Correlation Among Ocular Spherical Aberration, Corneal Spherical Aberration, and Corneal Asphericity Before and After LASIK for Myopic Astigmatism With the SCHWIND Amaris Platform

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ABSTRACT

PURPOSE: To determine the spherical wave aberration of the human eye based on corneal topography.

METHODS: Based on the pre- and postoperative status of 146 consecutive eyes (median patient age 36 years), the correlations between spherical aberration and asphericity and between corneal and ocular spherical aberrations were determined using simple linear regression methods. The asphericity (Q) values for which spherical aberration equals zero as well as the reference Q values for which corneal spherical aberration equals ocular spherical aberration have been determined. Patients underwent LASIK using the AMARIS excimer laser platform (SCHWIND eye-tech-solutions). All ablations were based on aspheric aberration-neutral profiles.

RESULTS: Corneal and ocular spherical aberrations correlate well with Q value and the value $p \cdot R^{-3}$ in patients before and after LASIK for myopic astigmatism. A Q value of −0.19 to −0.27 can provide zero ocular spherical aberration in patients before and after LASIK for myopic astigmatism. Ocular spherical aberration is induced at a rate of half the induced corneal spherical aberration. A reference Q value of −0.12 to +0.01 can provide corneal spherical aberration equal to ocular spherical aberration in patients before and after LASIK for myopic astigmatism.

CONCLUSIONS: Ocular and corneal wave aberrations are two different concepts that are not interchangeable. As for spherical aberration, a simple static model with a reference cornea deviating from a Cartesian oval can provide a 2:1 correspondence between corneal and ocular spherical aberration. [*J Refract Surg*. 2011;27(6):434-443.]

doi:10.3928/1081597X-20101001-01

Controversy exists regarding the proper definition of an optimal ablation profile for corneal refractive surgery. It has been known for many years that corneal refractive treatments induce a change in corneal asphericity[1] and recently it has been assumed and argued that corneal refractive treatments preserving the preoperative corneal asphericity (Q value) might be desirable, thus, asphericity-based profiles have been developed. Wavefront-optimized,[2] asphericity preserving, and Q-factor profiles[3] have been presented as solutions.

There has been some confusion in the market when using terms such as Q-value optimization[3] or aberration-free profiles.[2] The amount of corneal spherical aberration and the asphericity are intrinsically related; but this does not mean that maintaining the original spherical aberration after corneal treatments will maintain the original asphericity or vice versa.

Controversy remains regarding the proper definition of an optimal ablation profile for corneal refractive surgery.[4] To avoid the induction of aberrations and, moreover, to try to eliminate already existing aberrations, so-called "customized" treatments were developed.[5]

To compensate for already existing aberrations, customized treatments were developed that use either wavefront measurements of the whole eye[6] (obtained by Hartmann-Shack wavefront sensors) or corneal topography-derived wavefront analysis.[7] Topography-guided[8] and wavefront-driven[5] profiles have been presented as solutions.

In human eyes with normal aberrations, the weight C(n,m) of the Zernike terms Z(n,m) decreases with increasing Zernike order (n),[9] therefore theoretical impact of cyclotorsion ab-

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Received: May 7, 2010; Accepted: August 27, 2010

Posted online: October 15, 2010

lation is smaller than decentered ablation or edge effects[10] (coma and spherical aberration[11]).

Due to the smaller angle kappa associated with myopes compared with hyperopes,[12,13] centration issues are less apparent. However, angle kappa in myopes may be sufficiently large to show differences in results because it is always desirable to achieve as much standardization as possible and not to treat myopes using pupil center as the reference, whereas hyperopes use the corneal vertex.

The Indiana aberration study by Thibos et al[9] characterized the aberration structure and the effects of these aberrations on vision for a reasonably large population of normal, healthy eyes in young adults, and verified the hypothesis of bilateral symmetry. Porter et al[14] confirmed in a large population that although the pattern of aberrations varies from individual to individual, aberrations, including irregular ones, are correlated in left and right eyes of the same patient, indicating that they are not random defects. Wang et al[15] found that anterior corneal wave aberrations varied greatly among individuals, but a moderate to high degree of mirror symmetry existed between right and left eyes.

Using different input data sources in refractive surgery from different devices can lead to confusion due to the lack of standards,[16] different eye models,[17] and different refractive indices.

Different eye models are presented in the literature. Some examples include eye models with an aspheric Q value $-1/n^2$ and $-1/2n^2$, where n is the refractive index of the cornea, and eye models with an aspheric Q value −0.25. Different refractive indices are also used in the eye models. In some cases, the keratometric refractive index is used (1.3375), in others different corneal refractive indices are used (1.3775, 1.377, 1.376, or 1.372), and sometimes the tear film refractive index (1.332) is used.

Topographic systems measure and analyze the corneal surface as a single, thin-lens system mostly using the keratometric refractive index of 1.3375. Most topographic systems use an ideal "free-of-aberrations" lens as a reference surface, which is generated by the corresponding Cartesian oval[18] (an aspheric surface with a Q value of $-1/n^2$).

Statistical analysis of a population of human corneas has shown that the average best-fit aspheric surface is one with a Q value of approximately −0.25.[19,20] In general, the healthy human cornea has a "positive spherical aberration," which is balanced by the "negative spherical aberration" of the internal lens.[7] As individuals age, the refractive index of the crystalline lens changes (and possibly its asphericity as well), reducing the amount of spherical aberration that can be balanced or even showing a certain amount of positive spherical aberration, whereas the corneal asphericity thus, corneal spherical aberration, is relatively stable over time, which disrupts the equilibrium between the aberrations.

We describe a pseudo-empirical analysis of different eye models for evaluating the wave aberration based on corneal topography to determine the spherical aberration of the human eye.

PATIENTS AND METHODS

This retrospective analysis included 146 eyes (73 patients) that had been treated with the AMARIS Aberration-Free™ (aberration neutral) aspheric ablation profile (SCHWIND eye-tech-solutions, Kleinostheim, Germany).

Inclusion criteria for review were bilateral surgery on the same day with a target of emmetropia, preoperative corrected distance visual acuity (CDVA) 20/25 or better (logMAR 0.1 or better) in both eyes, no signs of amblyopia, and completion of 3-month follow-up.

Three-month follow-up data were available for all 146 (100%) eyes. Preoperative mean manifest defocus refraction was −3.60±1.54 diopters (D) (range: −7.50 to −1.25 D) and mean manifest astigmatism magnitude was 0.79±0.74 D (range: 0.0 to 4.00 D). Corneal topography[21] was obtained in all eyes, and derived corneal wavefront aberrations[7,22] up to the 7th Zernike order (36 terms) (Keratron-Scout; OPTIKON 2000, Rome, Italy), manifest refraction, uncorrected distance visual acuity[23] (UDVA), and CDVA were measured. Measurements were performed preoperatively and at 1 and 3 months after surgery.

All ablations were non-wavefront-guided but were based on aspheric[24] aberration-neutral profiles (and not on the profiles proposed by Munnerlyn[25]) to balance the induction of spherical aberration[26,27] (prolateness optimization[28]). This approach included a multidynamic aspheric transition zone, aberration and focus shift compensation due to tissue removal, pseudo-matrix-based spot positioning, and enhanced compensation for the loss of efficiency[29]—all based on theoretical equations validated with ablation models and clinical evaluations.

A 6.3-mm, central, fully corrected optical zone was used for myopia; a 7.0-mm optical zone was used for high astigmatism. A variable transition zone that was automatically provided by the laser depending on the planned refractive correction (6.5 to 9.2 mm) was also used. The ablation was performed using the AMARIS excimer laser (SCHWIND eye-tech-solutions), which is a flying-spot laser system that uses real ablative spot volume locally considered through a self-constructing algorithm and controls the local repetition rate to minimize the thermal load of the treatment.[30] Therefore, the ablated surface with the aspheric aberration neutral profiles should be very smooth, leading to possible benefits in terms of higher order aberrations. Finally, all of these optimizations theoretically diminish the induced wavefront aberration after LASIK.

The AMARIS laser system works at a true repetition rate of 500 Hz and produces a 0.54-mm beam size (full-width-at-half-maximum) and a super-Gaussian spot profile.[31,32] High-speed eye tracking (pupil and limbus tracker with cyclotorsional tracking[33]) with a 1050-Hz acquisition rate is accomplished with a 3-ms latency time.[34]

Optical errors centered on the line-of-sight, representing the wavefront aberration, are described by Zernike polynomials[35] and coefficients are presented using Optical Society of America standards[16] and analyzed for a standardized diameter of 6 mm.

All analysis sections have been evaluated for the same patients based on the diagnostic data taken preoperatively and at 3-month postoperative follow-up after LASIK.

Videokeratoscopy

Four corneal topographies[21] (Corneal Wavefront Analyzer, SCHWIND eye-tech-solutions based on Keratron-Scout) were obtained and corneal wavefront[22] analyses centered on the line-of-sight[36] were derived for each eye of the patient. The mean was extracted and the least representative measurement (ie, the one with the poorest similarity to the mean) was discarded. From the remaining three maps, the mean was calculated and the most representative measurement (ie, the one with the highest similarity to the mean) was selected.

Aberrometry

Aberrometry (Ocular Wavefront Analyzer, SCHWIND eye-tech-solutions, based on irx3, Imagine Eyes, Orsay, France) was performed three times for each eye of the patient in non-pharmacologically dilated pupils, non-cycloplegic conditions, and natural dim light conditions (to avoid pharmacologically induced pupil shifts[37-39]). Objective refraction for each eye of the patient was also obtained. To minimize potential accommodative response, patients were asked to “see-through-the-target” instead of “look at the target.” In doing so, patients did not try to obtain a sharp image from the +1.50-D fogged target. The mean value was extracted from the aberrometry evaluations and the most representative measurement was selected.

Corneal Asphericity

We have assumed that a corneal surface can be approximated satisfying Baker’s equation[40] for conicoids.

$$r^2 + (Q + 1)z^2 - 2zR = 0$$

$$p = Q + 1$$

$$z = \frac{R}{p}\left(1 - \sqrt{1 - p\left(\rho\frac{OZ}{2R}\right)^2}\right),$$

where z is the axis of revolution, r is the radial distance to the corneal apex, Q is the asphericity, and R is the apical radius of curvature. We have expressed the corneal surface within the optical zone disk (OZ) considered as the unit disk. Q represents how fast the real surface deviates from a perfect sphere, whereas p represents how fast the real surface deviates from a paraboloid.

We calculated corneal asphericity from the Zernike expansion of the corneal elevation as described previously[41]:

$$(1) \qquad C_4^0\sqrt{5} = \frac{(1-n)}{48}Rp\left(\frac{OZ}{2R}\right)^4 + 5C_6^0\sqrt{7} - 45C_8^0$$

$$(2) \qquad Q \simeq \frac{48(C_4^0\sqrt{5} - 5C_6^0\sqrt{7} + 15C_8^0 3)}{R(1-n)}\left(\frac{2R}{OZ}\right)^4 - 1.$$

To clarify, an “aberration-free” profile is different from an aspheric profile designed to preserve corneal asphericity,[42] where the goal is described in terms of elevation and shape parameters, rather than in terms of wavefront aberration.

The equation used to calculate Zernike coefficients from aspheric corneal properties is deducted in a “term-by-term of same radial order” fashion. That is, if a higher (or lower) order for the Taylor expansion was used, the obtained set of equations would have been slightly different by including more (or less) terms. Given the orthogonal properties of Zernike polynomials, inner products between the conic and Zernike functions may also be used to correlate the conic parameters (R,Q) with radially symmetrical Zernike coefficients (C[n,0]).[43]

Reference Asphericity for Corneal Spherical Aberration Equals Ocular Spherical Aberration

Considering a dynamic corneal model, the departure of the measured corneal topography from the theoretically optimal corneal surface was calculated. Ray tracing is a procedure classically performed by applying Snell’s law to the corneal surface. However, it is much simpler to understand corneal wavefront in terms of optical path difference and calculate it by Huygens-Fresnel or “least time” Fermat principles.[22,44]

In corneal wavefront analysis, the type and size of any optical error on the anterior corneal surface are registered, thus allowing a selective correction. The defects are corrected exactly at their origin—the anterior corneal surface. In this context, the precise localization of defects is crucial to successfully achieving optimal results in laser surgery. The corneal wavefront allows for precise diagnosis, thus providing an individual ablation of the cornea to obtain perfect results.

By applying this treatment strategy, measurement does not require pupil dilation of the eye, therefore, the treatment zone is not limited by the pupil and accommodation does not influence the measurements. In this way, forcing a fixed asphericity quotient on the eye through the treatment is avoided. Instead, this strategy employs a dynamic asphericity quotient specific for each eye.

Statistical Analysis

Scattergrams were plotted for corneal and ocular spherical aberrations versus the corneal asphericity, linear invariant for corneal asphericity and spherical aberration, corneal versus ocular spherical aberration, and induced corneal versus induced ocular spherical aberration. Slope and intercept of the correlations were analyzed. Statistical significance of the correlations was assessed using the Student *t* test and the coefficient of determination (r^2), and the significance of the correlations was evaluated considering a metric distributed approximately as t with N–2 degrees of freedom where N is the size of the sample. Statistical significance was $P<.05$.

RESULTS

Mean patient age was 34±7 years (median: 36 years; range: 20 to 51 years). No adverse events or complications were observed intra- or postoperatively. No patient underwent retreatment of either eye.

Manifest Refraction

Concerning refractive outcomes, at 3 months postoperative both the spherical equivalent and cylinder were significantly reduced to subclinical values: mean residual defocus refraction was −0.08±0.36 D (range: −1.12 to +0.75 D; $P<.0001$) and mean residual astigmatism magnitude was 0.16±0.21 D (range: 0.00 to 0.75 D; $P<.001$). In addition, 86% of eyes (n=126) were within ±0.50 D of emmetropia, and 98% of eyes (n=143) were within ±0.50 D of emmetropia for astigmatism.

Aberrometry

Preoperatively, mean corneal spherical aberration was +0.315±0.076 µm (median: +0.321 µm, range: +0.115 to +0.583 µm) and mean ocular spherical aberration was +0.036±0.091 µm (median: +0.042 µm, range: −0.233 to +0.288 µm). Postoperatively, mean corneal spherical aberration was +0.419±0.117 µm (median: +0.411 µm, range: +0.105 to +0.813) and mean ocular spherical aberration was +0.100±0.126 µm (median: +0.078 µm, range: −0.348 to +0.416 µm).

The difference between ocular spherical aberration minus corneal spherical aberration can be used as a metric for the internal spherical aberration, introduced mainly by the crystalline lens. Preoperatively, mean internal spherical aberration was −0.279±0.095 µm (median: −0.277 µm, range: −0.029 to −0.545 µm). Postoperatively, mean internal spherical aberration was −0.318±0.127 µm (median: −0.305 µm, range: −0.001 to −0.666 µm).

Corneal Asphericity

Preoperatively, mean corneal asphericity was −0.057±0.121 (median: −0.049, range: −0.376 to +0.369). Postoperatively, mean corneal asphericity was +0.268±0.287 (median: +0.244, range: −0.370 to +1.205).

Corneal Asphericity and Spherical Aberration

Corneal and ocular spherical aberrations were correlated in a statistically significant manner to corneal asphericity ($P<.0001$ for all four correlations) (Fig 1). Analyzing the slope and intercept of the correlations for ocular spherical aberration, an asphericity quotient of −0.19 to −0.27 can provide zero ocular spherical aberration in patients before and after LASIK for myopic astigmatism.

Linear Invariant for Corneal Asphericity and Spherical Aberration

Corneal and ocular spherical aberrations were correlated in a statistically significant manner to the term $p \cdot R^{-3}$ ($P<.0001$ for all four correlations) (Fig 2). Analyzing the slope and intercept of the correlations for ocular spherical aberration, a term $p \cdot R^{-3}$ of 1.99e-3 to 1.82e-3 can provide zero ocular spherical aberration in patients before and after LASIK for myopic astigmatism.

Corneal Spherical Aberration Versus Ocular Spherical Aberration

Corneal and ocular spherical aberrations were correlated in a statistically significant manner ($P<.0001$ for both correlations) (Fig 3). Analyzing the slope and intercept of the correlations, ocular spherical aberration increases at a rate of half the corneal spherical aberration in patients before and after LASIK for myopic astigmatism.

Reference Asphericity for Corneal spherical aberration Equals Ocular Spherical Aberration

Considering a dynamic corneal model (a dynamic asphericity quotient specific for each eye), the

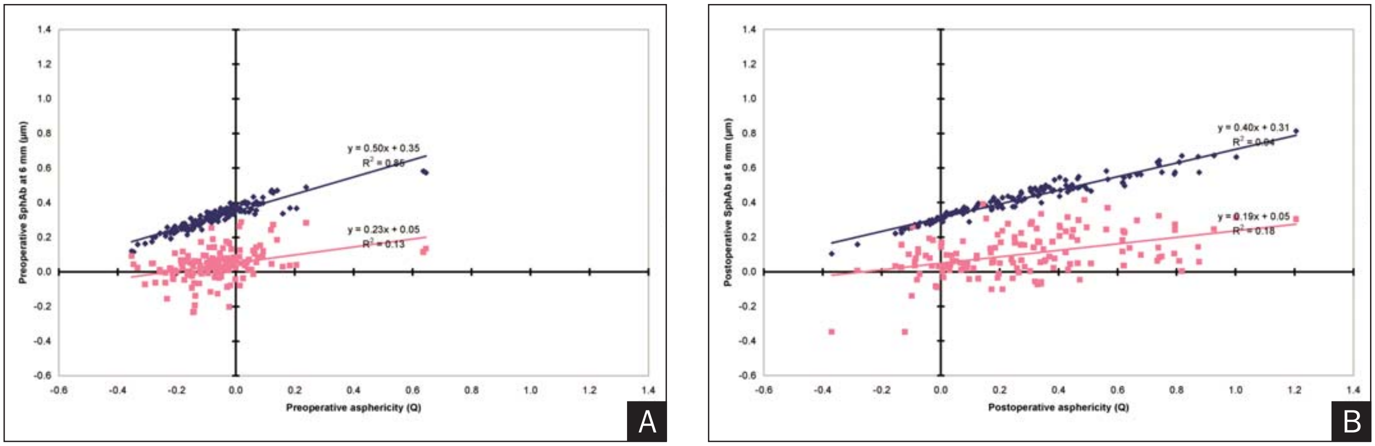

Figure 1. Corneal (black diamonds) and ocular (red squares) spherical aberrations versus the corneal asphericity for **A)** preoperative and **B)** postoperative analyses. Corneal and ocular spherical aberrations were correlated in a statistically significant manner to corneal asphericity ($P<.0001$ for all four correlations). Analyzing the slope and intercept of the correlations for ocular spherical aberration, an asphericity quotient of −0.19 to −0.27 can provide zero ocular spherical aberration in patients before and after LASIK for myopic astigmatism. Both pre- and postoperative corneal spherical aberration increased approximately twice as fast as ocular spherical aberration. Both corneal and ocular spherical aberrations increased at approximately the same rate pre- and postoperatively.

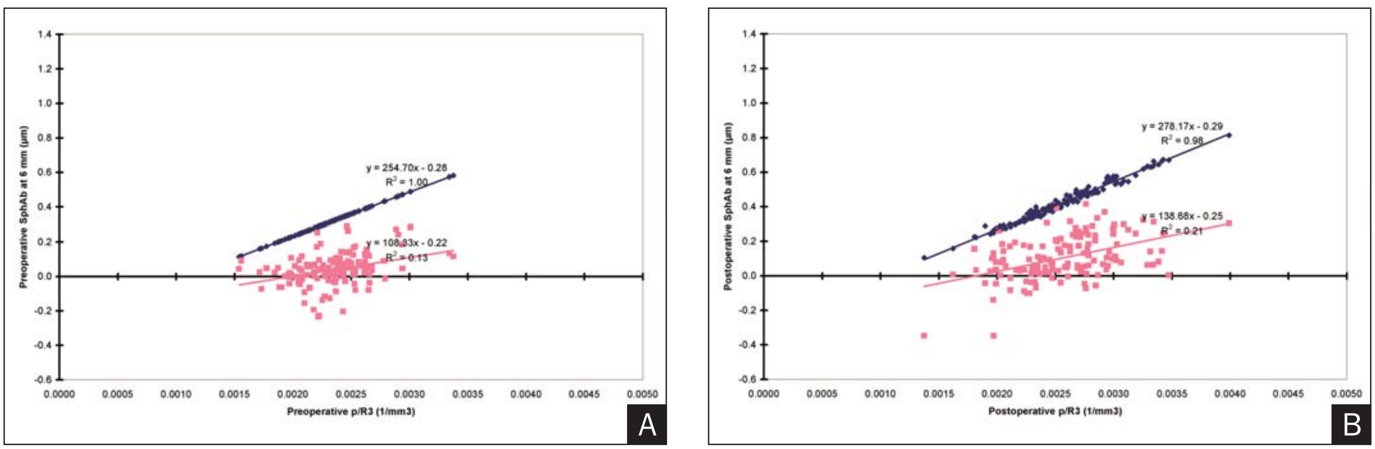

Figure 2. Corneal (black diamonds) and ocular (red squares) spherical aberrations versus the term $p \cdot R^{-3}$ for **A)** preoperative and **B)** postoperative analyses. Corneal and ocular spherical aberrations were correlated in a statistically significant manner to the term $p \cdot R^{-3}$ ($P<.0001$ for all four correlations). Analyzing the slope and intercept of the correlations for ocular spherical aberration, a term $p \cdot R^{-3}$ of 1.99e-3 to 1.82e-3 can provide zero ocular spherical aberration in patients before and after LASIK for myopic astigmatism. Both pre- and postoperative corneal spherical aberration increased approximately twice as fast as ocular spherical aberration. Both corneal and ocular spherical aberrations increased at approximately the same rate pre- and postoperatively.

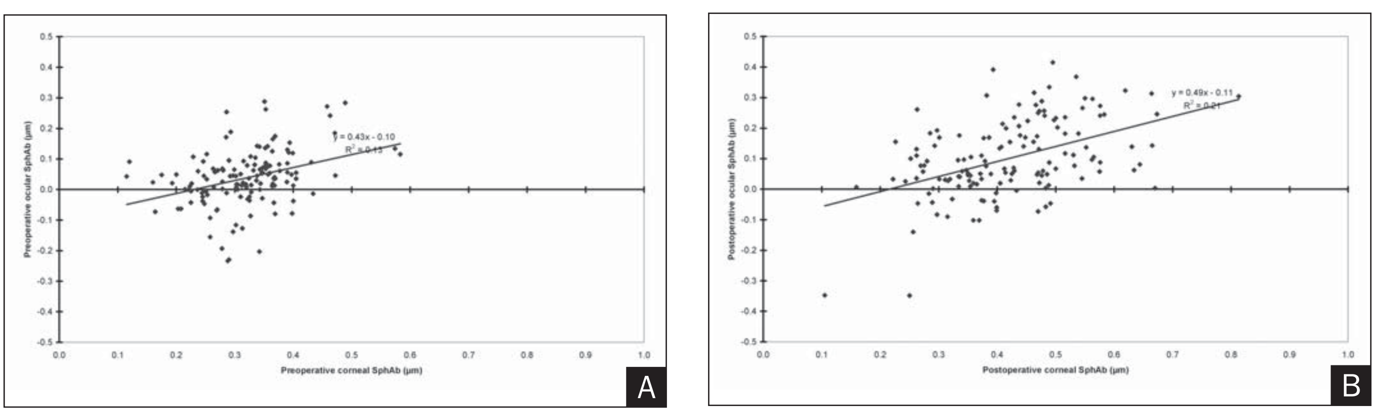

Figure 3. Ocular spherical aberrations versus corneal spherical aberrations for **A)** preoperative and **B)** postoperative analyses. Corneal and ocular spherical aberrations were correlated in a statistically significant manner ($P<.0001$ for both correlations). Analyzing the slope and intercept of the correlations, ocular spherical aberration increases at a rate of half the corneal spherical aberration in patients before and after LASIK for myopic astigmatism, both pre- and postoperatively.

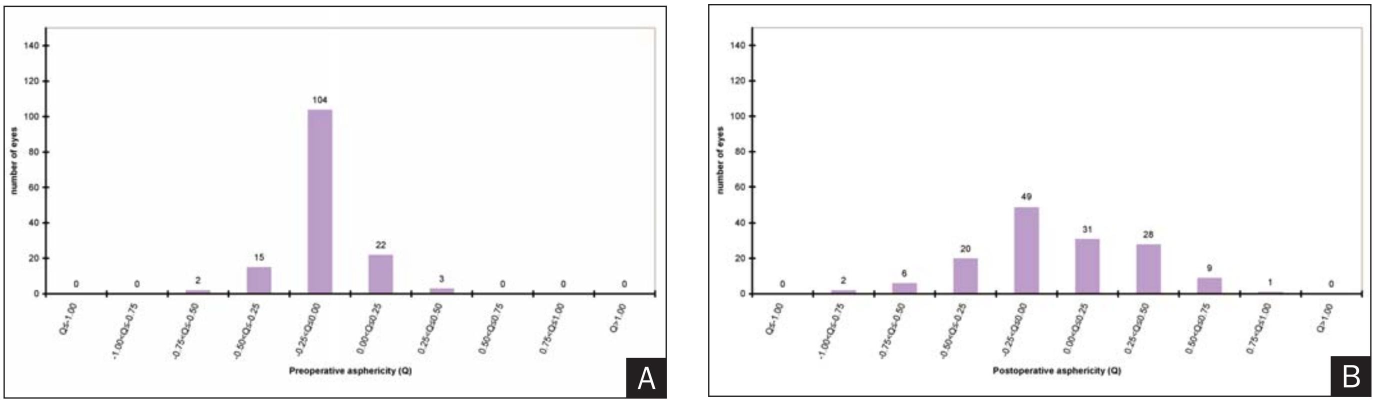

Figure 4. Reference Q value to provide corneal spherical aberration equal to ocular spherical aberration for **A)** preoperative and **B)** postoperative analyses. A reference Q value between −0.25 and 0.00 can provide corneal spherical aberration equal to ocular spherical aberration in patients before and after LASIK for myopic astigmatism. The distribution in the histogram is much narrower preoperatively than postoperatively. A tendency to more oblate reference surface postoperatively can be observed.

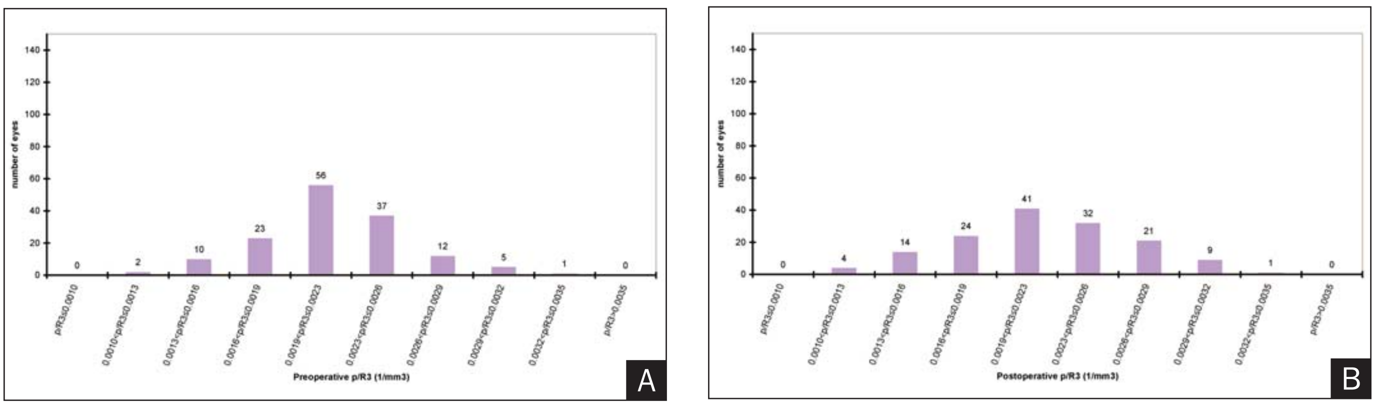

Figure 5. Reference $p \cdot R^{-3}$ value to provide corneal spherical aberration equal to ocular spherical aberration for **A)** preoperative and **B)** postoperative analyses. Similarly, a reference value between 1.9e-3 and 2.3e-3 can provide corneal spherical aberration equal to ocular spherical aberration. The distribution in the histogram is slightly wider postoperatively than preoperatively. No general shift of the reference surface postoperatively can be observed.

departure of the measured corneal topography from the theoretically optimal corneal surface was calculated. A reference Q value of −0.12±0.15 (median: −0.12, range: −0.514 to +0.308) to +0.01±0.321 (median: −0.02, range: −0.789 to +0.893) can provide corneal spherical aberration equal to ocular spherical aberration in patients before and after LASIK for myopic astigmatism (Fig 4). Similarly, a reference value of 2.18e-3±0.37e-3 (median: 2.17e-3, range: 1.20e-3 to 3.23e-3) to 2.18e-3±0.46e-3 (median: 2.14e-3, range: 1.04e-3 to 3.43e-3) can provide corneal spherical aberration equal to ocular spherical aberration (Fig 5).

Induced Corneal Versus Induced Ocular Spherical Aberration

The difference between the spherical aberration postoperatively minus the preoperative baseline value can be used as a metric for the induced spherical aberration, introduced mainly during refractive surgery treatment. Pre- to postoperatively, mean induced corneal spherical aberration was +0.103±0.117 µm (median: +0.086 µm, range: −0.183 to +0.333 µm), whereas mean induced ocular spherical aberration was +0.064±0.108 µm (median: +0.047 µm, range: −0.203 to +0.346 µm).

A scattergram was plotted for the induced ocular spherical aberration (the difference between the ocular spherical aberration postoperatively minus the preoperative baseline value) versus the induced corneal spherical aberration (the difference between the corneal spherical aberration postoperatively minus the preoperative baseline value) (Fig 6). Induced corneal and ocular spherical aberrations were correlated in a statistically significant manner ($P<.0001$). Analyzing the slope and intercept of the correlation, ocular spherical aberration is induced at a rate of half the induced corneal spherical aberration in patients before and after LASIK for myopic astigmatism.

DISCUSSION

In our study, preoperative mean corneal spherical aberration was similar but slightly larger than other

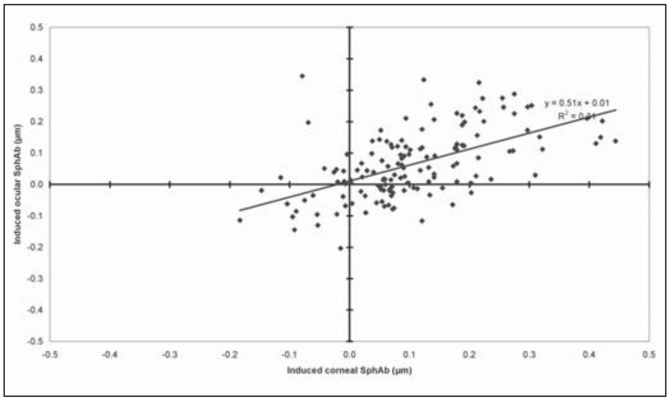

Figure 6. Induced ocular spherical aberration (difference between the ocular spherical aberration postoperatively minus the preoperative baseline value) versus induced corneal aberration (difference between the corneal spherical aberration postoperatively minus the preoperative baseline value). Induced corneal and ocular spherical aberrations were correlated in a statistically significant manner ($P < .0001$). Analyzing the slope and intercept of the correlation, ocular spherical aberration is induced at a rate of half the induced corneal spherical aberration in patients before and after LASIK for myopic astigmatism.

values reported in the literature,[7,15] whereas mean ocular spherical aberration was comparable to other studies,[9,14,45] ie, mean internal spherical aberration was also slightly larger than the values reported in the literature.

In general, the human cornea manifests a natural corneal spherical aberration of approximately 0.23 µm[7] (OSA standard[16]).

It should be noted that corneal spherical aberrations are not "absolute values" but are derived from the topographic system using an ideal corneal, single, thin-lens approach, referred to as a Cartesian-oval model, and will be different after measurement of the ocular aberrations[7,10] and definitively close to zero when using a balanced-eye model. It can be said that the corneal wavefront values in the topographic system are "overestimated" compared to the ocular wavefront values.[7]

This is consistent with our findings on asphericity. Preoperatively, mean corneal asphericity was less prolate than the values reported in the literature.[19,20,28]

Based on our data, an asphericity quotient of −0.19 to −0.27 can provide zero ocular spherical aberration in patients before and after LASIK for myopic astigmatism. These values are definitely less prolate than the values reported in the literature. An explanation may be the age of the patients treated, who were on average relatively young. Thus, their internal aberration might have been more negative, compensating more of the corneal positive spherical aberration.

It is possible to directly calculate the corneal wavefront aberration from the measured surface data. In the case of a rotationally symmetric cornea, the surface shape that will be free of aberrations is a conic surface (aspheric surface) with a Q value equal to $-1/n^2$ (Cartesian-oval model). Any departure from this surface will result in aberrations. The relative elevation of the cornea compared to the best-fit Cartesian-oval model is the "surface aberration," and if this is known, the corneal wavefront aberration can be computed considering the refractive indices.[22]

Using a more pragmatic definition, as the corneal surface shape that best represents the average human cornea is a conic surface (aspheric surface) with a Q value equal to −0.25 (balanced-eye model), any departure from this surface can be considered an aberration. The relative elevation of the cornea compared to this balanced-eye model can be considered as the "surface aberration," and the corneal wavefront aberration can be computed.

Because asphericity is a dependent parameter with "non-linear" behavior (ie, it has no meaning if the apical curvature is not taken into consideration), we have selected the term $p \cdot R^{-3}$ as a simple yet more flexible asphericity characterization metric than Q. In this way, we are not fixing the asphericity, but relating the optimum asphericity to the apical radius of curvature. A term $p \cdot R^{-3}$ of 1.99e-3 to 1.82e-3 can provide zero ocular spherical aberration in patients before and after LASIK for myopic astigmatism.

Corneal and ocular spherical aberrations were correlated in a statistically significant manner, with ocular spherical aberration increasing at a rate of half of the corneal spherical aberration in patients before and after LASIK for myopic astigmatism.

Because even healthy individuals with 20/20 or better high contrast visual acuity present a measurable degree of aberration in their wavefront, and it has been observed that individuals with smaller wavefront aberration do not always have the best visual outcomes,[45,46] we determined the reference corneal asphericity for which corneal spherical aberration equals ocular spherical aberration. A reference Q value of −0.12 to +0.01 or a reference $p \cdot R^{-3}$ value of 2.18e-3 to 2.18e-3 can provide corneal spherical aberration equal to ocular spherical aberration in patients before and after LASIK for myopic astigmatism. These values are less prolate than the values reported in the literature.[3,4,47,48]

However, a balanced-eye model corneal wavefront approach is still based on the critical assumption that an aspheric cornea with a Q value of −0.25 will balance its "positive" spherical aberration with the "negative" contribution of the internal lens (which is true on average for the non-treated population[7,9]). On the other hand, the best-fit aspheric Q value could be used as the reference corneal surface for each individual cornea. This will lead to the critical assumption that the overall "ocular" spherical aberration for each individual eye is close to zero (which is also true on average for the non-treated population[7,9]).

Induced corneal and ocular spherical aberrations were correlated in a statistically significant manner, with ocular spherical aberration being induced at a rate of half the induced corneal spherical aberration in patients before and after LASIK for myopic astigmatism.

Studies in which direct comparison of induced corneal and ocular wavefront aberrations over the same sample showed that the induction of anterior corneal aberrations was always, at least, as high as the induction of ocular wavefront aberrations for the entire eye. Marcos et al[10] found that ocular and corneal aberrations increased statistically significantly after myopic LASIK by an average factor of 1.92 (ocular) and 3.72 (corneal). They found a good correlation ($P<.0001$) between the aberrations induced in the entire optical system and those induced in the anterior corneal surface. However, anterior corneal aberrations increased more than ocular aberrations, suggesting changes occurred in the posterior corneal surface. Lee et al[49] found that after laser refractive surgery, anterior corneal aberration and ocular aberration increased equally and showed statistically significant correlations. They found no statistically significant differences in internal optics aberration values in coma, spherical aberration, and root-mean-square for higher order aberrations. Arbelaez et al[50] found that comparing corneal and ocular aberrations, the amount of induced aberrations was similar for spherical aberration and coma. Root-mean-square for higher order corneal-induced aberrations was moderately higher, but not statistically significant, than ocular-induced aberrations.

To date, asphericity alone has not been proven to play a major role in the visual process.[51]

It is important to note that preserving preoperative aberrations is not equivalent to maintaining preoperative asphericity. Tuan and Chernyak[52] analyzed the impact of corneal asphericity on wavefront-guided LASIK at six clinical sites and found no significant correlation between corneal shape and visual acuity or contrast sensitivity. Pop and Payette[53] studied the relationship between contrast sensitivity, Zernike wavefront aberrations, and asphericity after LASIK to correct myopia. Contrast sensitivity was not correlated with asphericity but was correlated with wavefront aberrations as expected. The change in asphericity was correlated with the refractive change and was predicted by the parabolic Munnerlyn equation.

Despite some remarkable theoretical works,[47,48] there is no proof that more negative quotients of asphericity provide better visual quality, or that an absolute optimum exists. When a patient is selected for noncustomized aspheric treatment, the global aim of the surgeon should be to leave all existing higher order aberrations unchanged because the patient's CDVA has been unaffected by the pre-existing aberrations.[46] Hence, all factors that may induce higher order aberrations, such as biomechanics, need to be taken into account prior to treatment to ensure that the preoperative higher order aberrations are unchanged after treatment.[27,28]

Although the amount of corneal spherical aberration and asphericity are intrinsically related, the goal of any refractive surgery procedure is always described in terms of change in spherical aberration,[11] as this is the factor related to the quality and sharpness of the retinal image.

From this analysis, we propose:

1) A dynamic aspheric eye model, in which the best-fit aspheric Q value for each individual cornea is used, will be more appropriate for characterizing untreated healthy eyes.
2) A balanced-eye model with a term $p \cdot R^{-3}$ of 2e-3 corneal wavefront will be more appropriate for planning refractive surgery retreatments, where the natural balance has already been disrupted.
3) A Cartesian-oval model with a Q value $-1/n^2$ corneal wavefront will be more appropriate for planning lens surgeries.

Depending on the patient case history and the application for which corneal wavefront information will be used, the most suitable eye model should be selected to derive the corneal aberration.

AUTHOR CONTRIBUTIONS

Study concept and design (S.A.M., D.O.); data collection (D.O.); analysis and interpretation of data (S.A.M.); drafting of the manuscript (S.A.M., D.O.); critical revision of the manuscript (D.O.); statistical expertise (S.A.M.)

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