Ocular Higher-Order Aberrations and Contrast Sensitivity after Conventional Laser In Situ Keratomileusis

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PURPOSE. To investigate prospectively the relation between induced changes in higher-order aberrations of the eye and changes in contrast sensitivity by conventional laser in situ keratomileusis (LASIK) for myopia.

METHODS. In 200 eyes of 110 consecutive patients (mean age, 32.7 ± 8.4 years) undergoing LASIK, ocular aberrations and contrast sensitivity function were determined before and 1 month after surgery. The amount of myopic correction was 5.2 ± 2.8 D (range, 1.0–13.0). Ocular higher-order aberrations were measured for a 4-mm pupil using the Hartmann-Shack wavefront analyzer (KR-9000PW; Topcon, Tokyo, Japan). The root mean square (RMS) of the third- and fourth-order Zernike coefficients was used to represent coma- and spherical-like aberrations, respectively. Total higher-order aberrations were calculated as the RMS of the third- and fourth-order coefficients. Contrast sensitivity and low-contrast visual acuity were measured from the contrast sensitivity data, the area under the log contrast sensitivity function (AULCSF) was calculated. From the contrast sensitivity data, the area under the log contrast sensitivity function decreases as the wavefront variances increase after LASIK.2 The changes in AULCSF by LASIK showed significant correlations with changes in total higher-order (Pearson r = −0.221, P = 0.0053), coma-like (r = −0.205, P = 0.006), and spherical-like (r = −0.171, P = 0.022) aberrations. The changes in logMAR low-contrast visual acuity by surgery significantly correlated with changes in total higher-order (r = 0.222, P = 0.005), coma-like (r = 0.201, P = 0.007), and spherical-like (r = 0.207, P = 0.005) aberrations.

RESULTS. LASIK significantly improved logMAR best corrected visual acuity (Wilcoxon signed-rank test, P < 0.001), but significantly reduced AULCSF (P < 0.001) and low-contrast visual acuity (P = 0.007). Total higher-order (P < 0.001), coma-like (P < 0.001), and spherical-like (P < 0.001) aberrations were significantly increased after LASIK. The greater the amount of achieved myopia correction was, the more the changes in contrast sensitivity function and ocular higher-order aberrations were. The induced changes in AULCSF by LASIK showed significant correlations with changes in total higher-order (Pearson r = −0.221, P = 0.0053), coma-like (r = −0.205, P = 0.006), and spherical-like (r = −0.171, P = 0.022) aberrations. The changes in logMAR low-contrast visual acuity by surgery significantly correlated with changes in total higher-order (r = 0.222, P = 0.005), coma-like (r = 0.201, P = 0.007), and spherical-like (r = 0.207, P = 0.005) aberrations.

CONCLUSIONS. Conventional LASIK significantly increases ocular higher-order aberrations, which compromise the postoperative contrast sensitivity function. (Invest Ophthalmol Vis Sci. 2004; 45:3986–3990) DOI:10.1167/iows.04-0629

As refractive surgery evolves, laser in situ keratomileusis (LASIK) has gained widespread popularity as the procedure of choice to correct refractive errors. LASIK can reduce refractive error and improve uncorrected visual acuity, but several problems still must be resolved regarding postoperative visual function. Previous studies have demonstrated that LASIK compromises contrast sensitivity after surgery,1,4–8 as does radial keratotomy (RK)9,10 and photorefractive keratectomy (PRK).10–12 Others have reported that higher-order aberrations increase after LASIK.13–18 RK,9,19,20 and PRK.13,21,22 Applegate et al.20 reported that the area under the contrast sensitivity function decreases as the wavefront variances increase after RK.9 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 PRK.21 There has been no report, however, on the relation between changes in contrast sensitivity and changes in ocular aberrations after LASIK. In this prospective study, we investigated the relation between changes in higher-order aberrations of the eye and changes in contrast sensitivity caused by conventional LASIK.

PATIENTS AND METHODS

We studied 200 eyes of 110 consecutive patients (69 males, 41 females) undergoing LASIK for myopia. Their ages ranged from 17 to 52 years (mean, 32.7 ± 8.4 [SD]), and preoperative refraction was −1.25 to −13.25 D (−5.34 ± 2.64 D). These were consecutive patients who were operated on between February 2001 and October 2002. The research adhered to the tenets of the Declaration of Helsinki, and informed consent was obtained from all subjects after explanation of the nature and possible consequences of the study.

All surgery was performed by one surgeon (KM) with an excimer laser system (Star S2; 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, 0.35 mm. Aspiration air flow was used for debris removal. An automated microkeratore (MK-2000; Nidek Ltd., Gama-gori, Japan) was used to create a hinged corneal flap of 160-μm thickness (nominal value).

LogMAR (logarithm of the minimum angle of resolution) uncorrected visual acuity (UCVA), logMAR best spectacle-corrected visual acuity (BCVA), contrast sensitivity function, and wavefront aberrations were evaluated before and 1 month after surgery. We tested two indices of contrast sensitivity function: contrast sensitivity on one system (CSV-1000E) and low-contrast visual acuity on a second system (CSV-1000/LanC10; both from Vector Vision Co., Greeneville, OH).

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TABLE 1. Patients’ Clinical Data before and after LASIK

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>After</th>
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<tbody>
<tr>
<td>Spherical equivalent (D)</td>
<td>−5.34 ± 2.64</td>
<td>−0.06 ± 0.45*</td>
</tr>
<tr>
<td>logMAR UCVA</td>
<td>1.34 ± 0.28</td>
<td>−0.14 ± 0.16*</td>
</tr>
<tr>
<td>logMAR BSCVA</td>
<td>−0.17 ± 0.03</td>
<td>−0.21 ± 0.08*</td>
</tr>
<tr>
<td>AULCSF</td>
<td>1.36 ± 0.937</td>
<td>1.28 ± 0.121*</td>
</tr>
<tr>
<td>Low-contrast visual acuity</td>
<td>0.11 ± 0.147</td>
<td>0.15 ± 0.138*</td>
</tr>
<tr>
<td>Total higher-order aberrations (µm)</td>
<td>0.118 ± 0.044</td>
<td>0.192 ± 0.081*</td>
</tr>
<tr>
<td>Coma-like aberrations (µm)</td>
<td>0.096 ± 0.044</td>
<td>0.163 ± 0.090*</td>
</tr>
<tr>
<td>Spherical-like aberrations (µm)</td>
<td>0.063 ± 0.020</td>
<td>0.092 ± 0.052*</td>
</tr>
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Data are expressed as the mean ± SD. *P < 0.001, †P < 0.01: significant differences between pre- and postoperative values (Wilcoxon signed-rank test).

These tests were performed with best spectacle correction both before and after surgery. Ocular higher-order aberrations for a 4-mm pupil were measured with the Hartmann-Shack wavefront analyzer (KR-9000PW; Topcon, Tokyo, Japan).

The CSV-1000E provides a fluorescent luminance source that retroilluminates a translucent chart and automatically calibrates to 85 cd/m². Four spatial frequencies—3, 6, 12, and 18 cyc/deg—are present, and each spatial frequency has eight different levels of contrast. The test was performed monocularly with the eye in the undilated state at 2.5 m. With the patient’s manifest refraction in place, the contrast sensitivity was calculated according to the method of Applegate et al.9 The log of contrast sensitivity was plotted as a function of log spatial frequency, and the RMS of the fourth-order coefficients was used to denote the amount of achieved myopia correction. The amount of ocular aberrations were evaluated in relation to the magnitude of deterioration in AULCSF.

RESULTS

Measurement results are summarized in Table 1. LASIK significantly improved UCVA (Wilcoxon signed-rank test, P < 0.001) and BSCVA (P < 0.001). After surgery, contrast sensitivity significantly decreased at all spatial frequencies from 3 to 18 cyc/deg (Fig. 1). There were significant reductions in AULCSF calculated from the measurements (P < 0.001) and low-contrast visual acuity (P = 0.007). As for ocular aberrations, total higher-order (P < 0.001), coma-like (P < 0.001), and spherical-like (P < 0.001) aberrations were significantly increased after LASIK.

The magnitude of induced changes in contrast sensitivity and ocular aberrations were evaluated in relation to the amount of achieved myopia correction. The amount of changes in total higher-order (Pearson correlation coefficient r = 0.463, P < 0.001), coma-like (r = 0.455, P < 0.001), and spherical-like (r = 0.475, P < 0.001) aberrations had a significant positive correlation with the amount of myopia correction. The magnitude of deterioration in AULCSF (r = 0.322, P < 0.001) and low-contrast visual acuity (r = −0.165, P < 0.001) was significantly correlated with the amount of achieved myopia correction.

These findings suggest that LASIK surgery significantly reduced contrast sensitivity at all these frequencies (*P < 0.001, Wilcoxon signed-rank test).

The magnitudes of the coefficients of the Zernike polynomials are represented as the root mean square (RMS; in micrometers) and are used to show the wavefront aberrations. The 0-order component in the Zernike polynomials has one term that represents a piston. The first order represents tilt with two terms. The second order includes three terms that represent defocus and astigmatism. The third order has four terms that represent coma and trefoil astigmatism. The fourth order has five terms that include the spherical aberrations. Spectacles can correct only the second-order aberrations. The RMS of the third-order Zernike coefficients was used to represent the coma-like aberration, and the RMS of the fourth-order coefficients was used to denote the spherical-like aberration. Total higher-order aberrations were calculated as the RMS of the third- and fourth-order coefficients.
0.05) had significant correlations with the amount of achieved correction.

The changes in AULCSF by LASIK showed significant correlations with changes in total higher-order \( (r = -0.221, P = 0.003) \), coma-like \( (r = -0.205, P = 0.006) \), and spherical-like \( (r = -0.171, P = 0.022) \) aberrations. The changes in logMAR low-contrast visual acuity by surgery significantly correlated with changes in total higher-order \( (r = 0.222, P = 0.003) \), coma-like \( (r = 0.201, P = 0.007) \), and spherical-like \( (r = 0.207, P = 0.005) \) aberrations.

**DISCUSSION**

As shown in the results, LASIK significantly improved BSCVA, probably because retinal image became enlarged after surgery due to the disuse of spectacle lenses for myopia correction. Conflicting reports exist regarding the changes in BSCVA after LASIK. Several studies have reported improvement of BSCVA after LASIK,\(^5,25\) whereas others have reported reduction\(^26\) or no change of BSCVA by surgery.\(^27\) At present, we do not have a clear explanation for these discrepancies, but we suppose that the deference in surgical techniques, surgeon’s skill, instrumentation, or sampling size may have played some roles.

In the present study, we assessed two indices of contrast sensitivity function; contrast sensitivity (sine wave gratings, CSV-1000E; Vector Vision Co.) and low-contrast visual acuity (CSV-1000LanC10%, Vector Vision Co). It was found that LASIK for myopia significantly deteriorated both contrast sensitivity parameters, in good agreement with previous studies.\(^1-8\) Pérez-Santonja et al.\(^4\) showed that decreased contrast sensitivity after LASIK recovered in 3 months after surgery. Chan et al.\(^2\) found that recovery of contrast sensitivity after LASIK took at least 6 months. In the present study, postoperative data were taken only 1 month after surgery, and longitudinal assessment was not conducted. The longer-term relation between changes in contrast sensitivity and ocular aberration is an important issue, which would be the subject of future studies.

Contrast sensitivity is usually measured at several different spatial frequencies. We tested four spatial frequencies: 3, 6, 12, and 18 cyc/deg (Fig. 1). We used AULCSF as a representative for the contrast sensitivity data, which was defined as the area...
under the third-order polynomial curve fitted to the plotted logarithmic contrast sensitivity results. Because contrast sensitivity is generally reduced across a wide range of spatial frequencies after LASIK, it seems that AULCSF can represent the contrast sensitivity data as one number, making the statistical analysis easier. If all the contrast sensitivity data were analyzed individually, multiple comparisons would be required, which may increase the risk of statistical error.

As has been reported previously, higher-order aberrations significantly increased after LASIK. Increases in higher-order aberrations showed significant positive correlations with the amount of myopia correction. These results indicate that the larger the attempted corrections are, the greater the amount of central corneal tissue that is removed by laser ablation, making the cornea more oblate and unphysiological in shape.

Kuroda et al. found that increases in higher-order aberration of the eye contributed to the loss of contrast sensitivity in eyes with cataract. Applegate et al. demonstrated that increases in the optical aberrations of the cornea after radial keratotomy correlated with decreases in AULCSF. Tomidokoro et al. showed that increases in corneal irregular astigmatism after photorefractive keratectomy significantly correlates with a loss of contrast sensitivity. In eyes after LASIK, however, no reports have been available on the relation between changes in optical aberration and changes in the contrast sensitivity function. In the present study, the contrast sensitivity function deteriorated after LASIK, depending on the amount of changes in higher-order aberration of the eye. In the current series of patients, there was no case with obvious corneal haze, elevated intraocular pressure, retinal problems, or other complications that may affect postoperative visual function. Thus, we conclude that increases in the postoperative higher-order aberration of the eye were responsible for the decline of contrast sensitivity function after LASIK.

Among the previous reports of wavefront aberrations after refractive surgery, only a few research groups have assessed total optical aberrations of the eye as in the current study, and others have measured the aberrations that arise from the anterior corneal surface. Total ocular aberrations are not necessarily equal to aberrations of the anterior corneal surface because of the presence of other refractive components within the eye. Marcos et al. reported that LASIK increased both corneal and total aberrations, but the spherical aberration of the anterior corneal surface significantly exceeded that of the whole eye, suggesting a change in the spherical aberration of the posterior corneal surface. Several groups have reported changes in the posterior corneal curvature after excimer laser keratorefractive surgery. Thus, to discuss the influence of refractive surgery on visual quality, total ocular aberrations, as used in the present study, should be a better index than anterior corneal aberrations.

Recently, application of adaptive optics and implementation of evolving technology and technique have made possible wavefront-guided LASIK, or customized ablation, to correct refractive errors. Wavefront-guided LASIK attempts to detect and correct higher-order aberrations that exist in normal individuals, as well as in patients after ocular surgery, whereas conventional LASIK corrects only second-order aberrations such as myopia, hyperopia, and astigmatism. Although several investigators have reported the clinical results of wavefront-guided LASIK, there has been no unanimous opinion about its definite clinical usefulness and advantages over conventional LASIK. Whereas some studies have demonstrated that postoperative higher-order aberration did not differ between wavefront customized ablation and standard ablation, others have reported that wavefront- and topography-guided LASIK lead to improved visual performance by decreasing higher-order aberrations. Judging from the results of the present study, if wavefront-guided LASIK induces a lesser amount of aberration than the conventional treatment, the least amount of changes in contrast sensitivity function would be anticipated. Future studies should be conducted to investigate this question.

Our result indicated that conventional LASIK for myopia significantly deteriorated contrast sensitivity function, despite good UCVA and BSCVA after surgery. Nelson et al. reported that subjective visual disability in patients with glaucoma had a strong relationship with contrast sensitivity and glare disability, but not with 100% contrast visual acuity. The visual disability questionnaire used in their study focused on the difficulties encountered in daily life, such as seeing a bus number and walking in the dark. Thus, it seems that, on the assumption that BSCVA is above a certain level, visual disability in daily life is better reflected by the contrast sensitivity test than by the 100% contrast visual acuity test. So far, refractive surgery has concentrated on the reduction of spherical and cylindrical defocus, and much less attention has been directed toward the higher-order aberrations. As shown in the present study, increases in higher-order ocular aberration can contribute to the loss of contrast sensitivity after LASIK. In consideration of quality of life and vision in patients after LASIK, further atten-
tion should be paid to the influence of surgery on higher-order aberration and visual function in detail, rather than on Snellen visual acuity alone.

References


