# Increase in Corneal Asphericity After Standard Laser in situ Keratomileusis for Myopia is not Inherent to the Munnerlyn Algorithm

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## ABSTRACT

**PURPOSE: Standard refractive surgery for myopia induces a shift in corneal asphericity toward positive values, resulting in an increase of spherical aberration. Analytical studies of changes in theoretical corneal shape after application of standard algorithms have yielded controversial conclusions. This study tries to resolve this controversy and discusses causes of optical degradation after refractive surgery.**

**METHODS: Computationally, we subtracted from real preoperative corneas the ablation depth given by the Munnerlyn equation and the parabolic approximation of the Munnerlyn equation. We compared the predicted postoperative corneal asphericity (and corneal spherical aberration) with real postoperative corneal asphericities of the same eyes, after laser in situ keratomileusis (LASIK).**

**RESULTS: Corneal asphericity increased after LASIK in real eyes, with an increase proportional to the amount of correction. This increase was not predicted by the computational application of the Munnerlyn algorithm, which predicted a slight decrease of corneal asphericity. The parabolic approximation of the Munnerlyn algorithm produced an increase in corneal asphericity that correlated with the amount of correction, but was less than the clinical findings.**

**CONCLUSION: Potential causes for increased asphericity (radial changes in laser efficiency, epithelial healing, and biomechanical response) are discussed. These conclusions are important for the design of optimized and customized ablation algorithms, since the theoretical performance of a given ablation algorithm (ie, Munnerlyn algorithm) can differ drastically from real outcomes. [*J Refract Surg* 2003;19:S592-S596]**

Measurement of aberrations induced by conventional refractive surgery (laser in situ keratomileusis [LASIK] and photorefractive keratectomy [PRK]) has revealed two major issues: 1) Although refractive surgery can correct conventional refractive errors (defocus and astigmatism), it induces higher order aberrations, particularly spherical aberration, which degrades optical quality[1-4] and subsequently visual quality[5,6], particularly for large pupils; and 2) Measurement of higher order aberrations, in combination with the generalization of flying-spot excimer lasers, which allow generation of asymmetric ablation profiles, opens the theoretical possibility of compensating for refractive errors beyond conventional defocus and astigmatism, therefore facilitating customized ablation.[7-10]

Interest in developing new ablation algorithms has not paralleled basic research on causes of why standard algorithms induce high amounts of spherical aberration, even within the optical zone of the treatment. Several authors[11,12] have proposed that the corneal biomechanical response and epithelial wound healing could induce an increase in corneal asphericity and consequently an increase in spherical aberration.[13] However, to our knowledge, only two groups have studied the actual changes induced by the standard ablation algorithms, both using a theoretical approach. Gatinel and colleagues[14] applied the Munnerlyn algorithm analytically on theoretical aspherical corneas, and using routines

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written in Excel, found the best fitting conic to the simulated postoperative surface. Jiménez and colleagues[15] conducted analytical calculations on theoretical corneas. They used a 2nd order truncation of the equations (ie, a parabolic approximation of the Munnerlyn algorithm) and a least-square procedure to analytically solve the resulting integrals. They found that postoperative corneal asphericity should increase, proportionally, to the amount of correction.

We computationally applied the Munnerlyn equation and its parabolic approximation to real preoperative corneas that underwent LASIK for myopia. We used the real parameters (spherocylindrical correction, optical, and transition zones) of each individual surgery. We compared the predicted computational changes in corneal asphericity and in wave aberrations to real outcomes after LASIK for myopia.

## MATERIALS AND METHODS

Corneal elevation maps were obtained by videokeratoscopy (Carl Zeiss Meditec, Dublin, CA) on a group of 13 eyes of 7 patients (mean age 28.9 ± 5.4 years, preoperative spherical equivalent refraction -6.10 ± 2.70 diopters [D]; range -2.00 to -11.50 D) before and after (>1 month) LASIK for myopia. LASIK was conducted using a scanning-spot excimer laser (Chiron Technolas 217-C equipped with the PlanoScan program; Bausch & Lomb Surgical, Madrid, Spain) that emitted 50 light pulses per second with a wavelength of 193 nm. Optical zone diameter ranged from 4.4 to 7 mm.

Postoperative corneas were computationally simulated by subtracting from preoperative corneas the amount of tissue predicted by the Munnerlyn equation[16] (below, top) and its parabolic approximation (below, bottom)

$$f_{\mathrm{Mun}}(\rho)=\sqrt{R_1^2-\rho^2}-\sqrt{\left(\frac{R_1(n-1)}{n-1+R_1\Phi}\right)^2-\rho^2}-\sqrt{R_1^2-\frac{D^2}{4}}+\sqrt{\left(\frac{R_1(n-1)}{n-1+R_1\Phi}\right)^2-\frac{D^2}{4}}$$

$$f_{\mathrm{Par}}(\rho)=\frac{4\Phi\rho^2}{3}-\frac{\Phi D^2}{3},$$

where ρ is the radial coordinate, ϕ is the correction in diopters (negative for myopia), $R_1$ is the apical radius of curvature of the initial cornea, *n* is the refractive index of the cornea, and *D* is the optical zone diameter.

We used in the computer simulations both the spherical-cylindrical correction and the optical zone diameter applied during surgery.

Corneal asphericity (preoperative and real and simulated postoperative asphericities, *Q*), were estimated by fitting real and simulated corneal shapes to biconics, described by the following function[10]:

$$\mathrm{b}(\rho,\theta)=\frac{\rho^2\left(\frac{\cos(\theta-\theta_x)}{R_x}+\frac{\sin(\theta-\theta_x)}{R_y}\right)}{1+\sqrt{1-\rho^2\left((Q_x+1)\frac{\cos^2(\theta-\theta_x)}{R_x^2}+(Q_y+1)\frac{\sin^2(\theta-\theta_x)}{R_y^2}\right)}},$$

where the variables ρ and θ are the polar coordinates. The parameters $R_x$ and $R_y$ are the maximum and minimum apical radii of curvature, in the directions respectively determined by the angles $\theta_x$ and $\theta_x + \pi/2$. $Q_x$ and $Q_y$ are the respective asphericities. We take the mean asphericity as $(Q_x + Q_y)/2$. The fitting was performed using custom routines written in Matlab. Corneal aberrations were obtained by computer ray tracing through the corneal surfaces, using Zemax.[3,18,19] Estimations were obtained both using the corneal apex and the pupil center as a reference.

## RESULTS

Figure 1 shows corneal wave aberrations for three eyes before and after LASIK for myopia, and simulations after computationally applying the Munnerlyn and the parabolic approximation of the Munnerlyn algorithm. Real and simulated postoperative corneas showed similar apical radius of curvatures, but there was a significant discrepancy between real and simulated postoperative asphericity and corneal spherical aberration. Figure 2 shows preoperative, real postoperative, and simulated postoperative asphericities (A) and corneal spherical aberration (B) for all 13 eyes. The eyes are ranked by increasing preoperative spherical refractive error. Corneal asphericities were calculated by fitting to a biconic surface the corneal height data within each individual optical zone, although results were similar when using a smaller fitting area (4.4 mm). Mean preoperative corneal asphericity was negative (-0.14 ± 0.14) and increased to positive values after LASIK (1.1 ± 1.3). Corneal spherical aberrations were calculated in all corneas for a diameter of 4.4 mm, which was the smaller optical zone. The spherical aberration (4th order coefficient in the Zernike polynomial expansion, $C_4^0$) was evaluated at the plane of best focus. Mean $C_4^0$ Zernike coefficient increased from 0.08 ± 0.04 µm to

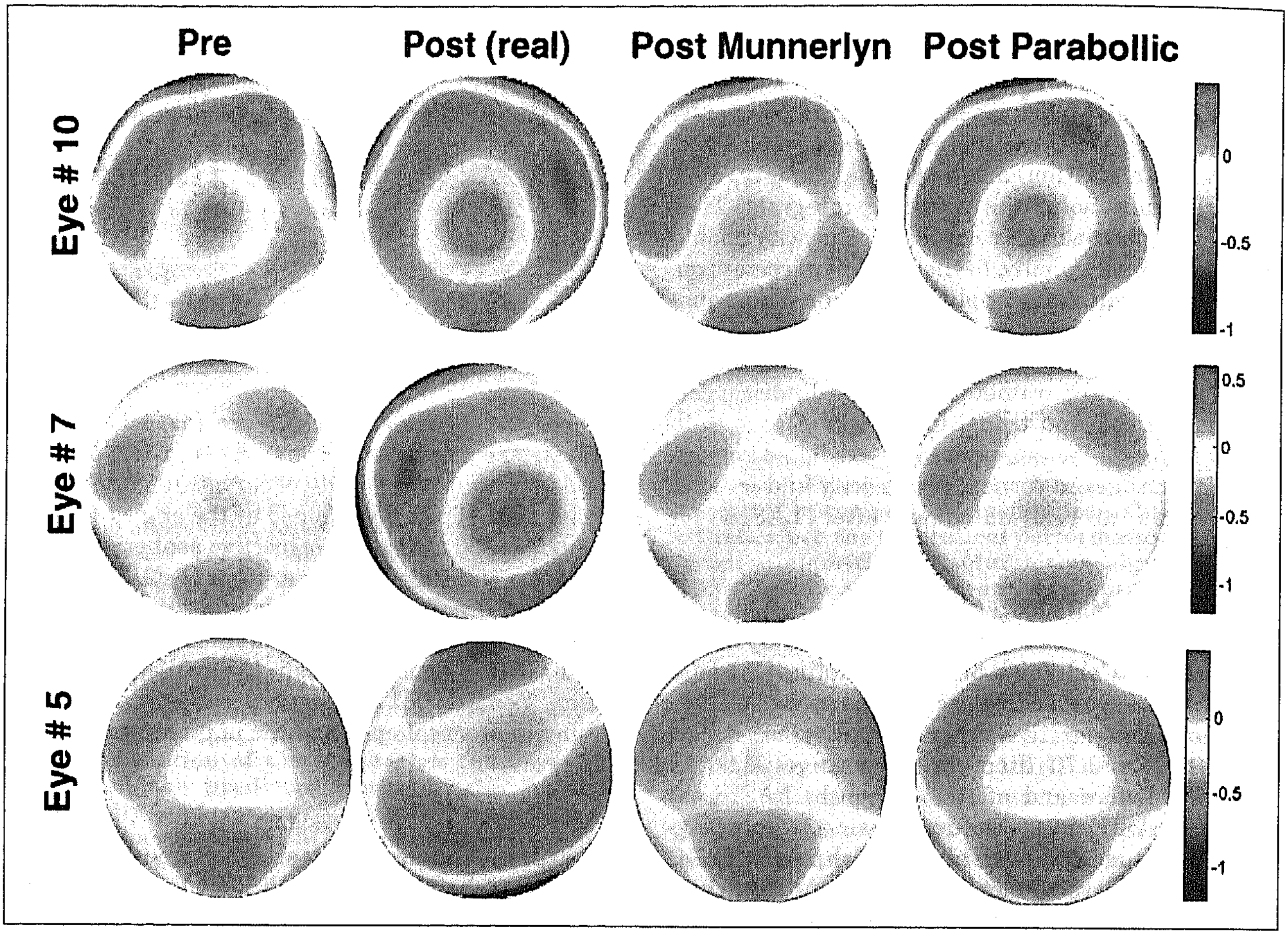

**Figure 1.** Examples of wave aberration patterns (3rd and higher order aberration) preoperatively (1st column), postoperatively (2nd column), simulation of Munnerlyn ablation (3rd column), and simulation of parabolic approximation of Munnerlyn ablation (4th column) for three typical eyes: eye #10 (preoperative spherical equivalent refraction -7.50 D), eye #7 (-6.25 D), eye #5 (-5.375 D).

0.17 ± 0.10 µm in real eyes. However, the predicted mean postoperative corneal asphericity from the Munnerlyn algorithm was -0.21 ± 0.19 and the predicted postoperative corneal spherical aberration was 0.05 ± 0.03 µm. Thus, the increase of corneal asphericity (and spherical aberration) was not inherent to the Munnerlyn algorithm. A parabolic approximation of the Munnerlyn equation predicted increased postoperative asphericity (0.3 ± 0.4) and spherical aberration (0.11 ± 0.04 µm).

The increase of corneal asphericity (and spherical aberration) after LASIK for myopia was highly correlated with the preoperative spherical error ($r=0.91$, $P<.0001$), as opposed to predictions from the computational application of the Munnerlyn algorithm, which show no correlation between the change in asphericity and the preoperative spherical error ($r=0.54$, $P=.12$). As found analytically by Gatinel and colleagues[14], we found a relationship between preoperative and postoperative corneal asphericity ($r=0.6$, $P=.02$). The parabolic approximation of the Munnerlyn algorithm predicts a slight increase of induced asphericity with increased preoperative spherical error ($r=0.89$, $P<.0001$).

Results from the aforementioned simulations were obtained by application of the ablation pattern (Munnerlyn and its parabolic approximation) centered at the corneal apex. We also simulated application of the ablation pattern centered at the pupil center. We found no significant differences in corneal asphericities between applications centered at the corneal apex or applications centered at the pupil center. Predicted postoperative asphericity when applying the ablation pattern centered at the pupil center was -0.2 ± 0.3 for the Munnerlyn equation and 0.4 ± 0.5 for its parabolic approximation.

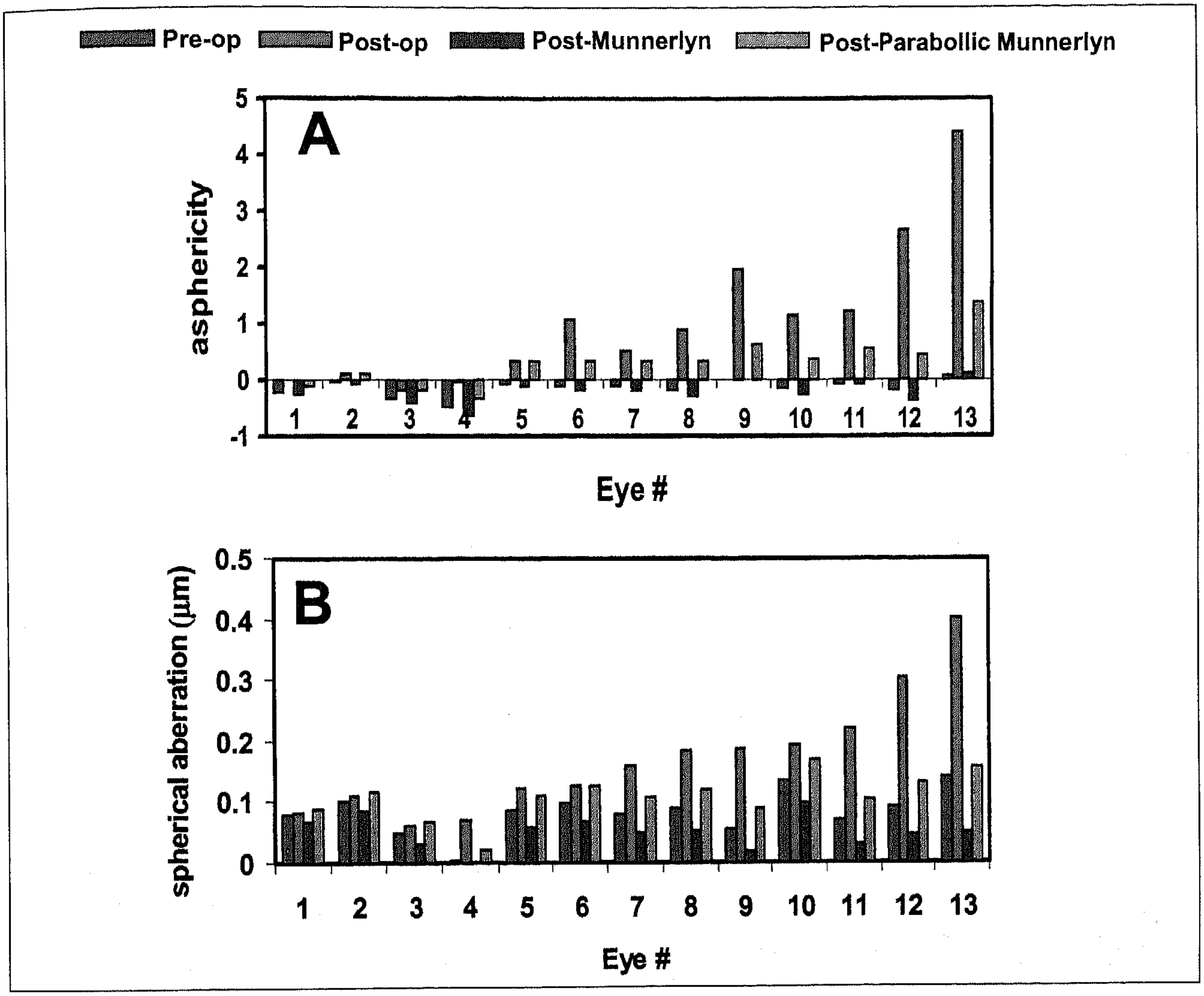

**Figure 2.** **A)** Preoperative, postoperative, postoperative Munnerlyn simulation, and postoperative parabolic Munnerlyn simulation corneal mean asphericity (estimated within the optical zone); **B)** Preoperative, postoperative, postoperative Munnerlyn simulation, and postoperative parabolic Munnerlyn simulation 4th order corneal spherical aberration (for 4.4-mm pupils), for all eyes. Eyes are ranked by increasing preoperative spherical equivalent refraction.

## DISCUSSION

Our results based on computer simulations on real corneas confirmed analytical data from Gatinel and colleagues[14] that the standard Munnerlyn algorithm should not induce an increase of corneal asphericity and spherical aberration found clinically after LASIK for myopia. We have shown that a parabolic approximation of this algorithm used in the theoretical analysis by Jiménez and colleagues[15] produced an increase in corneal asphericity, solving the apparent controversy found in previous analytical studies. Our results, based on real corneas, allow a direct, individual, comparison of predictions and real outcomes and show that there is an important disagreement between expected and actual postoperative corneal asphericity. Causes for the increase of spherical aberration do not rely on the theoretical definition of the algorithm, but on the actual application of the ablation pattern and possible biomechanical and epithelial wound healing effects.

A major limitation of the study is that ablation algorithms are proprietary and as a consequence, we cannot be sure about the actual ablation pattern programmed into the laser system. We conducted ablation experiments on polymethylmethacrylate (PMMA) flat surfaces and showed that the ablation approximated a parabolic profile, closer than the exact Munnerlyn function (with the appropriate adjustment of ablation rates of PMMA versus corneal tissue).[20] The computational application of these experimental profiles on actual corneas showed a slight increase of corneal asphericity with increased correction, in a similar way to the Munnerlyn parabolic approximation.

Several authors have shown that the efficiency of the laser changes across the cornea[21,22], primarily because of the enlargement of the laser spot as it moves away from the corneal apex and marginally because of differences in reflected/absorbed energy as a function of angle of incidence. Using computer simulations on the same eyes in this study, we have shown that these effects produced an additional increase in corneal asphericity[23], but are not sufficient to fully explain the clinical postoperative asphericities. Proposed trends toward increased asphericity induced by wound healing[12] and biomechanical response of the cornea[11] may account for the remaining differences.

We have presented a computational evaluation of the standard ablation algorithms on real corneas, which can be extended to customized algorithms. It represents an appropriate framework upon which to build a model that incorporates the effects of geometrically-induced laser efficiency changes as well as biological processes.

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