Analysis of Customized Corneal Ablations: Theoretical Limitations of Increasing Negative Asphericity

Damien Gatinel,[1] Jacques Malet,[2] Thanh Hoang-Xuan,[1] and Dimitri T. Azar[1,3]

Purpose. To determine the ablation depths of customized myopic excimer laser photoablations performed to change corneal asphericity after laser in situ keratomileusis (LASIK) and photorefractive keratectomy (PRK).

Methods. A mathematical model of aspheric myopic corneal laser surgery was generated. The initial corneal surface was modeled as a conic section of apical radius R_1 and asphericity Q_1. The final corneal surface was modeled as a conic section of apical R_2 and asphericity Q_2, where R_2 was calculated from the paraxial optical formula for a given treatment magnitude (D), and Q_2 was the intended final asphericity. The aspheric profile of ablation was defined as the difference between the initial and final corneal profiles for a given optical zone diameter (S), and the maximal depth of ablation was calculated from these equations. Using the Taylor series expansion, an equation was derived that allowed the approximation of the central depth of ablation (t_0) for various magnitudes of treatment, optical zone diameters, and asphericity. In addition to the Munnerlyn term (M), incorporating Munnerlyn's approximation ($-D \cdot S^2/3$), the equation included an asphericity term (A) and a change of asphericity term (Δ). This formula ($t_0 = M + A + \Delta$) was used to predict the maximal depth of ablation and the limits of customized asphericity treatments in several theoretical situations.

Results. When the initial and final asphericities were identical (no intended change in asphericity; $Q_1 = Q_2$; $\Delta = 0$), the maximal depth of ablation ($t_0 = M + A$) increased linearly with the asphericity Q_1. To achieve a more prolate final asphericity ($Q_2 < Q_1$; $dQ < 0$; $\Delta > 0$), the maximal depth of ablation ($M + A + \Delta$) was increased. For treatments in which Q_2 was intended to be more oblate than Q_1 ($Q_2 > Q_1$; $dQ > 0$; $\Delta < 0$), the maximal depth of ablation was reduced. These effects sharply increased with increasing diameters of the optical zone(s). Similarly, in the case of PRK, the differential increase in epithelial thickness in the center of the cornea compared with the periphery resulted in increased oblateness.

Conclusions. Aspheric profiles of ablation result in varying central depths of ablation. Oblateness of the initial corneal surface, intentional increase in negative asphericity, and enlargement of the optical zone diameter result in deeper central ablations. This may be of clinical importance in planning aspheric profiles of ablation in LASIK procedures to correct spherical aberration without compromising the mechanical integrity of the cornea. (*Invest Ophthalmol Vis Sci.* 2002;43:941–948)

Current excimer photoablations correct spherical myopic errors by removing a certain volume of corneal tissue to flatten the central corneal surface. Although the specific algorithms used by laser systems are proprietary, they generally derive from paraxial theoretical models similar to that of Munnerlyn et al.,[1] in which the initial and final corneal surfaces are assumed to be spherical. Spherical aberrations have been shown to be exaggerated after various excimer laser treatments to correct myopic refraction errors including photorefractive keratectomy (PRK)[2–4] and laser in situ keratomileusis (LASIK).[5,6] The corneal asphericity is modified after PRK[7] and LASIK,[5] and this may account for the observed increase in spherical aberrations,[4,8] in which there is no refractive error in the center of the pupil but an increasing error in the annular zones surrounding the center of the entrance pupil. Even if the image formed by the eye is focused on the retina after the refractive surgical procedure, the quality of this image may be altered by spherical aberrations, especially in patients with large pupil diameters.

Enlargement of the ablation diameter may be helpful in reducing the optical aberrations after excimer photoablation, but this results in increased depth of ablation. Deep ablations could weaken the mechanical integrity of the cornea,[9] as suggested by several reports of keratectasia after LASIK in cases with high myopia corrections.[10–12] Some investigators have proposed aspheric patterns of ablation to minimize spherical aberrations.[13–16] However, the influence of the aspheric ablations on the depth of ablation and on mechanical stability of the cornea are not known. In this study, we used a mathematical analysis to predict the theoretical maximal depth of ablation for customized aspheric ablations that would allow correction of myopia as well as adjustment of the final corneal asphericity to desired values. We investigated the influence of the initial corneal apical radius of curvature, initial asphericity, intended diopteric correction, diameter of treatment, and intended change in corneal asphericity on the maximal depth of ablation.

Materials and Methods

Maximal Depth of Ablation in Aspheric Treatments

The preoperative corneal profile in a single meridian was modeled as a conic section as described by Baker's equation[17]:

$$y^2 = 2R_1x - (1 + Q_1)x^2 \qquad (1)$$

where x and y are the coordinates on a Cartesian system with the axis of revolution along the x-axis, R_1 is the preoperative apical radius of curvature, and Q_1 is the preoperative shape factor.

From the [1]Ophthalmology Service, Bichat Hospital, Rothschild Foundation, Paris VII University, Paris, France; the [2]Institute of Statistics, Pierre et Marie Curie University, Paris, France; and the [3]Massachusetts Eye and Ear Infirmary and Schepens Eye Research Institute, Harvard Medical School, Boston, Massachusetts.

Supported by the Research to Prevent Blindness Lew R. Wasserman Merit Award (DTA), the Corneal Transplantation Research Fund, Boston, Massachusetts (DTA), and the Massachusetts Lions Eye Research Award, Northborough, Massachusetts (DTA).

Submitted for publication July 30, 2001; revised October 26, 2001; accepted November 6, 2001.

Commercial relationships policy: N.

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be marked "*advertisement*" in accordance with 18 U.S.C. §1734 solely to indicate this fact.

Corresponding author: Dimitri T. Azar, Director, Cornea and Refractive Surgery Services, Massachusetts Eye and Ear Infirmary, 243 Charles Street, Boston, MA 02114; dazar@meei.harvard.edu.

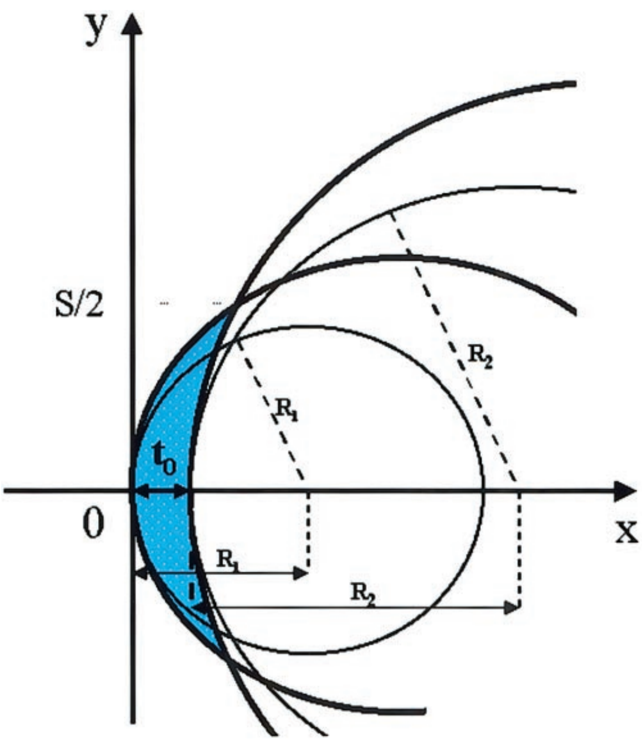

FIGURE 1. The aspheric profile of ablation (*blue* zone) corresponds to the difference in sagittal height between the initial and final corneal surfaces on an optical zone of diameter S. The initial and final corneal profiles are aspheric and modeled as conic sections of apical radii R_1 and R_2, and asphericities of Q_1 and Q_2, respectively. The maximal depth of ablation (t_0) occurs at the center of the optical zone.

The postoperative corneal profile was modeled as a conic section of apical radius R_2 and shape factor Q_2:

$$y^2 = 2R_2x - (1 + Q_2)x^2 \quad (2)$$

where Q_2 is the intended shape factor, and R_2 is calculated from the intended magnitude of treatment (D) by the paraxial formula:

$$D = (n - 1) \cdot \left(\frac{1}{R_2} - \frac{1}{R_1}\right) \quad (3)$$

where $R_2 > R_1$ for myopia; $D < 0$.

The intended change in asphericity (dQ) was calculated as the difference between the preoperative and the postoperative asphericities: $dQ = (Q_2 - Q_1)$. When $dQ < 0$ ($Q_1 > Q_2$), the final corneal surface is more prolate (or less oblate). When $dQ > 0$ ($Q_1 < Q_2$), the final surface is more oblate (or less prolate). When $dQ = 0$, the initial and final corneal surfaces have the same asphericity.

The pattern of ablation within an optical zone of diameter (S) was calculated as the difference in sagittal height between corresponding points of the initial and final surfaces, intersecting at the edge of the optical zone ($y = S/2$), which corresponds to the material removed between two aspheric surfaces whose curvature difference results in the targeted change in apical power and asphericity (Fig. 1). The depth of ablation is zero at $y = S/2$. It increases as y approaches 0 (Fig. 1).

The maximal depth of ablation (t_0) occurred at the center of the optical zone ($y = 0$). We used finite analysis to calculate t_0:

$$t_0 = \frac{R_1 - \sqrt{R_1^2 - (1 + Q_1)\left(\frac{S}{2}\right)^2}}{(1 + Q_1)} - \frac{R_2 - \sqrt{R_2^2 - (1 + Q_2)\left(\frac{S}{2}\right)^2}}{(1 + Q_2)} \quad (4)$$

The Taylor Series Expansion for Depth Approximation

By using the Taylor series expansion up to the second order, t_0 could be approximated by:

$$t_0 = \frac{-S^2D}{3} + \left(\frac{3S^2}{16R_1^2}\right)\left(\frac{-S^2D}{3}\right) + \left(\frac{3Q_1S^2}{16R_1^2}\right)\left(\frac{-S^2D}{3}\right) - \frac{dQS^4}{128R_1^3} \quad (5)$$

or:

$$t_0 = M + A + \Delta \quad (6)$$

where

$$M = \frac{-S^2D}{3} + \left(\frac{3S^2}{16R_1^2}\right)\left(\frac{-S^2D}{3}\right) \quad (7)$$

$$A = \left(\frac{3Q_1S^2}{16R_1^2}\right)\left(\frac{-S^2D}{3}\right) \quad (8)$$

and

$$\Delta = \frac{-dQS^4}{128R_1^3} \quad (9)$$

Equations 5 and 6 allow prediction of the effect of various surgical (D, S, dQ) and clinical parameters (R_1, Q_1) on the maximal depth of ablation (t_0), which is the sum of three terms, each featuring the several clinical and surgical adjustable parameters. The first term is the Munnerlyn term M, which is the sum of Munnerlyn approximation $\left(\frac{-S^2D}{3}\right)$ and the second-order paraxial binomial expansion (equation 7). The second term is the initial asphericity term (A) and is a function of the initial shape factor (Q_1) and of the Munnerlyn approximation (equation 8). The third term is the asphericity change term (Δ) which is a function of the intended change in corneal asphericity (dQ), the diameter of the optical zone to the fourth power (S^4), and the initial apical corneal radius of curvature to the third power (R_1^3; equation 9).

Comparison of Munnerlyn, Analytical, and Approximation Methods

The theoretical maximal depths of ablations were compared for R_1 of 7.8 mm, Q_1 of -0.2, and S of 6 mm, using our approximation method (equation 5), and the analytical method (equation 4). Comparisons were performed for -2, -6, and -10 D corrections, while varying Q_2 between -0.6 and $+0.2$. The contributions of the Munnerlyn term (M; equation 7), the asphericity term (A; equation 8), and the asphericity change term (Δ; equation 9) were also calculated for R_1 of 7.8 mm, Q_1 of 0.2, and Q_2 of -0.2 (dQ of -0.4). They were compared for magnitudes of treatments of -3, -6, -9, -12, and -15 D.

Ablation Depth Comparisons for Various Values of Q_1 and dQ

We calculated the depths of ablation for treatment magnitudes of -1 to -15 D as a function of the initial asphericity Q_1. For $dQ = 0$ ($Q_1 = Q_2$), we varied Q_1 between -0.7 and $+0.5$ and compared the depths of ablation. For situations in which more prolate asphericity was intended ($dQ < 0$), we calculated the depths of ablation for $R_1 = 7.8$ mm, $Q_1 = -0.2$, and $S = 6$ mm. The magnitude of treatment varied between -1 and -15 D, and the depths of ablation were compared for $dQ = 0$, -0.2, -0.4, and -0.6. We also calculated and tabulated the incremental increase in ablation depth resulting from intentional in-

Table 1. Comparisons of Ablation Depths Using Equations 7, 5, and 4

Magnitude of Treatment (D)	Munnerlyn Term*	Approximated Depth†	Actual Depth‡
−1	13.35	14.83	15.00
−2	26.70	29.67	29.91
−3	40.06	44.50	44.74
−4	53.41	59.34	59.50
−5	66.76	74.17	74.17
−6	80.12	89.00	88.77
−7	93.47	103.84	103.30
−8	106.82	118.67	117.76
−9	120.18	133.51	132.15
−10	133.53	148.35	146.47
−11	146.90	163.18	160.74
−12	160.24	178.01	174.95
−13	173.60	192.85	189.10
−14	186.94	207.68	203.20

Data are maximal depth of ablation in micrometers. $R_1 = 7.8$ mm, $Q_1 = Q_2 = 1$, $S = 6$ mm.

* Equation 7.

† Equation 5.

‡ Equation 4.

crease in prolateness of the cornea ($dQ < 0$; equation 9) for treatment diameters of 4 to 8 mm and for R_1 of 7.5, 7.8, and 8.1 mm.

Influence of Epithelial Hyperplasia after PRK on Corneal Asphericity

In a previous study,[18] we showed that after conventional excimer laser treatment for myopia conforming to the Munnerlyn paraxial formula,[1] the postoperative theoretical corneal asphericity can be accurately approximated by a best-fit conic section. In initially prolate corneas, we noted a discrepancy between the clinically reported oblateness after excimer laser surgery for myopia and the theoretical prediction of increased prolateness. The discrepancy may be related to laser nomogram departures from the Munnerlyn formula, low accuracy of videotopographic measurements, and wound healing (epithelial hyperplasia, stromal remodeling).

Epithelial remodeling may modify the specific effect induced by the myopia ablation and could account for the observed clinical trend to oblateness. We used equation 9 to calculate the theoretical change in corneal asphericity induced by the difference of epithelial thickness in the center compared to the periphery of the treatment zone after a −5-D PRK myopia treatment conforming to the Munnerlyn equation. We varied the increment of central epithelial thickness between 0 and 30 μm for initial asphericity of −0.2 and R_1 of 7.8 mm. The induced increase in asphericity (oblateness) was determined for treatment diameters of 5 to 8 mm.

Results

Comparison of Munnerlyn, Analytical, and Approximation Methods

Table 1 compares the maximal depths of ablation conforming to Munnerlyn's paraxial spherical assumptions calculated from equation 7 for myopic correction of −1 to −14 D. These calculations of the sum of the Munnerlyn approximation $\left(\frac{-S^2D}{3}\right)$ and the second-order paraxial binomial expansion, were compared to theoretical aspheric treatments, by using the finite analysis method (equation 4) and our method of approximation (equation 5). The theoretical maximal depths of tissue ablation for different magnitudes of spherical myopic, treatments as calculated using equation 5, are very similar to the maximal depths of ablation calculated using equation 4. Figure 2 shows the theoretical maximal depth of laser ablation using our approximation method (equation 5) compared with the finite analysis method (equation 4) in corneas with initial radius of curvature of 7.8 mm and preoperative asphericity (Q_1) of −0.2. Both methods of calculation show that the maximal depth of ablation increases if an increase in negative asphericity is intended.

Figure 3A shows the depths of ablation predicted by the Munnerlyn approximation (left) compared with those predicted by equations 6 and 4. The contributions of equation 6 (the Munnerlyn term M, the asphericity term A, and the asphericity change term Δ), are shown for intended corrections of −3, −6, −9, −12, and −15 D and for initial R_1, Q_1, and Q_2 of 7.8 mm, +0.2, and −0.2, respectively. The Munnerlyn approximation underestimates the maximal depth of ablation compared with M of equation 6. The intended change of asphericity (dQ of −0.4; more prolate) requires additional tissue ablation of 8.5 μm.

Figure 3A confirms that, as for the profiles of ablation based on spherical models, the maximal depth of tissue ablation is proportional to the magnitude of treatment. It is also proportional to the initial asphericity (Q_1) and to the intended variation of the corneal asphericity, as the second and third terms increase linearly with their respective values.

Figure 3B shows the influence of initial asphericity on maximal depth of ablation for intended similar corrections. Figure 3B shows that the depths of ablation needed to maintain preoperative asphericity ($dQ = 0$) are greatest for oblate corneas ($Q_1 = +0.2$) and lowest for prolate corneas ($Q_1 = -0.2$). The depths of ablation are increased when an intentional change in the prolate direction is intended ($dQ = -0.4$). This increase in depth (Δ) is determined by R_1 and S, but is unrelated to Q_1 or to the magnitude of diopteric correction (D).

Ablation Depth Comparisons for Various Values of Q_1 and dQ

Equation 5 allows estimation of the maximal depth of ablation for a myopic spherical treatment: in this case, $Q_1 = 0$, and $dQ = 0$. Figure 4 shows the linear variations of the theoretical maximal depth of ablation as a function of the initial asphericity in oblate ($Q_1 > 0$) and prolate ($Q_1 < 0$) corneas.

When the final and initial asphericities are different (i.e., variation in asphericity), the maximal depth of ablation is modified from the value predicted by spherical models by an amount proportional to the absolute value of the difference between the initial and final asphericities (Fig. 5). When the final asphericity is less than the initial asphericity ($Q_2 < Q_1$; $dQ < 0$), the Δ (equation 6) is positive, and the maximal depth of ablation is increased. Conversely, when the final asphericity is more oblate ($Q_2 > Q_1$), the maximal depth of ablation is decreased. In both cases, Δ increases with the optical zone diameter to the fourth power and decreases with the apical radius of curvature to the third power. The value of this additional depth as predicted by equation 6 is independent of any variations of the magnitude of correction. Table 2 shows the values of this additional depth for an intended change of asphericity (dQ) of 0.1 and for different values for various treatment diameters (S) and for initial radii of curvature (R_1) representing normal ($R_1 = 7.8$ mm), steep ($R_1 = 7.5$ mm), and flat ($R_1 = 8.1$ mm) human corneas.

Influence of Epithelial Hyperplasia after PRK on Corneal Asphericity

Figure 6 shows the variation in corneal asphericity resulting from thickening of the central epithelium relative to the

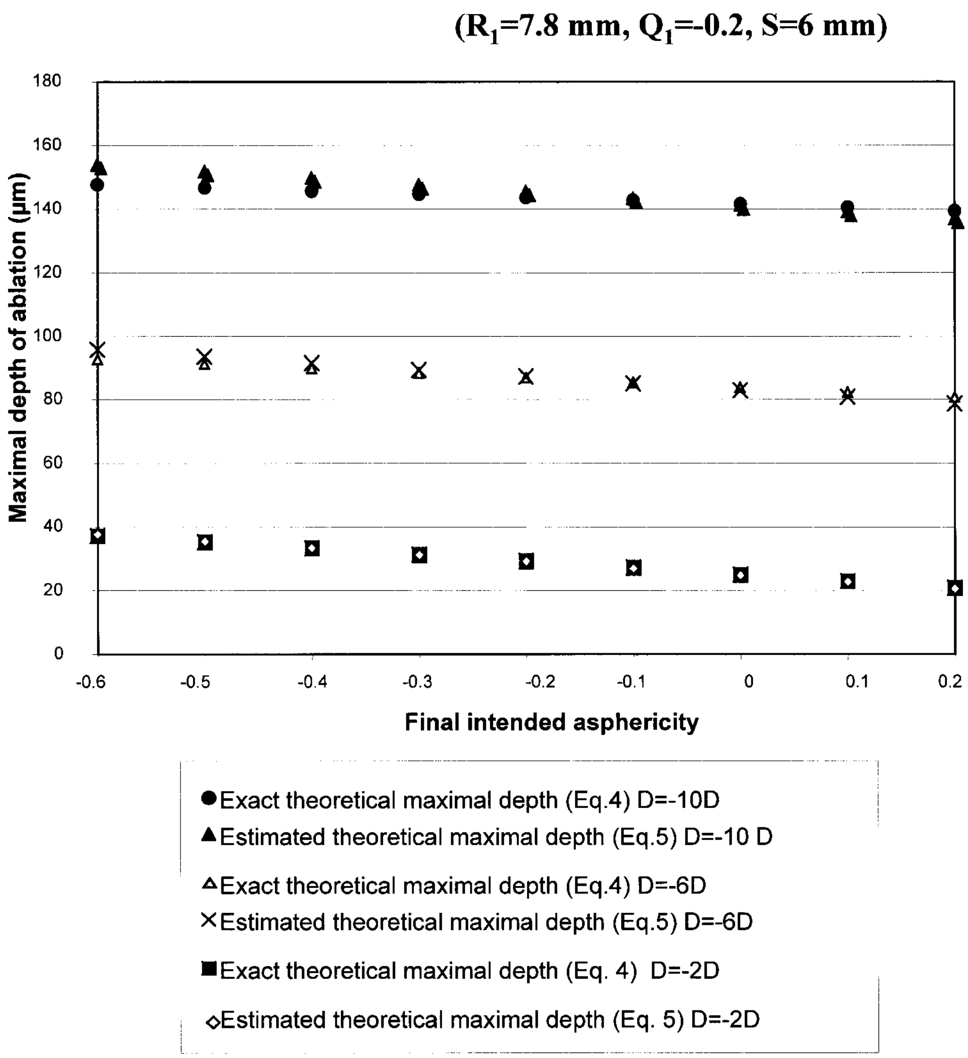

FIGURE 2. Comparison between the exact and estimated maximal depth of ablation of an aspheric profile of ablation for various final intended asphericities (Q_2). The calculations were based on the following: R_1 = 7.8 mm, Q_1 = 0.2, and S = 6 mm. For high magnitude of myopia treatment, equation 5 tends to slightly overestimate the maximal depth of ablation when the intended shape factor is less than the initial factor. Note the negative correlation between the maximal depth of ablation and the value of the final intended asphericity (Q_2).

periphery, after excimer laser surgery for myopia for optical zone diameters of 5, 6, and 8 mm, as calculated from equation 9. Any increase in central epithelial thickness results in a shift toward increased oblateness ($dQ > 0$). The smaller the optical zone diameter, the more pronounced is the shift. The latter may partly explain the difference between the theoretical predicted increase in prolateness and the observed increase in oblateness after conventional excimer laser surgery.

Based on our previous results, not taking the variation of epithelial thickness into account, after a 6-mm paraxial myopia treatment of −5 D applied to a cornea of apical radius of curvature of 7.8 mm and initial asphericity of −0.2, the theoretical postoperative apical radius of curvature and asphericity within the optical zone would be calculated as 8.8 mm and −0.3, respectively.[19] Thus, any variation greater than 0.3 in the asphericity induced by epithelial hyperplasia would be sufficient to induce an oblate postoperative profile ($Q_2 > 0$) instead of the predicted prolate Q_2 of −0.3. Computed from equation 9, Table 2, and Figure 6, the amounts of central additional epithelial thickness needed to induce increased oblateness of 0.3 are 3.0 and 6.4 µm, for optical zone diameters of 5.0 and 6.0 mm, respectively. This amount increases to 21 µm for an optical zone diameter of 8 mm (Fig. 6).

DISCUSSION

Recent improvements in laser technology have led to improved outcomes of conventional refractive surgery. The combination of height and curvature data obtained from corneal topographers and the use of aberrometers have lead to continual refinements of the profiles of excimer laser ablation.[20] Adjusting the postoperative corneal asphericity and enlarging the functional optical zone diameter (based on the patient's scotopic pupil) represent potential refinements for myopic excimer laser corrections. Such modifications, however, may result in increased maximal depths of ablation. Several recent reports[10–12] of corneal ectasia after surgery have emphasized the risks of excessive corneal tissue ablation without leaving a residual corneal bed of sufficient thickness after the flap cut and laser tissue removal. The identification of the factors influencing the maximal depth of customized LASIK ablation to correct myopia may improve the safety of this procedure. In this study, we have provided a method for estimating the additional depth of ablation needed for various customized myopic corrections and illustrated the potential limitations of increasing negative asphericity and treatment diameters in patients undergoing keratorefractive surgery for myopia.

Our mathematical model predicts that achieving an increase in corneal prolateness after excimer laser surgery requires greater depth of central photoablation, which is independent

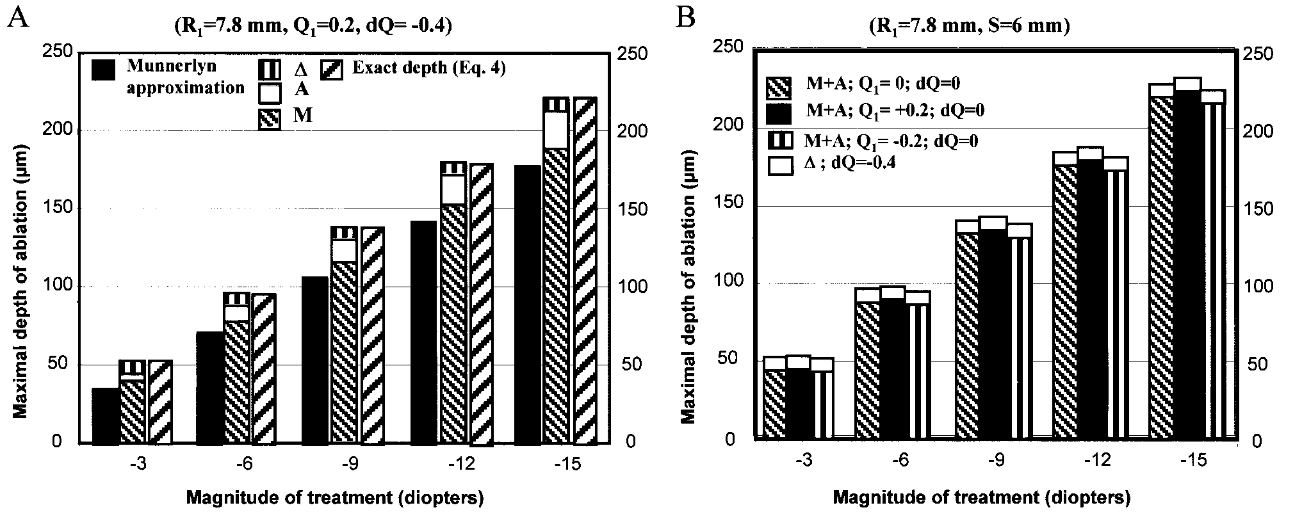

FIGURE 3. (A) Comparison between the maximal depths of ablation predicted by the Munnerlyn approximation $\left(\frac{-S^2D}{3}\right)$ and equations 6 and 4. The *M*, *A*, and Δ components of equation 6 are also shown. The calculations were performed for an initial apical radius of curvature (R_1) of 7.8 mm, an initial oblate asphericity (Q_1) of +0.2, an intended prolate change in asphericity (*dQ*) of −0.4, and for myopic corrections of −3, −6, −9, −12, and −15 D. Note that *M* increases linearly with increasing diopteric corrections, whereas Δ is constant. (B) Similar calculations as in (A), using equation 6 and showing the differences in maximal ablation depths for initial asphericities of Q_1 + 0.2, and −0.2. The least amount of tissue removal ($M + A$) occurred when the initial asphericity was prolate ($Q_1 = -0.2$). The influence of Q_1 on ablation depth increased for higher degrees of diopteric corrections.

of the initial asphericity. Furthermore, in corneas that are initially prolate ($Q_1 < 0$) the depth of ablation necessary to maintain initial asphericity ($dQ = 0$) is less than that required to preserve asphericity of initially oblate or spherical corneas. Accordingly, for patients with initially oblate corneas ($Q_1 > 0$) in whom an aspheric ablation profile is intended to generate a prolate postoperative corneal shape ($Q_2 < 0$; $dQ < 0$), the maximal depth of tissue ablation increases substantially, given the original oblateness (positive asphericity, *A*) and the intentional reduction in asphericity (positive Δ; equation 8). This concept is illustrated in Figure 3B.

Our theoretical analysis shows that further depth limitations may arise from attempting to increase the treatment diameter *S*. This effect can be predicted from the Munnerlyn equation,[1] but our analysis shows that this effect is exaggerated if an increase in negative asphericity is attempted in initially oblate corneas. This can be deduced from equations 6, 8, and 9, which indicate that asphericity (*A*) and asphericity change (Δ) are both proportional to the fourth power of the treatment diameter (*S*).

In conventional noncustomized excimer laser surgery for myopia, the goal is to correct the refractive error using arc-based mathematical calculus. Paraxial spherical models correspond to a particular case of our model, in which initial and final corneal asphericities are assumed to be identical and equal to 1. Munnerlyn et al.[1] derived from their paraxial model a simplified approximation of the maximal depth of ablation for myopic spherical corrections, (depth of ablation = diopters of correction × ablation diameter^2/3), which is incorporated into equation 7. The Munnerlyn approximation was achieved by

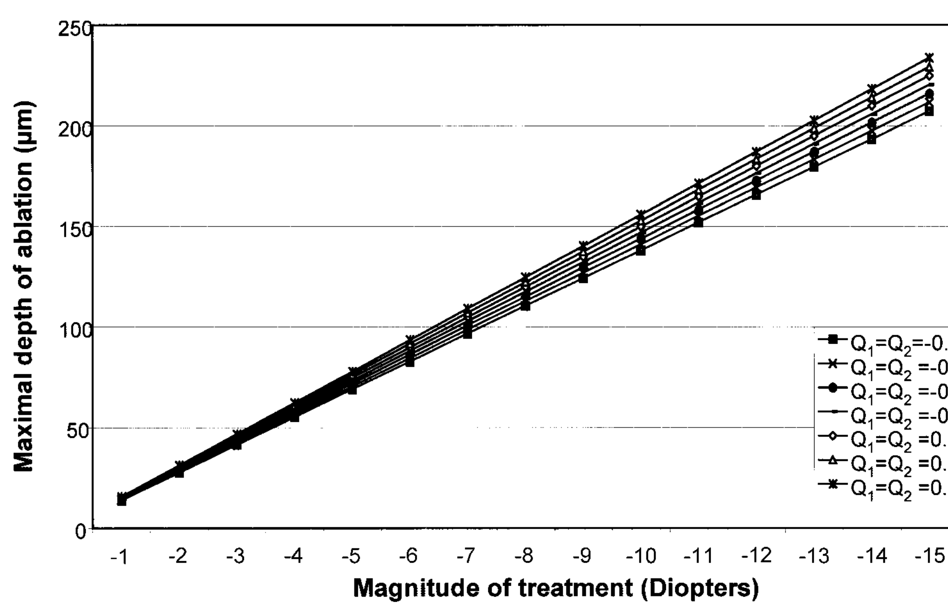

FIGURE 4. A linear relationship is seen between the maximal depth of tissue ablation and the magnitudes of myopic treatments for identical initial and final asphericities ($dQ = 0$) in prolate and oblate corneas. When the initial asphericity (Q_1) is preserved, the slope of the depth of ablation linear increase is proportional to Q_1.

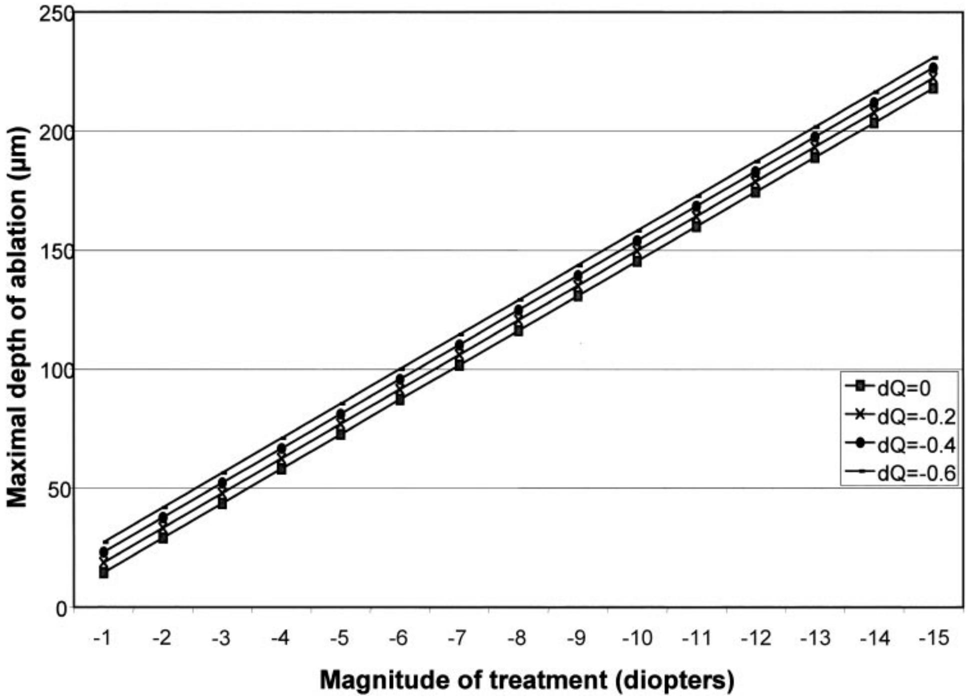

Figure 5. The influence of the variation of asphericity on the maximal depth of ablation. For the same magnitude of myopia treatment, the maximal depth of ablation increases when dQ is negative (increased prolateness of the final corneal profile). This additional depth is proportional to the absolute value of dQ and is independent of the initial asphericity or the magnitude of diopteric correction.

using binomial expansion. However, equation 5 shows that the predicted theoretical depth calculated from the Munnerlyn approximation underestimates the actual theoretical depth, because the binomial expansion was taken up only to the first order. In addition to the Munnerlyn approximation, equation 7 incorporates a second term that allows better estimation of the maximal theoretical depth of ablation induced by paraxial profiles of myopia ablation that do not take asphericity into consideration ($Q_1 = Q_2 = 0$; $dQ = 0$; Table 1). The value of this term is proportional to the magnitude of treatment and to the fourth power of the treatment diameter, thus assuming greater clinical relevance in patients with large pupils and for magnitudes of treatment greater than 7 D (Fig. 3).

The normal human cornea is not spherical. Despite its shortcomings, modeling the corneal shape in cross section as a conic section is a better approximation and has been widely used[21–24] since its introduction by Mandell and St. Helen in 1971.[25] Most normal human corneas conform to a prolate ellipse and flatten from the center to the periphery (negative asphericity; $Q_1 < 0$), but some corneas are oblate and steepen from the center to the periphery (positive asphericity; $Q_1 > 0$). Figure 4 shows that the maximal theoretical depth of ablation when the surgeon seeks to maintain the initial corneal asphericity ($Q_1 = Q_2$) is slightly reduced for prolate corneas ($Q_1 < 0$), compared with spherical and oblate corneas, when all other parameters are identical.

Table 2. Increments in Depths of Ablation Corresponding to Increased Negative Asphericity of −0.1 Units

Optical Zone Diameter (mm)	Initial Radius of Curvature (R_1, mm)		
	7.8	**7.5**	**8.1**
4.0	0.42	0.47	0.37
4.5	0.67	0.76	0.60
5.0	1.03	1.16	0.91
5.5	1.51	1.69	1.34
6.0	2.13	2.40	1.90
6.5	2.94	3.30	2.62
7.0	3.95	4.44	3.53
7.5	5.21	5.86	4.65
8.0	6.74	7.58	6.02

Data are depths of ablation in micrometers for the R_1 shown.

Determining the ideal postoperative asphericity for a given eye and a given myopia correction is beyond the scope of this article. Using a model eye featuring aspheric ocular interfaces and a gradient refractive index within the lens, Patel et al.[19] have predicted that optimal optical imagery is produced when the corneal profile is represented by a flattening ellipse whose asphericity is between −0.35 and −0.15. Two recent studies using mathematical modeling and ray-tracing techniques to determine the ideal low spherical aberration ablation profile for the correction of myopia found it to be deeper and steeper, suggesting a lower intended postoperative asphericity.[14,15] Conversely, using an optical design software to build a two conic surface model of the cornea, Munger[16] determined that the optimal postoperative corneal asphericity that would maintain the preoperative aberrations increased nonlinearly (i.e., became more oblate) as a function of the magnitude of refractive correction. Further studies involving the use of ray-tracing techniques or the collection of wavefront sensing data may help in determining the best postoperative corneal profile in a given patient. However, it seems reasonable to postulate that customized ablations should retain the physiologic prolate corneal shape. In a recent theoretical study, we demonstrated that after conventional myopic excimer laser treatment conforming to the Munnerlyn paraxial formula, the postoperative theoretical corneal asphericity could be accurately approximated by a best-fit conic section. We also found that for initially oblate corneas ($Q_1 > 0$), oblateness increased ($Q_2 > Q_1 > 0$), whereas for prolate corneas ($Q_1 < 0$), prolateness increased ($Q_2 < Q_1 < 0$) within the treated zone after myopia treatment.[18] The present study is in agreement with these results: the theoretical maximal depth of ablation induced by a paraxial treatment (spherical assumption) is deeper than needed for a prolate cornea to maintain its prolateness.

In practice, however, the cornea becomes oblate after conventional refractive excimer laser treatment for myopia.[5,7] Holladay et al.[5] have recently suggested that the loss of negative

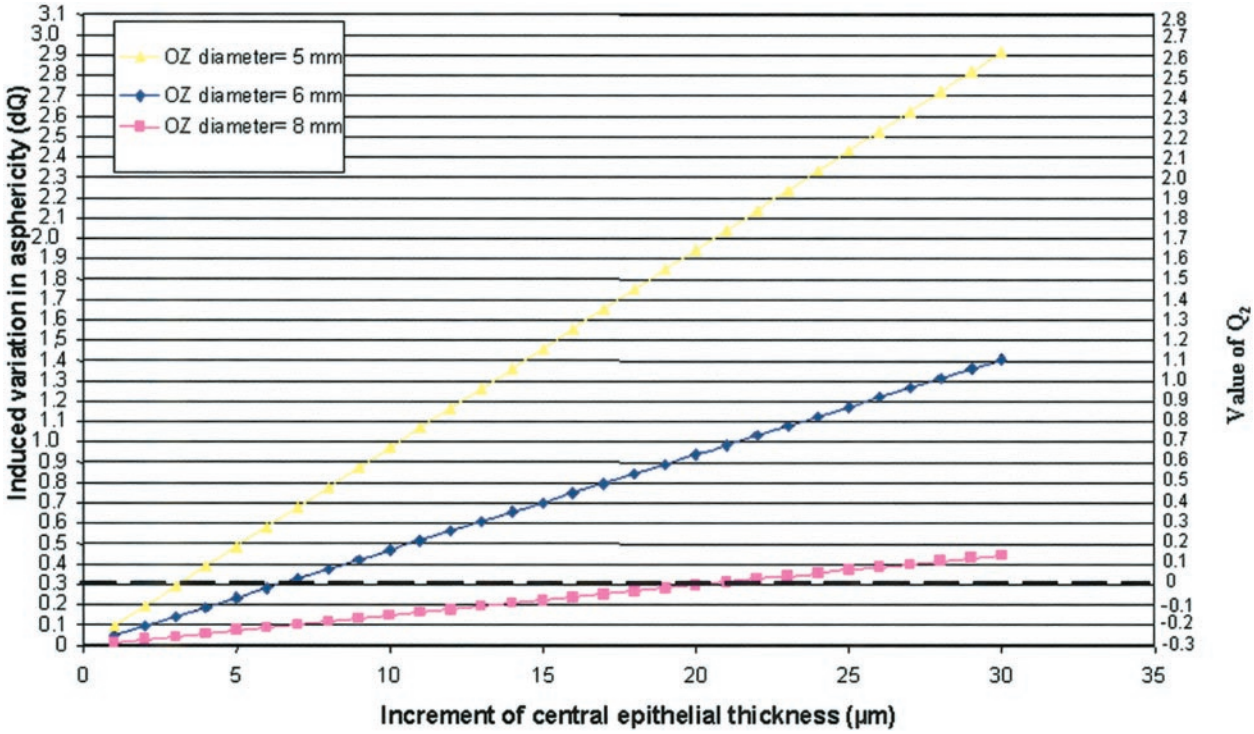

FIGURE 6. The theoretical induced variation in asphericity consecutive to different maximal central epithelial thickening with no paraxial refractive change after excimer laser correction of myopia is shown for different optical zone (OZ) diameters. The *y*-axis shows the value of the modified asphericity (Q_2) for an initial asphericity of -0.3. For an optical zone of 6 mm, 7 μm of central epithelial hyperplasia is sufficient to induce an oblate final corneal contour ($Q_2 > 0$). The corresponding magnitudes of epithelial hyperplasia for optical zones of 5 and 8 mm are 3 and 21 μm, respectively.

asphericity may be the predominant factor in the functional decrease in vision. Our clinical experience confirms the results of this study, showing a significant association between increased postoperative asphericity and greater myopia correction. Because the patterns of ablation of the existing laser devices are proprietary, we do not have access to them, and thus we cannot study separately the respective specific roles of the patterns of ablation and the biological healing, so as to explain the clinical observation of increased postoperative oblateness. The latter may be due to variations of the applied fluence on the corneal surface, to the incorporation of laser pretreatment protocols intended to reduce the incidence of postoperative central islands, or to stromal and epithelial remodeling after surgery. Another explanation is that the laser may become less efficient as we move peripherally, and the depth centrally would not be changed but less tissue than planned peripherally would be removed.

Epithelial hyperplasia after PRK may be a predominant factor in explaining the discrepancy between the clinical findings and the theoretical predictions. Topographical patterns have been shown to change with time,[26] and variations of the epithelial thickness have been associated with refractive regression occurring after LASIK and PRK.[27–31] Figure 6 illustrates that in addition to its effect on the apical power, an increase in central corneal thickness during wound healing could induce a modification in the corneal asphericity. The extent of epithelial and stromal thickening during wound healing after PRK are greater than those after LASIK.[27–29,32] The in vivo clinical observations that epithelial hyperplasia is more common in eyes treated with small ablation zone diameters or with high magnitudes of treatment[29] are consistent with the predictions of our model. To our knowledge, no clinical study has either compared the modification in asphericity after LASIK and PRK or investigated the possible correlation between the variation in corneal asphericity, apical power, and central corneal thickness.

Two studies have used corneal topography (Holladay Diagnostic Summary; EyeSys Laboratories, Houston, TX) to determine the corneal asphericity after excimer laser refractive surgery. In the study by Hersh et al.,[7] mean asphericity for all patients 1 year after myopic PRK was $Q_2 = +1.05$ ($p_2 = +2.05$); preoperative asphericity was not reported. The mean preoperative corneal asphericity (Q_1) measured under similar conditions, was reported to be -0.16 by Holladay et al.[5] All corneas changed from a prolate to an oblate shape (mean Q_2 − of $+0.47$), 6 months after LASIK for myopia. The shift toward oblateness was greater after PRK than after LASIK.

One limitation of our approach is the contribution of the crystalline lens to the reduction of optical aberrations, especially in that age-related lens changes may affect the determination of the ideal asphericity.[33–35] The cornea would have to be progressively more prolate with age to compensate. Taking these clinical observations into consideration, certain features of our mathematical model may have to be modified to compensate for the postoperative trend toward increased oblateness. One possibility is to increase the reduction of postoperative asphericity by an amount similar to that reported in previous clinical studies.[5,7] Based on Table 2, an aspheric profile of ablation designed to preempt an oblate shift of $+1.0$ after LASIK would require an additional ablation depth of approximately 20 μm (optical zone diameter = 6 mm) compared with a Munnerlyn-based noncustomized ablation. Although this approach may improve the predictability of postoperative asphericity, it may not be sufficient, because the additional ablation, may exacerbate the biological healing and induce more regression after PRK, or may compromise corneal stability after LASIK, especially for large optical zone diameters and for high myopia corrections.

Another limitation of our theoretical analysis is that it is based on a static-shape subtraction model in which the postoperative corneal shape is determined only by the difference between the preoperative shape and the ablation profile. The biological effects of healing and the variations of the applied fluence at the cornea are not considered. Furthermore, our model neglects the influence of the transition zone. The increased curvature at the edges of the treated zone may introduce substantial optical aberrations under conditions of dim illumination. This increases the demand for larger treatment diameters, which would increase dramatically the depth of ablation (equations 6–9).

In summary, our model provides a basis for predicting the variation in theoretical maximal depth of ablation induced by aspheric custom ablations to correct myopic refraction errors. Increasing negative asphericity without increasing the risk of ectasia for high magnitudes of treatment may be achieved by reducing the treatment diameter. The reduction of the optical zone diameter, however, may induce undesirable optical edge effects and may counterbalance the positive effect of restoring the prolate shape of the central cornea. Future studies of the relationships between optimal asphericity, based on the classic *Q* value, and wavefront aberration and further experimental work and clinical trials are necessary to compliment our theoretical calculations to refine the profiles of ablation and allow adequate control of postoperative corneal asphericity.

References

1. Munnerlyn CR, Koons SJ, Marshall J. Photorefractive keratectomy: a technique for laser refractive surgery. *J Cataract Refract Surg.* 1988;14:46–52.
2. Martinez CE, Applegate RA, Howland HC, Klyce SD, McDonald MB, Medina JP. Changes in corneal aberration structure after photorefractive keratectomy [ARVO Abstract]. *Invest Ophthalmol Vis Sci.* 1996;37(3):S933. Abstract nr 4277.
3. Oliver KM, Hemenger RP, Corbett MC, et al. Corneal optical aberrations induced by photorefractive keratectomy. *J Refract Surg.* 1997;13:246–254.
4. Seiler T, Kaemmerer M, Mierdel P, Krinke HE. Ocular optical aberrations after photorefractive keratectomy for myopia and myopic astigmatism. *Arch Ophthalmol.* 2000;118:17–21.
5. Holladay JT, Dudeja DR, Chang J. Functional vision and corneal changes after laser in situ keratomileusis determined by contrast sensitivity, glare testing, and corneal topography. *J Cataract Refract Surg.* 1999;25:663–669.
6. Hong X, Thibos LN. Longitudinal evaluation of optical aberrations following laser in situ keratomileusis surgery. *J Refract Surg.* 2000;16(suppl):S647–S650.
7. Hersh PS, Shah SI, Holladay JT. Corneal asphericity following excimer laser photorefractive keratectomy. Summit PRK Topography Study Group. *Ophthalmic Surg Lasers.* 1996;27(suppl 5):S421–S428.
8. Budak K, Khater TT, Friedman NJ, Holladay JT, Koch DD. Evaluation of relationships among refractive and topographic parameters. *J Cataract Refract Surg.* 1999;25:814–820.
9. Probst LE, Machat JJ. Mathematics of laser in situ keratomileusis for high myopia. *J Cataract Refract Surg.* 1998;24:190–195.
10. Seiler T, Quurke AW. Iatrogenic keratectasia after LASIK in a case of forme fruste keratoconus. *J Cataract Refract Surg.* 1998;24:1007–1009.
11. McLeod SD, Kisla TA, Caro NC, McMahon TT. Iatrogenic keratoconus: corneal ectasia following laser in situ keratomileusis for myopia. *Arch Ophthalmol.* 2000;118:282–284.
12. Joo CK, Kim TG. Corneal ectasia detected after laser in situ keratomileusis for correction of less than −12 diopters of myopia. *J Cataract Refract Surg.* 2000;26:292–295.
13. Seiler T, Genth U, Holschbach A, Derse M. Aspheric photorefractive keratectomy with excimer laser. *Refract Corneal Surg.* 1993;9:166–172.
14. MacRae S, Schwiegerling J, Snyder RW. Customized and low spherical aberration corneal ablation design. *J Refract Surg.* 1999;15(suppl):S246–S248.
15. Schwiegerling J, Snyder RW. Corneal ablation patterns to correct for spherical aberration in photorefractive keratectomy. *J Cataract Refract Surg.* 2000;26:214–221.
16. Munger R. New paradigm for the treatment of myopia by refractive surgery. *J Refract Surg.* 2000;16(suppl):S651–S653.
17. Baker TY. Raytracing through non-spherical surfaces. *Proc R Soc.* 1943;55:361–364.
18. Gatinel D, Hoang-Xuan T, Azar D. Determination of corneal asphericity after myopic surgery with the excimer laser: a mathematical model. *Invest Ophthalmol Vis Sci.* 2001;42:1736–1742.
19. Patel S, Marshall J, Fitzke FW III. Model for predicting the optical performance of the eye in refractive surgery. *Refract Corneal Surg.* 1993;9:366–375.
20. Mrochen M, Kaemmerer M, Seiler T. Clinical results of wavefront-guided laser in situ keratomileusis 3 months after surgery. *J Cataract Refract Surg.* 2001;27:201–207.
21. Kiely PM, Smith G, Carney LG. The mean shape of the human cornea. *Opt Acta.* 1982;8:1027–1040.
22. Bennett AG. Aspherical and continuous curve contact lenses. *Optom Today.* 1988;28:11–14.
23. Douthwaite WA, Sheridan M. The measurement of the corneal ellipse for the contact lens practitioner. *Ophthalmic Physiol Opt.* 1989;9:239–242.
24. Mandell RB. The enigma of the corneal contour. *Contact Lens Assoc Ophthalmol.* 1992;18:267–273.
25. Mandell RB, St. Helen R. Mathematical model of the corneal contour. *Br J Physiol Opt.* 1971;26:183–197.
26. Simon G, Ren Q, Kervick GN, Parel JM. Optics of the corneal epithelium. *Refract Corneal Surg.* 1993;9:42–50.
27. Wu WCS, Stark WJ, Green WR. Corneal wound healing after193-nm excimer laser keratectomy. *Arch Ophthalmol.* 1991;109:1426–1432.
28. Fagerholm P, Hamberg-Nyström H, Tengroth B. Wound healing and myopic regression following photorefractive keratectomy. *Acta Ophthalmol.* 1994;72:229–234.
29. Gauthier CA, Epstein D, Holden BA, et al. Epithelial alterations following photorefractive keratectomy for myopia. *J Refract Surg.* 1995;11:113–118.
30. Lohmann CP, Güell JL. Regression after LASIK for the treatment of myopia: the role of the corneal epithelium. *Semin Ophthalmol.* 1998;13:79–82.
31. Spadea L, Fasciani R, Necozione S, Balestrazzi E. Role of the corneal epithelium in refractive changes following laser in situ keratomileusis for high myopia. *J Refract Surg.* 2000;16:133–139.
32. Møller-Pedersen T, Cavanagh HD, Petroll WM, Jester JV. Stromal wound healing explains refractive instability and haze development after photorefractive keratectomy: a 1-year confocal microscopic study. *Ophthalmology.* 2000;107:1235–1245.
33. Glasser A, Campbell MC. Presbyopia and the optical changes in the human crystalline lens with age. *Vision Res.* 1998;38:209–229.
34. Guirao A, Artal P. Corneal wave aberration from videokeratography: accuracy and limitations of the procedure. *J Opt Soc Am A.* 2000;17:955–965.
35. Guirao A, Gonzalez C, Redondo M, Geraghty E, Norrby S, Artal P. Average optical performance of the human eye as a function of age in a normal population. *Invest Ophthalmol Vis Sci.* 1999;40:203–213.