Comparison of Corneal Wavefront Aberrations After Photorefractive Keratectomy and Laser In Situ Keratomileusis

TETSURO OSHIKA, MD, STEPHEN D. KLYCE, PhD, RAYMOND A. APPLEGATE, OD, PhD,
HOWARD C. HOWLAND, PhD, AND M. ALAA EL DANASOURY, MD, FRCSEd

• PURPOSE: To compare changes in the corneal wavefront aberrations after photorefractive keratectomy and laser in situ keratomileusis.

• METHODS: In a prospective randomized study, 22 patients with bilateral myopia received photorefractive keratectomy on one eye and laser in situ keratomileusis on the other eye. The procedure assigned to each eye and the sequence of surgery for each patient were randomized. Corneal topography measurements were performed preoperatively, 2 and 6 weeks, 3, 6, and 12 months after surgery. The data were used to calculate the wavefront aberrations of the cornea for both small (3-mm) and large (7-mm) pupils.

• RESULTS: Both photorefractive keratectomy and laser in situ keratomileusis significantly increased the total wavefront aberrations for 3- and 7-mm pupils, and values did not return to the preoperative level throughout the 12-month follow-up period. For a 3-mm pupil, there was no statistically significant difference between photorefractive keratectomy and laser in situ keratomileusis at any postoperative point. For a 7-mm pupil, the post–laser in situ keratomileusis eyes exhibited significantly larger total aberrations than the post–photorefractive keratectomy eyes, where a significant intergroup difference was observed for spherical-like aberration, but not for coma-like aberration. This discrepancy seemed to be attributable to the smaller transition zone of the laser ablation in the laser in situ keratomileusis procedure. Before surgery, simulated pupillary dilation from 3 to 7 mm caused a five- to six-fold increase in the total aberrations. After surgery, the same dilation resulted in a 25- to 32-fold increase in the photorefractive keratectomy group and a 28- to 46-fold increase in the laser in situ keratomileusis group. For a 3-mm pupil, the proportion of coma-like aberration increased after both photorefractive keratectomy and laser in situ keratomileusis. For a 7-mm pupil, coma-like aberration was dominant before surgery, but spherical-like aberration became dominant postoperatively.

• CONCLUSIONS: Both photorefractive keratectomy and laser in situ keratomileusis increase the wavefront aberrations of the cornea and change the relative contribution of coma- and spherical-like aberrations. For a large pupil, laser in situ keratomileusis induces more spherical aberrations than photorefractive keratectomy. This finding could be attributable to the smaller transition zone of the laser ablation in the laser in situ keratomileusis procedure. (Am J Ophthalmol 1999;127:1–7. © 1999 by Elsevier Science Inc. All rights reserved.)

WITH ACCUMULATING EXPERIENCE AND CONtinuing sophistication of techniques, the safety and efficacy of refractive surgery have dramatically increased during recent years. In principle, refractive surgical procedures focus on the elimination or reduction of spherical and cylindrical defocus, the most important ocular optical aberration to correct. On the other hand, much less attention has been directed to the higher order aberrations of the cornea. The human eye has a substantial

Accepted for publication July 16, 1998.

From the Department of Ophthalmology, University of Tokyo School of Medicine, Tokyo, Japan (Dr Oshika); LSU Eye Center, New Orleans, Louisiana (Drs Oshika and Klyce); Department of Ophthalmology, School of Medicine, University of Texas Health Science Center at San Antonio, San Antonio, Texas (Dr Applegate); Neurobiology and Behavior Section, Cornell University, Ithaca, New York (Dr Howland); and El Maghraby Eye and Ear Center, Abu Dhabi, United Arab Emirates (Dr El Danasoury).

This work was supported in part by U.S. Public Health Service grants EY03311 (Dr Klyce) and EY02377 (LSU Eye Center); EY08520 and EY08520-03S1 (Dr Applegate), and EY02994 (Dr Howland) from the National Eye Institute, National Institutes of Health, Bethesda, Maryland; a San Antonio Area Foundation Grant (Dr Applegate), a Kerr Foundation Grant (Dr Applegate); and an unrestricted research grant to the Department of Ophthalmology, University of Texas Health Science Center at San Antonio, Texas, from Research to Prevent Blindness, New York, New York.

Dr Klyce is a paid consultant to Computed Anatomy, manufacturers of the Tomey TMS topographer. The other authors have no financial or proprietary interest in any methods or materials described within this article.

Reprint requests to Tetsuro Oshika, MD, Department of Ophthalmology, University of Tokyo School of Medicine, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8655 Japan; fax: +81-3-3817-0798; e-mail: oshika-tky@umin.ac.jp

0002-9394/99/$20.00
PII S0002-9394(98)00288-8

amount of aberrations.[1–3] These naturally occurring higher order aberrations, combined with the aberrations induced by refractive surgery, can affect the visual performance after surgery.

After refractive corneal surgery for myopia, the asphericity of the cornea typically reverses (that is, less curvature in the central cornea than in the peripheral cornea). This would be expected to increase the spherical aberration of the cornea, which might diminish the quality of the retinal image. Previous studies have indicated that higher order corneal aberrations increase after radial keratotomy[4–6] and photorefractive keratectomy.[7–9] The increases in wavefront aberrations after radial keratotomy were shown to depend on the magnitude of refractive correction,[6] and they were correlated to a decrease in contrast sensitivity.[10] However, the changes in optical quality of the cornea after laser in situ keratomileusis have not been well studied, and no data are available on the influence of laser in situ keratomileusis procedures on corneal aberrations. We conducted the current prospective study to compare the amount of wavefront aberrations of the cornea after photorefractive keratectomy and laser in situ keratomileusis.

PATIENTS AND METHODS

FORTY-FOUR EYES OF 22 PATIENTS WITH BILATERAL MYOPIA were enrolled in a prospective randomized study. Patient age ranged from 19 to 45 years (26.7 ± 5.9 years; mean ± standard deviation). Every patient received photorefractive keratectomy on one eye and laser in situ keratomileusis on the other eye. All patients had both eyes operated on during the same surgical session. The procedure assigned to each eye and the sequence of surgeries for each patient were randomized using a random number table.

The mean preoperative spherical equivalent refraction was -3.23 ± 0.63 diopters (range, -2.50 to -5.00 diopters) in photorefractive keratectomy eyes and -3.44 ± 0.72 diopters (range, -2.25 to -5.50 diopters) in laser in situ keratomileusis eyes. There was no statistically significant difference in the baseline manifest refraction between the two groups. Eleven eyes (50%) of each group, which underwent the combined spherical and astigmatic ablation, had a refractive cylinder of 0.50 or more. The mean preoperative refractive cylinder was 0.44 ± 0.57 diopters (range, 0 to 2.25 diopters) in the photorefractive keratectomy group and 0.38 ± 0.40 diopters (range, 0 to 1.50 diopters) in the laser in situ keratomileusis group.

Patients selected for the study met inclusion criteria including age of at least 18 years, documented stable refraction for 1 year, spherical equivalent refraction between -2.00 and -5.50 diopters of myopia, refractive astigmatism less than 2.50 diopters, spectacle-corrected visual acuity of 20/20 or better, and realistic expectations concerning the outcome. Exclusion criteria included previous refractive surgery, central corneal thickness of less than 490 μm by ultrasonic pachymetry, keratoconus, or keratoconus suspect by videokeratography, active ocular disease, systemic disease likely to affect corneal wound healing (for example, connective tissue disease), and inability to achieve the strict follow-up example, schedule that was given to the patients before surgery. There was no upper age limit in this trial; however, presbyopic patients who preferred undercorrection of one eye (monovision) were not enrolled in the study, therefore emmetropia was the refractive goal in all eyes. All patients signed an informed consent in their native language as approved by El Maghraby Health Corporation Research Committee. The study protocol was approved by the Human Investigation Committee in El Maghraby Eye and Ear Center.

The Nidek EC-5000 excimer laser (Nidek Co, Gamagori, Japan) was used for all eyes. The laser system parameters were: wavelength, 193 nm; pulse repetition rate, 30 Hz; fluence, 140 mJ/cm^2; ablation depth between 0.20 and 0.26 μm per scan (mean, 0.25 μm) in polymethylmethacrylate and between 0.48 and 0.62 μm per scan (mean, 0.60 μm) on the cornea; no aspiration air flow; ablation zone diameter of 5.5 mm; and transition zone diameter of 7.0 mm in photorefractive keratectomy procedures and 6.5 mm in laser in situ keratomileusis procedures. The shaping system of the beam involved a rectangular cross-sectional beam of up to 2 mm by 9 mm and an expanding diaphragm. Beam delivery was achieved by linear scan of 10 overlapped rectangular cross-sectional beams, combined with rotation of the rectangle by 120 degrees on completion of each scan. The astigmatism correction combined the opening diaphragm with an opening slit with the long axis aligned with the flattest corneal meridian and was performed after the spherical correction in all spherocylindrical ablations.

Photorefractive keratectomy was performed by mechanical scraping of the epithelium from the central 8.0 mm of the cornea with a No. 69 beaver blade without damaging the Bowman layer. The patient fixated a blinking green diode light coaxial with the laser beam. Topical diclofenac sodium 0.1% (Naclof, Ciba Vision Ltd, Hettlingen, Switzerland) was applied four times daily for 3 days, topical tobramycin 0.3% (Tobrex, Alcon-Couvreur, Belgium) was applied four times daily for 1 week, and topical fluorometholone 0.1% (Flucon, Alcon-Couvreur) was used four times daily initially, then tapered over 4 months. No contact lenses or patches were used.

The Automated Corneal Shaper, sequence number 332, adjustable ALK style (Chiron Vision, Irvine, California) was used in all laser in situ keratomileusis procedures. Surgical steps included marking the cornea with three radial marks, applying suction of more than 65 mm Hg to the eye, creating a flap of approximately 8.0 mm diameter and about 160 μm thickness based on a hinge of approximately 1.0 mm width and 30-degree arc length, centering the laser aiming beam over the entrance pupil, ablating the stromal bed, washing the stromal surface of the flap and the stromal bed with sterile balanced saline solution, and repositioning of the flap guided by the three radial marks. In this series, no pilocarpine was used before the procedure as the miosis induced by the aiming beam of the Nidek EC-5000 was sufficient for centration over the entrance pupil. Postoperative treatment included topical tobramycin 0.3% combined with prednisolone acetate 1% (Econopred, Alcon-Couvreur) every 6 hours for 1 week.

Corneal topography was evaluated (TMS-1, Computed Anatomy, Inc, New York, New York) preoperatively, and at 2 and 6 weeks, 3, 6, and 12 months postoperatively. For each eye, measurements were repeated at least three times to obtain a well-focused, properly aligned image of the eye. The files containing information about corneal elevation, curvature, power, and position of the pupil were downloaded on a removable media and used for the following analysis.

The calculation of wavefront aberrations was performed using the descriptive polynomial method of Howland and Howland.[1] The center of the pupil was identified on the topography video screen and its deviation from the videokeratographic axis was measured. Using the method of least squares, the reference sphere for the central 3.0-mm cornea for each eye was calculated by determining the best-fit sphere to the elevation data of the preoperative cornea. The elevations of the best-fit sphere of the preoperative cornea were subtracted from the measured elevations to define a surface termed the remainder lens. To calculate the optical effects of the remainder lens, the elevations of that lens were multiplied by 0.3375 (the keratometric index of refraction of the cornea minus the refractive index of air). Using the method of least squares, the resulting data were fit with the Taylor polynomial of the form[1,11,12]:

$$\begin{aligned} W(x,y) &= A + Bx + Cy + Dx^2 + \\ & Exy + Fy^2 + Gx^3 + Hx^2y + Ixy^2 + \\ & Jy^3 + Kx^4 + Lx^3y + Mx^2y^2 + Nxy^3 + \\ & Oy^4 + Px^5 + Qx^4y + Rx^3y^2 + Sx^2y^3 + \\ & Txy^4 + Uy^5 + Vx^6 + Wx^5y + Xx^4y^2 + \\ & Yx^3y^3 + Zx^2y^4 + A_2xy^5 + A_3y^6 \end{aligned}$$

where (x,y) are Cartesian coordinates of the cornea in millimeters with their origin being taken on the pupil center. This is a two-dimensional, sixth order Taylor representation of the wave aberration surface with the positive axis pointing away from the retina. The coefficients were scaled so that the function $W(x,y)$ is given in micrometers when x and y are given in millimeters. A represents a shift of the entire wavefront along the optical axis; B and C represent the vertical and horizontal prism components. D through E include the conventional ophthalmic prescription: sphere, cylinder, and axis. G through J express coma-like aberration, and K through O express spherical-like aberration.[1] P through U are the fifth order Taylor coefficients, and V through A_3 denote the sixth order Taylor coefficients.

The Taylor polynomial was then converted to the Zernike polynomial to obtain orthogonal coefficients.[1,13] Zernike coefficients 7 through 28 (Z_7 through Z_{28}) were calculated from linear combinations of Taylor coefficients as described by Howland and Howland.[1] Coefficient Z_7 through Z_{10} correspond to coma-like aberration; Z_{11} through Z_{15} correspond to spherical-like aberration; Z_{16} to Z_{21} express the fifth order Zernike coefficients; and Z_{22} through Z_{28} are the sixth order Zernike coefficients.

These Zernike coefficients were then used to calculate the global descriptors of monochromatic corneal aberrations, which are represented by the terms, S_3, S_4, S_5, and S_6.[13] Because spherical and coma aberrations refer to symmetrical systems and the eye is not rotationally symmetrical, the terms spherical-like and coma-like aberrations are used in this paper. The S_3 (third order component of the wavefront aberration) represents the mean squared wavefront variance from that of a perfect spherocylinder attributable to coma-like aberration. Similarly, S_4 (fourth order component of the wavefront aberration) represents the mean squared wavefront variance from that of a perfect spherocylinder attributable to spherical-like aberration. The S_5 and S_6 are the fifth and sixth order components of the wavefront aberrations, respectively. Because the variances of each term are independent, the total wavefront variance was computed by summing the individual variances and served as a parameter of total wavefront aberrations (Su). The odd order aberrations ($S_3 + S_5$) were summed to examine the magnitude of coma-like aberrations, and the even order aberrations ($S_4 + S_6$) were summed to evaluate the changes in spherical-like aberrations. These calculations were done for both 3- and 7-mm pupils.

RESULTS

BY THE FIRST POSTOPERATIVE TOPOGRAPHY MEASUREMENT in the second week, all post–photorefractive keratectomy eyes had their epithelium healed and clear, and all post–laser in situ keratomileusis eyes had clear flaps with barely identifiable edges. The number of topographies available for the analysis was 22 pairs of eyes preoperatively, 19 at 2 weeks, 19 at 6 weeks, 20 at 3 months, 19 at 6 months, and 20 at 12 months postoperatively.

Both photorefractive keratectomy and laser in situ keratomileusis induced statistically significant amounts of total wavefront aberrations (Table 1). Regardless of the pupil size, postoperative total wavefront aberrations (Su) were significantly larger than the preoperative aberrations, and the values did not return to the preoperative level even 12 months after surgery.

The time course of changes in the total wavefront aberrations is illustrated in Figures 1 and 2. For a 3-mm pupil, there was no statistically significant difference be-

TABLE 1. Total Wavefront Aberrations (Su) Before and After Surgery

	Preoperative (n = 22)	Postoperative 2 weeks (n = 19)	6 weeks (n = 19)	3 months (n = 20)	6 months (n = 19)	12 months (n = 20)
3-mm pupil						
PRK	0.074 ± 0.052	0.159 ± 0.106[‡]	0.115 ± 0.084[‡]	0.112 ± 0.074[†]	0.100 ± 0.052[†]	0.106 ± 0.080[†]
LASIK	0.077 ± 0.039	0.126 ± 0.076[†]	0.151 ± 0.118[†]	0.122 ± 0.067[‡]	0.131 ± 0.076[‡]	0.135 ± 0.102[*]
7-mm pupil						
PRK	0.348 ± 0.214	2.893 ± 1.311[‡]	2.347 ± 1.530[‡]	2.346 ± 1.263[‡]	2.124 ± 1.362[‡]	1.826 ± 1.010[‡]
LASIK	0.376 ± 0.242	3.866 ± 1.237[‡]	3.954 ± 2.707[‡]	3.383 ± 2.566[‡]	2.992 ± 2.134[‡]	2.724 ± 1.670[‡]

LASIK = laser in situ keratomileusis; PRK = photorefractive keratectomy.

Mean ± standard deviation (μm^2). [*]$P < .05$, [†]$P < .01$, [‡]$P < .001$: significantly higher than the preoperative value (Wilcoxon signed rank test). The comparisons between PRK and LASIK groups are shown in Figures 1 and 2.

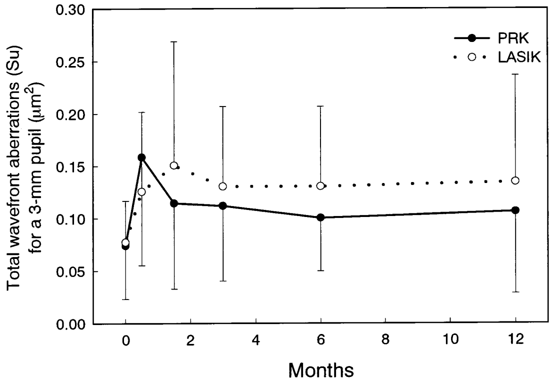

FIGURE 1. The time course of changes in total wavefront aberrations (Su) after photorefractive keratectomy (PRK) and laser in situ keratomileusis (LASIK) for a 3-mm pupil. Bars indicate standard deviation of the mean.

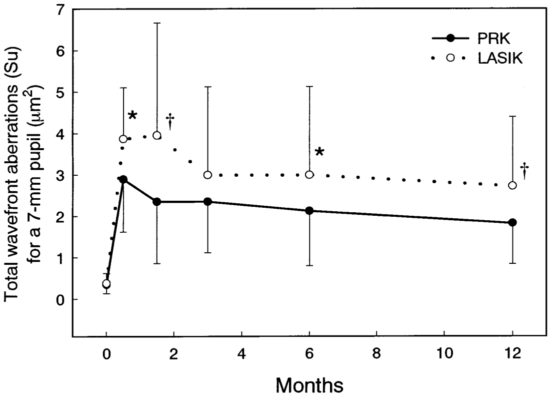

FIGURE 2. The time course of changes in total wavefront aberrations (Su) after photorefractive keratectomy (PRK) and laser in situ keratomileusis (LASIK) for a 7-mm pupil. Bars indicate standard deviation of the mean. [*]$P < .05$, [†]$P < .01$; values were significantly different between photorefractive keratectomy and laser in situ keratomileusis groups (Wilcoxon signed rank test).

tween photorefractive keratectomy and laser in situ keratomileusis at any point. For a 7-mm pupil, the laser in situ keratomileusis group exhibited significantly larger aberrations than the photorefractive keratectomy group at 2 weeks ($P = .018$, Wilcoxon signed rank test), 6 weeks ($P = .006$), 6 months ($P = .036$), and 12 months ($P = .009$) postoperatively.

Before surgery, simulated pupillary dilation from 3 mm to 7 mm caused a five- to six-fold increase in the aberrations. After surgery, the same dilation resulted in a 25- to 32-fold increase in the photorefractive keratectomy group, and a 28- to 46-fold increase in the laser in situ keratomileusis group (Figure 3). Post–laser in situ keratomileusis eyes were affected by pupillary dilatation to a larger degree than the post-photorefractive keratectomy eyes, and intergroup difference was statistically significant at 2 weeks ($P = .005$).

The changes in coma-like ($S_3 + S_5$) and spherical-like ($S_4 + S_6$) aberrations are shown in Tables 2 and 3. Both aberrations increased significantly and persistently after surgery, except for the spherical-like aberration for a 3-mm pupil of which increases were transient (Table 3). The coma-like aberration did not differ significantly between photorefractive keratectomy and laser in situ keratomileusis for both pupil sizes. The spherical-like aberration for a 3-mm pupil was similar between the two groups (Figure 4), but spherical-like aberration for a 7-mm pupil was larger in laser in situ keratomileusis than in photorefractive keratectomy (Figure 5).

The ratio of coma-like aberration and spherical-like aberration was compared (Table 4). For a 3-mm pupil, the proportion of coma-like aberration increased after both photorefractive keratectomy and laser in situ keratomileusis, but spherical-like aberration still accounted for more than 50% even after surgery. For a 7-mm pupil, coma-like aberration was dominant before surgery, but postoperatively, spherical-like aberration became dominant, representing approximately 60% of the total aberrations.

Decentration of the laser ablation was defined as the

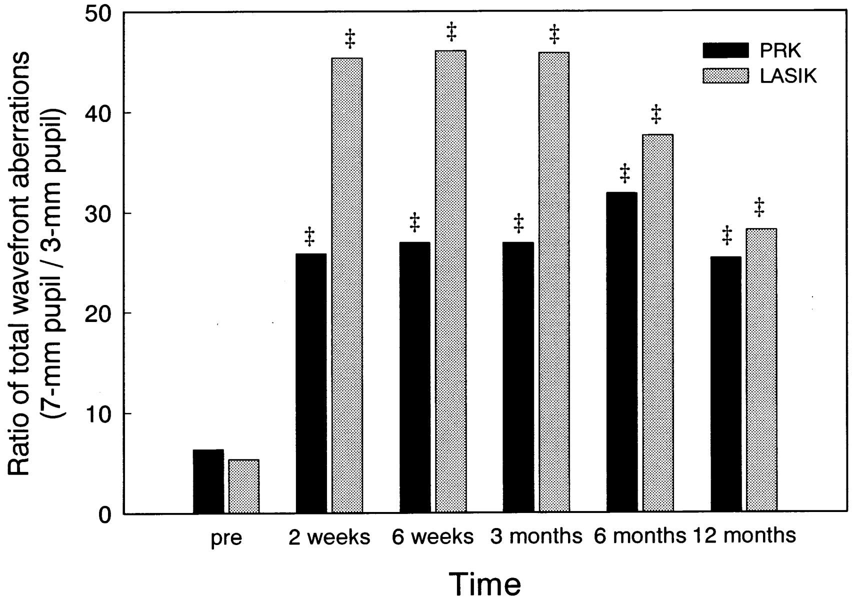

FIGURE 3. Effect of pupillary dilation from 3 to 7 mm on total aberrations (Su). ‡$P < .001$; significantly different from the preoperative ratio (Wilcoxon signed rank test). The difference between photorefractive keratectomy (PRK) and laser in situ keratomileusis (LASIK) was significant at 2 weeks postoperatively ($P < .01$).

TABLE 2. Coma-Like Aberration ($S_3 + S_5$) Before and After Surgery

	Preoperative	Postoperative				
		2 weeks	6 weeks	3 months	6 months	12 months
3-mm pupil						
PRK	0.020 ± 0.015	0.055 ± 0.038‡	0.040 ± 0.032†	0.032 ± 0.026*	0.031 ± 0.014†	0.032 ± 0.023†
LASIK	0.023 ± 0.015	0.046 ± 0.038*	0.053 ± 0.053*	0.043 ± 0.040*	0.045 ± 0.039†	0.053 ± 0.052*
7-mm pupil						
PRK	0.274 ± 0.204	0.963 ± 0.628†	1.088 ± 0.763†	0.883 ± 0.679†	0.882 ± 0.781†	0.717 ± 0.566†
LASIK	0.293 ± 0.186	1.266 ± 0.978‡	1.798 ± 1.589†	1.436 ± 1.397†	1.311 ± 1.370†	1.104 ± 0.937†

LASIK = laser in situ keratomileusis; PRK = photorefractive keratectomy.

Mean ± standard deviation (μm^2). *$P < .05$, †$P < .01$, ‡$P < .001$: significantly higher than the preoperative value (Wilcoxon signed rank test). For both pupil sizes, there were no significant differences between PRK and LASIK groups on any pre- or postoperative occasions.

distance from the center of the entrance pupil to the center of the treated area, and was calculated to be 0.47 ± 0.19 mm and 0.40 ± 0.23 mm for the photorefractive keratetomy and laser in situ keratomileusis groups, respectively. The amount of decentration did not correlate with the magnitude of total aberrations, spherical aberration, nor coma-like aberration (Spearman rank correlation test).

DISCUSSION

AS SHOWN IN THE RESULTS, BOTH PHOTOREFRACTIVE KERatectomy and laser in situ keratomileusis significantly increased the wavefront aberrations of the cornea, and those changes were persistent throughout the 12-month follow-up period. For a 3-mm pupil, there was no statistically significant difference in the amount of total aberrations between photorefractive keratectomy and laser in situ keratomileusis at any postoperative point (Figure 1). For a 7-mm pupil, however, the laser in situ keratomileusis group exhibited significantly larger total wavefront aberrations than the photorefractive keratectomy group (Figure 2). Moreover, simulated pupillary dilation from 3 to 7 mm induced more aberrations in the post–laser in situ keratomileusis eyes than in the post–photorefractive keratectomy eyes (Figure 3). When examined more closely, the amount of coma-like aberration for a 7-mm pupil did not differ between photorefractive keratectomy and laser in situ keratomileusis, but spherical-like aberration was significantly larger in the post–laser in situ keratomileusis eyes than the post–photorefractive keratectomy eyes (Figure 5). These results indicate that there was no intergroup differ-

TABLE 3. Spherical-Like Aberration ($S_4 + S_6$) Before and After Surgery

	Preoperative	Postoperative 2 weeks	6 weeks	3 months	6 months	12 months
3-mm pupil						
PRK	0.050 ± 0.040	$0.066 \pm 0.051^*$	$0.058 \pm 0.046^\dagger$	$0.060 \pm 0.043^\dagger$	0.052 ± 0.037	0.053 ± 0.042
LASIK	0.051 ± 0.034	$0.064 \pm 0.038^*$	0.054 ± 0.038	0.053 ± 0.036	0.054 ± 0.030	0.056 ± 0.036
7-mm pupil						
PRK	0.071 ± 0.037	$1.920 \pm 1.200^\ddagger$	$1.255 \pm 1.161^\ddagger$	$1.455 \pm 0.961^\ddagger$	$1.234 \pm 0.907^\ddagger$	$1.104 \pm 0.741^\ddagger$
LASIK	0.082 ± 0.085	$2.593 \pm 0.798^\ddagger$	$2.138 \pm 1.179^\ddagger$	$1.941 \pm 1.367^\ddagger$	$1.673 \pm 0.912^\ddagger$	$1.613 \pm 0.932^\ddagger$

LASIK = laser in situ keratomileusis; PRK = photorefractive keratectomy.

Mean ± standard deviation (μm^2). $^*P < .05$, $^\dagger P < .01$, $^\ddagger P < .001$: significantly higher than the preoperative value (Wilcoxon signed rank test). Comparisons between PRK and LASIK groups are shown in Figures 4 and 5.

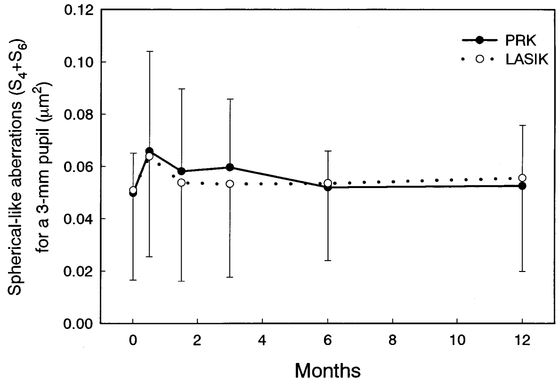

FIGURE 4. **The time course of changes in spherical-like aberration ($S_4 + S_6$) after photorefractive keratectomy (PRK) and laser in situ keratomileusis (LASIK) for a 3-mm pupil. Bars indicate standard deviation of the mean.**

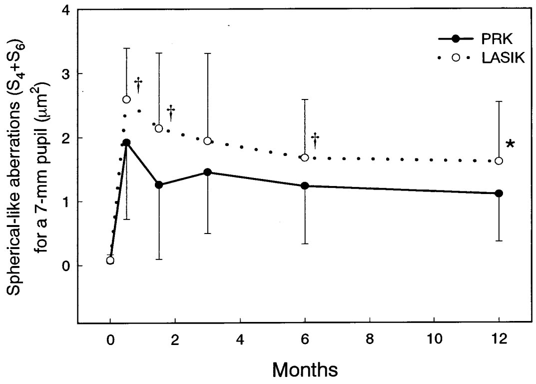

FIGURE 5. **The time course of changes in spherical-like aberration ($S_4 + S_6$) after photorefractive keratectomy (PRK) and laser in situ keratomileusis (LASIK) for a 7-mm pupil. Bars indicate standard deviation of the mean. $^*P < .05$, $^\dagger P < .01$; values were significantly different between photorefractive keratectomy and laser in situ keratomileusis groups (Wilcoxon signed rank test).**

ence in terms of decentration, tilt, and asymmetry of the corneal surface, which are among the sources of coma-like aberration. On the other hand, the different transition zone size of the laser ablation is the most likely cause of the discrepancy in spherical-like aberrations between the two procedures. The diameter of the transition zone was 7.0 mm in photorefractive keratectomy procedures and 6.5 mm in laser in situ keratomileusis procedures. The microkeratome used in this series had an adjustable suction ring that gives a flap diameter between 7.2 and 8.0 mm. To prevent ablation on the stromal side of the hinge, we had to use a transition zone of 6.5 mm for the laser in situ keratomileusis eyes. In addition, there is a possibility that the edge of the corneal flap (8.0 mm in diameter) was included in the 7-mm analysis zone in some cases.

Before surgery, simulated pupillary dilation from 3 to 7 mm caused a five- to six-fold increase in the aberrations. After surgery, the same dilation resulted in a 25- to 32-fold increase in the photorefractive keratectomy group, and a 28- to 46-fold increase in the laser in situ keratomileusis group (Figure 3). These results are in agreement with the previous studies that reported a marked increase in aberrations with pupil dilatation in photorefractive keratectomy corneas.[7–9]

The coma-like aberration was significantly increased after surgery and remained at a high level throughout the 1-year study period (Table 2). On the other hand, the increase of spherical-like aberration for a 3-mm pupil was found to be transient (Table 3). Values returned to the preoperative level at 6 months after photorefractive keratectomy and at 6 weeks after laser in situ keratomileusis, in contrast to the persistent increase in spherical-like aberration for a 7-mm pupil. It is not surprising that spherical-like aberration with a smaller pupil is less affected than that with a larger pupil.

The detailed clinical data of the current patients will be reported in another article (MA El-Danasoury, A El-Maghraby, SD Klyce, K Mehrez, personal communication), where visual acuity results after both photorefractive keratectomy and laser in situ keratomileusis were found to

TABLE 4. Contribution to Total Wavefront Aberrations by Coma-Like and Spherical-Like Aberrations

			Postoperative				
	Aberrations	Preoperative	2 weeks	6 weeks	3 months	6 months	12 months
3-mm pupil							
PRK	Coma-like	28.9%	45.5%†	40.9%*	35.1%	37.6%*	37.6%
	Spherical-like	71.1%	54.5%	59.1%	64.9%	62.4%	62.4%
LASIK	Coma-like	31.7%	41.9%†	49.8%†	44.6%†	45.5%†	48.8%†
	Spherical-like	68.3%	58.1%	50.2%	55.4%	54.5%	51.2%
7-mm pupil							
PRK	Coma-like	79.5%	33.4%†	46.4%†	37.8%†	41.7%†	39.4%†
	Spherical-like	20.5%	66.6%	53.6%	62.2%	58.3%	60.6%
LASIK	Coma-like	78.1%	32.8%‡	45.7%‡	42.5%‡	43.9%‡	40.6%‡
	Spherical-like	21.9%	67.2%	54.3%	57.5%	56.1%	59.4%

*$P < .05$, †$P < .01$, ‡$P < .001$; significantly different from the preoperative ratio (Wilcoxon signed rank test).

be excellent. Thus, as far as the high contrast visual acuity is concerned, the increase in wavefront aberrations after photorefractive keratectomy and laser in situ keratomileusis observed herein seems to be a subclinical phenomenon, and clinical efficiency of these refractive surgical procedures is not necessarily outweighed. To elucidate the exact influence of aberrations on the visual performance, however, further studies are needed in which more in-depth parameters have to be investigated, such as contrast sensitivity, glare visual acuity, and modulation transfer function. In fact, several studies demonstrated that many patients experience reduced contrast sensitivity as a consequence of photorefractive keratectomy[14–17] and laser in situ keratomileusis.[16,18] Seiler and associates[7] found a high inverse correlation between the effective aberration and visual acuity under glare conditions after photorefractive keratectomy. The exact level of total wavefront aberrations that affect the visual function of the eye is currently unknown and awaits further studies.

REFERENCES

1. Howland HC, Howland B. A subjective method for the measurement of monochromatic aberrations of the eye. J Opt Soc Am 1977;67:1508–1518.
2. Walsh G, Charman WN, Howland HC. Objective technique for the determination of monochromatic aberrations of the human eye. J Opt Soc Am A 1984;1:987–992.
3. Liang J, Williams DR. Aberrations and retinal image quality of the normal human eye. J Opt Soc Am A 1997;14:2873–2883.
4. Hemenger RP, Tomlinson A, Caroline PJ. Role of spherical aberration in contrast sensitivity loss with radial keratotomy. Invest Ophthalmol Vis Sci 1989;30:1997–2001.
5. Applegate RA, Howland HC, Buettner J, Cottingham AJ Jr, Sharp PP, Yee RW. Changes in the aberration structure of the RK cornea from videokeratographic measurements. Invest Ophthalmol Vis Sci 1994;35(suppl):1740.
6. Applegate RA, Hilmantel G, Howland HC. Corneal aberrations increase with the magnitude of radial keratotomy refractive correction. Optom Vis Sci 1996;73:585–589.
7. Seiler T, Reckmann W, Maloney RK. Effective spherical aberration of the cornea as a quantitative descriptor in corneal topography. J Cataract Refract Surg 1993;19:155–165.
8. Oliver KM, Hemenger RP, Corbett MC, et al. Corneal optical aberrations induced by photorefractive keratectomy. J Refract Surg 1997;13:246–254.
9. Martínez CE, Applegate RA, Klyce SD, McDonald MB, Medina JP, Howland HC. Effect of pupil dilation on corneal optical aberrations after photorefractive keratectomy. Arch Ophthalmol 1998;116:1053–1062.
10. Applegate RA, Howland HC, Sharp RP, Cottingham AJ, Yee RW. Corneal aberrations, visual performance and refractive surgery. J Refract Surg 1998;14:397–407.
11. Walsh G, Charman WN. Measurement of the axial wavefront aberration of the human eye. Ophthalmic Physiol Opt 1985;5:23–31.
12. Howland HC, Beuttner J. Computing high order wave aberration coefficient from variations of best focus for small artificial pupils. Vision Res 1989;29:979–983.
13. Malacara D, DeVore SL. Interferogram evaluation and wavefront fitting. In: Malacara D, editor. Optical shop testing. 2nd ed. New York: John Wiley & Sons, 1992:455–499.
14. Lhmann CP, Fitzke FW, O'Bart DPS, Kerr Muir M, Marshall J. Halos—a problem for all myopes? A comparison between spectacles, contact lenses and photorefractive keratectomy. Refract Corneal Surg 1993;9(suppl):S72–S75.
15. Butuner Z, Elliott DB, Gimbel HV, Slimmon S. Visual function one year after excimer laser photorefractive keratectomy. J Refract Corneal Surg 1994;10:625–630.
16. Wang Z, Chen J, Yang B. Comparison of laser in situ keratomileusis and photorefractive keratectomy to correct myopia from -1.25 to -6.0 diopters. J Refract Surg 1997;13:528–534.
17. Ghaith AA, Daniel J, Stulting RD, Thompson KP, Lynn M. Contrast sensitivity and glare disability after radial keratotomy and photorefractive keratectomy. Arch Ophthalmol 1988;116:12–18.
18. Pérez-Santonja JJ, Sakla HF, Alió JL. Contrast sensitivity after laser in situ keratomileusis. J Cataract Refract Surg 1998;24:183–189.