Contrast Sensitivity Function and Ocular Higher-Order Aberrations following Overnight Orthokeratology

Takahiro Hiraoka,[1] *Chikako Okamoto,*[1] *Yuko Ishii,*[1] *Tetsuhiko Kakita,*[2] *and Tetsuro Oshika*[1]

PURPOSE. To evaluate relationships among contrast sensitivity function, ocular higher-order aberration, and myopic correction in eyes undergoing overnight orthokeratology for myopia.

METHODS. A prospective study was conducted in 46 eyes of 23 patients undergoing orthokeratology. Inclusion criteria were spherical equivalent refraction between −1.00 and −4.00 diopters (D), refractive astigmatism up to 1.00 D, and best-corrected visual acuity of 20/20 or better. Ocular higher-order aberrations and contrast sensitivity function were determined before and 3 months after initiation of the procedure. We measured three indices of contrast sensitivity function: contrast sensitivity, low-contrast visual acuity, and letter contrast sensitivity with the CSV-1000 charts (Vector Vision Co., Greenville, OH). Area under the log contrast sensitivity function (AULCSF) was calculated from the contrast sensitivity data.

RESULTS. Orthokeratology significantly improved logMAR uncorrected visual acuity ($P < 0.0001$; paired *t*-test) but significantly increased ocular higher-order aberrations ($P < 0.0001$) and decreased contrast sensitivity function, including AULCSF ($P < 0.0001$), low-contrast visual acuity ($P = 0.0025$), and letter contrast sensitivity ($P < 0.0001$; Wilcoxon signed-rank test). The induced changes in AULCSF, low-contrast visual acuity, and letter contrast sensitivity by orthokeratology showed significant correlation with changes in third-order (Pearson $r = -0.430$, $P = 0.0026$; $r = 0.423$, $P = 0.0031$; and Spearman $r_s = -0.351$, $P = 0.0186$, respectively), fourth-order ($r = -0.418$, $P = 0.0035$; $r = 0.425$, $P = 0.0029$; and $r_s = -0.566$, $P = 0.0001$, respectively), and total higher-order ($r = -0.460$, $P = 0.0011$; $r = 0.471$, $P = 0.0008$; and $r_s = -0.434$, $P = 0.0036$, respectively) aberrations. The induced changes in contrast sensitivity function and higher-order aberrations significantly correlated with the amount of myopic correction ($P < 0.01$).

CONCLUSIONS. Orthokeratology significantly increases ocular higher-order aberrations and compromises contrast sensitivity function, depending on the amount of myopic correction. (*Invest Ophthalmol Vis Sci.* 2007;48:550–556) DOI:10.1167/iovs.06-0914

Orthokeratology, also known as corneal refractive therapy or corneal reshaping, is a method of temporarily changing refraction in myopic patients by the programmed application of specially designed rigid contact lenses. It was introduced in the early 1960s.[1] The central cornea is flattened and thinned, resulting in a reduction in myopia and an improvement in unaided vision.[2–5] In the 1980s, application of the orthokeratology lens during sleep became possible with the development of higher gas-permeable lens materials. This wearing modality, called overnight orthokeratology, allowed satisfactory daytime vision without contact lenses or eyeglasses. In addition, the advent of sophisticated lens designs (reverse geometry design) caused much faster, more accurate, and greater achievement of corneal and refractive changes.[4,6–8] Overnight orthokeratology has come into greater use as a treatment modality to correct refractive errors, and its efficacy has been confirmed in terms of high-contrast visual acuity.[4,7–9]

In recent years, with the development of a wavefront sensing technique that can quantify optical aberration, increasing attention has been paid to changes in the optical quality of the eye after refractive procedures. Several studies have reported increases in ocular higher-order aberrations after photorefractive keratectomy (PRK)[10,11] and laser in situ keratomileusis (LASIK).[12–14] Increases in higher-order aberrations are among the main causes of reduced visual performance after PRK and LASIK.[10,11,15–18] These procedures are designed to correct defocus by surgical modification of the corneal curvature and to produce a nonphysiological oblate cornea with a flat central area and increasing power toward the periphery. Similarly, an oblate cornea is created by orthokeratology,[7] and previous studies have demonstrated that orthokeratology increases corneal and ocular higher-order aberrations.[19–21] A paucity of information exists about contrast sensitivity function after orthokeratology.[21] Moreover, the impact of higher-order aberrations induced by orthokeratology on contrast sensitivity function has not been reported. We conducted the current prospective study to analyze the relationship between changes in contrast sensitivity function and changes in ocular higher-order aberrations in eyes undergoing overnight orthokeratology.

SUBJECTS AND METHODS

Subjects

Forty-six eyes of 23 subjects (12 men, 11 women) were included in this prospective study. Subjects were selected based on the following inclusion criteria; age between 20 and 35 years, spherical equivalent refraction between −1.00 and −4.00 diopters (D), refractive astigmatism up to 1.00 D, mean keratometry readings between 40.00 and 46.25 D, best-corrected visual acuity of 20/20 or better, and no ocular or systemic disease. Subjects' ages ranged from 21 to 33 years (24.2 ± 3.3 years [mean ± SD]). Baseline uncorrected visual acuity (logMAR) ranged from 0.22 to 1.52 (0.77 ± 0.31). Myopic refractive error ranged from −1.00 to −4.00 D (−2.38 ± 0.98 D). Subjects did not have previous experience with orthokeratology and did not wear contact lenses for at least 3 weeks before enrolling in the study. The research adhered to the tenets of the Declaration of Helsinki, the research protocol was approved by the institutional review board, and informed consent was obtained from each subject before participation and after

---

From the [1]Department of Ophthalmology, Institute of Clinical Medicine, University of Tsukuba, Ibaraki, Japan; and [2]Kakita Eye Clinic, Chiba, Japan.

Submitted for publication August 3, 2006; revised September 7 and 12, 2006; accepted December 5, 2006.

Disclosure: **T. Hiraoka**, None; **C. Okamoto**, None; **Y. Ishii**, None; **T. Kakita**, None; **T. Oshika**, 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: Takahiro Hiraoka, Department of Ophthalmology, Institute of Clinical Medicine, University of Tsukuba, 1-1-1, Tennoudai, Tsukuba, Ibaraki 305-8575, Japan; thiraoka@md.tsukuba.ac.jp.

the nature and possible consequences of the study had been fully explained.

Lenses

A four-zone reverse geometry lens (Boston XO; Polymer Technology Corp., Wilmington, MA) composed of fluorosilicone acrylate with an oxygen permeability (Dk) of 100×10^{-11} (cm^2/sec)(mL O$_2$/mL · mm Hg) was used for all subjects. The lens has a base curve (central optical zone) diameter of 6.0 mm, a reverse curve of 0.6-mm width, an alignment curve of 1.0-mm width, and a peripheral curve of 0.4-mm width. Lenses were fitted according to the instructions recommended by the manufacturer. In brief, for the first lens selection, alignment curve was decided based on the flatter keratometry reading, and base curve was determined as target power plus 0.75 D. For a fit to be deemed acceptable, the contact lens had to be well centered vertically and horizontally on the cornea and to move approximately 1 mm on a blink. The overall fluorescein pattern resembled a bull's eye, with 3 to 5 mm of central touch surrounded by a narrow and deep annulus of tears trapped in the reverse curve area. Lenses that decentered superiorly were considered loose, and those that decentered inferiorly were considered too tight. Lateral decentration was resolved by increasing the lens diameter to 10.6 mm. After confirmation of fine centration, proper movement, and appropriate fluorescein pattern, each patient underwent a 2-hour trial. Subsequently, corneal topography was performed to evaluate the efficacy of correction. If a central flat area appeared and the center was within 0.5 mm of the pupil center on the map, it was considered that an acceptable fit was achieved. Overrefraction was then performed, and the final lens was ordered. After lenses were dispensed, subjects consistently wore their contact lenses overnight. The lens design was modified in the event of poor topographic changes or inadequate improvement of uncorrected visual acuity. Total diameter of these lenses was 10.0 mm in most cases and 10.6 mm in several cases. Subjects were asked to wear their contact lenses at least 7 hours per night. To verify continuing ocular health and to observe any effects of lens wear, slit lamp biomicroscopy, including fluorescein staining, was performed in detail at each visit.

Measurements

At the time of enrollment, all patients underwent comprehensive ocular examination that included manifest refraction, uncorrected and corrected visual acuity, refraction, keratometry, slit lamp evaluation, dilated fundus evaluation, corneal topography, wavefront aberration measurements, and contrast sensitivity testing. Similar examinations, excluding dilated fundus evaluation, were repeated at each visit after the start of treatment. To minimize the influence of diurnal variation, all measurements were conducted between 9 AM and 11 AM, and subjects were instructed to attend the examinations from 2 to 4 hours after lens removal.

We measured three indices of contrast sensitivity function: contrast sensitivity (with the CSV-1000E chart), low-contrast visual acuity (with the CSV-1000LanC10% chart), and letter contrast sensitivity (with the CSV-1000LV chart; all from Vector Vision Co., Greenville, OH). These tests were performed monocularly in eyes with undilated pupils at the testing distance of 2.5 m under best spectacle correction. Background illumination of the translucent chart was provided by a fluorescent luminance source of the instrument and was automatically calibrated to 85 cd/m^2.

The CSV-1000E chart presents vertical sine wave gratings at four spatial frequencies—3, 6, 12, and 18 cyc/deg—and each spatial frequency has eight different levels of contrast. Each row consists of eight pairs of circular patches, including sine waves of a single spatial frequency. In each pair, one patch presents a grating, and the other patch is blank. The patient was asked to identify which patch had a grating, and the contrast level of the last correct response was defined as the contrast threshold in logarithmic values for each frequency.[22] From these data, the area under the log contrast sensitivity function (AULCSF) was calculated according to the method of Applegate et al.[23] In brief, the AULCSF was determined as the integration of the fitted third-order polynomials of the log contrast sensitivity units between the fixed limits of 0.48 (corresponding to 3 cyc/deg) and 1.26 (18 cyc/deg) on the log spatial frequency scale. This can represent contrast sensitivity data as one number and make statistical analysis easier.

The CSV-1000LanC10% chart uses the Landolt ring as the optotype under 10% low contrast. This presents five letters per line, and each one-line step represents a change of 0.1 logMAR units. Low-contrast visual acuity was scored by giving a credit of 0.02 logMAR units for each letter correctly identified.

The CSV-1000LV chart uses letter optotypes, each of which is the same size and is of low spatial frequency (2.4 cyc/deg). There are eight contrast levels (standard, 35.5%, 17.8%, 8.9%, 6.3%, 4.5%, 2.2%, and 1.1%), and each contrast level has three letters. Test results were recorded not as the contrast sensitivity or contrast threshold but as the number of correctly identified letters.[17,24]

Ocular wavefront aberrations for a 4-mm pupil were measured with a wavefront analyzer (Hartmann-Shack; KR-9000 PW; Topcon Co., Tokyo, Japan) whose details have been described.[16,25] Data were expanded with the normalized Zernike polynomials. Magnitudes of the coefficients of the Zernike polynomials were represented as the root mean square (RMS; in micrometers) and were used to show the wavefront aberrations. The RMS of the third-order Zernike coefficients was used to denote coma-like aberrations, and the RMS of the fourth-order coefficients was used to represent spherical aberrations. Total higher-order aberrations were calculated as the RMS of the third- and fourth-order coefficients. Measurements were repeated at least four times for each eye, and the three best-focused images were selected and averaged. The averaged values were used for subsequent analyses.

Statistical Analysis

Data obtained 3 months after the start of orthokeratology were compared with the baseline measurements using the paired *t* test and the Wilcoxon signed-rank test. Relationships among changes in ocular higher-order aberrations, changes in contrast sensitivity function, and amount of myopic correction were evaluated by Pearson and Spearman correlation tests. The amount of myopic correction was defined as the reduction in manifest refractive spherical equivalent at the 3-month visit. All analyses were two tailed, and $P < 0.05$ was considered statistically significant.

RESULTS

Subject data are summarized in Table 1. Manifest refraction significantly decreased from −2.38 ± 0.98 D at baseline to −0.24 ± 0.71 D at 3 months after treatment ($P < 0.0001$; paired *t*-test), and uncorrected visual acuity improved from 0.77 ± 0.31 to −0.03 ± 0.16 logMAR ($P < 0.0001$) by orthokeratology. Best-corrected visual acuity did not change significantly, with −0.10 ± 0.07 logMAR before and −0.09 ± 0.06 logMAR after the procedure ($P = 0.4895$). Treatment significantly increased third-order RMS from 0.074 ± 0.028 to 0.259 ± 0.150 μm ($P < 0.0001$), fourth-order RMS from 0.038 ± 0.020 to 0.134 ± 0.061 μm ($P < 0.0001$), and total higher-order RMS from 0.085 ± 0.032 to 0.297 ± 0.152 μm ($P < 0.0001$).

Treatment resulted in significant decreases in contrast sensitivity at all spatial frequencies from 3 to 18 cyc/deg ($P = 0.0004$ for 3, $P < 0.0001$ for 6, $P = 0.0003$ for 12, and $P = 0.0175$ for 18 cyc/deg; Fig. 1), and AULCSF calculated from the data of this chart was significantly reduced from 1.451 ± 0.120 to 1.291 ± 0.177 ($P < 0.0001$). The 10% low-contrast visual acuity significantly worsened from 0.02 ± 0.09 to 0.11 ± 0.14 logMAR ($P = 0.0025$). Letter contrast sensitivity significantly decreased from 24 ± 0 to 22.8 ± 1.9 ($P < 0.0001$; Wilcoxon signed-rank test).

TABLE 1. Clinical Data of Patients at Baseline and 3 Months after Orthokeratology

Clinical Data	Baseline	After Treatment
Manifest refraction (D)	−2.38 ± 0.98 (−4.00–−1.00)	−.24 ± 0.71 (−2.75–1.25)*
UCVA (logMAR)	0.77 ± 0.31 (0.22–1.52)	−0.03 ± 0.16 (−0.18–0.40)*
BCVA (logMAR)	−0.10 ± 0.07 (−0.30–0.00)	−0.09 ± 0.06 (−0.18–0.15)
Third-order RMS (μm)	0.074 ± 0.028 (0.022–0.133)	0.259 ± 0.150 (0.029–0.758)*
Fourth-order RMS (μm)	0.038 ± 0.020 (0.010–0.101)	0.134 ± 0.061 (0.037–0.275)*
Total higher-order RMS (μm)	0.085 ± 0.032 (0.035–0.161)	0.297 ± 0.152 (0.084–0.791)*
AULCSF	1.451 ± 0.120 (1.177–1.615)	1.291 ± 0.177 (0.834–1.570)*
Low-contrast visual acuity (logMAR)	0.02 ± 0.09 (−0.20–0.24)	0.11 ± 0.14 (−0.18–0.50)†
Letter contrast sensitivity (no. of letters)	24 ± 0 (all 24)	22.8 ± 1.9 (18–24)‡

Data are mean ± SD (range). UCVA, uncorrected visual acuity; BCVA, best-corrected visual acuity.

* $P < 0.0001$; † $P < 0.01$ (paired *t* test); ‡ $P < 0.0001$ (Wilcoxon signed-rank test): significant differences between pretreatment and posttreatment values.

The induced changes in contrast sensitivity function were analyzed in relation to the changes in ocular higher-order aberrations. Changes in AULCSF showed significant negative correlation with the changes in third-order (Pearson correlation coefficient; $r = -0.430$, $P = 0.0026$; Fig. 2A), fourth-order ($r = -0.418$, $P = 0.0035$; Fig. 2B), and total higher-order ($r = -0.460$, $P = 0.0011$; Fig. 2C) RMS. Changes in low-contrast visual acuity showed significant positive correlation with the changes in third-order ($r = 0.423$, $P = 0.0031$; Fig. 3A), fourth-order ($r = 0.425$, $P = 0.0029$; Fig. 3B), and total higher-order ($r = 0.471$, $P = 0.0008$; Fig. 3C) RMS. Changes in letter contrast sensitivity demonstrated significant negative correlation with changes in third-order (Spearman rank correlation coefficient; $r = -0.351$, $P = 0.0186$; Fig. 4A), fourth-order ($r = -0.566$, $P = 0.0001$; Fig. 4B), and total higher-order ($r = -0.434$, $P = 0.0036$; Fig. 4C) RMS.

The induced changes in contrast sensitivity function and higher-order aberrations were analyzed in relation to the amount of myopic correction. Significant correlation was observed between the amount of myopic correction and the induced changes in AULCSF (Pearson correlation coefficient; $r = -0.462$, $P = 0.0010$; Fig. 5A), low-contrast visual acuity ($r = 0.353$, $P = 0.0154$; Fig. 5B), and letter contrast sensitivity (Spearman rank correlation coefficient; $r = -0.641$, $P < 0.0001$; Fig. 5C). Significant correlation was observed between the amount of myopic correction and the induced changes in third-order (Pearson correlation coefficient; $r = 0.650$, $P < 0.0001$), fourth-order ($r = 0.582$, $P < 0.0001$), and total higher-order ($r = 0.671$, $P < 0.0001$) RMS.

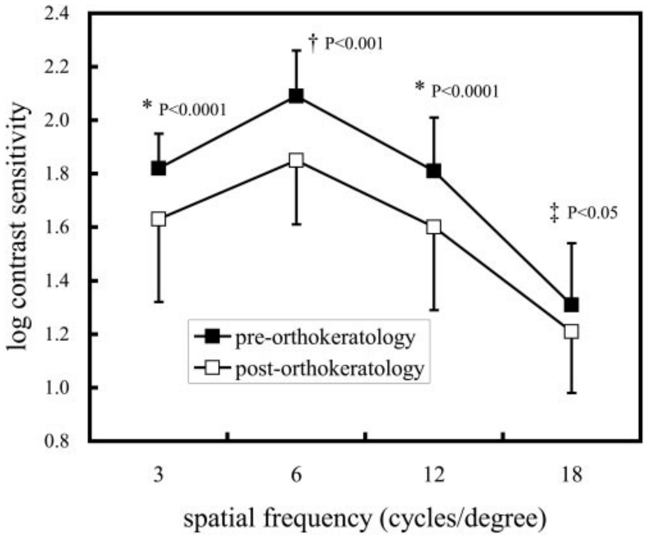

FIGURE 1. Contrast sensitivity at four specific frequencies before and after treatment. Orthokeratology significantly decreased contrast sensitivity at all spatial frequencies (*$P < 0.0001$, †$P < 0.001$, ‡$P < 0.05$; paired *t* test). Values are expressed as mean ± SD.

DISCUSSION

Contrast sensitivity, which is defined as the ability to detect differences in luminance between adjacent areas, is a fundamental feature of vision, and this measurement can provide useful information about visual function that may not be obtained by standard visual acuity testing.[26–31] Several studies have shown that contrast sensitivity function significantly correlates with some abilities associated with quality of life, such as reading speed,[32,33] mobility, walking speed,[34] driving performance,[35] and computer task accuracy.[36] In addition, contrast sensitivity declines in eyes with various ocular abnormalities[30,37–42] and after refractive surgery.[11,15–18,23,24,26–29,43–45] Hence, it is extremely important to assess contrast sensitivity function in eyes undergoing any treatment that can affect ocular shape and optical quality. In orthokeratology practice, patients sometimes report visual disturbances even though visual acuity is excellent according to high-contrast acuity chart testing. In such patients, it is possible that the quality of vision has deteriorated. The impact of orthokeratology on visual performance, however, has not been studied in detail. Therefore, in this prospective study, we investigated changes in contrast sensitivity function as representative of vision quality using three indices in eyes undergoing overnight orthokeratology.

As shown in the results, uncorrected visual acuity significantly improved after orthokeratology, best-corrected visual acuity did not change, and all indices of contrast sensitivity function significantly deteriorated after the procedure, indicating that orthokeratology causes an overall reduction of contrast sensitivity function even in clinically successful cases.

We also found that orthokeratology significantly increased ocular higher-order aberrations and that the induced changes in contrast sensitivity function significantly correlated with changes in ocular higher-order aberrations. As for the relationship between contrast sensitivity and higher-order aberrations, Applegate et al.[23] reported that contrast sensitivity after radial keratotomy decreased in parallel with increases in corneal higher-order aberrations. Mierdel et al.[10] found a highly significant correlation between loss of contrast sensitivity and increase in ocular aberrations after PRK. Marcos[15] demonstrated that contrast sensitivity was significantly reduced after conventional LASIK as corneal aberrations increased. We herein report similar results in eyes undergoing orthokeratology.

Until now, only one study had reported the influence of ocular higher-order aberrations induced by orthokeratology on

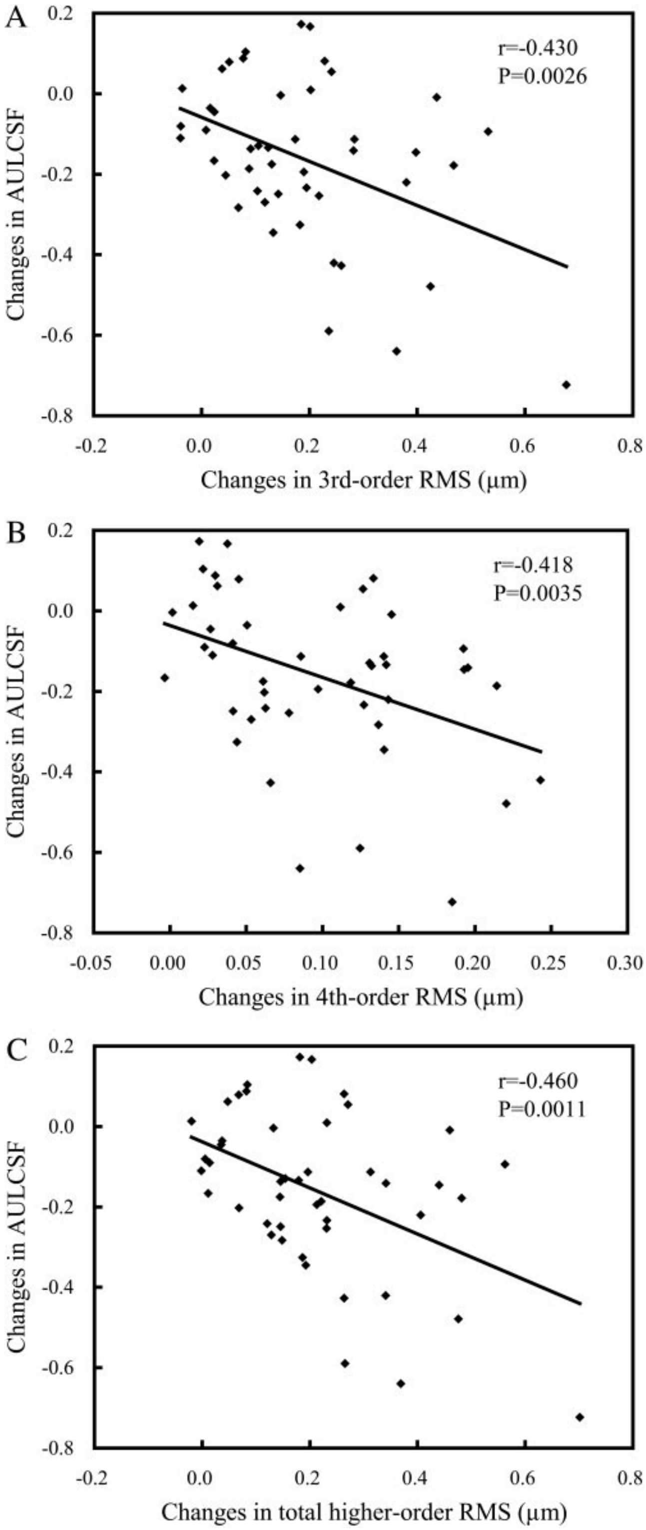

FIGURE 2. Changes in ocular higher-order aberrations and in AULCSF. (**A**) Significant correlation between third-order RMS and changes in AULCSF (Pearson correlation coefficient; $r = -0.430$, $P = 0.0026$). (**B**) Significant correlation between fourth-order RMS and changes in AULCSF (Pearson correlation coefficient; $r = -0.418$, $P = 0.0035$). (**C**) Significant correlation between total higher-order RMS and changes in AULCSF (Pearson correlation coefficient; $r = -0.460$, $P = 0.0011$).

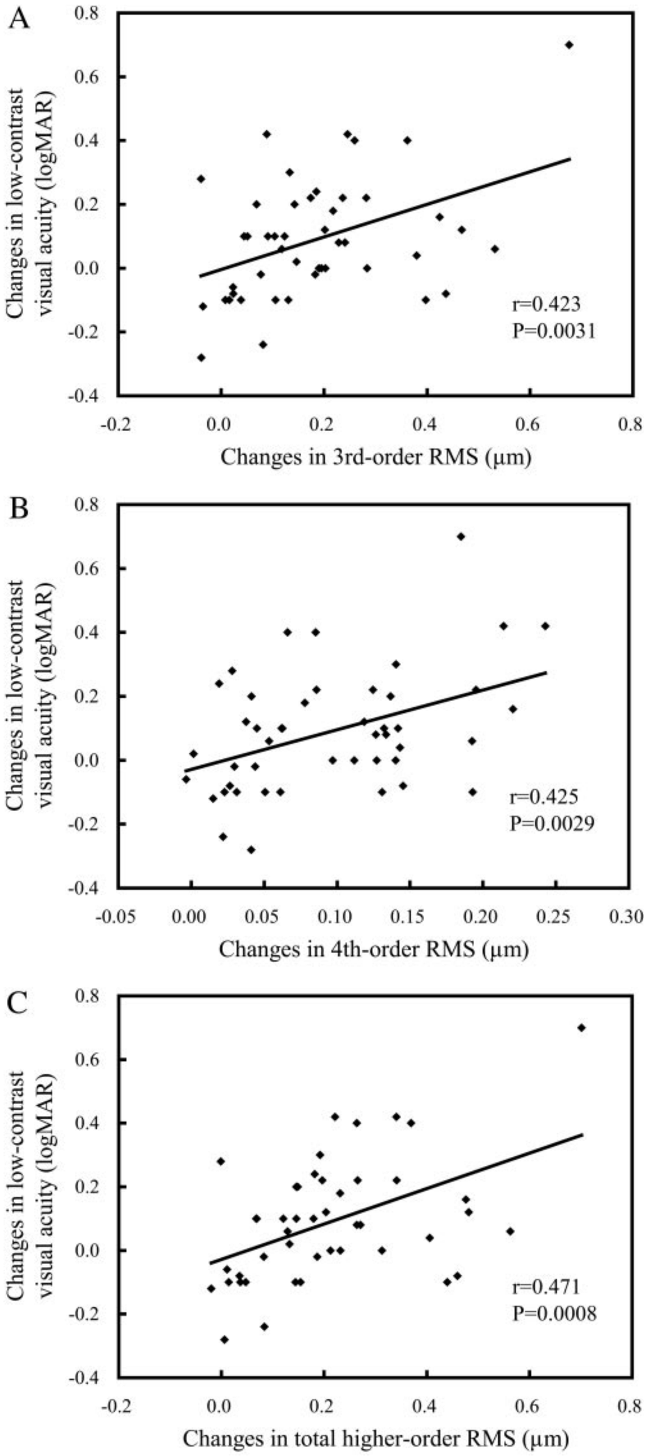

FIGURE 3. Changes in ocular higher-order aberrations and in low-contrast visual acuity. (**A**) Significant correlation between third-order RMS and changes in low-contrast visual acuity (Pearson correlation coefficient; $r = 0.423$, $P = 0.0031$). (**B**) Significant correlation between fourth-order RMS and changes in low-contrast visual acuity (Pearson correlation coefficient; $r = 0.425$, $P = 0.0029$). (**C**) Significant correlation between total higher-order RMS and changes in low-contrast visual acuity (Pearson correlation coefficient; $r = 0.471$, $P = 0.0008$).

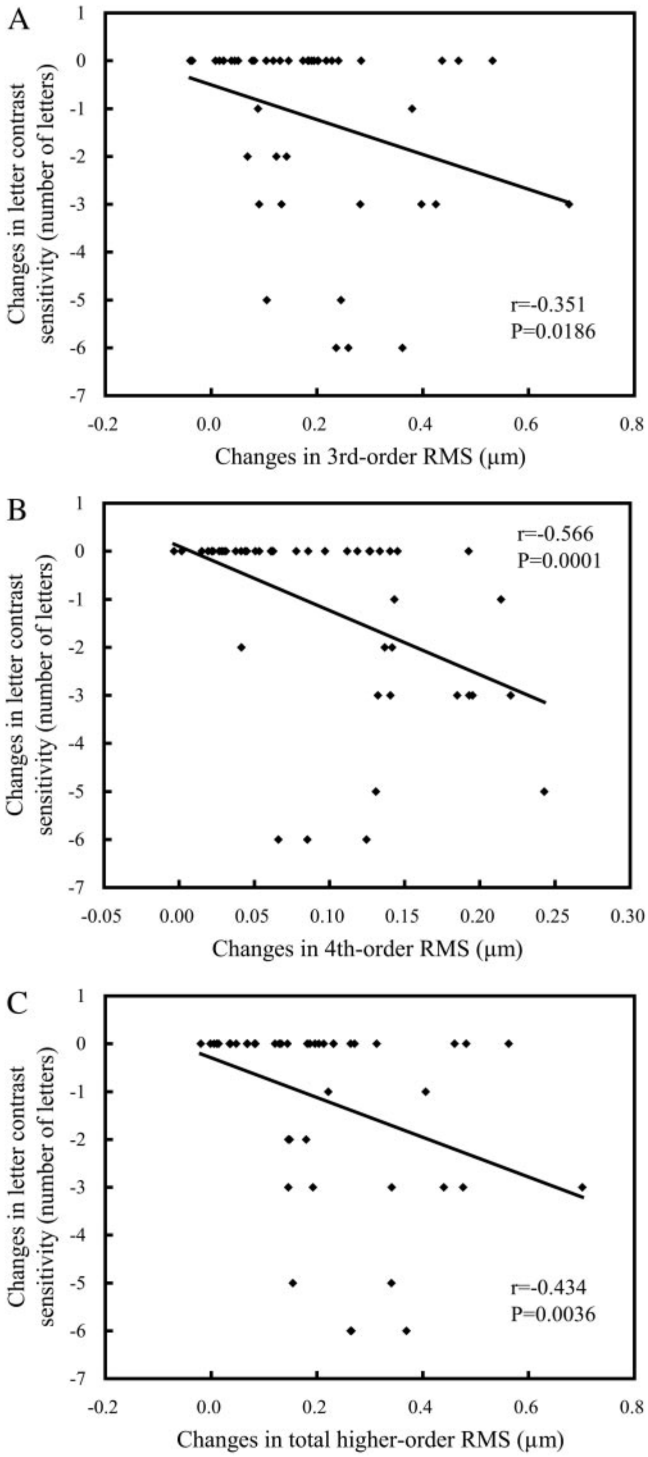

FIGURE 4. Changes in ocular higher-order aberrations and in letter contrast sensitivity. (**A**) Significant correlation between third-order RMS and changes in letter contrast sensitivity (Spearman rank correlation coefficient; $r = -0.351$, $P = 0.0186$). (**B**) Significant correlation between fourth-order RMS and changes in letter contrast sensitivity (Spearman rank correlation coefficient; $r = -0.566$, $P = 0.0001$). (**C**) Significant correlation between total higher-order RMS and changes in letter contrast sensitivity (Spearman rank correlation coefficient; $r = -0.434$, $P = 0.0036$).

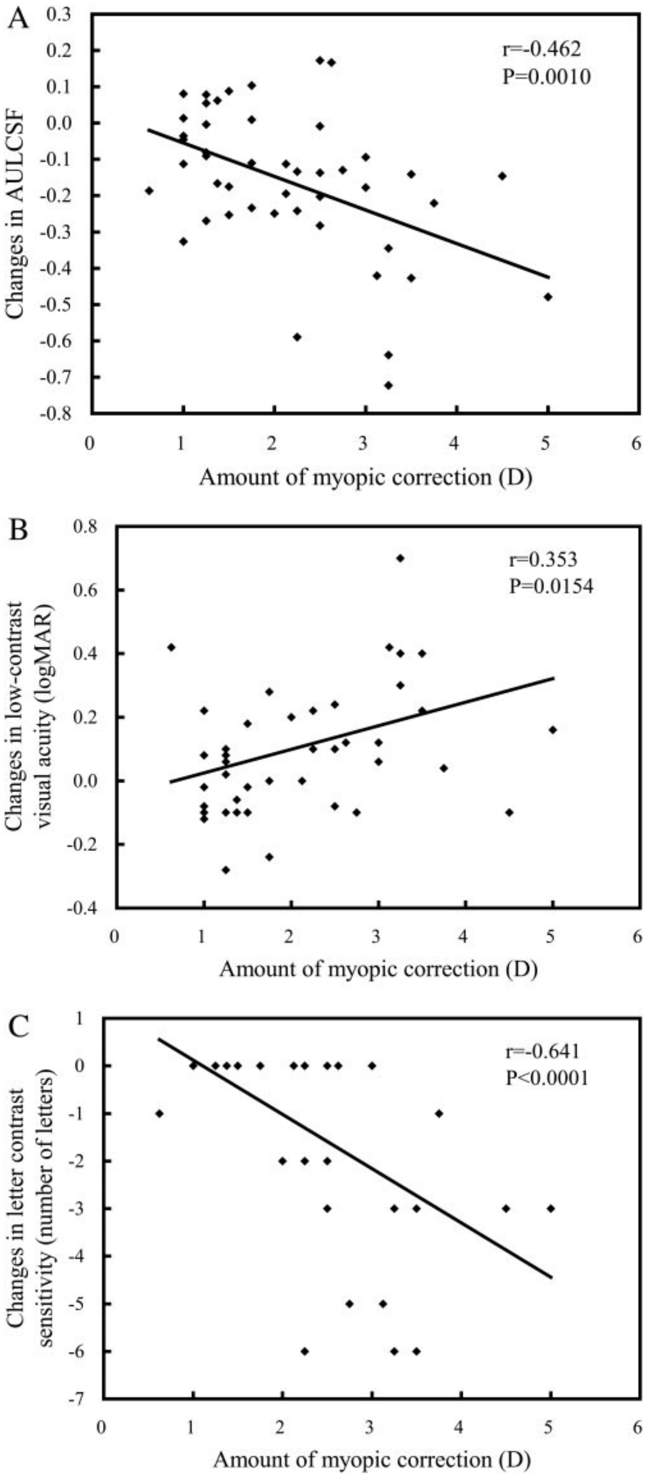

FIGURE 5. Amount of myopic correction and changes in contrast sensitivity function. (**A**) Significant correlation between amount of myopic correction and changes in AULCSF (Pearson correlation coefficient; $r = -0.462$, $P = 0.0010$). (**B**) Significant correlation between amount of myopic correction and changes in low-contrast visual acuity (Pearson correlation coefficient; $r = 0.353$, $P = 0.0154$). (**C**) Significant correlation between amount of myopic correction and changes in letter contrast sensitivity (Spearman rank correlation coefficient; $r = -0.641$, $P < 0.0001$).

visual performance.[21] The authors measured low-contrast visual acuity with dilated and undilated pupils and found a significant reduction in dilated low-contrast visual acuity that was significantly associated with the increase in higher-order aberrations after orthokeratology. Although we did not assess contrast sensitivity with dilated pupils, contrast sensitivity function after orthokeratology deteriorated in proportion to the increases in higher-order aberrations, even with undilated pupils. Moreover, the changes in ocular higher-order aberrations and contrast sensitivity function induced by orthokeratology significantly correlated with the amount of myopic correction. These results indicated that orthokeratology increases ocular higher-order aberrations, leading to decreases in contrast sensitivity function, and that these changes depend on the amount of myopic correction. The present study represents the first reported investigation into the relationship among contrast sensitivity, higher-order aberrations, and myopic correction in subjects undergoing overnight orthokeratology. In eyes that underwent conventional LASIK, Yamane et al.[16] demonstrated that the greater the amount of achieved myopia correction, the greater the changes in contrast sensitivity function and ocular higher-order aberrations. The findings of the present orthokeratology study fully corresponds to those of this LASIK study.

In this study, third-order and fourth-order aberrations significantly correlated with the reduction in contrast sensitivity function. The total higher-order aberrations also correlated with contrast sensitivity loss. After PRK[18] and LASIK,[16] decreases in contrast sensitivity function were found to have significant correlation with coma-like and spherical aberrations. Berntsen et al.[21] demonstrate that after orthokeratology, increases in spherical aberration play the major role in the loss of visual performance with dilated pupils but that increases in coma-like aberration do not. Our results, however, indicated that spherical and coma-like aberrations deteriorated contrast sensitivity after orthokeratology. The most likely explanation for this discrepancy is the difference in the contact lenses used in each study. Every lens has a peculiar design, material, and fitting philosophy. Given that increased coma aberration reflects contact lens decentration,[19,20] it may be that the lens centration was better in their study than in ours. In addition, the amount of myopic refractive error was different between these two studies: −2.38 ± 0.98 D (range, −1.00 to −4.00 D) for our study and −3.11 ± 0.96 D (−1.00 to −5.50 D) for their study. Theoretically, spherical aberration increases as larger myopic correction is attempted; this may be why the influence of spherical aberration became dominant in the Berntsen et al.[21] study. In addition, Berntsen et al.[21] reported that ocular higher-order aberrations significantly increased not only for 5-mm but also for 3-mm pupils and that undilated low-contrast visual acuity also decreased significantly after orthokeratology.[21] They did not, however, find a significant association between increased higher-order aberrations and reduced contrast sensitivity with undilated pupils, whereas we found a significant correlation between these two parameters. Because they did not discuss the reason for decreased low-contrast visual acuity with undilated pupils, we have no clear explanation for the different results in our study and theirs. Further investigation is needed to clarify these points.

Current orthokeratology procedures focus on the reduction of spherical defocus, the most visually significant optical aberration. On the other hand, optical quality of the eye and visual performance can be compromised in patients after orthokeratology, as in other refractive surgeries for the correction of myopia. For better quality of vision and of life, more attention should be paid to optical quality of the eye. In orthokeratology, the increase in spherical aberration is mainly attributed to the nonphysiological oblate cornea after treatment, and the increase in coma aberration reflects contact lens decentration.[19,20] Therefore, the larger the myopic correction, the greater the induction of spherical and coma aberrations. Large myopic correction should be avoided in orthokeratology so as not to induce large aberrations or contrast sensitivity loss, and fitting and centration of the treatment lens should be strictly performed. It may be that ocular higher-order aberrations are good predictors of visual performance in orthokeratology practice.

Our study had some limitations. First, we evaluated contrast sensitivity function at only one time point (3 months). Several reports indicate that contrast sensitivity function fluctuates over time after PRK[46] and LASIK.[43,44,46] Although we do not have data at present, it would be interesting to know how contrast sensitivity function changes after orthokeratology. Second, we did not investigate the influence of pupil size on contrast sensitivity function. It is known that contrast sensitivity function is influenced by pupil size.[47–49] Further studies are needed to elucidate the relationship between pupil size and contrast sensitivity function after orthokeratology. Third, we evaluated contrast sensitivity function only under photopic conditions. It is possible that mesopic visual performance and glare visual function are more compromised in patients after orthokeratology, as they are after refractive surgery.[50–55] This will be the theme of future studies.

In conclusion, overnight orthokeratology for myopia significantly increases ocular higher-order aberrations, which deteriorate contrast sensitivity function, even after clinically successful orthokeratology. These changes depend on the magnitude of myopic correction. Reduced contrast sensitivity function significantly correlated with increased coma-like and spherical aberrations.

References

1. Jessen G. Orthofocus techniques. *Contacto*. 1962;6:200–204.
2. Coon LJ. Orthokeratology, II: evaluating the Tabb method. *J Am Optom Assoc*. 1984;55:409–418.
3. Swarbrick HA, Wong G, O'Leary DJ. Corneal response to orthokeratology. *Optom Vis Sci*. 1998;75:791–799.
4. Nichols JJ, Marsich MM, Nguyen M, Barr JT, Bullimore MA. Overnight orthokeratology. *Optom Vis Sci*. 2000;77:252–259.
5. Alharbi A, Swarbrick HA. The effects of overnight orthokeratology lens wear on corneal thickness. *Invest Ophthalmol Vis Sci*. 2003;44:2518–2523.
6. Lui WO, Edwards MH. Orthokeratology in low myopia, 1: efficacy and predictability. *Contact Lens Anterior Eye*. 2000;23:77–89.
7. Mountford J. An analysis of the changes in corneal shape and refractive error induced by accelerated orthokeratology. *ICLC*. 1997;24:128–143.
8. Rah MJ, Jackson JM, Jones LA, Marsden HJ, Bailey MD, Barr JT. Overnight orthokeratology: preliminary results of the Lenses and Overnight Orthokeratology (LOOK) study. *Optom Vis Sci*. 2002;79:598–605.
9. Cheung SW, Cho P. Subjective and objective assessments of the effect of orthokeratology—a cross-sectional study. *Curr Eye Res*. 2004;28:121–127.
10. Mierdel P, Kaemmerer M, Krinke HE, Seiler T. Effects of photorefractive keratectomy and cataract surgery on ocular optical errors of higher order. *Graefes Arch Clin Exp Ophthalmol*. 1999;237:725–729.
11. Seiler T, Kaemmerer M, Mierdel P, Krinke HE. Ocular optical aberrations after photorefractive keratectomy for myopia and myopic astigmatism. *Arch Ophthalmol*. 2000;118:17–21.
12. Hong X, Thibos LN. Longitudinal evaluation of optical aberrations following laser in situ keratomileusis surgery. *J Refract Surg*. 2000;16:S647–S650.
13. Moreno-Barriuso E, Lloves JM, Marcos S, Navarro R, Llorente L, Barbero S. Ocular aberrations before and after myopic corneal refractive surgery: LASIK-induced changes measured with laser ray tracing. *Invest Ophthalmol Vis Sci*. 2001;42:1396–1403.

14. Marcos S, Barbero S, Llorente L, Merayo-Lloves J. Optical response to LASIK surgery for myopia from total and corneal aberration measurements. *Invest Ophthalmol Vis Sci*. 2001;42:3349–3356.
15. Marcos S. Aberrations and visual performance following standard laser vision correction. *J Refract Surg*. 2001;17:S596–S601.
16. Yamane N, Miyata K, Samejima T, et al. Ocular higher-order aberrations and contrast sensitivity after conventional laser in situ keratomileusis. *Invest Ophthalmol Vis Sci*. 2004;45:3986–3990.
17. Ninomiya S, Maeda N, Kuroda T, Fujikado T, Tano Y. Comparison of ocular higher-order aberrations and visual performance between photorefractive keratectomy and laser in situ keratomileusis for myopia. *Semin Ophthalmol*. 2003;18:29–34.
18. Tanabe T, Miyata K, Samejima T, Hirohara Y, Mihashi T, Oshika T. Influence of wavefront aberration and corneal subepithelial haze on low-contrast visual acuity after photorefractive keratectomy. *Am J Ophthalmol*. 2004;138:620–624.
19. Joslin CE, Wu SM, McMahon TT, Shahidi M. Higher-order wavefront aberrations in corneal refractive therapy. *Optom Vis Sci*. 2003;80:805–811.
20. Hiraoka T, Matsumoto Y, Okamoto F, et al. Corneal higher-order aberrations induced by overnight orthokeratology. *Am J Ophthalmol*. 2005;139:429–436.
21. Berntsen DA, Barr JT, Mitchell GL. The effect of overnight contact lens corneal reshaping on higher-order aberrations and best-corrected visual acuity. *Optom Vis Sci*. 2005;82:490–497.
22. Pomerance GN, Evans DW. Test-retest reliability of the CSV-1000 contrast test and its relationship to glaucoma therapy. *Invest Ophthalmol Vis Sci*. 1994;35:3357–3361.
23. Applegate RA, Howland HC, Sharp RP, Cottingham AJ, Yee RW. Corneal aberrations and visual performance after radial keratotomy. *J Refract Surg*. 1998;14:397–407.
24. Maeda N, Sato S, Watanabe H, et al. Prediction of letter contrast sensitivity using videokeratographic indices. *Am J Ophthalmol*. 2000;129:759–763.
25. Kuroda T, Fujikado T, Maeda N, Oshika T, Hirohara Y, Mihashi T. Wavefront analysis of higher-order aberrations in patients with cataract. *J Cataract Refract Surg*. 2002;28:438–444.
26. Perez-Santonja JJ, Sakla HF, Alio JL. Contrast sensitivity after laser in situ keratomileusis. *J Cataract Refract Surg*. 1998;24:183–189.
27. Verdon W, Bullimore M, Maloney RK. Visual performance after photorefractive keratectomy: a prospective study. *Arch Ophthalmol*. 1996;114:1465–1472.
28. Ghaith AA, Daniel J, Stulting RD, Thompson KP, Lynn M. Contrast sensitivity and glare disability after radial keratotomy and photorefractive keratectomy. *Arch Ophthalmol*. 1998;116:12–18.
29. Krasnov MM, Avetisov SE, Makashova NV, Mamikonian VR. The effect of radial keratotomy on contrast sensitivity. *Am J Ophthalmol*. 1988;105:651–654.
30. Hawkins AS, Szlyk JP, Ardickas Z, Alexander KR, Wilensky JT. Comparison of contrast sensitivity, visual acuity, and Humphrey visual field testing in patients with glaucoma. *J Glaucoma*. 2003;12:134–138.
31. Rubin GS, West SK, Munoz B, et al. A comprehensive assessment of visual impairment in a population of older Americans: the SEE Study: Salisbury Eye Evaluation Project. *Invest Ophthalmol Vis Sci*. 1997;38:557–568.
32. Whittaker SG, Lovie-Kitchin J. Visual requirements for reading. *Optom Vis Sci*. 1993;70:54–65.
33. Crossland MD, Culham LE, Rubin GS. Predicting reading fluency in patients with macular disease. *Optom Vis Sci*. 2005;82:11–17.
34. Marron JA, Bailey IL. Visual factors and orientation-mobility performance. *Am J Optom Physiol Opt*. 1982;59:413–426.
35. Owsley C, Ball K, McGwin G Jr, et al. Visual processing impairment and risk of motor vehicle crash among older adults. *JAMA*. 1998;279:1083–1088.
36. Scott IU, Feuer WJ, Jacko JA. Impact of visual function on computer task accuracy and reaction time in a cohort of patients with age-related macular degeneration. *Am J Ophthalmol*. 2002;133:350–357.
37. Elliott DB, Hurst MA. Simple clinical techniques to evaluate visual function in patients with early cataract. *Optom Vis Sci*. 1990;67:822–825.
38. Ansari EA, Morgan JE, Snowden RJ. Psychophysical characterisation of early functional loss in glaucoma and ocular hypertension. *Br J Ophthalmol*. 2002;86:1131–1135.
39. Midena E, Degli AC, Blarzino MC, Valenti M, Segato T. Macular function impairment in eyes with early age-related macular degeneration. *Invest Ophthalmol Vis Sci*. 1997;38:469–477.
40. Bellmann C, Unnebrink K, Rubin GS, Miller D, Holz FG. Visual acuity and contrast sensitivity in patients with neovascular age-related macular degeneration: results from the Radiation Therapy for Age-Related Macular Degeneration (RAD) Study. *Graefes Arch Clin Exp Ophthalmol*. 2003;241:968–974.
41. Stavrou EP, Wood JM. Letter contrast sensitivity changes in early diabetic retinopathy. *Clin Exp Optom*. 2003;86:152–156.
42. Trobe JD, Beck RW, Moke PS, Cleary PA. Contrast sensitivity and other vision tests in the optic neuritis treatment trial. *Am J Ophthalmol*. 1996;121:547–553.
43. Mutyala S, McDonald MB, Scheinblum KA, Ostrick MD, Brint SF, Thompson H. Contrast sensitivity evaluation after laser in situ keratomileusis. *Ophthalmology*. 2000;107:1864–1867.
44. Chan JW, Edwards MH, Woo GC, Woo VC. Contrast sensitivity after laser in situ keratomileusis, one-year follow-up. *J Cataract Refract Surg*. 2002;28:1774–1779.
45. Holladay JT, Dudeja DR, Chang J. Functional vision and corneal changes after laser in situ keratomileusis determined by contrast sensitivity, glare testing, and corneal topography. *J Cataract Refract Surg*. 1999;25:663–669.
46. Montes-Mico R, Charman WN. Choice of spatial frequency for contrast sensitivity evaluation after corneal refractive surgery. *J Refract Surg*. 2001;17:646–651.
47. Hernandez C, Domenech B, Segui MM, Illueca C. The effect of pupil and observation distance on the contrast sensitivity function. *Ophthalmic Physiol Opt*. 1996;16:336–341.
48. Strang NC, Atchison DA, Woods RL. Effects of defocus and pupil size on human contrast sensitivity. *Ophthalmic Physiol Opt*. 1999;19:415–426.
49. Oshika T, Tokunaga T, Samejima T, Miyata K, Kawana K, Kaji Y. Influence of pupil diameter on the relation between ocular higher-order aberration and contrast sensitivity after laser in situ keratomileusis. *Invest Ophthalmol Vis Sci*. 2006;47:1334–1338.
50. Schlote T, Derse M, Wannke B, Bende T, Jean B. Impairment of mesopic vision following photorefractive keratectomy of myopia. *Klin Monatsbl Augenheilkd*. 1999;214:136–141.
51. Montes-Mico R, Charman WN. Mesopic contrast sensitivity function after excimer laser photorefractive keratectomy. *J Refract Surg*. 2002;18:9–13.
52. Nagy ZZ, Munkacsy G, Krueger RR. Changes in mesopic vision after photorefractive keratectomy for myopia. *J Refract Surg*. 2002;18:249–252.
53. Fan-Paul NI, Li J, Miller JS, Florakis GJ. Night vision disturbances after corneal refractive surgery. *Surv Ophthalmol*. 2002;47:533–546.
54. Montes-Mico R, Espana E, Menezo JL. Mesopic contrast sensitivity function after laser in situ keratomileusis. *J Refract Surg*. 2003;19:353–356.
55. Perez-Carrasco MJ, Puell MC, Sanchez-Ramos C, Lopez-Castro A, Langa A. Effect of a yellow filter on contrast sensitivity and disability glare after laser in situ keratomileusis under mesopic and photopic conditions. *J Refract Surg*. 2005;21:158–165.