Effect of Pupillary Dilation on Corneal Optical Aberrations After Photorefractive Keratectomy

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Background: Complaints of glare, halos, and disturbances of night vision after photorefractive keratectomy (PRK) probably result from changes in the corneal aberration structure induced by the laser ablation procedure. The purpose of this article is to characterize changes in the corneal aberration structure after PRK and to demonstrate the effect of pupil dilation on these changes.

Methods: Videokeratographs obtained preoperatively (n = 112) and at 1 (n = 94), 3 (n = 103), 6 (n = 91), 12 (n = 60), 18 (n = 53), and 24 (n = 44) months postoperatively from 112 eyes of 89 patients who had undergone PRK for myopia were analyzed. The data were used to calculate the wavefront variance of the cornea for both small (3-mm) and large (7-mm) pupils.

Results: For both the 3- and 7-mm pupil, coma-like aberrations increased significantly from preoperative values to 1-month postoperative values ($P<.05$ and $P<.001$, respectively); for 7-mm pupils, the postoperative values never returned to preoperative values ($P<.001$, 24 months). For the 3-mm pupil, spherical-like aberrations decreased significantly 1 month after surgery ($P<.001$), and never returned to preoperative values. For the 7-mm pupil, spherical-like aberrations increased significantly 1 month after surgery ($P<.001$) and did not return to preoperative values. Opening the pupil from 3 to 7 mm increased spherical-like aberrations only 7-fold before PRK. After PRK, however, pupillary dilation caused a 300-fold increase in this type of aberration. For both pupil sizes at all times after PRK, the magnitude of the surgically induced aberration correlated with the amount of the attempted correction ($P<.001$, $r^2 = 0.6$ at 1 month for a 7-mm pupil).

Conclusions: Photorefractive keratectomy increases the wavefront variance of the cornea; PRK changes the relative contribution of coma-like and spherical-like aberrations; after PRK, the diameter of the entrance pupil greatly affects the amount and character of the aberrations; and the magnitude of the aberration increases with the attempted correction.

Clinical Relevance: Quantitative characterization of irregular astigmatism with the measurement of aberration structures following corneal surgery and the correlation of these data with visual performance in clinical trials provide the basis for understanding patient complaints and for improving surgical approaches. Our analysis shows that, whereas induced aberrations are minimal for simulated daytime vision (3-mm pupil), the increase in aberrations measured for simulated night vision (7-mm pupil) supports the use of large treatment zones to reduce visual disturbances such as glare and halos.

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DESPITE the proven efficacy[1-8] and widespread use of excimer laser photorefractive keratectomy (PRK) for the correction of myopia, safety remains a concern.[4,9-12] Photorefractive keratectomy has been shown to decrease contrast sensitivity,[13] and patients can complain of glare, halos, and disturbances of night vision.[6,8,14,15] Depending on the magnitude of the attempted correction and the size of the ablation zone, past PRK studies have reported 15% to 60% of patients complaining of glare,[6] 26% to 78% complaining of halos,[16-19] and 12% to 45% complaining of difficulty with night vision.[14,16,17,20] As many as one third of patients after PRK have been reported to be disappointed with their results despite good uncorrected visual acuity or even emmetropia.[6,14] In some studies,[4,17,18,20] up to 10% of patients who underwent PRK with an ablation zone 4.00 mm in diameter considered the problem of halos severe enough to interfere with driving at night. These complaints have led to increases in optical zone size in more recent PRK series, with the expectation of diminished visual disturbances.

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Some authors[18,21-23] postulate that these problems are caused by corneal haze or corneal surface epithelial irregularities. However, contrast sensitivity has been shown to decrease immediately after ablation and before the development of haze,[13] and individuals with clinically clear

PATIENTS AND METHODS

PATIENTS

In a prospective study approved by the US Food and Drug Administration, patients underwent 193-nm excimer laser PRK (model 2020B, VISX, Inc, Santa Clara, Calif) for myopia as part of the phase III study at the LSU Eye Center, New Orleans, La (April 15, 1991-June 11, 1996). The inclusion criteria, PRK procedure, and preoperative and postoperative management have been described.[1,41,42] All studies were approved by the Louisiana State University Medical Center Institutional Review Board, and informed consent was obtained from all patients.

In this retrospective study, we looked at videokeratographs from a subset of patients for whom both clinical and topographical data were available and enhancement surgery was not performed during the follow-up period. A total of 112 eyes from 89 patients were included. Patients' ages ranged from 19 to 62 years (mean [± SE], 38.9 ± 0.9 years). Sixty-six eyes were right eyes and 46 were left eyes. Best spectacle-corrected visual acuity before surgery ranged from 20/20 to 20/25. Preoperative spherical equivalent refraction ranged from − 0.25 to − 8.9 diopters (D) (mean [± SE], − 3.9 ± 0.14 D). The average attempted correction was 3.7 D (range, 1.5-6.0 D). The ablation zone diameter was 5.00 mm in all cases.

CORNEAL TOPOGRAPHY

Corneal topography was evaluated (TMS-1, Computed Anatomy, Inc, New York, NY) preoperatively (n = 112), and at 1 (n = 94), 3 (n = 103), 6 (n = 91), 12 (n = 60), 18 (n = 53), and 24 months (n = 44) postoperatively. The evaluation provided computer files containing information about corneal elevation, curvature, and power and the position of the pupil. These files were transferred to a Pentium-based personal computer where the rest of the analysis was performed. In cases for which findings from the topographic analysis did not provide a pupillary file, custom software allowed the operator to interactively indicate the center, size, and position of the pupil. Poorly focused or poorly aligned videokeratographs and those with poor tracking caused by eye movement or tear film breakup were excluded.

CALCULATIONS

The ideal anterior corneal shape would provide optimal (diffraction limited) retinal image focus over all physiologic pupillary sizes.[43] We do not know this ideal shape nor do we know how to estimate this ideal shape from corneal topographic measurements alone.[43] Lacking this information does not mean that we cannot calculate corneal first-surface aberrations or the change in aberration induced by refractive surgery from topographic measurements. It simply means that our reference surface will not be ideal.

In the data we report herein, we have chosen to use a sphere as the reference shape.[28] An analysis program written in BASIC by two of us (H.C.H. and R.A.A.) was used to calculate the reference sphere for the central cornea for each eye by determining the best-fitting sphere by the method of least squares to the elevation data of the presurgical cornea out to a radius of 1.5 mm from the center of the pupil. Once the best-fitting sphere to the presurgical cornea was determined, the program subtracted the elevations of the best-fitting sphere from the measured elevations to define a surface termed the "remainder lens" (**Figure 1**).

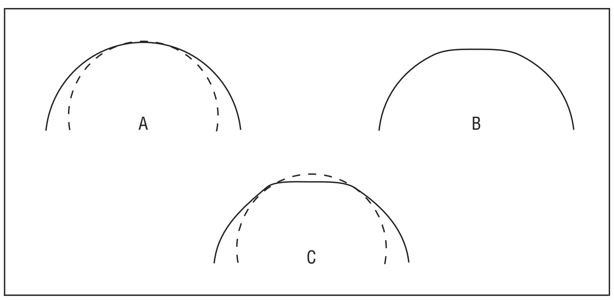

Figure 1. *A, The elevations of the presurgical cornea within 1.5 mm of the pupillary center are best fit with a sphere (dotted line) using the method of least squares. B, The postoperative cornea. C, The difference between the postoperative cornea and the best-fitting sphere of the preoperative cornea is found and termed the "remainder lens."*

corneas also experience these problems.[11,23,24] Also, O'Brart et al[4] showed that, typically, patients who complain of large halos have good corrections and little corneal haze. Furthermore, these complaints are not unique to PRK; they have also been seen after radial keratotomy,[24-28] automated lamellar keratectomy, and laser in situ keratomileusis. These observations support the idea that these visual problems are caused by direct changes in the corneal aberration structure induced by the refractive surgical procedure rather than by haze or epithelial irregularity.

Two common optical aberrations are spherical aberration and coma. Coma is an aberration of an optical system that produces "comet-like" blur at the retinal plane. Spherical aberration results from the central and peripheral rays passing through the pupil having different planes of focus. Peripheral corneal flattening and a radial gradient in the refractive index of the lens compensate for spherical aberration to some extent. Both of these aberrations are virtually absent from spectacle lenses of moderate power.

A quantitative descriptor of the corneal aberrations based on videokeratography would be useful in explaining current visual results and improving future optical outcomes, as well as in predicting potential visual acuity.[22,29,30] Previous efforts in this direction have included the Potential Acuity Index,[22] the Surface Regularity Index,[29] the Surface Asymmetry Index,[29] and the point spread function,[31] as well as Fourier analysis[32,33] of topographical data. Additionally, Seiler et al[23] showed that spherical aberration is highly correlated with best spherical-corrected visual acuity in normal eyes and with measured glare visual acuity in patients who had undergone PRK. Spherical aberration has also been implicated in the loss

To calculate the optical effects of the remainder lens, the elevations of the remainder lens were multiplied by 0.3375 (the keratometric index of refraction of the cornea minus the index of refraction of air) and the resulting data were fit with a Taylor polynomial of the form noted below:

$$W(x,y) = A + Bx + Cy + Dx^2 + Exy + Fy^2 + Gx^3 + Hx^2y + Ixy^2 + Jy^3 + Kx^4 + Lx^3y + Mx^2y^2 + Nxy^3 + Oy^4$$

using the method of least squares.

This is a 2-dimensional, fourth-order Taylor representation of the wave aberration surface with the positive axis pointing toward the retina; x and y are Cartesian coordinates of the cornea in millimeters with their origin on the center of the pupil. The coefficients *A* through *O* 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 *F* include the conventional ophthalmic prescription: sphere, cylinder, and axis. *G* through *J* express coma-like aberrations, and *K* through *O* express spherical-like aberrations.[35] To combine data from left and right eyes, the signs of odd coefficients (*G*, *I*, *L*, and *N*) of right eyes were reversed.[35]

Subtracting a sphere from the shape of the cornea allows the sphere to absorb most of the curvature of the cornea and leaves the polynomial as the representation of a thin remainder lens. However, Taylor coefficients are not orthonormal—ie, they are not independent of one another. To avoid this interdependence and the resulting ambiguity in interpretation, the Howland-Applegate program uses methods described by Malacara to convert the Taylor polynomial to a Zernike polynomial, which can be made orthonormal.[28,35,36,44-47] Zernike coefficients 7 through 15 (Z_7 through Z_{15}) were calculated for each pupillary radius from linear combinations of Taylor coefficients as described by Howland and Howland.[35] Coefficients Z_7 through Z_{10} correspond to coma-like aberrations; Z_{11} through Z_{15} correspond to spherical-like aberrations. Coefficients Z_7 and Z_9 are related to horizontal asymmetry, and Z_8 and Z_{10} are related to vertical asymmetry.[35] In general, Z_7 is used as an indicator of lateral coma, Z_8 of vertical coma, and Z_{11} of spherical aberration.[35]

These Zernike coefficients can be used to calculate global descriptors of monochromatic corneal aberrations (corneal and spherical), which are represented by the terms S_3 and S_4. Because spherical and coma aberrations refer to symmetrical systems and the eye is not rotationally symmetrical, we use the terms spherical-like and coma-like aberrations in this article. S_3 (third-order component of the wavefront aberration) represents the mean squared wavefront variance from that of a perfect spherocylinder due 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 due to spherical-like aberration. Because the variances of each term are independent, the total wavefront variance may be computed by summing the individual variances.[47]

STATISTICAL METHODS

Paired *t* tests were used to compare mean Taylor and Zernike coefficients at each postoperative interval with preoperative values. A Mann-Whitney rank sum test was applied to data not normally distributed. Differences at the $P<.05$ level were considered statistically significant. Errors were expressed as SEM. Correlations between factors were determined using the Spearman rank correlation coefficient, which does not assume a normal distribution.

of contrast sensitivity after radial keratotomy.[34] Strictly speaking, however, the term spherical aberration applies only to rotationally symmetrical systems; in addition, it is coma aberration, not spherical aberration, that has been shown to be the dominant aberration of the normal human eye.[35] The concept of wavefront aberration is, therefore, more appropriate.[35]

We report herein the results of calculated wavefront aberrations of the cornea before and after PRK with use of the descriptive polynomial of Howland and Howland[35] applied to data obtained from videokeratography.[36] This method has been demonstrated to be useful in explaining visual results following other kinds of refractive surgery and to correlate with visual performance[37,38]; a similar method has only recently been applied to corneas that have undergone PRK.[39] Using the method of Howland and Howland,[35] we computed the Taylor and Zernike coefficients for small (3-mm) and large (7-mm) pupils[40] before and after PRK from videokeratographs. Using these coefficients, we then calculated coma-like and spherical-like corneal aberrations before and after PRK. The changes in magnitude and character of the wavefront aberrations induced by PRK and their relationship to pupillary size, attempted correction, and best-corrected Snellen visual acuity are described.

RESULTS

Mean Taylor coefficients were calculated for a 3-mm pupil (**Table 1**) and a 7-mm pupil (**Table 2**) preoperatively and at intervals 1, 3, 6, 12, 18, and 24 months postoperatively. Mean Zernike coefficients for a 3-mm pupil (**Table 3**) and a 7-mm pupil (**Table 4**) were calculated similarly. Mean coma-like, spherical-like, and total aberrations for 3-mm pupils and 7-mm pupils are shown in **Table 5**.

COMA-LIKE ABERRATION

Taylor Coefficients

Taylor coefficients *G* through *J* are measures of a coma-like aberration. For a 3-mm pupil (Table 1), coefficients *H* and *J* increased postoperatively ($P<.05$). The remainder of the coma-like aberration terms did not show a statistically significant change. For a 7-mm pupil (Table 2), coefficients *G*, *I*, and *J* increased significantly 1 month postoperatively and never returned to preoperative values. At 24 months, the power of the test for coefficient *I* was not large enough to detect a significant difference.

Table 1. Induced Aberrations (Mean Taylor Coefficients) for a 3-mm Pupil

Taylor Coefficient	Correspondence	Preoperatively (n = 112)	Time After Surgery, mo: 1 (n = 94)	3 (n = 103)	6 (n = 61)	12 (n = 60)	18 (n = 53)	24 (n = 44)
A	Position shift	0.40	−0.09*	−0.04*	−0.05*	−0.05*	−0.04*	−0.05*
B	Vertical prism	−0.02	0	0.06	0.03	0.01	0.05	0.08‡
C	Horizontal prism	−0.03	−0.11	−0.15	−0.08	−0.03	−0.08	−0.05
D	Sphere	0.16	−2.33*	−1.83*	−1.81*	−1.74*	−1.70*	−1.45*
E	Cylinder	0.13	0.08	0.09	0.03	−0.02‡	−0.01‡	0.02
F	Axis	−0.11	−1.86*	−1.43*	−1.44*	−1.38*	−1.36*	−1.27*
G	Coma-like aberrations	0.01	−0.07	−0.10	−0.09	−0.11*	−0.12*	−0.13*
H		−0.05	−0.10‡	−0.08	−0.09	−0.13	−0.01	−0.01‡
I		−0.05	−0.04	−0.06	−0.07	−0.07	−0.08	−0.01
J		−0.01	−0.05‡	−0.02	−0.03	−0.02	−0.03	−0.08‡
K	Spherical-like aberrations	−0.20	0.09*	0.07*	0.11*	0.12*	0.10*	0.07*
L		−0.02	−0.04	−0.03	−0.03	0.01	−0.02	−0.01
M		−0.17	0.18*	0.17*	0.20*	0.19*	0.18*	0.11*
N		−0.06	−0.04	−0.06	−0.02	0	0.01‡	−0.02
O		0.06	0.03‡	0.04	0.06	0.06	0.04	0.02

*$P<.001$ compared with the preoperative value.
†$P<.01$ compared with the preoperative value.
‡$P<.05$ compared with the preoperative value.

Table 2. Induced Aberrations (Mean Taylor Coefficients) for a 7-mm Pupil

Taylor Coefficient	Correspondence	Preoperatively (n = 112)	Time After Surgery, mo: 1 (n = 94)	3 (n = 103)	6 (n = 91)	12 (n = 60)	18 (n = 53)	24 (n = 44)
A	Position shift	0.35	−0.06*	−0.38*	−0.44*	−0.40*	−0.41*	−0.31*
B	Vertical prism	−0.03	−0.20	−0.17	−0.21	−0.24‡	−0.18	−0.21
C	Horizontal prism	0.04	−0.12‡	−0.06	−0.03	0.06	−0.05	−0.14
D	Sphere	−0.15	−2.02*	−1.60*	−1.43*	−1.37*	−1.35*	−1.29*
E	Cylinder	0.05	0.05	0.02	0.02	0.01	0.01	0.05
F	Axis	0.11	−1.67*	−1.28*	−1.17*	−1.14*	−1.14*	−1.16*
G	Coma-like aberrations	0	−0.02†	−0.02†	−0.03*	−0.03	−0.03*	−0.03†
H		−0.07	−0.08	−0.07	−0.08	−0.08	−0.10†	−0.10†
I		0	−0.04†	−0.03‡	−0.03‡	−0.04*	−0.05*	−0.03
J		−0.04	−0.08†	−0.07	−0.07‡	−0.07‡	−0.08*	−0.09*
K	Spherical-like aberrations	−0.02	0.11*	0.09*	0.07*	0.06*	0.07*	0.06*
L		0	−0.01	0	0	0	0	−0.01
M		−0.02	0.25*	0.18*	0.16*	0.13*	0.15*	0.13*
N		0	−0.01	0	0	0	0	−0.01
O		−0.01	0.12*	0.09*	0.08*	0.07*	0.08*	0.07*

*$P<.001$ compared with the preoperative value.
†$P<.01$ compared with the preoperative value.
‡$P<.05$ compared with the preoperative value.

Zernike Coefficients

Third-order Zernike coefficients Z_7 through Z_{10} are indicators of coma-like aberrations. For a 3-mm pupil (Table 3), lateral coma, Z_7, did not differ significantly from zero preoperatively. However, it increased after surgery and never returned to the preoperative value ($P<.001$, 24 months). Vertical coma, Z_8, increased 1 month postoperatively ($P<.05$). Z_9, another measure of horizontal asymmetry, was positive preoperatively, became negative postoperatively, and never returned to preoperative values ($P<.001$).

For a 7-mm pupil (Table 4), lateral coma, Z_7, did not differ significantly from zero preoperatively. However, the term became negative and increased significantly ($P<.01$) 1 month after surgery and never returned to preoperative levels ($P<.01$). Vertical coma, Z_8, increased dramatically ($P<.01$) 1 month after surgery and never returned to preoperative values ($P<.001$).

Coma-like Aberration (S_3)

For a 3-mm pupil, the variance of the wavefront aberration caused by coma-like aberration increased slightly ($P<.05$) 1 month postoperatively (**Figure 2** and Table 5) but returned to preoperative values by 3 months ($P=.36$). For a 7-mm pupil, however, coma-like aberrations increased 4-fold 1 month postoperatively ($P<.001$), decreased to 2.9 times the preoperative value by 3 months ($P<.001$), and then stabilized at approximately 2.7 times the preoperative value, never returning to the preoperative value ($P<.001$ at 24 months).

Table 3. Induced Aberrations (Mean Zernike Coefficients) for a 3-mm Pupil

Zernike Coefficient (Z)	Correspondence	Preoperatively (n = 112)	Time After Surgery, mo					
			1 (n = 94)	3 (n = 103)	6 (n = 91)	12 (n = 60)	18 (n = 53)	24 (n = 44)
Z_7	Coma-like aberrations	0	−0.07	−0.10‡	−0.09‡	−0.11†	−0.12†	−0.14*
Z_8		−0.03	−0.07‡	−0.04	−0.05	−0.04	−0.06	−0.11†
Z_9		0.06	−0.02*	−0.03*	−0.01*	−0.03*	−0.03*	−0.02*
Z_{10}		−0.03	−0.04	−0.04	−0.05	−0.06	−0.06	−0.05
Z_{11}	Spherical-like aberrations	−0.06	0.06*	0.05*	0.07*	0.08*	0.06*	0.04*
Z_{12}		−0.17	0.04*	0.02*	0.03*	0.04*	0.04*	0.03*
Z_{13}		−0.03	−0.02	−0.03	−0.01	0	0	−0.01
Z_{14}		0.02	−0.03*	−0.04*	−0.03*	−0.01*	−0.02*	−0.01*
Z_{15}		0.02	0	0.01	−0.01‡	0.01	−0.02‡	0.01

**P*<.001 compared with the preoperative value.
†*P*<.01 compared with the preoperative value.
‡*P*<.05 compared with the preoperative value.

Table 4. Induced Aberrations (Mean Zernike Coefficients) for a 7-mm Pupil

Zernike Coefficient (Z)	Correspondence	Preoperatively (n = 112)	Time After Surgery, mo					
			1 (n = 94)	3 (n = 103)	6 (n = 91)	12 (n = 60)	18 (n = 53)	24 (n = 44)
Z_7	Coma-like aberrations	0.04	−0.37†	−0.33†	−0.44*	−0.44*	−0.55*	−0.39†
Z_8		−0.72	−1.16†	−0.95	−1.04‡	−1.00‡	−1.19*	−1.35*
Z_9		0.04	0.21	0.06	0.01	0.18	0.21‡	0.04
Z_{10}		−0.23	−0.02	−0.05	−0.12	−0.11	−0.18	−0.11
Z_{11}	Spherical-like aberrations	−0.30	2.93*	2.19*	1.90*	1.64*	1.81*	1.62*
Z_{12}		−0.11	−0.05	−0.03‡	−0.12	−0.11	−0.15	−0.18
Z_{13}		−0.05	−0.13	−0.03	−0.06	−0.04	−0.07	−0.15
Z_{14}		−0.07	−0.27*	−0.20*	−0.17	−0.09	−0.13	−0.11
Z_{15}		0.07	0.07	0.06	−0.04	0.05	−0.02	0.09

**P*<.001 compared with the preoperative value.
†*P*<.01 compared with the preoperative value.
‡*P*<.05 compared with the preoperative value.

Preoperatively, pupillary dilation from 3 to 7 mm caused a 12-fold increase in coma-like aberration (0.0255 to 0.9766, $P<.001$, Table 5 and **Figure 3**). Postoperatively, the same pupillary dilation caused a 40-fold increase (0.0208 to 0.2451, $P<.001$, Table 5 and Figure 3).

SPHERICAL-LIKE ABERRATION

Taylor Coefficients

Taylor coefficients *K* through *O* are measures of spherical aberration with respect to a best-fit sphere. Preoperatively, for a 3-mm pupil (Table 1), coefficients *K* through *N* showed negative spherical aberration. Postoperatively, *K* and *M* showed a shift toward positive spherical aberration ($P<.001$) that did not recover to preoperative values throughout the follow-up period ($P<.001$ at 24 months). Coefficient *O*, which was positive preoperatively, decreased slightly in the early postoperative period ($P<.05$) but returned to preoperative values by 3 months after laser surgery. The remainder of the spherical aberration terms did not show a statistically significant change.

For a 7-mm pupil (Table 2), coefficients *K*, *M*, and *O* also showed negative spherical aberration preoperatively, with a statistically significant ($P<.001$) shift in the positive direction 1 month after surgery. All 3 coefficients were positive by 1 month postoperatively and never returned to presurgical values ($P<.001$). Coefficients *L* and *N* did not vary significantly from zero preoperatively and were unaffected by PRK.

Zernike Coefficients

Fourth-order Zernike coefficients Z_{11} through Z_{15} are indicators of spherical-like aberration. When values were calculated for a 3-mm pupil (Table 3), Z_{11}, Z_{12}, and Z_{14} had changed by 1 month after surgery and never returned to preoperative values. In the 7-mm pupil calculations (Table 4), coefficients Z_{11} and Z_{14} had changed by 1 month after surgery ($P<.001$).

Spherical-like Aberration (S_4)

For a 3-mm pupil (**Figure 4** and Table 5), PRK resulted in a small but significant decrease in spherical-like aberration ($P<.05$). However, for a 7-mm pupil, spherical aberration increased 30-fold 1 month postoperatively ($P<.001$), decreased slightly to 19 times the preoperative value ($P<.001$) at 3 months, and then stabilized at approximately 24 times the preoperative value ($P<.001$) at 24 months. From Figure 3 and Table 5, one can see that

Table 5. Coma-like (S_3) and Spherical-like (S_4) Aberrations for 3- and 7-mm Pupils**

Aberration	Preoperatively (n = 112)	Time After Surgery, mo 1 (n = 94)	3 (n = 103)	6 (n = 91)	12 (n = 60)	18 (n = 53)	24 (n = 44)
3-mm Pupil							
S_3	0.0208 (57)	0.0255 (74)‡	0.0286 (70)	0.0194 (74)	0.0200 (81)	0.0202 (80)	0.0178 (84)
S_4	0.0154 (43)	0.0092 (26)*	0.0120 (30)*	0.0067 (26)*	0.0048 (19)*	0.0049 (20)*	0.0034 (16)*
SUM	0.0361	0.0346	0.0406	0.0261	0.0248	0.0251	0.0213‡
7-mm Pupil							
S_3	0.2451 (70)	0.9766 (31)*	0.7036 (35)*	0.6530 (40)*	0.5442 (43)*	0.7340 (48)*	0.6523 (43)*
S_4	0.0856 (30)	2.5934 (69)*	1.5906 (65)*	1.2154 (60)*	0.9999 (57)*	1.1520 (52)*	0.9881 (57)*
SUM	0.3303	3.5700*	2.2942*	1.8684*	1.5440*	1.8860*	1.6404*

*$P<.001$ compared with the preoperative value.
†$P<.01$ compared with the preoperative value.
‡$P<.05$ compared with the preoperative value.
**S_3 indicates third-order coma-like aberrations; S_4, fourth-order spherical-like aberrations; and SUM, the sum of the coma-like and spherical-like aberrations. The percentages in parentheses indicate the proportion of the SUM.

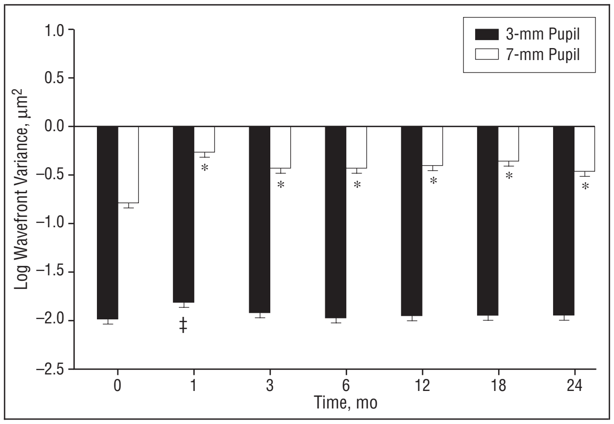

Figure 2. *Coma-like aberration (S_3). The log of the wavefront coma-like variance in square micrometers is plotted as a function of time after surgery in months. Note that for a 3-mm pupil, coma-like aberration increases 1 month after surgery but then returns to preoperative values by 3 months. For a 7-mm pupil, however, coma-like aberration increases and never returns to preoperative values. Asterisks indicate highly significant difference ($P<.001$) from preoperative value; double dagger, significant difference ($P<.05$); and error bars, SEM.*

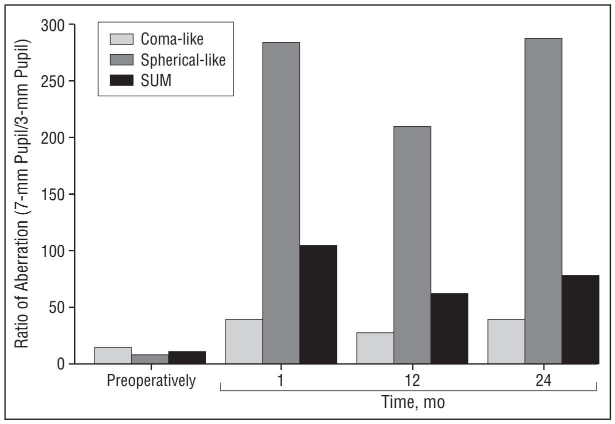

Figure 3. *Effect of pupillary dilation from 3 to 7 mm on coma-like (S_3), spherical-like (S_4), and total (SUM) aberration. Coma-like aberration is affected by pupillary dilation to a larger degree in the cornea after photorefractive keratectomy (40-fold) than in the preoperative cornea (12-fold). Spherical-like aberration shows only a small increase (6-fold) with pupillary dilation preoperatively, but a very large increase (300-fold) with pupillary dilation after photorefractive keratectomy. This change probably does not affect high-contrast Snellen acuity but may account for the halos experienced by some patients after photorefractive keratectomy and the loss of contrast sensitivity and low-contrast acuity reported by some investigators.*

preoperatively, pupillary dilation from 3 to 7 mm caused a 6-fold increase in spherical-like aberration (0.0154 to 0.0856; $P<.001$), whereas the same dilation caused a 280-fold increase in spherical-like aberration (0.0092 to 2.5934; $P<.001$) at 1 month postoperatively, and an average 200-fold increase thereafter.

TOTAL WAVEFRONT ABERRATION (SUM)

For a 3-mm pupil, there was no significant change in the total wavefront aberration (**Figure 5**). For a 7-mm pupil, the total wavefront aberration increased 11-fold from the preoperative value ($P<.001$) and never returned to the preoperative value ($P<.001$). Furthermore, whereas pupillary dilation from 3 to 7 mm in the preoperative eye caused only a 9-fold increase in total wavefront aberration, the same dilation caused a 100-fold increase 1 month after surgery, and an approximately 70-fold increase thereafter.

For a 3-mm pupil, coma-like aberrations were dominant before surgery (**Figure 6** and Table 5), accounting for approximately 60% of the total aberration, and remained dominant postoperatively. For a 7-mm pupil, however, coma-like aberrations were dominant before surgery (70% of the total aberration), but postoperatively, spherical aberration became dominant, representing about 70% of the total aberration at 1 month and about 60% thereafter. The magnitude of the induced aberration increased as a function of attempted correction (**Figure 7**).

VISUAL ACUITY

In the postoperative period, correlations between the induced aberrations and visual acuity showed some statistical significance (**Table 6**). These correlations, albeit weak, persisted throughout the follow-up period for the 3-mm pupil but were present only in the early postoperative period for the 7-mm pupil.

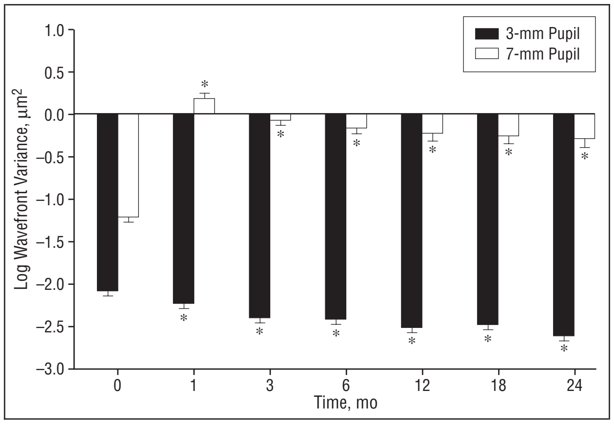

Figure 4. *Spherical-like aberration (S_4). The log of the wavefront spherical-like variance in square micrometers is plotted as a function of time after surgery in months. Note that for a 3-mm pupil, spherical-like aberration decreases 1 month after surgery and never returns to preoperative values whereas for a 7-mm pupil, spherical-like aberration increases markedly and never returns to preoperative values. Asterisks indicate highly significant difference (*P$<$*.001) from preoperative value; error bars, SEM.*

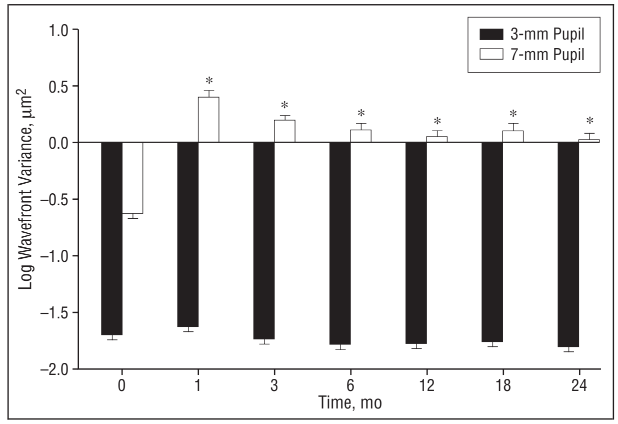

Figure 5. *Total wavefront aberration (SUM). The log of the wavefront variance in square micrometers is plotted as a function of time after surgery in months. Note that for a 3-mm pupil, the total aberration does not change significantly after photorefractive keratectomy. However, for a 7-mm pupil, it increases dramatically and never returns to preoperative values. Asterisks indicate highly significant difference (*P$<$*.001) from preoperative value; error bars, SEM.*

COMMENT

Because the eye lacks rotational symmetry, the concept of spherical aberration is not strictly applicable to the eye. In studies of the optics of the eye, the concept of wavefront aberration is more appropriate. Videokeratography, which produces an analysis of corneal surface curvature based on the radii of corneal curvature at points interpolated from reflected mires,[48,49] allows the wavefront aberration of the cornea to be calculated and separated into coma-like and spherical-like components.[36] Our results indicate that PRK increases the wavefront variance of the cornea and changes the relative contributions of coma-like and spherical-like aberrations to the total aberration. We found that, with respect to a reference sphere, the preoperative cornea displays negative spherical aberration as indicated by the average *K*, *M*, and *O* coefficients. This is consistent with the analysis of normal corneas by Howland et al[45] and predicts that the curvature of the normal cornea decreases as one proceeds away from the apex. The postoperative values reflect positive spherical aberration consistent with the changes seen on color-coded maps of increasing curvature as one proceeds away from the apex.

In addition, whereas pupillary dilation in the normal eye causes a minimal increase in aberration, pupillary dilation from 3 to 7 mm in the eye after PRK dramatically increased the amount and character of the aberrations. In the preoperative eye, opening the entrance pupil from 3 to 7 mm increased the total aberration 9-fold, the coma-like aberration 12-fold, and the spherical-like aberration about 6-fold. After PRK, the same pupillary dilation increased total aberration 100-fold; coma-like aberration, 40-fold; and spherical-like aberration, almost 300-fold. In effect, PRK may permanently increase the amount of coma-like aberration for a 7-mm pupillary diameter and spherical-like aberration for both 3- and 7-mm pupillary diameters. The magnitude of the induced aberration appears to be a function of attempted correction. These findings are in

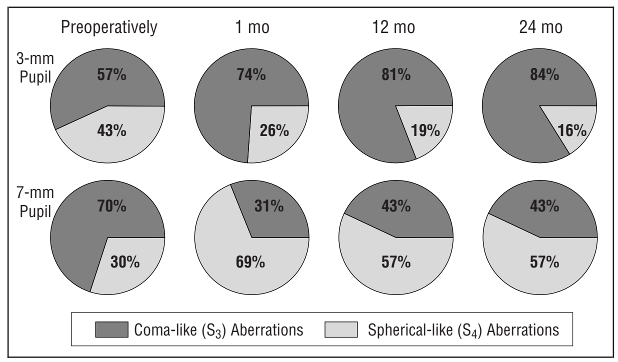

Figure 6. *Contributions to the total wavefront by coma-like and spherical-like aberrations with a 3- and a 7-mm pupil. With a 3-mm pupil, coma-like aberrations remain dominant throughout the follow-up period. With a 7-mm pupil, however, note the transition from the coma-dominant preoperative cornea to the cornea after photorefractive keratectomy dominated by spherical-like aberration.*

agreement with clinical findings of increasing incidence of glare, halos, and disturbances of night vision with smaller ablation diameter,[17-19,50,51] as well as larger pupillary size[18,50-53] and attempted correction.[6] They are also consistent with the findings of Seiler et al,[23] which describe an increase in spherical aberration with pupillary dilation in corneas that have undergone PRK but not in normal corneas, and the findings of O'Brart et al,[19,20] which show that patients who complain of large-diameter halos have pupillary sizes greater than 7 mm and large corrections. Similar calculations have been performed by Applegate et al[28,38] using data from patients who had undergone radial keratotomy; they found larger coma-like and spherical-like aberrations than those we found for PRK[38] and an excellent correlation between the square root of the surgically induced change in the wavefront variance and the surgically induced change in the equivalent spherical correction.[54] Further, in radial keratotomy, Applegate et al[38] demonstrated that for a 7-mm–diameter pupil, as the clear optical zone decreased in diameter, wavefront variance increased and visual performance decreased. Oliver et al[39] calculated modula-

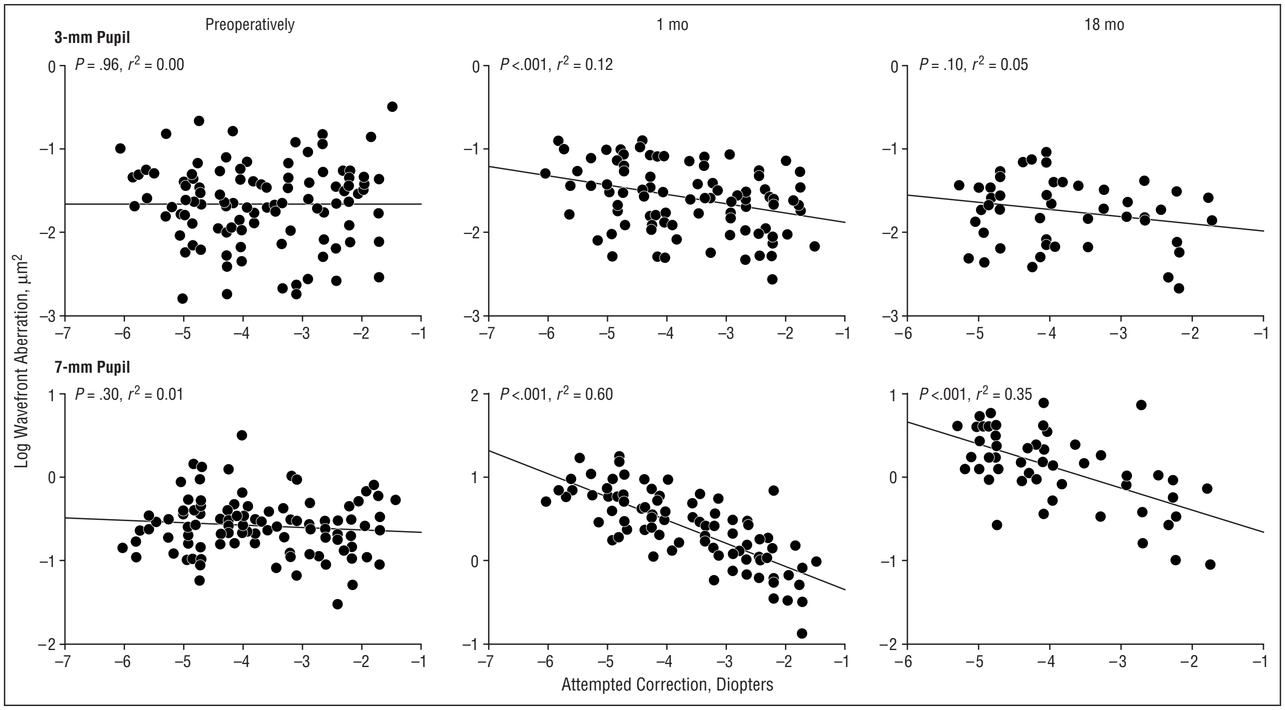

Figure 7. *The relationship between attempted correction and induced total aberration (SUM) for both 3- and 7-mm pupils. The amount of induced aberration increases with the amount of attempted correction.* P *values and regression coefficients for the linear regression are given for each graph.*

tion transfer functions after PRK and concluded that PRK induced significant optical aberrations, particularly for large-diameter pupils. They also demonstrated that these effects were ameliorated to some extent for the largest (6-mm) treatment zone.

The increase in spherical aberration after PRK for myopia and its dependence on pupillary size and attempted correction can probably be explained on the basis of a careful study of corneal topography. The normal cornea is aspheric, with less curvature peripherally than centrally, which partially compensates for spherical aberration. However, PRK for myopia creates a multifocal cornea in which the peripheral cornea is steeper than its central aspect. In the normal cornea, the paraxial rays are focused in front of the peripheral rays, whereas the change in corneal topography effected by PRK results in the paraxial rays being focused posterior to the peripheral rays. This is illustrated by coefficients *K* and *M*, which show negative spherical aberration preoperatively and positive spherical aberration postoperatively. As the pupil dilates, bringing in rays refracted at the junction of the treated and untreated cornea, increased aberration reduces contrast in the retinal image.[13,22] Larger attempted corrections, which result in deeper ablations and greater changes in corneal power from the treated to the untreated zones, are, as expected, correlated with greater amounts of induced aberration.

A novel finding in our analysis of corneas after PRK is the large amount of vertical coma-like aberration (Table 4, Z_8) in postoperative corneas with 7-mm pupils. Because there is no obvious asymmetry in the operative technique, it is possible that this aberration is due to sagging of the weakened cornea under the influence of gravity. We intend to test this theoretical explanation using the thin-shell corneal model of Howland et al.[55]

We agree with Hersh et al[22,56] that surface smoothing, an increase in ablation zone diameter, and the use of peripheral blend zones may in the future improve the optical results of PRK. Increasing the diameter of the ablation zone could push the edge of the ablated region peripherally beyond the edge of the entrance pupil. However, many patients undergoing PRK are young, with an average pupillary size of 7.5 mm; for such patients, this approach would require a large ablation diameter, and a larger ablation zone would also increase the sagittal depth of a spherical ablation, which could increase the incidence of stromal haze. One solution to avoid this potential complication is the use of an aspheric ablation.[57]

Seiler et al[23] also found a high inverse correlation between effective spherical aberration and visual acuity under glare conditions and between subjective glare and/or halo and attempted correction. The problem with devices that measure glare visual acuity is that they cause pupillary constriction, creating a pupil that is small (close to the diffraction limited pupil), and they provide little information about how the junction between the treated and untreated cornea affects vision. We did not look at glare visual acuity, but we did find a positive ($P<.001$), although weak ($r = 0.54$), correlation between visual acuity and coma-like, as well as spherical-like, aberrations 1 month after surgery, when these aberrations appeared to be greatest. We found it somewhat surprising that these aberrations reached levels high enough in the early postoperative period to affect Snellen acuity. Because most of the patients eventually achieved excellent best spectacle-corrected visual acuity, however, it is somewhat diffi-

Table 6. Correlation of Induced Aberrations to Best Spectacle-Corrected Visual Acuity**

Aberration	Preoperatively (n = 112)	Time After Surgery, mo 1 (n = 94)	3 (n = 103)	6 (n = 91)	12 (n = 60)	18 (n = 53)	24 (n = 44)
		3-mm Pupil					
S_3	0.008	0.384*	0.231‡	−0.009	0.248‡	0.397	0.461‡
S_4	−0.045	0.308†	0.226‡	−0.018	0.051	0.508‡	0.420‡
SUM	−0.014	0.534*	0.249‡	−0.002	−0.019	0.378	0.249
		7-mm Pupil					
S_3	−0.019	0.219‡	0.0489	0.155	0.035	0.244	0.138
S_4	−0.041	0.418*	0.151	0.177	0.055	0.066	0.301
SUM	−0.044	0.420*	0.213‡	0.155	0.008	0.131	0.250

*$P<.001$ compared with the preoperative value.
†$P<.01$ compared with the preoperative value.
‡$P<.05$ compared with the preoperative value.
**Values are Spearman rank correlations of the best spectacle-corrected visual acuity (logMAR) to the induced optical aberrations. S_3 indicates third-order coma-like aberrations; S_4, fourth-order spherical-like aberrations; and SUM, the sum of the coma-like and spherical-like aberrations.

cult to ascertain the predictive value of these coefficients beyond the first month after surgery.

It is not surprising that these correlations weaken or are absent by 6 months after surgery, in that this level of aberration would not be expected to affect high-contrast Snellen acuity, but effects on contrast sensitivity may account for some of the diffuse complaints that patients report after PRK, such as halos and glare and difficulty with driving at night. Recently, Verdon et al[58,59] reported losses in low-contrast acuity following PRK performed using erodible masks. In addition, Applegate et al[37,38] reported that after radial keratotomy, the area under the contrast sensitivity function decreases as the wavefront variances (similar to the amounts reported herein) increase. Our results indicate that the total aberration does not change for a 3-mm pupil after PRK but may be permanently affected for larger pupillary sizes.

Photorefractive keratectomy has been shown to be effective in the correction of myopia. However, it causes increases in both coma-like and spherical-like aberrations that are dependent on attempted correction and pupillary size. Qualitative topographic pattern classification has been shown not to correlate with subjective glare or halo.[56] Therefore, quantitative descriptors of corneal topography determined by computer algorithm and designed to augment the information given by videokeratography are needed.[29,60,61] Spherical aberration has been proposed as a quantitative descriptor of corneal topography[23]; however, our results show that the aberrations of both preoperative and postoperative corneas contain significant coma-like components. Wavefront analysis of the corneal aberrations includes and describes spherical aberration, but also includes quantitative descriptions of odd-order, coma-like terms.

This method has already been demonstrated to be useful in explaining visual results following refractive surgery.[37,38] However, calculating the exact corneal aberrations with respect to the ideal shape of the cornea that would render the eye diffraction limited over all physiologic pupillary diameters of interest requires knowledge of the total aberration of the eye's optical system and cannot be calculated from videokeratographic data alone.[43] Our corneal wavefront analysis has, by necessity, used arbitrary reference surfaces. In the future, measurements of the eye's total aberration may be used to design the ideal corneal first-surface shape to minimize the aberrations of the eye, and videokeratography in turn may be used to evaluate the error between the desired and obtained shape.[43] Until then, quantitative descriptors of the corneal aberrations based purely on videokeratography may be useful in explaining the current visual results and improving optical outcomes in the future.

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REFERENCES

1. McDonald MB, Liu JC, Byrd TJ, et al. Central photorefractive keratectomy for myopia: partially sighted and normally sighted eyes. *Ophthalmology.* 1991;98:1327-1337.
2. Seiler T, Wollensak J. Myopic photorefractive keratectomy with the excimer laser: one-year follow-up. *Ophthalmology.* 1991;98:1156-1163.
3. Butuner Z, Elliot DB, Gimbel HV, Slimmon S. Visual function one year after excimer laser photorefractive keratectomy. *J Refract Corneal Surg.* 1994;10:625-630.
4. O'Brart DPS, Lohmann CP, Fitzke FW, et al. Disturbances in night vision after excimer laser photorefractive keratectomy. *Eye.* 1994;8:46-51.
5. Piebenga LW, Matta CS, Deitz MR, Tauber J, Irvine JW, Sabates FN. Excimer photorefractive keratectomy for myopia. *Ophthalmology.* 1993;100:1335-1345.

6. Halliday B. Refractive and visual results and patient satisfaction after excimer laser photorefractive keratectomy for myopia. *Br J Ophthalmol*. 1995;79:881-887.
7. Waring GO III, O'Connell MA, Maloney RK, et al. Photorefractive keratectomy for myopia using a 4.5-millimeter ablation zone. *J Refract Surg*. 1995;11:170-180.
8. Shimizu K, Amano S, Tanaka S. Photorefractive keratectomy for myopia: one year follow up in 97 eyes. *J Refract Corneal Surg*. 1994;10(suppl):S178-S187.
9. Ambrosio G, Cennamo G, De Marco R, Loffredo L, Rosa N, Sebastiani A. Visual function before and after photorefractive keratectomy for myopia. *J Refract Corneal Surg*. 1994;10:129-136.
10. Harrison JM, Tennant TB, Gwin MC, et al. Forward light scatter at one month after photorefractive keratectomy. *J Refract Surg*. 1995;11:83-88.
11. Seiler T, Holschbach A, Derse M, Jean B, Genth U. Complications of myopic photorefractive keratectomy with the excimer laser. *Ophthalmology*. 1994;101:153-160.
12. Maguire LJ. Keratorefractive surgery, success, and the public health [editorial]. *Am J Ophthalmol*. 1995;117:394-398.
13. Ficker LA, Bates AK, Steele AD, et al. Excimer laser photorefractive keratectomy for myopia: 12 month follow-up. *Eye*. 1993;7:617-624.
14. Hamberg-Nystrom H, Fagerholm P, Tengroth B, Epstein D. Photorefractive keratectomy for low myopia at 5 mm treatment diameter: a comparison of two excimer lasers. *Acta Ophthalmol*. 1994;72:453-456.
15. Kim JH, Hahn TW, Lee YC, Joo CK, Sah WJ. Photorefractive keratectomy in 202 myopic eyes: one year results. *Refract Corneal Surg*. 1993;9(suppl):S11-S16.
16. Hamberg-Nystrom H, Tengroth B, Fagerholm P, Epstein D, van der Kwast EM. Patient satisfaction following photorefractive keratectomy for myopia. *J Refract Surg*. 1995;11(suppl):S335-S336.
17. O'Brart DPS, Lohmann CP, Fitzke FW, Smith SE, Kerr-Muir MG, Marshall J. Night vision after excimer laser photorefractive keratectomy: haze and halos. *Eur J Ophthalmol*. 1994;4:43-51.
18. Gartry DS, Kerr-Muir MG, Marshall J. Photorefractive keratectomy with an argon fluoride excimer laser: a clinical study. *Refract Corneal Surg*. 1991;7:420-435.
19. O'Brart DPS, Gartry DS, Lohmann CP, Kerr Muir MG, Marshall J. Excimer laser photorefractive keratectomy for myopia: comparison of 4.00- and 5.00-millimeter ablation zones. *J Refract Corneal Surg*. 1994;10:87-94.
20. O'Brart DPS, Lohmann CP, Fitzke FW, et al. Discrimination between the origins and functional implications of haze and halo at night after photorefractive keratectomy. *J Refract Corneal Surg*. 1994;10:S281.
21. Maguire LJ, Bechara S. Epithelial distortions at the ablation zone margin after excimer laser photorefractive keratectomy for myopia. *Am J Ophthalmol*. 1994; 117:809-810.
22. Hersh PS, Shah SI, Geiger D, Holladay JT, The Summit Photorefractive Keratectomy Topography Study Group. Corneal optical irregularity after excimer laser photorefractive keratectomy. *J Cataract Refract Surg*. 1996;22:197-204.
23. 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(suppl):155-165.
24. Maguire LJ, Zabel RW, Parker P, Lindstrom RL. Topography and raytracing analysis of patients with excellent visual acuity 3 months after excimer laser photorefractive keratectomy for myopia. *Refract Corneal Surg*. 1991;7:122-128.
25. Rashid ER, Waring GO III. Complications of refractive keratotomy. In: Waring GO III, ed. *Refractive Keratotomy for Myopia and Astigmatism*. St Louis, Mo: Mosby–Year Book; 1992:863-936.
26. Applegate RA, Trick LR, Meade DL, Hartstein J. Radial keratotomy increases the effects of disability glare: initial results. *Ann Ophthalmol*. 1987;19:293-297.
27. Applegate RA, Gansel KA. The importance of pupil size in optical quality measurements following radial keratotomy. *Refract Corneal Surg*. 1990;6:47-54.
28. Applegate RA, Howland HC, Buettner J, Cottingham AJ, Sharp RP, Yee RW. Corneal aberrations before and after radial keratotomy (RK) calculated from videokeratometric measurements. In: *Vision Science and Its Applications*. Washington, DC: Optical Society of America; 1994:58-61. 1994 Technical Digest Series, Vol 2.
29. Wilson SE, Klyce SD. Quantitative descriptors of corneal topography: a clinical study. *Arch Ophthalmol*. 1991;109:349-353.
30. Maloney RK, Bogan SJ, Waring GO III. Determination of corneal image-forming properties from corneal topography. *Am J Ophthalmol*. 1993;115:31-41.
31. Greivenkamp JE, Schwiegerling J, Miller JM, Mellinger MD. Visual acuity modeling using optical raytracing of schematic eyes. *Am J Ophthalmol*. 1995;120: 227-240.
32. Olsen T, Dam-Johansen M, Bek T, Hjortdal JO. Evaluating surgically induced astigmatism by Fourier analysis of corneal topography data. *J Cataract Refract Surg*. 1996;22:318-323.
33. Hjortdal JO, Erdmann L, Bek T. Fourier analysis of video-keratographic data: a tool for separation of spherical, regular astigmatic and irregular astigmatic corneal power components. *Ophthalmic Physiol Opt*. 1995;15:171-185.
34. 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.
35. Howland HC, Howland B. A subjective method for the measurement of monochromatic aberrations of the eye. *J Opt Soc Am*. 1977;67:1508-1518.
36. Howland HC, Glasser A, Applegate R. Polynomial approximations of corneal surfaces and corneal curvature topography. In: *Ophthalmic and Visual Optics*. Washington, DC: Optical Society of America; 1992:34-37. 1992 Technical Digest Series, Vol 3.
37. Applegate RA, Howland HC, Buettner J, Cottingham AJ, Sharp RP, Yee RW. Changes in the aberration structure of the RK cornea from videokeratographic measurements. *Invest Ophthalmol Vis Sci*. 1994;35(suppl):1740. Abstract.
38. Applegate RA, Howland HC, Sharp RP, Cottingham AG, Yee RW. Corneal aberrations and visual performance after radial keratotomy. *J Refract Surg*. 1998; 14:397-407.
39. Oliver KM, Hemenger RP, Corbett MC, et al. Corneal optical aberrations induced by photorefractive keratectomy. *J Refract Surg*. 1997;13:246-254.
40. Holladay JT, Lynn MJ, Waring GO III, Gemmill M, Keehn GC, Fielding B. The relationship of visual acuity, refractive error, and pupil size after radial keratotomy. *Arch Ophthalmol*. 1991;109:70-76.
41. Liu JC, McDonald MB, Varnell R, Andrade HA. Myopic excimer laser photorefractive keratectomy: an analysis of clinical correlations. *Refract Corneal Surg*. 1990;6:321-328.
42. McDonald MB, Frantz JM, Klyce SD, et al. Central photorefractive keratectomy for myopia: the blind eye study. *Arch Ophthalmol*. 1990;108:799-808.
43. Applegate RA, Howland HC. Refractive surgery, optical aberrations, and visual performance. *J Refract Surg*. 1997;13:295-299.
44. Howland HC, Buettner J. Computing high order wave aberration coefficients from variations of best focus for small artificial pupils. *Vision Res*. 1989;29:979-983.
45. Howland HC, Buettner J, Applegate RA. Computation of the shapes of normal corneas and their monochromatic aberrations from videokeratometric measurements. In: *Vision Science and Its Applications*. Washington, DC: Optical Society of America; 1994:54-57. 1994 Technical Digest Series, Vol 2.
46. Schwiegerling J, Greivenkamp JE, Miller JM. Representation of videokeratoscopic height data with Zernike polynomials. *J Opt Soc Am A*. 1995;12:2105-2113.
47. Malacara D, ed. *Optical Shop Testing*. 2nd ed. New York, NY: John Wiley & Sons, Inc; 1992:470-472.
48. Maguire LJ, Singer DE, Klyce SD. Graphic presentation of computer-analyzed keratoscope photographs. *Arch Ophthalmol*. 1987;105:223-230.
49. Klyce SD, Smolek MK. Corneal topography of excimer laser photorefractive keratectomy. *J Cataract Refract Surg*. 1993;19(suppl):S122-S130.
50. Anschütz T. Pupil size, ablation diameter, and halo incidence after photorefractive keratectomy. In: *Best Papers of Sessions: Symposium on Cataract, IOL and Refractive Surgery, April 1-5, 1995, San Diego, CA*. Fairfax, VA: American Society of Cataract and Refractive Surgery; 1995.
51. Roberts CW, Koester CJ. Optical zone diameters for photorefractive corneal surgery. *Invest Ophthalmol Vis Sci*. 1993;34:2275-2281.
52. Maloney RK. Corneal topography and optical zone location in PRK. *Refract Corneal Surg*. 1990;6:363-371.
53. Diamond S. Excimer laser photorefractive keratectomy (PRK) for myopia present status: aerospace considerations. *Aviat Space Environ Med*. 1995;66: 690-693.
54. Applegate RA, Howland HC, Hilmantel G. Corneal aberrations increase with the magnitude of the RK refractive correction. *Optom Vis Sci*. 1996;73:585-589.
55. Howland HC, Rand RH, Lubkin SR. A thin-shell model of the cornea and its application to corneal surgery. *Refract Corneal Surg*. 1992;8:183-186.
56. Hersh PS, Schwartz-Goldstein BH, Summit Photorefractive Keratectomy Topography Study Group. Corneal topography of phase III excimer laser photorefractive keratectomy: characterization and clinical effects. *Ophthalmology*. 1995; 102:963-978.
57. Seiler T, Genth U, Holschbach A, Derse M. Aspheric photorefractive keratectomy with excimer laser. *Refract Corneal Surg*. 1993;9:166-172.
58. Verdon W, Maloney RK, Bullimore MA. Visual performance following photorefractive keratectomy. In: *Vision Science and Its Applications*. Washington, DC: Optical Society of America; 1994:62-65. 1994 Technical Digest Series, Vol 2.
59. Verdon W, Bullimore M, Maloney RK. Visual performance after photorefractive keratectomy: a prospective study. *Arch Ophthalmol*. 1996;114:1465-1472.
60. Dingeldein SA, Klyce SD, Wilson SE. Quantitative descriptors of corneal shape derived from computer-assisted analysis of photokeratographs. *Refract Corneal Surg*. 1989;5:372-378.
61. Wilson SE, Klyce SD, McDonald MB, Liu JC, Kaufman HE. Changes in corneal topography after excimer laser photorefractive keratectomy for myopia. *Ophthalmology*. 1991;98:1338-1347.