Effect of Larger Ablation Zone and Transition Zone on Corneal Optical Aberrations After Photorefractive Keratectomy

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**Objective:** To evaluate the effects of photorefractive keratectomy on corneal optical aberrations using a 5.5-mm optical zone and a 7.0-mm transition zone.

**Methods:** Videokeratographs of 72 eyes from 47 patients treated for low to moderate (1-9 diopters) myopia were obtained at the preoperative and 1-, 3-, 6-, 12-, and 18-month postoperative examinations. The videokeratoscopy data files were used to calculate the wavefront variance of the corneas for small (3-mm) and large (7-mm) pupils using a previously described method.

**Results:** In general, all optical aberrations decreased postoperatively for 3-mm pupils and increased for 7-mm pupils compared with preoperative values. For 3-mm pupils, the 2 common optical aberrations (comalike [S3] and spherical-like [S4]) decreased postoperatively and never returned to preoperative values. For 7-mm pupils, however, comalike aberrations increased slightly and spherical-like aberrations increased by nearly an order of magnitude during the postoperative period. Similarly, for 3-mm pupils, the higher order S5 and S6 aberrations decreased throughout the postoperative period, with S6 values showing an approximately 23-fold reduction at 12 and 18 months. For 7-mm pupils, S5 and S6 aberrations increased slightly, more so for S5 (approximately 3-fold) than for S6. Total wavefront aberrations decreased an average of 2.3 times postoperatively for 3-mm pupils, and increased significantly (P<.05) at all postoperative examinations for 7-mm pupils. Opening the pupil from 3 mm to 7 mm before surgery produced a 14-fold increase in total aberrations, whereas this same change produced an average 113-fold increase after photorefractive keratectomy.

**Conclusions:** Corneal optical aberrations after photorefractive keratectomy with a larger ablation zone and a transition zone are less pronounced and more physiologic than those associated with first-generation (5-mm) ablations with no transition zone.

**Clinical Relevance:** Evaluating the postoperative corneal aberration structure will help us devise ways to minimize the wavefront aberrations of the eye through the creation of an ideal corneal first surface, thereby improving visual results for patients undergoing excimer laser ablations for refractive correction.

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**Refractive Surgical Procedures** attempt to improve unaided visual acuity and correct spherocylindrical errors by reshaping the central cornea. In myopic subjects, the curvature is reduced, whereas hyperopic subjects require an increase in the central curvature. Previous studies examining radial keratotomy (RK), photorefractive keratectomy (PRK), and laser-assisted in-situ keratomileusis have shown that, although spherical and cylindrical defocus are lessened postoperatively, these procedures markedly increase the naturally occurring third- (comalike [S3]) and fourth-order (spherical-like [S4]) aberrations, with a concomitant increase in patient complaints of visual disturbances. Comalike aberrations result from surface asymmetries and create a lateral blur that is “cometlike.” Spherical aberrations cause central and peripheral light rays to focus in different focal planes, resulting in a blur along the visual axis. The other higher-order aberrations (fifth [S5] and sixth orders [S6]) collectively represent irregular aberrations that vary considerably among individuals. Most experts agree that increased higher-order aberrations are largely responsible for postoperative patient complaints involving glare, halos, and disturbances with night vision. In fact, Applegate and Howland found that, for larger scotopic pupils, patients who had undergone RK showed a significant decrease in contrast sensitivity related to corneal aberrations induced by the procedure.
PATIENTS AND METHODS

PATIENTS

Photorefractive keratectomy was performed using a scanning slit-eximer laser (model EC-5000; Nidek Ltd, Gamagori, Japan) for the correction of low to moderate myopia as part of a clinical study approved by the Food and Drug Administration. Protocols were approved by the institutional review board of Memorial Medical Center, New Orleans, La, and informed consent was obtained in all cases.

In this retrospective study, videokeratographs were included only from patients who had clinical and topographic data available and who did not undergo enhancement surgery during follow-up. Seventy-two eyes from 47 patients were included. Patient ages ranged from 23 to 52 years (mean ±SE, 34.9 ± 1.13 years). Refractions before surgery ranged from −1.25 to −9.00 diopters (D) (mean ±SE, −5.00 ± 0.25 D). The average attempted correction was −4.94 D (range, −1.25 to −9.00 D). The configuration of the ablation included a 5.5-mm diameter ablation zone and a 7.0-mm transition zone in all cases.

CORNEAL TOPOGRAPHY

Videokeratographs (TMS-1 and TMS-2 version W1.2 software; Tomey Corp, Waltham, Mass) were reviewed for dioptric, height, and radius data at the preoperative and 1-, 3-, 6-, 12-, and 18-month postoperative examinations. We used 230 TMS-1 and 323 TMS-2 videokeratographs.

CALCULATIONS

The files were transferred to a personal computer where the corneal wavefront variance was determined using the best-fitting sphere to the central presurgical cornea, calculated from preoperative elevation data, as a reference shape, as previously described. The elevations of the best-fitting sphere were then subtracted from the measured postoperative elevations to produce the remainder lens. The reference centers for the calculations were the pupil centers measured from the videokeratographs. The calculated data were fitted with a Taylor polynomial extended from fourth order as used previously to sixth order to examine the potential role of fifth- (S5) and sixth- (S6) order corneal aberrations, as seen in the following equation:

\[
W(x,y) = A + Bx + Cy + Dx^2 + Exy + Gy^2 + Hz^2 + Ix^3 + Jxy^2 + Ky^3 + Lx^4 + Mxy^2 + Ny^4 + Ox + Py^2 + Qx^5 + Rx^4y + Sx^3y^2 + Tx^2y^3 + Uxy^4 + Vx^6 + Wy^5 + Zx^4y^2 + Ax^3y^3 + Bx^2y^4 + Cxy^5 + Dy^{10}
\]

This 2-D sixth-order polynomial represents the wavefront after it has passed through the anterior cornea. Coefficients A through DD were used to calculate Zernike polynomials. From these Zernike coefficients, the wavefront variances with respect to the best-fitting sphere attributable to the third- (S3) and fourth- (S4) order (S5 and S6) corneal aberrations were calculated.

STATISTICAL METHODS

Data from preoperative and postoperative 3- and 7-mm pupils were tested using a 1-way repeated-measures analysis of variance. Multiple comparisons of each postoperative interval with its respective preoperative value were calculated using the Dunnett test. Differences were considered statistically significant at \( P < 0.05 \).

RESULTS

COMALIKE (S3) ABERRATION

For 3-mm pupils, the variance of the wavefront aberration caused by comalike aberration decreased postoperatively, with significant differences at 1, 6, and 12 months (\( P < 0.05 \)) (Figure 1). For 7-mm pupils, however, S3 aberrations were generally increased, with significant differences at 3 and 18 months (\( P < 0.05 \)).

SPHERICAL-LIKE (S4) ABERRATION

For 3-mm pupils, spherical-like aberrations decreased by an order of magnitude during the postoperative period (\( P < 0.05 \)) (Figure 2). For 7-mm pupils, spherical-like aberrations increased by nearly an order of magnitude postoperatively for all postoperative periods (\( P < 0.05 \)). In both cases, however, there was a trend toward decreased aberrations from the 1- to the 18-month examination.

FIFTH-ORDER (S5) AND SIXTH-ORDER (S6) ABERRATIONS

Postoperative changes in the fifth-order (S5) and sixth-order (S6) corneal aberrations were similar. For 3-mm pupils, the variance of the wavefront aberration caused by S5 and S6 decreased by approximately an order of magnitude throughout the postoperative period (\( P < 0.05 \)) (Figure 3 and Figure 4). For S5 (Figure 3), an approximate 4-fold decrease was noted at 12 months and...
a 13-fold decrease was measured at 18 months postoperatively \((P < .05)\). For 7-mm pupils, comalike aberration increases postoperatively and remains elevated at 18 months. Asterisks indicate significant difference \((P < .05)\) from preoperative values; error bars, SEM.

**TOTAL WAVEFRONT (SUM) ABERRATION**

For 3-mm pupils, the total wavefront aberration decreased in the postoperative period by an average of 2.3 times \((P < .05)\) (Figure 5). For 7-mm pupils, total wavefront aberration increased 5-fold by 1 month postoperatively (Figure 5) and remained significantly increased throughout the 18-month follow-up \((P < .05)\), although the amount of the increase declined over time as seen previously with the spherical-like aberration component (Figure 2). This finding is curious and may suggest a beneficial tissue remodeling change taking place in the periphery of the ablation.

For 3-mm pupils, comalike \((S_3)\) aberrations represented the greatest contribution (31%) to the total wavefront aberration preoperatively, increasing to 61% at 3 months and 72% at 18 months. For 7-mm pupils, the proportion of comalike aberrations was even greater (60%) preoperatively. However, spherical-like aberrations became dominant in the early postoperative period (1, 3, and 6 months), with a return to comalike dominance at 18 months (Figure 6).

We also evaluated the changes in induced total aberration \((SUM)\) in relation to attempted correction in diopters. For 3- and 7-mm pupils, the magnitude of the induced aberration increased as a function of the attempted correction (Figure 7).

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\( \mu \text{m}^2 \)
EFFECT OF PUPILLARY DILATION

For comalike aberrations, preoperative opening of the pupil from 3 to 7 mm increased the measured wavefront variance nearly 20-fold. After PRK, however, the same pupillary dilation resulted in an average 75-fold increase in aberrations (Figure 8). For spherical-like aberrations, the 3- to 7-mm pupillary dilation produced a 23-fold increase in wavefront variance preoperatively, whereas the same change in pupillary diameter after PRK caused an average 290-fold increase. For total (SUM) aberrations, the increase was 14-fold preoperatively and averaged 113-fold after PRK.

COMMENT

Excimer laser ablation for the correction of myopia reverses the asphericity of the normal cornea. The effect is a reshaping of the naturally prolate, centrally steeper profile that helps to reduce spherical aberration in the eye into a flatter or more globally oblate surface. It is not surprising, therefore, to find that larger pupils are associated with an increase in both comalike and spherical-like corneal aberration postoperatively. Despite continued advances in refractive surgical techniques, these induced aberrations play a major role in the 15% to 50% of patients who reported a poor perceived quality of vision after PRK.12-14

For 3-mm pupils, each of the corneal aberrations (comalike, spherical-like, S5, and S6) decreased significantly postoperatively and never returned to preoperative levels. The resulting postoperative decrease in total wavefront aberration (SUM) (average of 2.3 times preoperative aberration) thus represents a potential improvement in postoperative visual performance. The opposite effect was noted for larger (7 mm) pupils, that is, all types of aberrations increased significantly postoperatively. For 7-mm pupils, the increase in total wavefront aberration (SUM) peaked 1 month after PRK (5-fold compared with preoperative levels) and, despite a slight downward trend, remained significant to the last follow-up examination at 18 months.

In addition, the effect of opening the preoperative pupil from 3 to 7 mm was found to increase the amount of measured aberrations somewhat, whereas the same pupillary dilation after PRK significantly increased the amount and changed the character of the aberrations. For the preoperative eye, total aberrations (SUM) increased 14-fold with a 3- to 7-mm change in entrance pupil size, whereas the same dilation after PRK produced an average 113-fold increase in total aberrations during the 18-month follow-up.

Figure 5. Total wavefront (SUM) aberration. The logarithm of the wavefront variance for SUM is plotted as a function of time after surgery. For 3-mm pupils, total aberration is significantly decreased throughout the postoperative period, compared with preoperative values. In contrast, for 7-mm pupils, a 5-fold increase is seen at 1 month postoperatively, and the difference remains significant to the 18-month examination, despite a trend back toward preoperative values. Asterisks indicate significant difference (P<.05) from preoperative values; error bars, SEM.

Figure 6. Contributions to the total wavefront by the comalike (S3), spherical-like (S4), and higher-order S5 and S6 aberrations for 3-mm and 7-mm pupils. Preoperatively, the contribution of comalike aberrations to the total wavefront is slightly greater than that of the other aberrations for 3-mm pupils. Postoperatively, the proportional contribution of comalike aberrations is markedly greater, rising to 61% at 3 months and 72% at 18 months. For 7-mm pupils, comalike aberrations are dominant (60%) preoperatively, with a shift to dominant spherical-like aberrations in the early postoperative period (52% at 3 months), and a return to comalike dominance (64%) at 18 months.
Also, consistent with previous reports by Applegate et al and Martinez et al, we found that the magnitude of the induced aberration appears to be a function of attempted correction (Figure 7).

Previous studies have measured increases in corneal aberrations after refractive procedures such as PRK. In particular, Martinez et al measured the effect of pupillary dilation on corneal aberrations after PRK was performed by using a “first-generation” excimer laser (model 2020B; VISX, Incorporated, Sunnyvale, Calif) that produced a 5.0-mm ablation zone with no transition zone. The results showed postoperative increases in coma-like aberrations and no change in total aberrations (SUM) for 3-mm pupils, in contrast to the decreases in both found in the present study of third-generation laser ablations. Also, for 7-mm pupils, the earlier study revealed a postoperative shift from the cornea’s natural coma-like aberration dominance to a spherical-like dominance throughout the 24-month follow-up, whereas the present study demonstrated such a shift only for the early postoperative period (1 and 3 months), with a return to coma-like dominance at 6, 12, and 18 months.

These differences may be the result of several factors. For instance, the earlier generations of excimer lasers were not equipped with the “smoothing” ablation technology available in third-generation lasers today. This new technology could account for some portion of the decreased aberrations seen for 3-mm pupils, in terms of reduced asymmetry of the ablation, a known component of coma-like aberrations.

It is likely, however, that the most significant factors in the reduction of aberrations are the larger (5.5 mm) ablation zone and the addition of the transition zone (7.0 mm). In 1998, Applegate et al showed that RK and PRK shift the distribution of aberrations from normal third-order dominance (coma-like aberrations) to postoperative fourth-order dominance (spherical-like aberrations) for larger pupils. For RK, the induced aberrations and loss in contrast sensitivity diminished with increasing clear zone size. Thus, for 7-mm pupils, we would expect the spherical-like aberrations to be most affected by extending the treatment zone diameter. In fact, this may play a role in...
the decreased relative contribution of the spherical-like aberrations in the present study. The result is a more physiologic or return to preoperative comalike dominance for larger pupils in the patients treated with an increased ablation zone size and a transition zone. Further studies are needed to examine whether maintaining a more natural aberration structure is reflected in an improvement in the patients' subjective evaluation of quality of vision.

Through an understanding of how current refractive techniques alter the corneal aberration structure, we may better use new technologies designed to eliminate the induction of total optical aberrations by the creation of an ideal corneal first surface. In our effort to provide the best possible image after surgery for visual correction, however, a hinderance may be the physical dimensions of the cornea, as correction for high myopia can require the removal of more central stromal material than is possible without the induction of iatrogenic central corneal ectasia. On the plus side, the Stiles-Crawford effect reduces the importance of peripheral light rays in the perception of a crisp image. Also, neural adaptation may play an important role, but little is known in this area with respect to refractive surgery. Ultimately, improvements in technology may serve to eliminate induced aberrations, and better understanding of basic visual mechanisms may help us to overcome at least some of the natural limitations to surgical visual correction.

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REFERENCES


From the Archives of the Archives

A look at the past . . .

Miss Ida C. Mann showed, for Mr Leslie Paton, a patient with Leber’s atrophy, whose 4 brothers had also been shown before the Section with the same condition. There were in the family 6 brothers and 4 sisters. None of the women were so affected.