Magnitude and Orientation of Zernike Terms in Patients with Keratoconus

Ryo Kosaki,1,2 Naoyuki Maeda,1 Kenichiro Bessho,3 Yuichi Hori,1 Kohji Nishida,1 Asaki Suzuki,5 Yoko Hirobara,4 Toshifumi Mibashi,4 Takashi Fujikado,3 and Yasuo Tano1

PURPOSE. To measure the magnitude and orientation of the Zernike terms in keratoconic eyes, with and without rigid gas-permeable (RGP) contact lenses.

METHODS. A total of 76 eyes with keratoconus, 58 eyes with keratoconus suspect, and 105 normal eyes were studied. To determine the effect of RGP lenses, 19 eyes with keratoconus, 9 eyes with keratoconus suspect, and 17 normal eyes, with and without an RGP lens, were compared. Ocular higher-order aberrations (HOAs) were measured with a wavefront sensor for a 4-mm-diameter pupil, and the magnitudes, axes of trefoil, and coma were calculated by vector analysis.

RESULTS. Zernike vector analysis showed prominent vertical coma with an inferior slow pattern, with mean axes of 82.5° or 91.0° in the patients with keratoconus or keratoconus suspect, respectively. The mean axes of trefoil in patients with keratoconus (93.8°) and keratoconus suspect (100.6°) differed from that in normal subjects (35.4°), indicating that keratoconus has a reverse trefoil pattern from that of normal eyes. Although the total HOAs were significantly (keratoconus and keratoconus suspect, P < 0.001 and P = 0.012, respectively) reduced with an RGP lens, the patterns of the axes of coma and trefoil were reversed with the lens.

CONCLUSIONS. In addition to the larger amount of trefoil, coma, tetrafoil, and secondary astigmatism, keratoconic eyes tend to have a reverse coma pattern and reverse trefoil aberrations compared with normal eyes. Although RGP lenses correct the irregular astigmatism, smaller comet-like retinal images in the opposite direction remain due to residual vertical coma.

From the Departments of 1Ophthalmology and 3Applied Visual Science, Osaka University Medical School, Suita, Japan; the 2Department of Ophthalmology, Nissay Hospital, Osaka, Japan; and the 4Technical Research Institute, Topcon Corporation, Tokyo, Japan.


Supported in part by the Grant 18591919 from the Japanese Ministry of Education, Science, Sports, and Culture, Tokyo, Japan, and by the Osaka Eye Bank Foundation, Suita, Japan.

Submitted for publication October 25, 2006; revised February 13, 2007; accepted April 9, 2007.

Disclosure: R. Kosaki, None; N. Maeda, Topcon Corp. (F); K. Bessho, None; Y. Hori, None; K. Nishida, None; A. Suzuki, None; Y. Hirobara, Topcon Corp. (E); T. Mibashi, Topcon Corp. (E); T. Fujikado, None; Y. Tano, None

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be marked ‘advertisement’ in accordance with 18 U.S.C. §1734 solely to indicate this fact.

Corresponding author: Naoyuki Maeda, Department of Ophthalmology, Osaka University Medical School, Room J-7, 2-2 Yamada-aoka, Suita, Osaka, 565-0871, Japan; nmaeda@ophthal.med.osaka-u.ac.jp.

Keratoconus is a noninflammatory corneal disorder characterized by thinning of the central stroma and anterior corneal protrusion.1,2 To correct the irregular astigmatism induced by ectasia, rigid gas-permeable (RGP) contact lenses are used most commonly, because the spherical anterior surface of the RGP lens is unaffected by the underlying corneal shape.3

Wavefront technology has been used recently to measure irregular astigmatism as the ocular higher-order aberrations (HOAs) in the clinic.4–7 However, the presence of pairs in the Zernike terms with positive or negative values makes it difficult to recognize the characteristics of the HOAs and perform statistical analyses.8–10

Campbell11 proposed reducing the number of Zernike terms by replacing each pair of Zernike terms with one Zernike vector term. The representation of wavefront error data expressed as Zernike coefficients presented in magnitude and axis form has been described in the American National Standards Institute standards (Z80.28-2004). Describing the Zernike terms as vector components is similar to expressing regular astigmatism by the cylindrical power and axis. Thus, Guirao et al.12 using Zernike vector terms, also reported on the magnitude and orientation of regular astigmatism, coma, and trefoil aberrations after small-incision cataract surgery.

Several studies have reported that the corneal HOAs in patients with keratoconus used to analyze the corneal front surface aberration from the topography maps was significantly higher than that of normal subjects.13–16 The ocular and corneal HOAs using aberrometry also have been reported.17–19 In addition, Xie et al.20 reported that RGP lenses reduce the HOAs in keratoconic eyes. However, the characteristics of the ocular HOAs using Zernike vector analysis have not been investigated in patients with keratoconus. The purpose of the present study was to investigate the magnitude and orientation of the Zernike terms by using vector analysis in keratoconic eyes and to determine the effect of the RGP lens on the magnitude and orientation of the Zernike terms.

SUBJECTS AND METHODS

Two hundred and thirty-nine eyes of 206 subjects, including 76 eyes of 56 patients with keratoconus (KC group; mean age, 28.5 ± 7.6 years; mean ± SD), 58 eyes of 45 patients classified as keratoconus suspect or forme fruste keratoconus (KCS group; mean age, 28.4 ± 7.0 years), and 105 eyes of 105 normal control subjects (CONT group; mean age, 29.3 ± 7.2 years) were evaluated. The sphere and cylinder of the KC, KCS, and CONT groups were −4.67 ± 3.28 and −2.89 ± 1.99, −3.26 ± 2.83 and −3.91 ± 2.19, and −2.03 ± 1.49 and −0.81 ± 0.75 D, respectively. Only one eye of each normal control subject was used. For the patients with keratoconus, bilateral data were used when accurate data were available, because there are large differences in the severity of keratoconus between right and left eyes.

To compare the HOAs with and without an RGP lens, 19 eyes of 15 patients from the KC group, 9 eyes of 8 patients from the KCS group, and 17 eyes of 17 patients from the CONT group were evaluated. Only eyes of patients with keratoconus or keratoconus suspect and normal control eyes without contact lens-induced warpage were evaluated for

Copyright © Association for Research in Vision and Ophthalmology
the effects of the RGP lens. Selected subjects attended the outpatient clinic of the Department of Ophthalmology at Osaka University Medical School between February 2002 and September 2005. Subjects were excluded who had corneal scarring, cataract, or other ocular diseases and eyes with advanced keratoconus from which reliable wavefront measurements could not be obtained.

Keratoconus was defined as central thinning of the stroma, with a Fleischer’s ring, Vogt’s striae, or both observed by slit lamp examination. Patients with keratoconus suspect were defined as those with abnormal localized steepening observed in the axial power videokeratographic map, according to the 1.5-D scale (Klyce/Wilson scale) for visual inspection, without abnormal findings on the slit lamp examination and visual acuity examinations combined with a diagnosis of keratoconus in the contralateral eye. Subjects who had keratoconus suspect in both eyes were included in the study. The eyes in the CONT group had no ocular diseases except for refractive errors.

The research adhered to the tenets of the Declaration of Helsinki, and written informed consent was obtained from all subjects to perform the wavefront aberration measurements. The institutional review board/ethics committee of Osaka University Hospital approved the study.

The HOAs of the central 4-mm corneal diameter were obtained with the Hartmann-Shack wavefront analyzer (KR-9000PW; Topcon Corp., Tokyo, Japan). All subjects were diagnosed by one physician, whereas the wavefront measurements were performed by other physicians independently. The measurements were repeated in each eye at least three times to obtain well-focused, properly aligned Hartmann images in a dark room without mydriasis. The measurements from eyes evaluated for the effects of the RGP lens were taken when the RGP lens was in the resting position. Of the normal control subjects, none wore contact lenses before the wavefront measurement without an RGP lens. After not wearing the RGP lens for at least 30 minutes, the eyes of patients with keratoconus or those of keratoconus suspect were measured without the lens. All data from the wavefront analyzer (KR-9000PW; Topcon) database were extracted by using a prototype program for Zernike vector analysis. The Hartmann-Shack system has been described in detail.

For each pair of the standard Zernike terms for the third- and fourth-order aberrations, one value of the magnitude and axis was calculated by Zernike vector analysis. The coefficient for the Zernike vector analysis, which expresses the magnitude as the root mean square (RMS) in micrometers, is obtained by the formula

\[
RMS = \sqrt{\sum (c_{m,n}^2)} \quad (if \ m \neq 0).
\]

The values of the axes (in degrees) for the Zernike vector analysis are obtained by the formula

---

<table>
<thead>
<tr>
<th>Zernike vector term</th>
<th>Definition of axis</th>
<th>Range of axes (degrees)</th>
<th>Map</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trefoil</td>
<td>The apex of the slow (blue) triangle</td>
<td>0 - 120</td>
<td><img src="axis.png" alt="Image" /></td>
</tr>
<tr>
<td>Coma</td>
<td>The fast (red) side of the axis perpendicular to the fast-slow interface</td>
<td>0 - 360</td>
<td><img src="fast.png" alt="Image" /></td>
</tr>
<tr>
<td>Tetrafoil</td>
<td>The axis with slow wavefront</td>
<td>0 - 90</td>
<td><img src="slow.png" alt="Image" /></td>
</tr>
<tr>
<td>Secondary Astigmatism</td>
<td>Along the bowtie pattern with fast wavefront</td>
<td>0 - 180</td>
<td><img src="astigmatism.png" alt="Image" /></td>
</tr>
</tbody>
</table>

---

**FIGURE 1.** Definition of each Zernike vector term and map pattern. The axis of 30° of trefoil in which the fast wavefront is at 90°, 210°, and 330° on the circumference is referred to as a fast triangular pattern. The axis of 90° of trefoil in which the slow wavefront is at 90°, 210°, and 330° on the circumference is referred to as a slow triangular pattern. The axis of 90° of coma in which the slow area is inferior is referred to as an inferior slow pattern, and the axis of 270° is referred to as a superior slow pattern. The relationship of the fast triangular and slow triangular patterns is an opposite axis, the same as the inferior slow and superior slow patterns.

**FIGURE 2.** Simple averages of magnitude for total HOAs and each Zernike vector term. *P < 0.05, Kruskal-Wallis one-way ANOVA on ranks (Dunn method).
If $C_n^m \neq 0$

$$axis = \frac{1}{m} \tan^{-1} \left( \frac{c_n^m}{c_n^0} \right) \quad (c_n^m < 0)$$

$$axis = \frac{1}{m} \tan^{-1} \left( \frac{c_n^m}{c_n^0} + 180 \right) \quad (c_n^m > 0)$$

If $C_n^m = 0$

$$axis = \frac{90}{m} \quad (c_n^{-m} < 0)$$

$$axis = \frac{270}{m} \quad (c_n^{-m} > 0)$$

If $m = 0$, the magnitude is obtained using the formula

$$RMS = c_n^0$$

There is no axis associated with the terms where $m = 0$, because they are rotationally symmetrical.

For the third- and fourth-order aberrations, there are four pairs of Zernike terms for the same radial index value, $n$, and with the azimuthally indexed values $+m$ and $-m$. The number of the standard Zernike terms can be reduced from 9 to 5 by using Zernike vector analysis. The definitions of each Zernike vector term and Zernike vector map patterns are shown in Figure 1. The axes of the left eyes were reversed to the median line for enantiomorphism.24

The averages of the magnitude and axis for each Zernike vector term were calculated, not only by simple averaging of each magnitude but also by vector calculation, similar to the vector analysis of the cylinder used by Jaffe and Clayman.25 This method is widely used to calculate the induced regular astigmatism after cataract surgery. Although the cylindrical axis ranges from 0° to 180°, there are variations in the axial range for each Zernike vector term (Fig. 1). Based on the ranges of the axis in Zernike vector terms, the angles were doubled, tripled, or quadrupled during the calculation of the average magnitudes and axes in Zernike vector terms.

### Statistical Analyses

To compare the magnitudes of the total HOAs (third-order component $S_3$, fourth-order component $S_4$), trefoil, coma, tetrafoil, secondary astigmatism, and the spherical aberration among the three groups, the Kruskal-Wallis one-way analysis of variance (ANOVA) on ranks and the Dunn method was used. To compare the mean magnitude of total HOAs and Zernike vector terms, with and without an RGP lens in the three groups, paired $t$-tests were used if the values were normally distributed, and the Wilcoxon signed rank test was used when the values were not normally distributed. $P < 0.05$ was considered statistically significant. All tests of significance were performed with statistical software (SPSS for Windows, ver. 10.0J, 1999; SPSS Inc., Chicago, IL).

### RESULTS

#### HOAs in Eyes in the Three Study Groups

The magnitudes of the total HOAs, trefoil, coma, tetrafoil, secondary astigmatism, and spherical aberrations in the three
groups are shown in Figure 2. The means ± SD of the total HOAs in the KC group (0.82 ± 0.39 μm, RMS) and the KCS group (0.37 ± 0.28 μm) were both significantly higher than in the CONT group (0.10 ± 0.04 μm; P < 0.05). The magnitudes of trefoil, coma, tetrafoil, and secondary astigmatism aberrations in the KC and KCS groups were also significantly higher than those in the CONT group (P < 0.05 for all comparisons). The mean magnitude of the spherical aberration in the KC group (−0.03 ± 0.13 μm) was negative and that in the CONT group (0.02 ± 0.03 μm) was positive (P < 0.05). Although the spherical aberration differed significantly between the KC and CONT groups, the differences between the KC and the KCS groups and between the KCS and the CONT groups were not significant.

Each of the third- and fourth-order Zernike vector terms is shown on polar coordinates in Figures 3 and 4, respectively. For trefoil, the mean axis in the CONT group was 35.4° (Table 1), and most of the control eyes had a fast triangular pattern (Figs. 1, 3A). In contrast, most eyes in the KC and KCS groups had axes distributed around 90° (averages, 93.8° and 100.6°, respectively; slow triangular pattern, Fig. 1).

For coma, a superior slow pattern was dominant in the CONT group (mean axis, 253.7°), and the coma aberration in the CONT group was lower than that in the keratoconus group (Table 1). In the KC and KCS groups also had vertical coma, and most maps showed an inferior slow pattern (82.5° for KC and 91.0° for KCS) that differed from that in the CONT group (P < 0.001, †). The magnitudes of all Zernike vector terms were significantly reduced from 0.10 to 0.06 to 0.05 ± 0.04 by the RGP lens, the difference in the tetrafoil in the KCS group with and without the RGP lens was not significant. The magnitudes of the spherical aberration in the KC and KCS groups changed from negative to positive as a result of the RGP lens wear, but the difference between the values with and without the RGP lens was not significant. The magnitude of all Zernike vector terms in the CONT group were not significantly different with and without the RGP lens.

The changes due to RGP wear in trefoil and coma aberrations are shown as scatterplots on polar coordinates (Figs. 5, 6, respectively). Although trefoil tended to have its axis at around 90° (averages, 90.7° and 97.6°; slow triangular pattern) without an RGP lens in the KC and KCS groups, respectively, the axis changed to around 30° (averages, 20.2° and 53.0°; fast triangular pattern) with the RGP lens (Fig. 5B, Table 3). Similarly, the coma of eyes in the KC and KCS groups showed a reverse pattern at around 70° without the RGP lens (averages, 71.4° and 85.7°, respectively; inferior slow pattern), and around 250° (averages, 240.5° and 245.4°, respectively; superior slow pattern) with the RGP lens (Fig. 6B, Table 3). The magnitudes of trefoil, coma, and secondary astigmatism aberrations in the KC and KCS groups also were significantly reduced by the RGP lens. Although the magnitude of the tetrafoil aberration in the KC group was significantly (P = 0.003) reduced from 0.10 to 0.06 to 0.05 ± 0.04 by the RGP lens, the difference in the tetrafoil in the KCS group with and without the RGP lens was not significant. The magnitudes of all Zernike vector terms in the CONT group were not significantly different with and without the RGP lens.

| Group | RGP Lens | Total HOAs (S2 + S3) | Trefoil (C3 + C4) | Coma (C4 + C5) | Tetrafoil (C5 + C6) | Secondary Astigmatism (C4 - 2C5 + C6) | Spherical Aberration (C4)
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>KC</td>
<td>Without</td>
<td>0.72 ± 0.35*</td>
<td>0.22 ± 0.16†</td>
<td>0.62 ± 0.35*</td>
<td>0.10 ± 0.06†</td>
<td>0.15 ± 0.10†</td>
<td>-0.03 ± 0.13</td>
</tr>
<tr>
<td></td>
<td>With</td>
<td>0.31 ± 0.14*</td>
<td>0.09 ± 0.04‡</td>
<td>0.27 ± 0.14*</td>
<td>0.05 ± 0.04‡</td>
<td>0.07 ± 0.04‡</td>
<td>0.02 ± 0.07</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>&lt;0.001</td>
<td>0.006</td>
<td>&lt;0.001</td>
<td>0.003</td>
<td>0.001</td>
<td>0.177</td>
</tr>
<tr>
<td>KCS</td>
<td>Without</td>
<td>0.46 ± 0.29‡</td>
<td>0.21 ± 0.13‡</td>
<td>0.35 ± 0.29‡</td>
<td>0.05 ± 0.02‡</td>
<td>0.11 ± 0.07‡</td>
<td>-0.05 ± 0.11</td>
</tr>
<tr>
<td></td>
<td>With</td>
<td>0.19 ± 0.06‡</td>
<td>0.06 ± 0.04‡</td>
<td>0.16 ± 0.08‡</td>
<td>0.05 ± 0.02‡</td>
<td>0.04 ± 0.02‡</td>
<td>0.02 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>0.012</td>
<td>0.015</td>
<td>0.038</td>
<td>0.132</td>
<td>0.005</td>
<td>0.106</td>
</tr>
<tr>
<td>CONT</td>
<td>Without</td>
<td>0.10 ± 0.04</td>
<td>0.05 ± 0.02</td>
<td>0.06 ± 0.04</td>
<td>0.03 ± 0.02</td>
<td>0.03 ± 0.02</td>
<td>0.02 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>with</td>
<td>0.08 ± 0.02</td>
<td>0.04 ± 0.01</td>
<td>0.06 ± 0.02</td>
<td>0.03 ± 0.02</td>
<td>0.02 ± 0.01</td>
<td>0.01 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>0.197</td>
<td>0.363</td>
<td>0.895</td>
<td>0.535</td>
<td>0.052</td>
<td>0.432</td>
</tr>
</tbody>
</table>

* P < 0.001, † P < 0.01, ‡ P < 0.05, significantly reduced by a RGP lens (paired t-test).
§ P < 0.01, significantly reduced by a RGP lens (Wilcoxon signed rank test).
distribution of trefoil and coma in the CONT group did not differ with and without the RGP lens (Figs. 5A, 6A, Table 3). Zernike vector analysis of a typical keratoconic eye is shown in Figure 7. Vector maps of trefoil showed that the markedly slow triangular pattern without the RGP lens (magnitude @ axis for 4-mm-diameter pupil, 0.312 @ 79) changed to a mildly fast triangular pattern with the RGP lens (0.012 @ 28). Similarly, the vector map of coma showed that the high degree of the inferior slow pattern without the RGP lens (0.668 @ 88) changed to a reduced superior slow pattern by the RGP lens (0.287 @ 287).

Simulated retinal images of the Landolt rings showed that cometike, ghostly patterns oriented inferiorly without the RGP lens changed to smaller comet-like ghostly patterns oriented superiorly with the RGP lens.

**DISCUSSION**

Several studies have reported that the main characteristic of the HOAs in keratoconic eyes is a marked increase in coma, especially vertical coma. Schwiegerling and Greivenkamp reported that the high degree of the trefoil Zernike terms in keratoconic eyes was also higher than in normal eyes. Our results confirmed that coma and trefoil in keratoconic eyes were markedly higher, according to Zernike vector analysis.

One of the most interesting points in the Zernike vector analysis was the distribution of the axes for coma and trefoil. The color-coded maps of the HOAs in keratoconic eyes showed a vertical coma pattern with a relatively slower wavefront in the inferior cornea and relatively advanced wavefront in the superior cornea. Usually, the cone is displaced from the central to the inferior or inferotemporal cornea, and the asymmetry in the distribution of the corneal power probably results from the displacement of the corneal apex. We suggest that the inferior slow pattern in keratoconic eyes is caused by this inferosuperior asymmetric pattern in power distribution. However, we are uncertain why keratoconic eyes have a trefoil with a slow triangular pattern in the direction opposite that of the fast triangular pattern in normal eyes.

The magnitudes of the trefoil and coma aberrations and the total HOAs were reduced significantly by RGP lens wear. These results confirm that irregular astigmatism can be corrected by RGP lenses in eyes with keratoconus and are comparable to previously published values. However, trefoil and coma showed a reverse pattern with an RGP lens in Zernike vector analysis. The RGP lens corrected the irregular astigmatism of the anterior corneal surface because the anterior lens surface was the new interface between the air and the eye. In such cases, the posterior corneal surface, the crystalline lens, and the retina play more important roles in the overall image quality. The HOAs resulting from these interfaces are presumably relatively small in the eyes of young and normal subjects, and, except for keratoconus, our subjects did not have ocular disorders, such as cataract and retinal disease.

We suggest that although a decentered RGP lens and the pooling of irregular tear film under the lens may induce irregular astigmatism, the residual irregular astigmatism with the RGP lens in keratoconic eyes may be caused primarily by the
posterior corneal surface. The relatively smaller difference in the refractive indices between the corneal stroma and aqueous, as opposed to large differences between the air and the tear film, is associated with a small amount of irregular astigmatism due to the posterior corneal surface and the large degree of irregular astigmatism due to the anterior surface. Increases in the refractive index at the anterior surface yield plus power, and decreases in the refractive index at the posterior surface induce minus power. The combination of these two factors may play a role in creating the reverse pattern in coma and trefoil.

Our study had some limitations. We excluded patients with advanced keratoconus because of the difficulty of digitizing the Hartmann images. The HOAs were measured only for a 4-mm-diameter pupil, to determine the optical quality for day vision and because of the difficulty digitizing the Hartmann images accurately up to the 6-mm diameter in some subjects. In addition, the HOAs might change because of movement of the contact lenses. It is necessary to analyze the serial changes of each Zernike term with the contact lenses in keratoconic eyes when considering the effects of centration or movement of the contact lenses on HOAs. Another limitation is that our study may have included some effects of contact lens–induced corneal warpage that were undetectable on topographic maps. Although it is necessary to stop wearing the RGP lens to avoid its effects before measurements are obtained, it is very difficult for patients with keratoconus to stop wearing the RGP lenses for long periods before measurements. Finally, Smolek and Klyce reported that a large number of Zernike terms were needed to fit corneal aberrations, depending on the keratoconic stage to analyze the topography maps for the 6-mm diameter with image-analysis software. It will be necessary to analyze larger-order and Zernike terms.

Corneal topography is highly appropriate for evaluating the optical quality of the cornea. However, videokeratoscopy cannot evaluate the effects of abnormal topography of the posterior surface on optical quality. Although slit-scanning corneal topographers can measure the posterior corneal surface, no commercially available instruments can show the HOAs attributable to the posterior corneal surface. Further investigations are needed to analyze the anterior and posterior corneal HOAs directly to strengthen our hypothesis and compare the results from the present study and those from the posterior corneal surface.

**TABLE 3. Vector Calculation of Mean Magnitudes and Axes of Trefoil and Coma in Three Groups with and without RGP Lens**

<table>
<thead>
<tr>
<th>Group</th>
<th>Trefoil</th>
<th>Coma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without RPG</td>
<td>With RPG</td>
<td>Without RPG</td>
</tr>
<tr>
<td>KC</td>
<td>0.110 @ 90.7</td>
<td>0.040 @ 20.2</td>
</tr>
<tr>
<td>KCS</td>
<td>0.090 @ 97.6</td>
<td>0.040 @ 53.0</td>
</tr>
<tr>
<td>CONT</td>
<td>0.030 @ 40.5</td>
<td>0.020 @ 63.7</td>
</tr>
</tbody>
</table>

The mean magnitude (in micrometers) @ the mean axis (in degrees) was calculated from the vector component in all cases.

**FIGURE 7.** Zernike vector analysis and simulated retinal image of a typical keratoconus case without (A) and with (B) an RGP lens: 4 mm, measurements for the central 4-mm diameter, and 6 mm, measurements for the central 6-mm diameter. The magnitude (μm) @ axis (degrees) was measured (KR-9000PW; Topcon Corp., Tokyo, Japan).
The axes of trefoil and coma were reversed when an RGP lens was worn. When patients with keratoconus were asked about the image quality without an RGP lens, they often reported comet-like, ghostly images oriented mainly inferiorly (Fig. 7A). Although the RGP lens provides better correction, patients sometimes reported a smaller comet-like ghost oriented superiorly while wearing the RGP lens (Fig. 7B). These observations indicate that even if patients with keratoconus wear an RGP lens and the visual acuity improves, the quality of vision is not as good as that of normal patients, due to the residual irregular astigmatism possibly from the posterior corneal surface.

We believe that Zernike vector analysis is a simplified method for determining and understanding the characteristics of HOAs and that can be used in the clinic setting. This method allows easy quantification of the characteristics of the HOAs from the maps and statistical analysis, not only for keratoconic eyes but also for eyes before and after refractive surgery and cataract surgery and in the presence of various corneal disorders.

References