Influence of Pupil Diameter on the Relation between Ocular Higher-Order Aberration and Contrast Sensitivity after Laser In Situ Keratomileusis

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Purpose. To investigate the influence of pupil diameter on the relation between induced changes in ocular higher-order wavefront aberrations and changes in contrast sensitivity by conventional laser in situ keratomileusis (LASIK) for myopia.

Methods. In 215 eyes of 117 patients (age, 33.2 ± 8.3 years) undergoing LASIK for myopia of −1.25 to −13.5 D (−5.28 ± 2.55 D), ocular wavefront aberrations and contrast sensitivity function were determined before and 1 month after surgery. Preoperative photopic pupil diameter was measured with a digital camera. Ocular higher-order aberrations were measured for a 4-mm pupil with a Hartmann-Shack wavefront analyzer. The root-mean-square (RMS) of the third- and fourth-order Zernike coefficients was used to represent coma- and spherical-like aberration, respectively. From the contrast-sensitivity data, the area under the log contrast sensitivity function (AULCSF) was calculated.

Results. One hundred five eyes had a photopic pupil diameter of 4 mm or larger, and the remaining 110 had a photopic pupil diameter smaller than 4 mm. There were no statistically significant differences in the background clinical data between these two groups. In the eyes with a photopic pupil diameter of 4 mm or larger, the changes in third-order comalike aberrations did not correlate with the changes in AULCSF (Pearson correlation coefficient, r = 0.037, P = 0.723) and 10% low-contrast visual acuity (r = 0.125, P = 0.224), but fourth-order spherical-like aberrations correlated significantly with the changes in AULCSF (r = 0.229, P = 0.024) and 10% low-contrast visual acuity (r = 0.221, P = 0.038). In the eyes with photopic pupil size smaller than 4 mm, there were significant correlations between the changes in comalike aberrations and the changes in AULCSF (r = 0.487, P < 0.001) and 10% low-contrast visual acuity (r = 0.310, P = 0.003), but spherical-like aberrations showed no correlation with the changes in AULCSF (r = 0.078, P = 0.485) and 10% low-contrast visual acuity (r = 0.208, P = 0.158).

Conclusions. In eyes with larger photopic pupil diameter, increases in spherical-like aberration dominantly affect contrast sensitivity, whereas in eyes with smaller pupil size, changes in comalike aberration exert greater influence on visual performance. (Invest Ophthalmol Vis Sci. 2006;47:1334–1338) DOI:10.1167/iovs.05-1154

Previous studies have demonstrated that laser in situ keratomileusis (LASIK) significantly increases higher-order wavefront aberrations of the eye1–9 and reduces contrast sensitivity.9–19 There is a report that the induced increases in ocular higher-order aberration significantly correlated with the changes in contrast sensitivity function by LASIK.9 It has been known that the amount and character of higher-order aberrations of the eye is greatly affected by the diameter of the entrance pupil.1,20–25 It has been shown that contrast sensitivity function is also related to pupil diameter.24,25 There have been no reports, however, about the influence of pupil diameter on the relation between higher-order aberration and contrast sensitivity function after LASIK. The assessment of pupil size is one of the most important and essential preoperative examinations when selecting patients for refractive surgery, increasing the safety of refractive surgery procedures, planning the surgical strategy, and identifying patients at risk of development of symptoms or declines in visual performance after excimer laser keratorefractive surgery.26–29 We conducted the present study to investigate the influence of photopic pupil diameter on ocular aberration and visual performance after LASIK.

Methods

Two hundred and fifteen eyes of 117 consecutive patients (male 73, female 44) undergoing LASIK for myopia were studied. Their ages ranged from 17 to 54 years (mean, 33.2 ± 8.3 [SD]), and preoperative refraction was −1.25 to −13.5 D (mean, −5.28 ± 2.55 D). The research protocol had institutional review board approval, and written informed consent was obtained from each patient. The study adhered to the tenets of the Declaration of Helsinki.

All surgeries were performed by one surgeon (KM; using the VISIX STAR S2 excimer laser system; VISX Inc., Santa Clara, CA). Laser parameters included the following: wavelength, 193 nm; radiant exposure (fluence), 160 mJ/cm²; pulse repetition rate, 10 Hz; average ablation depth per pulse, 0.23 μm on the cornea; ablation zone diameter, 6.0 mm; and transition zone, 0.55 mm. Airflow was used for debris removal. The automated microkeratome (MK-2000; Nidek Ltd., Gamagori, Japan) was used to create a hinged corneal flap of 160-μm thickness (nominal value).

Logarithm of minimum angle of resolution (logMAR) uncorrected visual acuity (UCVA), logMAR best spectacle-corrected visual acuity (BSCVA), ocular wavefront aberration, and contrast sensitivity function were evaluated before and 1 month after surgery. Pupil diameter in a photopic condition (270 lux) was measured before surgery by using digital camera (model E-300; Olympus, Tokyo, Japan). Accommodation was controlled by instructing the subjects to fixate on a 4-mm target. Photographs were transferred to a computer, and pupil diameter was measured with a specialized analysis software (not commer-
Pupil Diameter and Aberration and Contrast Sensitivity after LASIK

RESULTS

Data were analyzed according to the preoperative photopic pupil diameter. One hundred five eyes had a pupil diameter of 4 mm or larger, and the remaining 110 eyes had a pupil diameter smaller than 4 mm. Their background data are summarized in Table 1. There were no statistically significant differences in the clinical data between these two groups.

In the eyes with photopic pupil diameter of 4 mm or larger, the changes in third-order comalike aberrations did not correlate with the changes in AULCSF (Pearson correlation coefficient, $r = -0.037$, $P = 0.723$, Fig. 1) and 10% low-contrast visual acuity ($r = 0.125$, $P = 0.224$, Fig. 2), but fourth-order spherical-like aberrations correlated significantly with the changes in AULCSF ($r = -0.029$, $P = 0.204$, Fig. 3) and 10% low-contrast visual acuity ($r = 0.221$, $P = 0.038$, Fig. 4).

In the eyes with a photopic pupil size smaller than 4 mm, there were significant correlations between the changes in comalike aberrations and the changes in AULCSF ($r = -0.487$, $P < 0.001$, Fig. 5) and 10% low-contrast visual acuity ($r = 0.310$, $P = 0.003$, Fig. 6), but spherical-like aberrations showed no correlation with the changes in AULCSF ($r = -0.078$, $P = 0.485$, Fig. 7) and 10% low-contrast visual acuity ($r = 0.208$, $P = 0.158$, Fig. 8).

DISCUSSION

We investigated the influence of ocular higher-order wavefront aberration on contrast sensitivity function in relation to photopic pupil size. The results indicated that in the eyes with large pupils, contrast sensitivity was influenced by spherical-like aberration more than by comalike aberration. In contrast, in the eyes with small pupils, comalike aberration exerted greater influence than did spherical-like aberration on contrast sensitivity. In eyes after photorefractive keratectomy (PRK), it has been reported that pupillary dilatation causes greater increases in corneal spherical-like aberration than in corneal comalike aberration.20 Another study has demonstrated that for a large pupillary aperture, comalike aberration was dominant before PRK and LASIK, but spherical-like aberration be-

Data are expressed as the mean ± SD.

Table 1. Patients’ Clinical Data according to Preoperative Photopic Pupil Diameter

<table>
<thead>
<tr>
<th>Preoperative</th>
<th>≥4 mm</th>
<th>&lt;4 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>32.0 ± 8.7</td>
<td>33.6 ± 8.2</td>
</tr>
<tr>
<td>Spherical equivalent (D)</td>
<td>−5.50 ± 2.50</td>
<td>−5.16 ± 2.71</td>
</tr>
<tr>
<td>UCVA (logMAR)</td>
<td>1.359 ± 0.280</td>
<td>1.312 ± 0.286</td>
</tr>
<tr>
<td>BCSCVA (logMAR)</td>
<td>−0.170 ± 0.037</td>
<td>−0.171 ± 0.022</td>
</tr>
<tr>
<td>Total higher-order aberration (μm)</td>
<td>0.120 ± 0.019</td>
<td>0.115 ± 0.037</td>
</tr>
<tr>
<td>Comalike aberration (μm)</td>
<td>0.100 ± 0.048</td>
<td>0.092 ± 0.038</td>
</tr>
<tr>
<td>Spherical-like aberration (μm)</td>
<td>0.063 ± 0.021</td>
<td>0.063 ± 0.020</td>
</tr>
<tr>
<td>Amount of ablation (μm)</td>
<td>56.7 ± 23.5</td>
<td>52.8 ± 25.4</td>
</tr>
<tr>
<td>Amount of correction (diopter)</td>
<td>5.45 ± 2.70</td>
<td>5.10 ± 2.77</td>
</tr>
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Postoperative

| Spherical equivalent (D) | −0.06 ± 0.42 | −0.06 ± 0.47 |
| UCVA (logMAR) | −0.135 ± 0.143 | −0.145 ± 0.172 |
| BCSCVA (logMAR) | −0.205 ± 0.082 | −0.217 ± 0.082 |
| Total higher-order aberration (μm) | 0.200 ± 0.080 | 0.182 ± 0.082 |
| Comalike aberration (μm) | 0.172 ± 0.084 | 0.152 ± 0.085 |
| Spherical-like aberration (μm) | 0.094 ± 0.031 | 0.091 ± 0.032 |

Additional data and analyses were conducted by one experienced examiner.

Ocular higher-order aberrations for a 4-mm pupil were measured with a Hartmann-Shack wavefront aberrometer (model KR-9000PW; Topcon, Tokyo, Japan). The root-mean-square (RMS) of the third-order Zernike coefficients was used to represent comalike aberration, and the RMS of the fourth-order coefficients was used to denote spherical-like aberration.

We tested two indices of contrast sensitivity function: contrast sensitivity (with the CSV-1000E charts; Vector Vision Co., Greenville, OH) and low-contrast visual acuity (with the CSV-1000LanC10% charts; Vector Vision Co.). These tests were performed with best spectacle correction at 2.5 mm, both before and after surgery. The area under the log contrast sensitivity function (AULCSF) was calculated from the data obtained with the CSV-1000E sine wave gratings chart. AULCSF was determined according to the method of Applegate et al.31 The log of contrast sensitivity was plotted as a function of log spatial frequency, and third-order polynomials were fitted to the data. The fitted function represents a change of 0.1 logMAR units (logarithm of the minimum angle of resolution). Low contrast visual acuity was scored by giving a credit of 0.02 logMAR units for each letter correctly identified.

Figure 1. Relation between changes in ocular comalike aberrations and changes in AULCSF (Pearson correlation coefficient, $r = -0.037$, $P = 0.723$) in eyes with a photopic pupil diameter of 4 mm or larger.
came dominant after surgery. In myopic eyes, Wang et al. reported that the change in spherical aberration was greater than that in comalike aberration when the pupil was enlarged. The results obtained herein are compatible with findings in these previous studies, indicating that the influence of ocular higher-order aberration on visual performance after LASIK varies depending on pupil diameter. In eyes with a larger pupil, spherical aberration caused more pronounced influence, while the impact of comalike aberration was greater in eyes with a smaller pupil.

In the present study, we evaluated the relation between changes in wavefront aberration and changes in contrast sensitivity, instead of the relation between the postoperative wavefront aberration and postoperative contrast sensitivity. It has been reported that the ocular higher-order aberration and contrast sensitivity significantly correlate with each other even in normal subjects (Takahira T, et al. IOVS 2005;46:ARVO E-Abstract 2007). Thus, to demonstrate that increases in wavefront aberrations deteriorate visual performance, the surgically induced change in wavefront aberrations and the surgically induced change in contrast sensitivity must be analyzed.

One of the weaknesses of our study is the timing of the pupil diameter measurements. We recorded pupil size before but not after surgery. There has been a report of relative mydriasis after PRK, whereas others have described that real pupil size is unchanged by PRK for mild to moderate refractive errors. Clinically, we observed the entrance pupil, which is a virtual image of the anatomic pupil. The entrance pupil is magnified and displaced anteriorly by the corneal refractive power. The relation between the real pupil (RP) and entrance pupil (EP) is described by the equation RP = EP (1 - AK/1.3375), where A is anterior chamber depth expressed in meters, K is the central corneal refractive power, and 1.3375 is the corneal standard refractive index. According to this equation, a reduction in K by myopia treatment leads to a decrease in clinically measured pupil diameter. When this equation is

![Figure 2](http://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/933597/)

**FIGURE 2.** Relation between changes in ocular comalike aberrations and changes in low-contrast visual acuity (Pearson correlation coefficient, \( r = 0.125, P = 0.224 \)) in eyes with photopic pupil diameter of 4 mm or larger.

![Figure 3](http://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/933597/)

**FIGURE 3.** Significant correlation between changes in ocular spherical-like aberrations and changes in AULCSF (Pearson correlation coefficient, \( r = -0.229, P = 0.024 \)) in eyes with photopic pupil diameter of 4 mm or larger.

![Figure 4](http://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/933597/)

**FIGURE 4.** Significant correlation between changes in ocular comalike aberrations and changes in low-contrast visual acuity (Pearson correlation coefficient, \( r = 0.221, P = 0.038 \)) in eyes with photopic pupil diameter of 4 mm or larger.

![Figure 5](http://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/933597/)

**FIGURE 5.** Significant correlation between changes in ocular comalike aberrations and changes in AULCSF (Pearson correlation coefficient, \( r = -0.487, P < 0.001 \)) in eyes with photopic pupil diameter smaller than 4 mm.
applied to a hypothetical patient, however, with RP of 4.0 mm, A of 4.0 mm, and central K of 44 D decreasing to 39 D by PRK for myopia, the EP is reduced by 0.08 mm or 1.7%—a small change that seems negligible.

The current findings appear to possess clinical relevance in the practice of excimer laser keratorefractive surgery. The recent excimer laser platforms incorporate both the eye-tracking function and the wavefront-guided treatment system. In view of the aforementioned results, patients with a larger photopic pupil will best benefit from the wavefront-guided excimer laser surgery strategy, which attempts to reduce or suppress the induction of higher-order wavefront aberrations, especially spherical aberration. In contrast, patients with a smaller pupil diameter draw a greater advantage from the eye-tracking system, so that decentration of laser ablation is minimized, leading to less induction of coma aberrations. The verification or negation of these speculations awaits future studies.

References


