Functional Optical Zone of the Cornea

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Purpose. When keratorefractive surgery is used to treat a central corneal diameter smaller than the resting pupil, visual symptoms of polyopia, ghosting, blur, haloes, and glare can be experienced. Progress has been made to enlarge the area of surgical treatment to extend beyond the photopic pupil; however, geometric limitations can pose restrictions to extend the treatment beyond the mesopic pupil diameter and can lead to impediments in night vision. The size of the treated area that has achieved good optical performance has been defined as the functional optical zone (FOZ). In this study the authors developed three objective methods to measure the FOZ.

Methods. Corneal topography examination results from 1 eye of 34 unoperated normal eyes and 32 myopic eyes corrected by laser in situ keratomileusis (LASIK) were evaluated in three ways. First, a uniform axial power method (FOZ_A) assessed the area of the postoperative cornea that was within a ±0.5-D window centered on the mathematical mode. Second, FOZ was determined based on the corneal wavefront true RMS error as a function of the simulated pupil size (FOZ_R). Third, FOZ was determined from the radial MTF, established at the retinal plane as a function of pupil size (FOZ_M).

Results. Means for each of the FOZ methods (FOZ_A, FOZ_R, and FOZ_M) were 7.6, 9.1, and 7.7 mm, respectively, for normal eyes. For LASIK-corrected eyes, these means were 6.0, 6.9, and 6.0 mm. Overall, an average decrease of 1.8 mm in the functional optical zone was found after the LASIK procedure. Correlations between the FOZ methods after LASIK showed acceptable and statistically significant values ($R = 0.71$, 0.70, and 0.61; $P < 0.01$).

Conclusions. These methods will be useful to more fully characterize corneal treatment profiles after keratorefractive surgery. Because of its ease of implementation, direct spatial correspondence to corneal topography, and good correlation to the other more computationally intensive methods, the semiempiric uniform axial power method (FOZ_A) appears to be most practical in use. The ability to measure the size of the FOZ should permit further evolution of keratorefractive surgical lasers and their algorithms to reduce the night vision impediments that can arise from functional optical zones that do not encompass the entire mesopic pupil. (*Invest Ophthalmol Vis Sci.* 2007;48:1053–1060) DOI:10.1167/iovs.06-0867

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The development of excimer laser keratorefractive surgery has provided alternative procedures to correct defocus and astigmatism. However, early procedures tended to induce higher order aberrations that affected visual performance. In recent years, the use of new techniques to measure aberrations in the living eye[1,2] opened the possibility to correct, at least in part, some of the higher order aberrations. With this leap in technology, algorithms have been extended beyond the original Munnerlyn approach[3] in the attempt to individualize corneal refractive treatment so that the quality of postoperative vision would exceed the level that could be provided by correcting sphere and cylinder alone. A number of studies have dealt with theoretical limitations and considerations with this methodology, which include laser beam characteristics, alignment issues, corneal tissue thickness, and spatial ablation efficiency.[4–7] Other studies have considered the influence of tissue biomechanics[8] and healing response[9] on the alteration of the intended surface structure prescribed for a given treatment. However, how closely the surgical result corresponds to the intended correction is not well defined by traditional measures of postoperative refraction and measures of visual acuity.

For example, when keratorefractive surgery is used to treat a central corneal diameter smaller than the resting pupil, visual symptoms of polyopia, ghosting, blur, haloes, and glare can result. This has been a particular difficulty for patients with large pupils, who then have night vision problems. Although night vision problems have decreased with improvements in laser algorithms,[10] there is a direct correlation between postsurgical vision aberrations and larger pupil diameters, particularly with the early surgical techniques.[11,12]

Evaluation of the refractive surgery result relies on the measurement of the postoperative refractive status of the eye with regard to proximity to the intended correction. With continual refinements to the procedure, it becomes important to compare the result obtained with the predicted anatomic and functional characteristics envisioned by the algorithm used. To study the surgical consequences of refractive surgery, a common descriptive language must be adopted. Although terminology describing elements of refractive surgery is in common use, many of the descriptors are weak. An example is *optical zone*. In the past this term was used to designate the region of the cornea given the full intended refractive correction. With the recognition that the sharp curvature change between the optical zone and the peripheral cornea often created significant visual symptoms, the *transition zone* was modified to smoothly blend the prescriptive correction into the curvature of the peripheral cornea. This blend was intended to eliminate the discontinuity in curvatures known to contribute to the *red ring* observed with instantaneous corneal topographic maps.

Although optical zone is the traditional term, it can be misleading because it implies that the entire corneal surface within the region contributes to quality functional vision and that the region outside does not contribute. With the historical observations of corneal irregularities such as central islands, smaller than anticipated regions of uniform central corneal power, and decentered treatments, it is easily understood that not all the intended optical zone will provide functional or quality vision. Furthermore, if the algorithms defining the transition zone are clever enough, there is no a priori reason that portions of this blend zone would not also contribute to functional vision.

With these considerations, the terminology used in this study includes the *full correction zone* (FCZ), which is the corneal region of full intended refractive correction. The transitional treatments outside the FCZ are called the *transition zone* (TSZ). The *functional optical zone* (FOZ) describes the area of the corneal surface, after laser sculpting, that provides reasonable quality vision. It is possible that the FOZ could be larger than the FCZ if it encompasses some portions of the TSZ.

Although FCZ and TSZ are parameters defined by the laser treatment algorithms, FOZ must be determined postoperatively and may change with time because of healing and biomechanical effects. Methods for determining FOZ have been used previously. Roberts and Koester[13] developed a ray-tracing program to define FOZ after photorefractive keratectomy. A ray-tracing approach has also been used to measure FOZ with commercial software after conductive keratoplasty (CK) and laser in situ keratomileusis (LASIK).[14,15] A more direct approach has been used to measure FOZ after refractive surgery by manually determining the transition region between the treated and untreated areas from corneal topography maps.[16–18] Each of these methods established an optical performance criterion for area inclusion in the FOZ; the commercial application used a criterion of visual function for visual acuity better than 20/32.[14,15]

In this study, we compared three objective methods to determine FOZ in normal eyes and in eyes after keratorefractive surgery to provide assessment techniques to evaluate, compare, and improve keratorefractive surgical algorithms.

Methods

Topography examinations (Nidek Magellan; Nidek Technologies Srl, Padua, Italy) were obtained from collaborating clinics. All examinations were screened for freedom of processing error and tear film artifact. One eye was chosen randomly from each of 66 patients, 32 of whom underwent standard LASIK refractive surgery for the correction of mild to moderate myopia and 34 of whom had unoperated mild to moderate myopia in eyes that were otherwise normal. In this retrospective study, topographic examples were chosen from several available clinical trial sets at different time frames in the development of LASIK to obtain a broad spectrum of full correction zones. Collection and maintenance of a Health Insurance Portability and Accountability Act (HIPAA)–compliant database at the Louisiana State University Eye Center of corneal topography examinations received institutional review board approval, and the study conformed to the Declaration of Helsinki concerning ethical research.

Three different methods were developed to estimate FOZ. All used the same data set from corneal topography examinations to measure the area of FOZ, and the results are expressed in terms of equivalent diameter in millimeters. The description of each method's optical quality parameters is presented in section A. Once these parameters were calculated as a function of pupil diameter, FOZ was evaluated after establishing threshold levels for each method; these are described in section B.

Section A: Optical Quality Parameters Used to Calculate FOZ

Uniform Axial Power Method (FOZ_A). Traditional refractive surgery attempts to leave the zone of full correction with a uniform curvature. This can be assessed directly with axial power map data (axial power = 337.5/radius of curvature). In the absence of any accommodation, −0.5 D of defocus decreases visual acuity, on average, to 20/32 (logMAR = 0.2). With this as a guideline to the minimum value providing functional visual acuity, a routine was constructed to determine the most frequently occurring corneal axial power (the statistical mode) over the central 4 mm of analyzed surface topography using a histogram bin width of 0.1 D. The areas represented by powers within a ±0.5-D range about the mode were summed as a function of simulated pupil size from 2 to 9 mm, in 1-mm intervals. (Although it was not the aim of this study, the centroid of the area determined with the axial power method was also calculated, and its polar coordinates [r, θ] were stored to indicate the centration of FOZ relative to the corneal vertex. Given that topographers generally indicate the center of the pupil, these data also can be used to calculate centration relative to the apparent entrance pupil.) The area highlighted in Figure 1 represents an example of this for one subject. For each of these pupil sizes, this area was subtracted from the corresponding total pupil area. The result of this calculation represents the corneal area for each pupil size, which contributes to the worsening of optical quality by more than 0.5 D. The larger this area, the lower will be the optical quality. This parameter was used in this way was to maintain coherence among all three methods in the calculation of FOZ parameters (see Section B: Threshold Values). Otherwise, correlations with different signs would need cumbersome normalization. The former calculations were developed, tested, and implemented on a software platform (VolPro, version 6.87; Sarver and Associates, Carbondale, IL). Area totals, A, were converted to equivalent diameters, D ($D = 2 \times \mathrm{sqrt}(A/\pi)$) and were plotted as a function of pupil diameter (Fig. 2, upper panels). Curves were fit to the data points using a cubic spline function.

Total Corneal RMS Error Method (FOZ_R). The total higher order RMS error for corneal wavefronts can be calculated with a modified Zernike polynomial method for various simulated apparent pupil sizes. For the current method, an eighth-order Zernike fit was used to calculate the higher order RMS error, and this error was summed with the RMS error of the residual corneal distortion that was not fit to include all distortions relevant to visual acuity.[19] This was repeated for simulated pupil sizes from 2 to 9 mm in 1-mm intervals, and, again, curves were fit to the data points using a cubic spline function (Fig. 2, middle panels). Computations were made using a Zernike decomposition utility developed, tested, and implemented on the topography software platform (Nidek Magellan, version 3.8; Nidek Technologies Srl).

Modulation Transfer Function Method (FOZ_M). The two methods described above reference the corneal plane. It seemed appropriate to evaluate methods to assess FOZ that also examined the corneal optical properties at the retinal image plane. Therefore, corneal wavefronts were calculated from the corneal topographer elevation data. We used a slightly modified procedure from a similar methodology previously described.[20,21] Briefly, the surface was fit with an eighth-order Taylor expansion using least squares fitting routines (Mathematica; Wolfram Research, Champaign, IL), and a rectangular Cartesian grid of points from this surface was calculated (Zemax

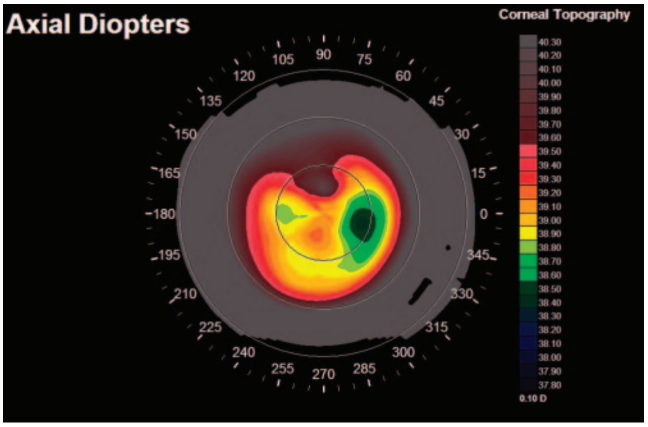

Figure 1. In the uniform axial power method, FOZ_A, the highlighted area in the topography map represents zones within ±0.5 D variation from the mode calculated from the central 4 mm.

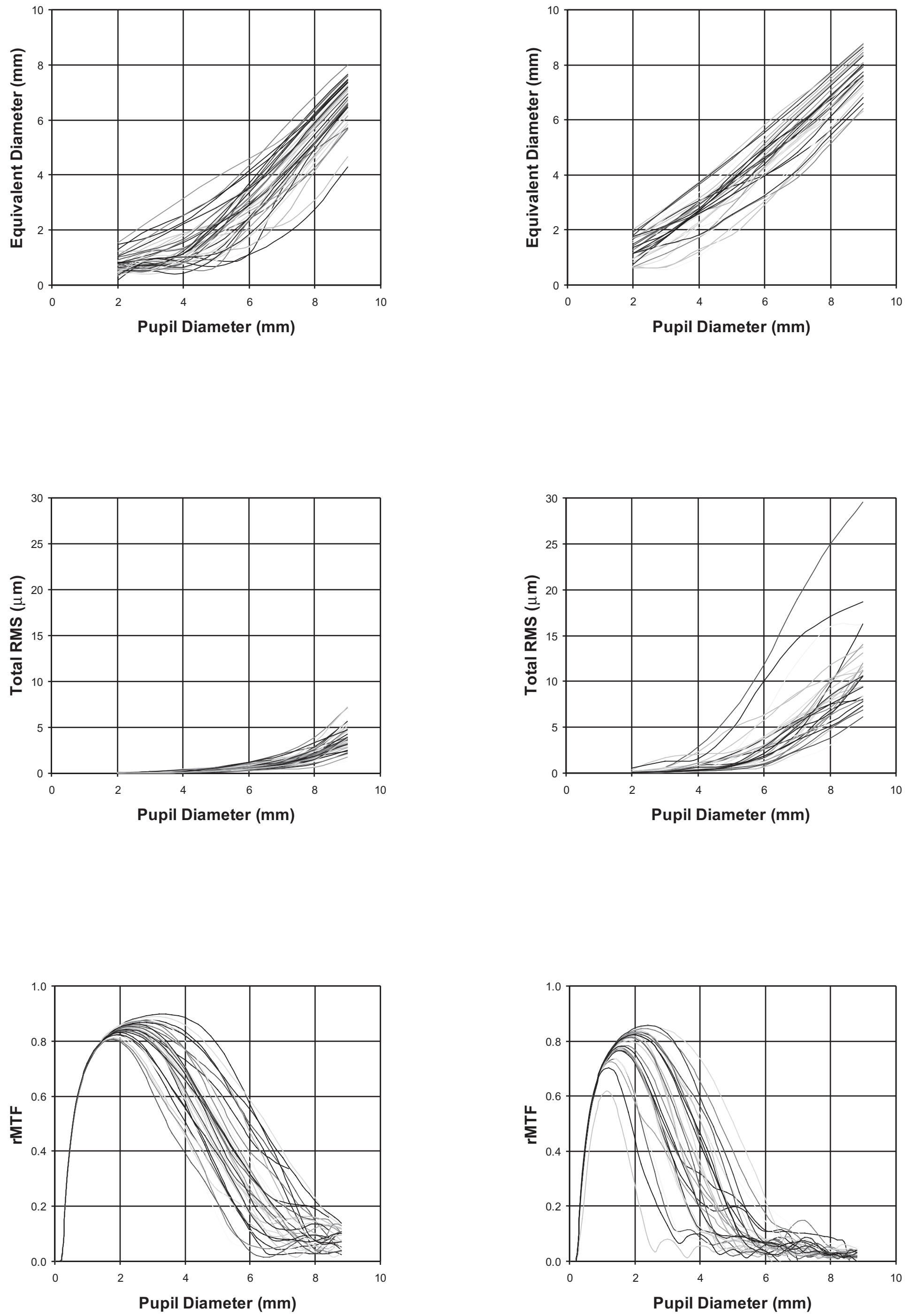

FIGURE 2. Variation of calculated parameters as a function of pupil diameters for the non-LASIK group (*left*) and the LASIK groups (*right*). *Upper*: equivalent diameter used for FOZ_A. *Middle*: total RMS as a function of pupil diameter used to calculate FOZ_R. *Lower*: radial modulation transfer function (rMTF) at 9 cyc/deg as a function of pupil diameter used to calculate FOZ_M.

software; Zemax Development Corp., San Diego, CA) to fit a bicubic spline function. Zemax was used to perform a point-by-point ray tracing to estimate the aberrations produced by the corneal surface. Two-dimensional modulation transfer functions (MTFs) were calculated and were averaged radially to obtain a one-dimensional radial MTF. This calculation was repeated for pupil diameters measuring 2 to 9 mm in 0.2-mm intervals. Modulations at 9 cyc/deg were used to estimate FOZ (Fig. 2, lower panel).

Section B: Threshold Values

To establish the relationship among the three methods for calculating the FOZ and visual function, we correlated each one at a pupil diameter of 4 mm with the clinical prediction of visual acuity[22] (logMAR) for each patient undergoing refractive surgery for myopia (Fig. 3).

Our definition of FOZ is the largest pupil size that includes an area whose total optical quality is consistent with 0.2 logMAR (Snellen equivalents, 20/32 and 6/10) or better vision; this is the same criterion used in the Boxler-Wachler studies.[14,15] For example, the visual acuity of a patient with 6-mm FOZ is worse than 0.2 logMAR if the pupil diameter is larger than 6 mm but is better than 0.2 logMAR if the pupil diameter is smaller than 6 mm. Figure 3 provides threshold values consistent with 0.2 logMAR for each optical quality and are listed in Table 1.

For each of the three methods, the FOZ parameter is calculated directly from Figure 2 as the pupil diameter that provides the threshold value for each analyzed patient. This is obtained from the abscissa of the intersection point of the constant threshold line with each of the plots of optical quality parameters as a function of pupil diameter.

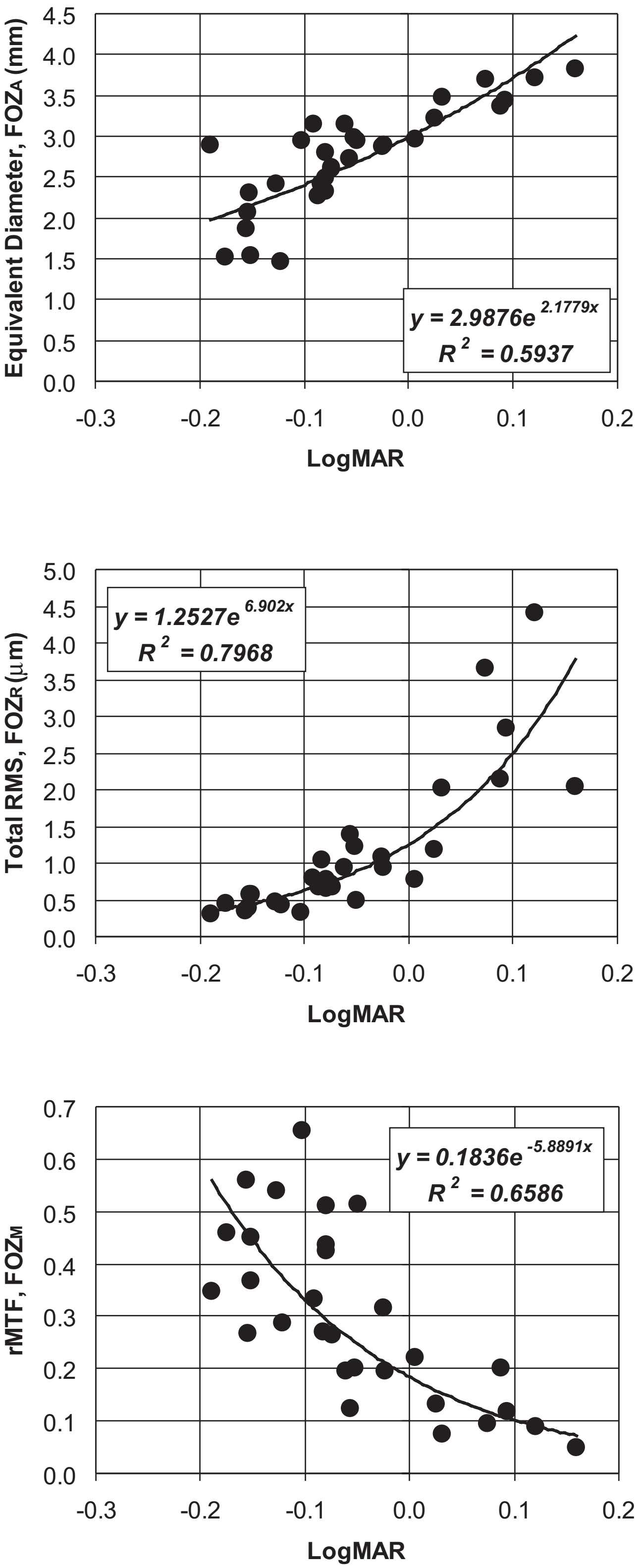

Figure 3. Variation of calculated parameters (within a 4-mm diameter) with visual acuity (logMAR). *Upper*: equivalent diameter used for FOZ_A. *Middle*: total RMS used to calculate FOZ_R. *Lower*: radial modulation transfer function (rMTF) at 9 cyc/deg used to calculate FOZ_M.

Figure 4 illustrates the procedure for one subject with myopia. These plots represent the equivalent diameter, total RMS, and radial MTF (9 cyc/deg) as a function of pupil diameter. The horizontal line represents the threshold value for each method (Table 1). The x-coordinate of the interception point between both lines represents the corresponding value of the FOZ_A, FOZ_R, and FOZ_M for this subject.

Results

Figure 5 shows the correlations among the FOZ parameters calculated with each of the three methods. Assuming a linear relationship among them, Table 2 summarizes the results in terms of the Pearson product moment correlation coefficient. The highest degree of linear correlation was obtained between FOZ_R and FOZ_A parameters ($R = 0.71$), whereas the correlation between FOZ_R and FOZ_M shows a more scattered plot but it is still statistically, significantly correlated ($R = 0.61$).

Figure 6 shows the data for FOZ_A sorted from the lowest to the highest value. Topography maps are shown for the subjects with the smaller and higher FOZ_A. The three corneas with the smallest FOZs showed large variation in central corneal axial power, whereas the three corneas with the largest FOZs had smooth, less variable apparent treatment zones. The methods are able to clearly distinguish between corneas with limited FOZs and those with FOZs that more successfully represented the zone of intended correction. Average values of the FOZ calculated with the three methods for the LASIK population included in this study are shown in Table 3.

Average FOZ was slightly larger with the RMS method (6.9 mm) than with the other two optical quality methods (6.0 mm for FOZ_A and FOZ_M; $P < 0.001$). Standard deviations were similar for all three methods (0.7–1.1).

As an initial example to show the capability of the methods, we calculated FOZ_A, FOZ_R, and FOZ_M in a population of 34 subjects who did not undergo LASIK. With FOZ_R, however, because of the relatively small values (see Fig. 2), the interception point with the threshold was found by extrapolation fitting the data with an exponential function: $a \times e^{b \times \text{pupil diameter}}$. Interceptions lying outside the pupil diameter range of 2 to 9 mm were calculated using this fit. The average R^2 from all the fits was 0.96 ± 0.05.

FOZ diameters calculated for each of the normal and LASIK corneas are shown in Figure 7. These plots are useful to compare the differences between the two groups and among the three methods. Average decreases in the three FOZ parameters after LASIK were 1.6, 2.2, and 1.7 mm. Therefore, FOZ was clearly smaller in the LASIK group than in the non-LASIK group. However, an overlapping region between both groups was observed. Some patients in the LASIK group had FOZ values that fell within the range of the normal group. Because the groups were not paired (preoperative and postoperative corneas from the same patient) and because the cohort intentionally selected recent and early clinical trial corneas, the reduced functional optical zone sizes reported here should not be taken as representative of modern outcomes.

Discussion

It is important to assess FOZ as lasers performing refractive surgery are continually improved and new, sophisticated treatment algorithms are developed. Because corneal topography remains an important tool in the assessment of visual function and corneal dysfunction, previous studies have developed definitions for the FOZ and strategies for its calculation based on

Table 1. Threshold Values for Each Method

	FOZ_A	FOZ_R	FOZ_M
Threshold (0.2 LogMar)	4.6	4.9	0.06

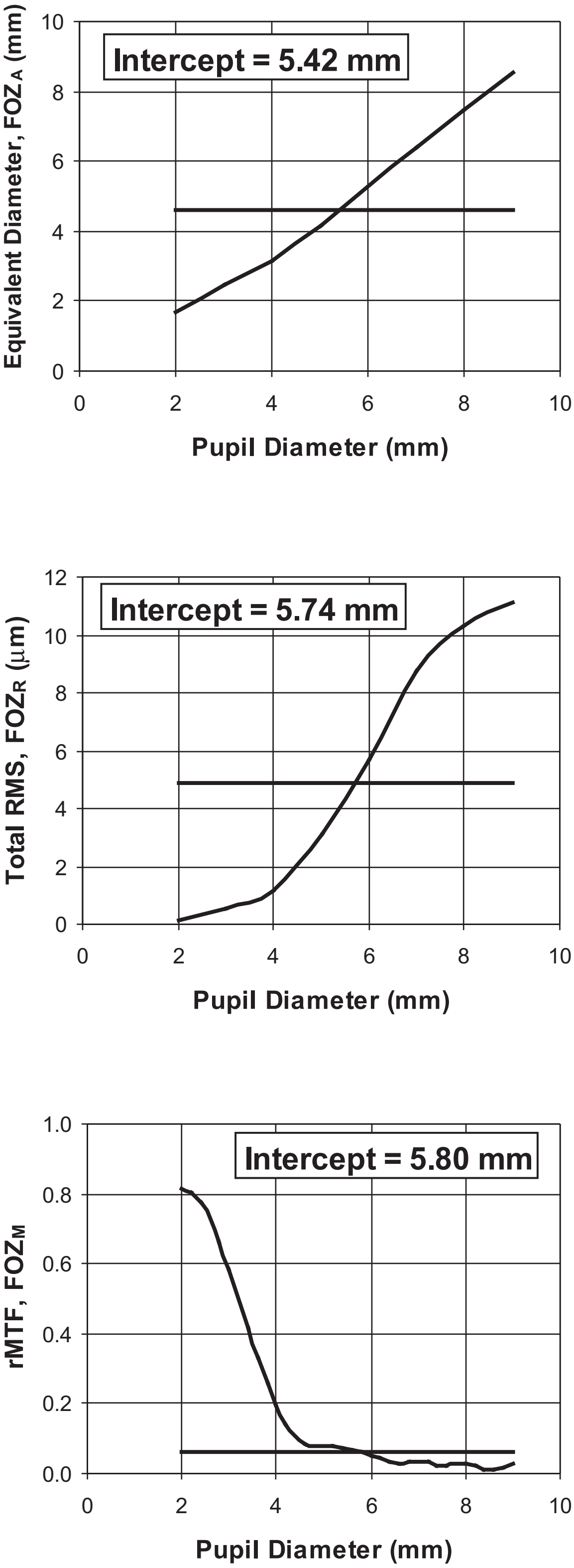

Figure 4. Illustration of the procedure for calculating the FOZ with the three methods developed in this study for one cornea. *Horizontal line* represents the threshold for each parameter used to determine the functional optical zone from the intercept.

topographic data. Nepomuceno et al.[15] used topography software to perform a ray-tracing procedure and to calculate the optimal optical zone that provides visual acuity better than 20/32. Unfortunately, they did not provide a theoretical basis for their calculations, and the optical parameter they used to calculate FOZ remains unclear. Others[23] have used corneal topography data and an algorithm that averages powers within a central corneal zone of 3 mm (seed area) and tested external neighboring points for those remaining within 1.33 SD of the seed area average power. If not, that point would mark the limit of the FOZ. The latter approach would be similar to the

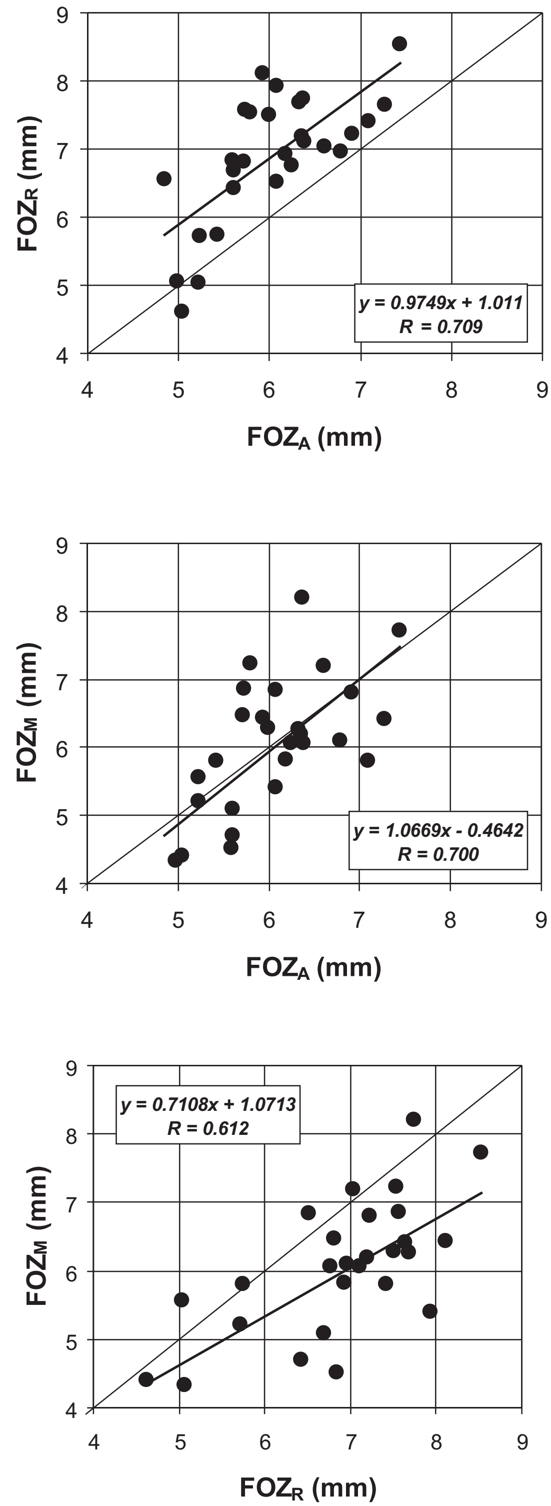

Figure 5. Correlations among FOZ_A, FOZ_R, and FOZ_M are robust and statistically significant ($P < 0.01$).

TABLE 2. Correlations between Methods

	FOZ_A	FOZ_R	FOZ_M
FOZ_A	1	.71*	.70*
FOZ_R	.71*	1	.61*
FOZ_M	.70*	.61*	1

* Correlation was significant at the 0.01 level (two-tailed).

TABLE 3. FOZ Means with the 3 Methods

	FOZ_A	FOZ_R	FOZ_M
Non-LASIK group			
Mean	7.6	9.1	7.7
Range	6.2–9.0	8.1–10.9	5.6–9.0
SD	0.6	0.5	1.0
LASIK group			
Mean	6.0	6.9	6.0
Range	5.0–7.4	4.6–8.5	4.3–8.2
SD	0.7	0.9	1.1

Non-LASIK group, $n = 34$. LASIK group, $n = 32$.

FOZ_A method for smooth corneas; however, for corneas with central irregularities, the SD would increase, and the method would encompass an area of poor optical quality.

Our approach intends to link corneal optical quality with visual acuity thresholds. It addresses the question of what an optimal optical zone is, in terms of refractive errors (aberrations) and visual acuity. Our definition of FOZ is based on the pupillary area needed to remain below the limit of 0.2 logMAR visual acuity. It is not intended to be a rigid definition, and more exigent threshold definitions in terms of visual quality are possible. However, this study sets a baseline for possible additional studies. What is envisioned is the application of adaptive optics technologies, similar to those used in recent experiments,[24] to relate specific corneal aberrations, pupil diameter, and visual performance. This could provide a more robust determination of the appropriate threshold values.

Along these lines, at first glance, it seems curious that the functional optical zones found for normal unoperated corneas were generally smaller than the entire corneal surface. The horizontal diameter of the cornea averages 11.7 mm (range, 10.7–12.6 mm) in the human adult,[25] whereas average functional optical zones for the unoperated normal group in the present study ranged from 7.6 to 9.1 mm (Table 3). From a teleological point of view, this apparent functional disparity between corneal size and functional optical zone size would leave transparent peripheral corneal regions without visual contribution. However, in this study, the visual threshold for the functional optical zone was set at minimum high-contrast acuity of 20/32 (logMAR 0.2). It is well known that visual acuity diminishes with luminance level. Under very low light conditions, when rod function dominates, visual acuity can fall to as low as 20/100 to 20/200.[26,27] Hence, if the threshold for the functional optical zone were reduced below the 20/32 level to better meet conditions under dim light, this should extend the size more peripherally, perhaps to encompass the entire corneal surface. In addition, in relatively young healthy subjects, the compensatory effect of the crystalline lens (balancing corneal spherical aberration) could also play a significant role to increase the size of the functional optical zone.

In this study we have developed three novel methods for functional optical zone identification and measurement. FOZ_A is the only method that preserves its relationship to the underlying corneal shape, and this is used to display specific areas of the cornea that form the putative optical zone (Fig. 1). The other two methods (making use of a Zernike fitting method to assess RMS and calculation of the modulation transfer function) correlate well with FOZ_A, substantiating the semiempiric approach. Of the three methods, the axial power method is the most straightforward because it does not require Zernike fitting or ray-tracing analysis, and the method has already been implemented in commercially available general purpose software that can input topography data from a wide variety of corneal topographers (see Methods). Hence, the axial power method (FOZ_A) appears to be the most practical choice for routine analysis. The correlation of visual performance and visual acuity has been studied extensively. Although it is clear that visual function in patients undergoing surgery (keratoconus, PRK, LASIK) and in those with certain abnormalities (e.g., cataract) is mainly influenced by degraded ocular optics, in healthy subjects other factors in the visual pathway could play a more important role than optical quality. In our LASIK population, the main source of aberrations and the cause of visual dysfunction was principally the corneal surface affected by surgery, and the strong correlations that were obtained were expected.

A possible limitation of our work is that we did not include aberrations of the lens, which could be important in young, healthy subjects compensating corneal spherical aberration[28] and coma.[29] However, the methods were developed primarily for the analysis of corneal optical quality after keratorefractive

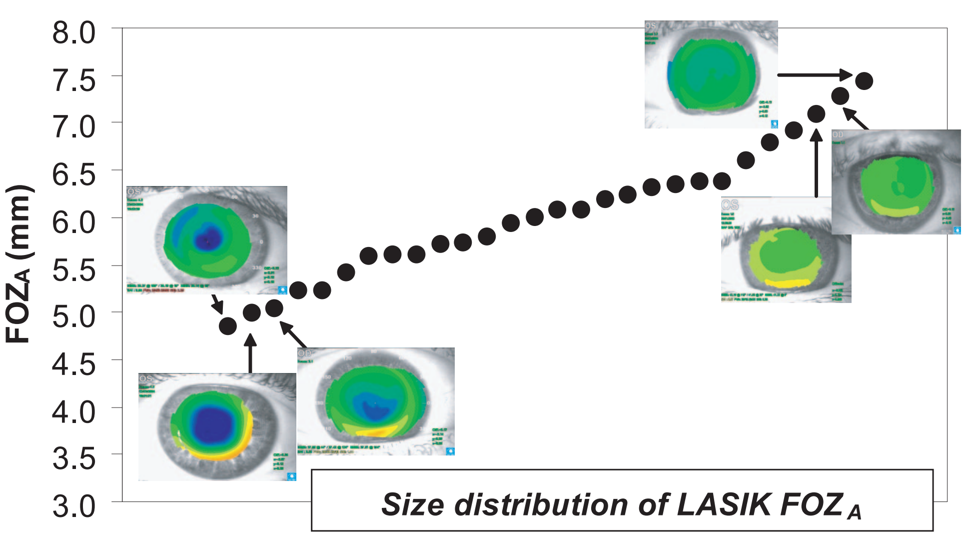

FIGURE 6. Distribution of FOZ_A and its relationship to the corneal topographies for the three smallest and three largest functional optical zones. Note the correspondence between the measured size and the apparent size on the corneal topography maps.

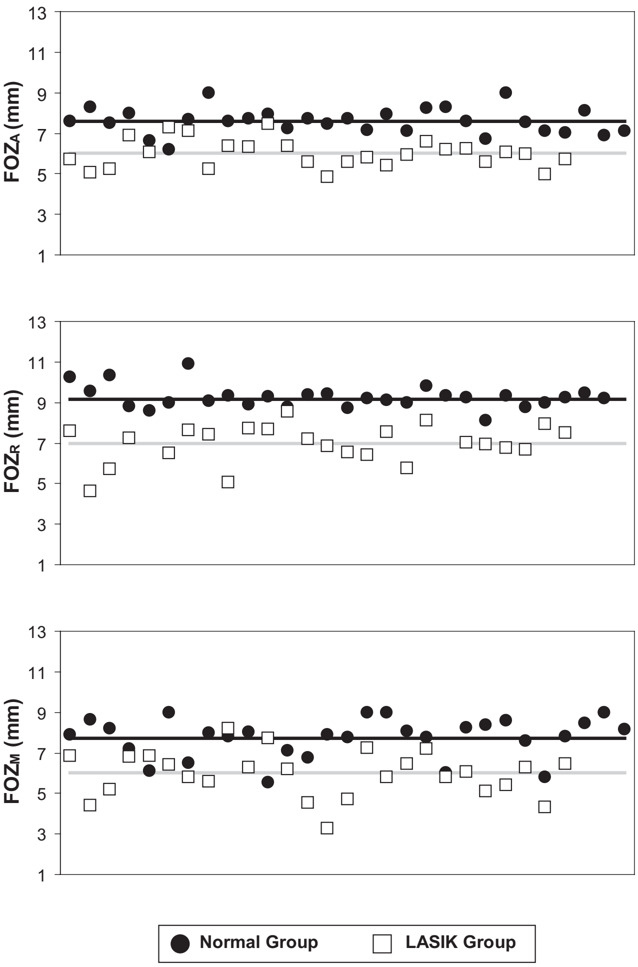

FIGURE 7. Comparison of the functional optical zones for each cornea for the three methods. *Horizontal lines* represent the average values for the two groups. Note that FOZ_R values are consistently approximately 1 mm larger than either FOZ_A or FOZ_M.

surgery, and they assume normal optical and neural function for the rest of the eye. In addition, the calculations were centered on the corneal apex and, in some subjects (primarily those with hyperopia), the pupil could be significantly decentered with respect to the topographical center. However, only patients who underwent LASIK surgery for myopia were included in the current analysis, limiting the potential effect from pupillary shift.

The correlation matrix among the three methods showed acceptable statistical output in terms of the Pearson correlation coefficient, though the correlation between FOZ_M and FOZ_R was lower than that of the other methods. To further understand this result, the nature of each parameter must be taken into account. The parameters of FOZ_M and FOZ_A are calculated from two related optical quantities, MTF and corneal power. However, FOZ_R is calculated from the RMS of the corneal surface and represents a measure of the surface irregularities. Therefore, it is a geometric parameter that influences optics, but its comparison to optical quality is less direct.

Each of the three methods characterizes different aspects of the optical nature of the cornea, and the relationship between any two of them may not be a one-to-one correlation. MTF is based on the ability of an optical system to distinguish spatial frequencies, and it represents an objective version of the contrast-sensitivity function. A possible drawback of using this parameter to obtain FOZ is that it decays quickly with increase in pupil size (Fig. 2). Therefore, the intercept with the selected threshold is in a zone with relatively large variations, which is why FOZ_M has the largest SD among the three methods.

The RMS of the corneal surface fit provides a quantitative measure of corneal surface irregularity. We used an improved RMS parameter, the sum of the RMS from the fitting plus the RMS of the residual surface, to capture all surface distortion.[19] FOZ_R provides larger values than FOZ_A or FOZ_M. Although subjects were selected from those with normal or myopic vision, astigmatism was removed from the RMS, which suggests a slightly larger value for the FOZ calculated with this parameter.

The axial power method is based on the tolerance of visual acuity to defocus, and it mainly represents the defocus shift (in 0.5-D steps) induced by the cornea when the corneal optical zone increases. Hence, these three methods provide information from different characteristics of the corneal surface. When FOZ was calculated from them, based on the procedure described to establish the threshold values, three independent objective measurements were obtained.

The application of the methodology to a group of patients who did not undergo surgery revealed a clear difference in the FOZ parameter compared with the group who underwent LASIK for myopia (Fig. 7). Average decreases (1.6, 1.7, and 2.2 mm for FOZ_A, FOZ_R, and FOZ_M) were consistent within the three methods. However, some patients in the LASIK population remained within the range of the non-LASIK population. This large variation was expected because of the temporal inhomogeneity of the cohort used. Several lasers were used to perform the surgery, from early prototypes to recently advanced devices. In addition, a wide range of myopic correction was attempted. Hence, this purposeful inclusion of a variety of LASIK outcomes produced a good range for the correlations.

Keratorefractive surgery is a dynamic field. The technology is changing rapidly, propelling new laser devices and surgical strategies that have the capability for corrections specifically designed to reduce aberrations in individual eyes. These enhancements require the use of well-defined assessment techniques. Our derived FOZ parameters provide an example of this. The methods discussed give a powerful metric suitable to evaluate the accuracy of the corneal topographic response to the new surgical techniques.

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