

Higher-order wavefront aberration and letter-contrast sensitivity in keratoconus

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Abstract

Aims To evaluate the relation between higher-order aberration of the eye and contrast sensitivity function in eyes with keratoconus.

Methods In 22 eyes of 14 patients with keratoconus (age 30.5 ± 8.4 years, means \pm SD) and 26 eyes of 13 normal controls (age 29.2 ± 6.7 years), ocular higher-order wavefront aberration for a 6-mm pupil was measured with the Hartmann-Schack aberrometer (KR-9000 PW, Topcon). The root mean square (RMS) of third- and fourth-order Zernike coefficients was used to represent higher-order aberrations. The letter-contrast sensitivity was examined using the CSV-1000LV contrast chart (Vector Vision).

Results In the keratoconus group, the letter-contrast sensitivity showed significant correlation with third-order (Spearman's correlation coefficient $r = -0.736$, $P < 0.001$) and fourth-order aberrations ($r = -0.464$, $P < 0.05$). There was borderline correlation between log MAR BSCVA and third-order ($r = 0.413$, $P = 0.070$) and fourth-order aberrations ($r = 0.394$, $P = 0.086$). In the normal group, the letter-contrast sensitivity had no significant correlation with third-order ($r = -0.170$, $P = 0.411$) and fourth-order aberrations ($r = -0.088$, $P = 0.673$), and log MAR best spectacle-corrected visual acuity (BSCVA) showed no correlation with third-order ($r = 0.063$, $P = 0.762$) and fourth-order aberrations ($r = -0.282$, $P = 0.165$).

Conclusions In eyes with keratoconus, there is significant correlation between contrast sensitivity and ocular higher-order wavefront aberrations.

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Keywords: keratoconus; wavefront aberration; higher-order aberration; contrast sensitivity; letter-contrast sensitivity

Introduction

Keratoconus is a chronic, non-inflammatory disease of the cornea associated with progressive thinning and anterior protrusion of the central cornea.^{1,2} Irregular astigmatism is often the first and most apparent clinical finding in keratoconus, and this is evidenced by a distortion of the corneal image as noted with the placido disc, retinoscope, keratometer, keratoscope, and computerized videokeratograph. Previous studies using videokeratography have quantitatively demonstrated that corneal irregular astigmatism is significantly greater in eyes with keratoconus than in normal eyes.^{3–6} In addition, recent studies using wavefront analysis technology showed that ocular and corneal higher-order aberration, particularly coma aberration, is significantly increased in keratoconus.^{7–10} Maeda *et al*¹¹ reported that corneal topographic indices significantly correlated with letter-contrast sensitivity in eyes with keratoconus. Applegate *et al*⁷ reported significant correlation between corneal aberration and contrast sensitivity in 91 eyes with a variety of corneal conditions, including 8 eyes with keratoconus, but such correlation in eyes with keratoconus was not assessed. To the best of our knowledge, the influence of ocular higher-order aberration on contrast sensitivity function in eyes with keratoconus has not been investigated. We conducted the current study to investigate the relationship between ocular wavefront aberration and letter-contrast sensitivity in keratoconus.

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Methods

We examined 22 eyes of 14 patients with keratoconus. There were seven men and seven women, and their age averaged 30.5 ± 8.4 years old. They were diagnosed with slit lamp biomicroscopy and corneal videokeratography. Eyes with corneal scarring or cataract were excluded from the subjects. The best spectacle-corrected visual acuity (BSCVA) ranged from 25/20 to 20/40. Twenty-six eyes of 13 patients served as age-matched normal controls. There were eight men and five women, and their age averaged 29.2 ± 6.7 years old. The BSCVA was 20/20 or better.

Ocular wavefront aberrations for 6-mm pupils were measured using a Hartmann–Shack wavefront analyser (KR-9000 PW, Topcon Corp., Tokyo, Japan) after the pupils were fully dilated with 1% tropicamide. Measurements were repeated three times for each subject, and the mean of the measurements was used for data analyses. All of the Hartmann images were revised to the pupil centre images.^{12–14} The obtained data were expanded into the set of orthogonal Zernike polynomials. The root mean square of third-order (Z_3^{-3} to Z_3^3) and fourth-order (Z_4^{-4} to Z_4^4) Zernike components were used to represent higher-order aberrations.^{15–19}

Letter-contrast sensitivity was measured with CSV-1000LV chart (Vector Vision, Columbus, OH, USA). This instrument uses letter optotypes all of which were the same size and of low spatial frequency (2.4 cycle/°).²⁰ There were eight contrast levels (standard, 35.5, 17.8, 8.9, 6.3, 4.5, 2.2, and 1.1%), and each contrast level had three letters. The measurements were performed at 2.5 m distance under full spectacle correction. The mean luminance was 81 cd/m². The test results were recorded, not as the contrast threshold or contrast sensitivity, but as the number of correctly identified letters out of 24 letters.^{11,21}

The study followed the tenets of the Declaration of Helsinki, and prestudy informed consent was obtained from all subjects after explanation of the nature and possible consequences of the study. The patients with keratoconus were instructed to refrain from wearing contact lenses for at least 2 weeks before the study examinations. A single experienced investigator performed all measurements.

Results

Measurement results are shown in the Table 1. The eyes with keratoconus showed significantly larger values than the normal controls in both third-order ($P < 0.0001$, Wilcoxon rank-sum test) and fourth-order aberrations ($P < 0.0001$). The log MAR BSCVA was significantly

Table 1 Measurement results

	Keratoconus	Normal controls
Third-order aberration (μm)	$1.585 \pm 0.799^*$	0.252 ± 0.119
Fourth-order aberration (μm)	$0.487 \pm 0.181^*$	0.170 ± 0.100
log MAR BSCVA	$0.037 \pm 0.169^*$	-0.118 ± 0.063
Letter-contrast sensitivity	$17.4 \pm 3.8^*$	21.8 ± 1.4

BSCVA, best spectacle-corrected visual acuity.

Mean \pm SD.

* $P < 0.0001$: significantly different from that of normal controls (Wilcoxon rank-sum test).

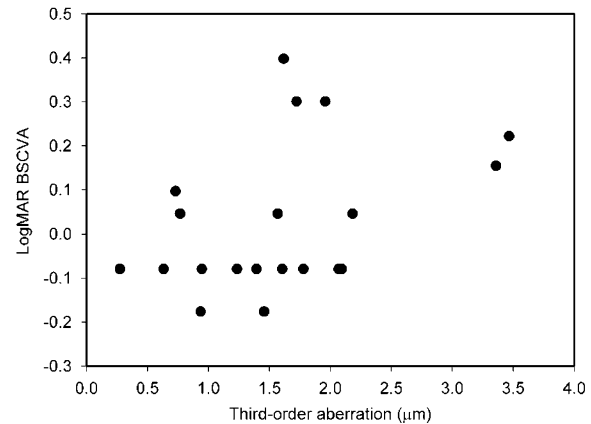


Figure 1 There was borderline correlation between log MAR BSCVA and third-order aberration (Spearman's correlation coefficient $r = 0.413$, $P = 0.07$) in eyes with keratoconus.

worse in eyes with keratoconus (0.037 ± 0.169) than in the normal controls (-0.118 ± 0.063) ($P < 0.001$). The letter-contrast sensitivity was significantly lower in eyes with keratoconus (17.4 ± 3.8 letters) than in the normal controls (21.8 ± 1.4 letters) ($P < 0.0001$). A total of 5 out of 26 eyes (19.2%) in the normal group could read all 24 letters, while no eye in the keratoconus group scored full marks.

The relation between visual function and higher-order aberration was evaluated. In the keratoconus group, there was borderline correlation between log MAR BSCVA and third-order (Spearman's correlation coefficient $r = 0.413$, $P = 0.070$; Figure 1) and fourth-order aberrations ($r = 0.394$, $P = 0.086$; Figure 2). The letter-contrast sensitivity showed significant correlation with third-order ($r = -0.736$, $P < 0.001$; Figure 3) and fourth-order aberrations ($r = -0.464$, $P < 0.05$; Figure 4).

In the normal group, there was no significant correlation between log MAR BSCVA and third-order ($r = 0.063$, $P = 0.762$) and fourth-order aberrations ($r = -0.282$, $P = 0.165$). The letter-contrast sensitivity also showed no significant correlation with third-order ($r = -0.170$, $P = 0.411$) and fourth-order aberrations ($r = -0.088$, $P = 0.673$).

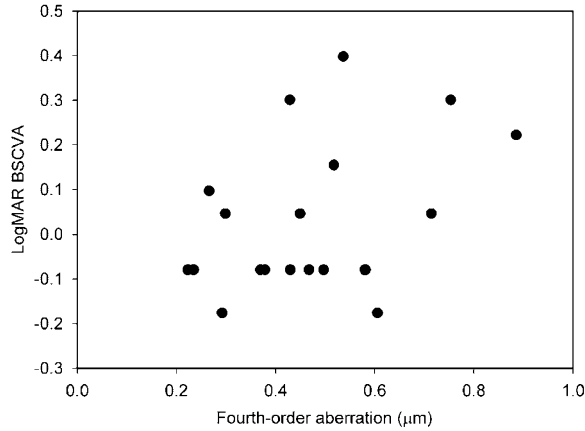


Figure 2 There was borderline correlation between log MAR BSCVA and fourth-order aberration (Spearman's correlation coefficient $r = 0.394$, $P = 0.086$) in eyes with keratoconus.

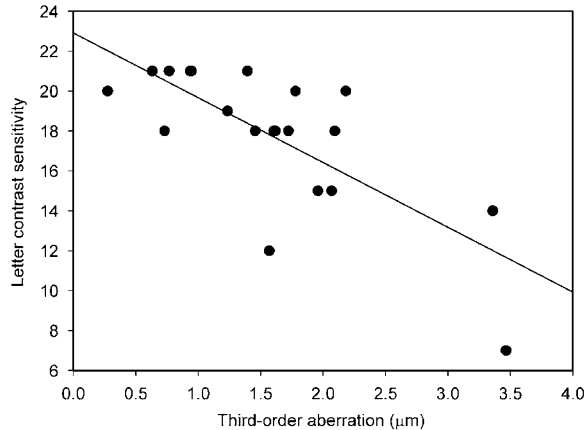


Figure 3 Significant correlation was found between letter-contrast sensitivity and third-order aberration (Spearman's correlation coefficient $r = -0.736$, $P < 0.001$) in eyes with keratoconus.

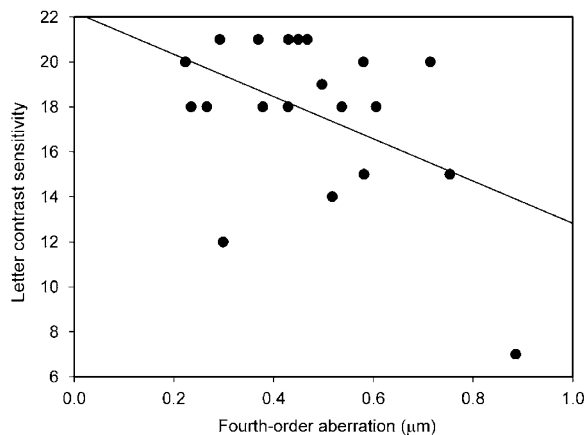


Figure 4 Significant correlation was found between letter-contrast sensitivity and fourth-order aberration (Spearman's correlation coefficient $r = -0.464$, $P < 0.05$) in eyes with keratoconus.

Discussion

Our study showed that ocular third- and fourth-order aberrations were significantly larger in eyes with keratoconus than in the normal controls. Previous studies also reported that coma and spherical aberrations significantly increased in eyes with keratoconus, with larger increases in coma aberration.⁷⁻¹⁰ Maeda *et al*⁸ found that coma aberration was 2.32 times larger than spherical aberration in eyes with keratoconus, and Barbero *et al*⁹ reported that coma aberration was 3.74 times higher in eyes with keratoconus than in normal controls. In the current study, third-order coma aberration was 3.25 times larger than fourth-order spherical aberration in eyes with keratoconus, and third-order aberration was 6.29 times higher in eyes with keratoconus than in the normal controls.

We found that letter-contrast sensitivity was significantly deteriorated in eyes with keratoconus, and both third- and fourth-order aberrations showed significant correlation with letter-contrast sensitivity. In normal controls, letter-contrast sensitivity did not correlate with either third- or fourth-order aberrations. In the CLEK study, it has been reported that low-contrast acuity deteriorated more rapidly than high-contrast visual acuity in eyes with keratoconus.²² Pesudovs *et al*²³ demonstrated that while visual acuity is an excellent test for comparing normal, keratoconus, and post-penetrating keratoplasty groups, additional useful information can be provided by low-contrast visual acuity and Pelli-Robson contrast sensitivity. Judging from these previous and current findings, it seems that contrast sensitivity testing is a highly sensitive measure to evaluate visual disturbance caused by increases in higher-order aberration of the eye.

In eyes with keratoconus, letter-contrast sensitivity had greater correlation with third-order coma aberration ($r = -0.736$) than with fourth-order spherical aberration ($r = -0.464$). This result seems to reflect the fact that coma aberration dominates over spherical aberration in eyes with keratoconus.⁸ In keratoconus, the apex is usually displaced from the centre of the cornea, resulting in asymmetry in corneal power distribution. The increases in topographic indices such as the inferior-superior²⁴ and surface asymmetry index²⁵ values represent the asymmetric power distribution in the cornea, which are in good agreement with the increase in coma aberration in keratoconus. The eyes with keratoconus often have their cones in the inferior part of the cornea, leading to relatively slower wavefront in the inferior part of the cornea and advanced wavefront in the superior area of the cornea.⁸

The current study has several weaknesses. First, only 22 eyes were tested in the keratoconus group. To exclude

the influence of non-optical factors on the visual performance, eyes with corneal scarring or cataract were not included in the subjects. Moreover, many subjects did not agree to participate in the current study, which entails time-consuming examinations, such as contrast sensitivity measurements and wavefront analysis. Second, the CSV-1000LV chart with which letter-contrast sensitivity was measured has some imperfection. This instrument uses eight contrast levels, but each level does not have equal interval between them. When the per cent contrast threshold is converted to logarithm of contrast sensitivity, the steps will be 0.45, 0.75, 1.05, 1.20, 1.35, 1.65, and 1.95. Some steps are 0.30 log units apart, and others are 0.15 log units apart. A chart having linear step increments will be more favourable to evaluate the subtle changes in visual function.

The relationship between contrast sensitivity and ocular higher-order aberration has been studied in a variety of ocular diseases.^{7,12,16,26–28} Eyes with cataract have decreased contrast sensitivity and increased higher-order aberration.¹² Applegate *et al*¹⁶ reported that the area under the contrast sensitivity function decreases as the wavefront variances increase after radial keratotomies. A study using aberroscope demonstrated that low-contrast visual acuity and glare visual acuity were adversely influenced by the increases in total ocular aberrations after photorefractive keratectomy.²⁶ Yamane *et al*²⁷ demonstrated that conventional laser *in situ* keratomileusis significantly increases ocular higher-order aberrations, which compromise the postoperative contrast sensitivity functions. The current study represents the first report of significant association between ocular higher-order aberration and contrast sensitivity in eyes with keratoconus. One of the clinical significances of our data is that an objective parameter (ocular higher-order aberration) correlated with subjective visual function, which has long been the only source of information to decide surgical intervention. Further refinements in the objective means to assess disease severity and progression would be of high clinical benefits in the practice of gradually progressive diseases, which deteriorates quality of vision.

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