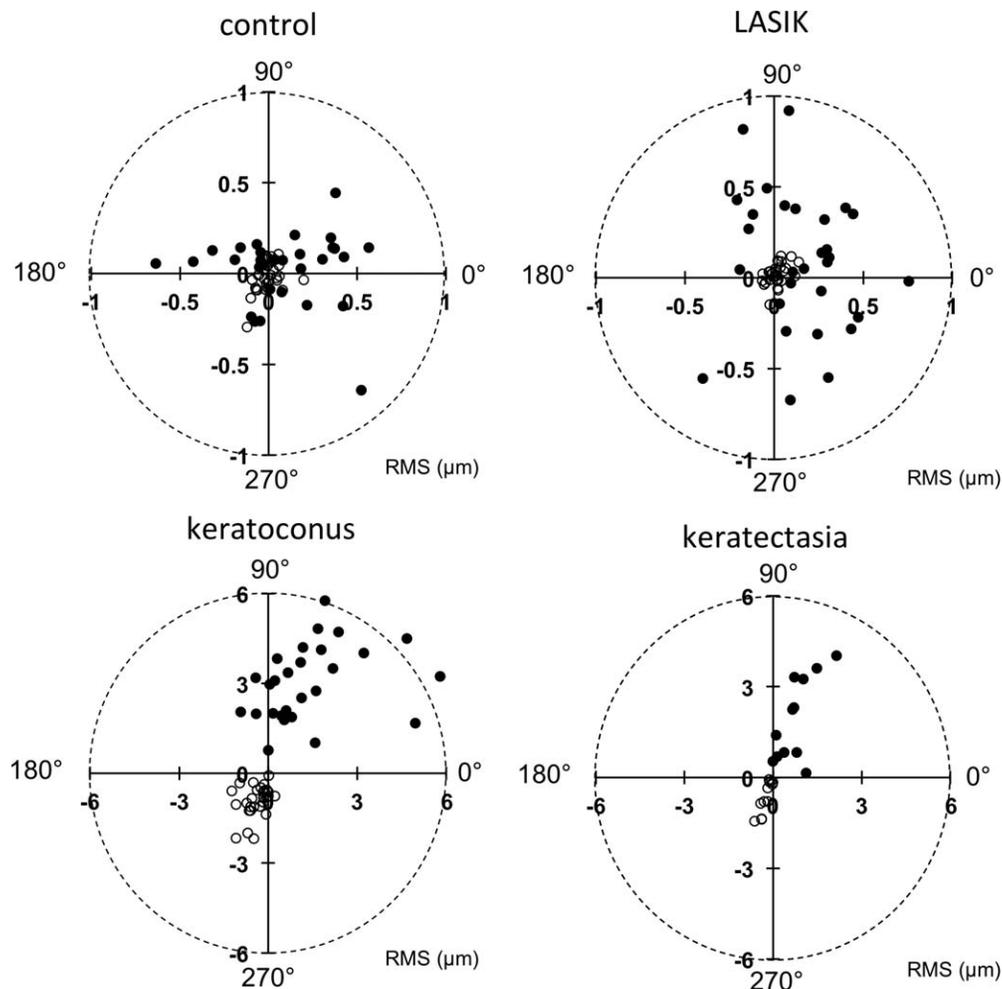


FIGURE 5. Scatterplots for the coma of the anterior and posterior corneal surfaces in control, LASIK, keratectasia, and keratoconic eyes. The axes of the coma caused by the anterior and posterior surfaces were generally in opposite directions in keratectasia and keratoconus.

accumulation of data of post-LASIK eyes with and without keratectasia will be necessary for a more detailed analysis.

A prospective study for clarifying the change of optical characteristics in keratectasia after LASIK will be necessary to establish the interventions needed for the disease, including the inhibition of keratectasia and maintaining or improving the quality of vision for the patient with the disease.

The preoperative risk factors also were not clear in keratectasia eyes that were examined in this study, because all cases had LASIK in other clinics and were referred to us. It will be interesting to evaluate the differences in the pattern of HOAs in the anterior and posterior corneal surfaces between eyes with preoperative abnormal topography and eyes with thin stromal beds.

In conclusion, keratectasia after LASIK revealed comadominant HOAs at both corneal surfaces, suggesting that the cornea in keratectasia had optical properties similar to those in keratoconus. Therefore, the treatment strategy for keratoconus might be applicable to keratectasia to improve the quality of vision and inhibit the progression of keratectasia after LASIK.

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