ARTICLE

Effect of the equivalent refractive index on intraocular lens power prediction with ray tracing after myopic laser in situ keratomileusis

Carmen Canovas, PhD, Marrie van der Mooren, MSc, Robert Rosén, PhD, Patricia A. Piers, PhD, Li Wang, MD, PhD, Douglas D. Koch, MD, Pablo Artal, PhD

PURPOSE: To determine the impact of the equivalent refractive index (ERI) on intraocular lens (IOL) power prediction for eyes with previous myopic laser in situ keratomileusis (LASIK) using custom ray tracing.

SETTING: AMO B.V., Groningen, the Netherlands, and the Department of Ophthalmology, Baylor College of Medicine, Houston, Texas, USA.

DESIGN: Retrospective data analysis.

METHODS: The ERI was calculated individually from the post-LASIK total corneal power. Two methods to account for the posterior corneal surface were tested; that is, calculation from pre-LASIK data or from post-LASIK data only. Four IOL power predictions were generated using a computer-based ray-tracing technique, including individual ERI results from both calculation methods, a mean ERI over the whole population, and the ERI for normal patients. For each patient, IOL power results calculated from the four predictions as well as those obtained with the Haigis-L were compared with the optimum IOL power calculated after cataract surgery.

RESULTS: The study evaluated 25 patients. The mean and range of ERI values determined using post-LASIK data were similar to those determined from pre-LASIK data. Introducing individual or an average ERI in the ray-tracing IOL power calculation procedure resulted in mean IOL power errors that were not significantly different from zero. The ray-tracing procedure that includes an average ERI gave a greater percentage of eyes with an IOL power prediction error within ± 0.5 diopter than the Haigis-L (84% versus 52%).

CONCLUSION: For IOL power determination in post-LASIK patients, custom ray tracing including a modified ERI was an accurate procedure that exceeded the current standards for normal eyes.

Financial Disclosure: Dr. Canovas, Mr. van der Mooren, Dr. Piers, and Dr. Artal hold a provisional patent application on the ray-tracing procedure. Dr. Canovas, Mr. van der Mooren, Dr. Rosén, and Dr. Piers are employees of AMO Groningen B.V. Dr. Koch is a consultant to Abbott Medical Optics, Inc., and Alcon Laboratories, Inc. No other author has a financial or proprietary interest in any material or method mentioned.

J Cataract Refract Surg 2015; 41:1030–1037 © 2015 ASCRS and ESCRS

Traditionally, intraocular lens (IOL) power calculation has been performed using paraxial optics and optimized regression constants.[1] However, it is well known that standard formulas have to be modified for patients who have had refractive surgery. In these patients, the refractive surgery has modified the anterior cornea. Therefore, the corneal power measured with standard keratometers and corneal topographers is no longer accurate. This causes an error in IOL power prediction directly due to the miscalculation in corneal power[2] and indirectly due to an incorrect effective lens position prediction.[3] In addition, it is well known that traditional laser in situ keratomileusis (LASIK) induces corneal aberrations.[4–6] Spherical aberration is the most prominent of these, although other aberrations (eg, coma) might also increase from LASIK

Published by Elsevier Inc.

http://dx.doi.org/10.1016/j.jcrs.2014.07.044
0886-3350

treatments and are thought to be associated with decentered ablation patterns.[7] The magnitude of the aberrations and errors induced depends on several factors, making them difficult to predict.

Although inaccuracies related to the incorrect measurement of corneal power can be ameliorated by developing new regressions, the impact of the errors induced by corneal spherical aberration cannot be directly introduced in current IOL power calculations due to their paraxial nature. To solve this issue, nonparaxial calculations have been shown to improve the prediction of IOL power in post-LASIK patients. Preussner et al.[8] showed the impact of considering corneal asphericity in post-LASIK patients. Recently published studies have also shown the better accuracy of a completely custom ray-tracing eye model, both for myopic and hyperopic post-LASIK patients, than with the current state of the art in IOL power calculations.[9] Despite its excellent predictive capabilities, a slight hyperopic average error was noted when myopic post-LASIK patients were considered separately.

The use of an equivalent refractive index (ERI) has been identified as a potential factor contributing to the positive residual refraction found in myopic post-LASIK eyes. The ERI is an artificial refractive index that helps account for the contribution of the posterior cornea to the total corneal power when only anterior corneal measurements are available. In previous publications, the ERI was calculated to achieve the power of the complete cornea in LeGrand's model eye using only the anterior surface of the cornea.[10] This was accomplished with a procedure similar to that described by Olsen.[11] The resulting value 1.330 agrees well with the value previously calculated from anatomic data for eyes that have not had refractive surgery.[12] These eyes will be referred to here as "normal eyes."

Submitted: February 20, 2014.
Final revision submitted: July 1, 2014.
Accepted: July 22, 2014.

From AMO Groningen B.V. (Canovas, van der Mooren, Rosén, Piers), Van Groningen, the Netherlands; Laboratorio de Optica (Canovas, Artal), Instituto Universitario de Investigacion en Optica y Nanofısica, Universidad de Murcia, Murcia, Spain; the Cullen Eye Institute (Wang, Koch), Department of Ophthalmology, Baylor College of Medicine, Houston, Texas, USA.

Supported by the Northern Netherlands Provinces (SNN), European Fund for Regional Development, and the Dutch Ministry of Economic Affairs, Peaks in the Delta, grants 086 and 087.

Presented at the annual meeting of the Association for Research in Vision and Ophthalmology, Fort Lauderdale, Florida, USA, May 2011.

Corresponding author: Carmen Canovas, PhD, AMO Groningen B.V., Van Swietenlaan 5, 9728NX, Groningen, the Netherlands. E-mail: carmen.canovas@amo.abbott.com.

However, the ERI might vary in post-LASIK patients.[13,14] The reason for this change with respect to the ERI in the normal population is the asymmetric modification imposed by LASIK surgery on the anterior cornea with respect to the posterior cornea. This reduces the fixed ratio between the posterior and anterior corneal radii, which is a determining factor in the calculation of ERI,[11,15] and results in an overestimation of corneal power and therefore an underestimation of predicted IOL power. This then leads to a hyperopic average error in myopic post-LASIK eyes.

This study evaluated impact of the ERI on our custom ray-tracing procedure for IOL power prediction in myopic post-LASIK patients when only the anterior corneal data are available. This was done by assessing the predictability of the ray-tracing procedure using different ERIs, such as that determined in a previous publication of unoperated eyes as well as those calculated using pre-LASIK or only post-LASIK data to determine the relevant data and level of customization required for myopic post-LASIK eyes.

PATIENTS AND METHODS

Patients and Measurements

This study retrospectively reviewed data from eyes of myopic post-LASIK cataract patients who were examined before and after cataract surgery between 2008 and 2009 at the Baylor College of Medicine, Houston, Texas, USA. All included were cataract patients with otherwise healthy eyes. The research followed the tenets of the Declaration of Helsinki.

Pre-LASIK history was available for all patients in the study. Therefore, there was access to the refractive correction performed by the LASIK procedure as well as pre-LASIK keratometry values. Corneal topography and biometry measurements (axial length and anterior chamber depth) were performed before cataract surgery with a Placido-based corneal topographer (Atlas, Carl Zeiss Meditec AG) and a low-coherence interferometer (IOLMaster, Carl Zeiss Meditec AG).

All cataract surgeries were performed by the same surgeon (D.D.K.) using a small-incision technique followed by implantation of an aspheric monofocal IOL (SN60WF, Alcon Laboratories, Inc.). The IOL power was selected by the surgeon according to his standard practice. Postoperative subjective refractive error was measured 1 month after surgery. From this refraction, the spherical equivalent (SE) was calculated and translated optically to the IOL plane. This value was added to the IOL power implanted, leading to the determination of the optimum IOL power for each patient.

Equivalent Refractive Index Calculation

Two approaches to calculate an individual ERI were considered. Figure 1 outlines these calculation methods. In both cases, the ERI was calculated using paraxial optics from the post-LASIK total corneal power using the Gaussian

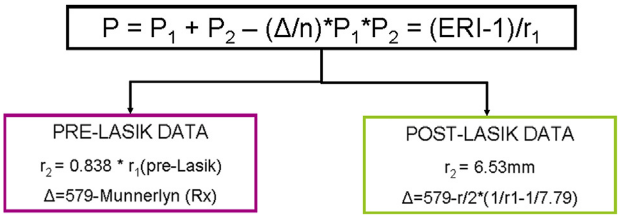

Figure 1. Diagram showing different approaches for ERI calculation used in this study (Δ = corneal thickness; ERI = equivalent refractive index; LASIK = laser in situ keratomileusis; P = post-LASIK total corneal power; P_1 = anterior corneal power; P_2 = posterior corneal power; r_1 = anterior corneal radius; r_2 = posterior corneal radius).

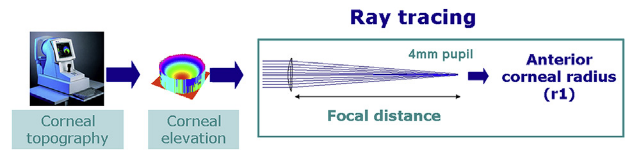

Figure 2. Diagram illustrating the procedure followed to determine post-LASIK anterior corneal radius from corneal topography by means of ray tracing.

thick-lens formula. In this formula, the power (P) is determined by coupling the powers (P1) and (P2) of the 2 refractive surfaces that are separated by a distance d and surrounded by a medium with refractive index n as follows:

$$P = P1 + P2 - (d/n) \times P1 \times P2 \qquad (1)$$

In this particular case, P represents the post-LASIK total corneal power while P1 and P2 are the anterior and posterior corneal powers, respectively; d is the central corneal thickness, and n is the corneal refractive index.

Anterior and posterior corneal powers (Pi with I = 1,2) are calculated by approximating the surfaces to be spherical and making use of equation 2.

$$Pi = (nA - nB)/ri \qquad (2)$$

where ri is the corresponding surface radius and nB and nA are the refractive indices corresponding to the media in front of and behind the surface.

To determine P1 for a post-LASIK cornea, the anterior corneal radius of curvature was calculated from the anterior corneal elevation maps measured by the corneal topographer before the cataract surgery. Figure 2 shows a schematic of the procedure. As an initial step, the elevation maps were recentered from the corneal apex to the pupil center. Ray tracing was then performed for a 4.0 mm pupil through these surfaces to determine the focal distance that minimizes the root-mean-square spot size at the image plane. As such, higher-order aberrations such as corneal spherical aberration are included in this determination of the focal length. Corneal radius was then back-calculated from this focal distance using paraxial optics.

Posterior corneal radius and corneal thickness were not part of the data that were available in this study. To take the posterior cornea into consideration in total corneal power and calculate the 2 remaining terms at equation 1 (ie, P2 and d), 2 procedures were used as indicated in Figure 1, 1 using pre-LASIK data while the other making use of only post-LASIK information. Both approaches assume that the posterior cornea is not affected by LASIK surgery[16,17] and make use of physiologic values.[12]

The calculation procedure that makes use of pre-LASIK data is summarized in the left column in Figure 1. In this case, the pre-LASIK anterior corneal values were used to calculate the posterior corneal radius using a fixed physiologic ratio of 0.838.[12] The post-LASIK corneal thickness (d) was estimated by subtracting the result of the Munnerlyn formula,[18] which uses the refraction corrected by LASIK from an average physiologic corneal thickness of 579 μm.[12]

The calculation procedure that uses post-LASIK information is outlined in the right column in Figure 1. In this approach, only post-LASIK data were used and the posterior corneal radius was assumed to be constant for the population (6.53 mm).[12] Corneal thickness was calculated by subtracting the change in corneal thickness due to the LASIK procedure calculated from the change in corneal radius from 579 μm as follows:

$$\Delta = r/2 \times (1/r1 - 1/7.79) \qquad (3)$$

where Δ is the change in corneal thickness due to the LASIK surgery; r is the ablation radius, considered here to be 3.0 mm; r1 is the calculated post-LASIK corneal radius; and 7.79 mm is the pre-LASIK radius taken from average physiologic values.[12]

In both calculation approaches, the ERI was calculated for every patient from

$$ERI = 1 + r1 \times P \qquad (4)$$

where r1 is the anterior corneal post-LASIK radius calculated from ray tracing and P is the total post-LASIK corneal power calculated from equation 1 using pre-LASIK information or only including post-LASIK data. Therefore, 2 different individual ERI values were calculated for each patient. In addition, 2 average ERI values were calculated from the individual ERI determined for the study population either from pre-LASIK or post-LASIK data.

Intraocular Lens Power Calculation

The IOL power was calculated using a custom ray-tracing procedure that has been described in detail.[10] To test the impact of the ERI on the predictability of the ray-tracing procedure, as well as the data (ie, pre-LASIK or post-LASIK) and required level of customization for its calculation (ie, customized or average), 4 IOL power predictions were generated for each eye using 4 different values for the ERI as follows: (1) the average for normal eyes found in a previous publication for normal eyes (1.330),[10] (2) an individual value calculated as described above including pre-LASIK data, (3) a customized ERI determined as described above from only post-LASIK data, and (4) the average ERI calculated for the study population. In the last case, the average ERI calculated from post-LASIK data is considered due to the similarity of the average ERI values provided by both calculation procedures, as will be further discussed in the results section.

In addition to our own calculation methods, the IOL power was also calculated using the Haigis-L formula.[19] This represents the current state of the art in IOL power calculations for myopic post-LASIK patients.[20]

Table 1. The ERI values calculated with different procedures.

	Custom ERI	
Data	Range	Mean ± SD
Post-LASIK	1.314, 1.331	1.325 ± 0.004
Pre-LASIK	1.316, 1.329	1.324 ± 0.003

ERI = equivalent refractive index; LASIK = laser in situ keratomileusis

To calculate the mean residual error (MRE) and the mean absolute residual error (MARE) for each case, the optimum IOL power for each eye was calculated by adding the residual refractive error power (translated to the IOL plane) to the implanted IOL and then subtracting the predicted IOL power from the optimum IOL power. In addition, the percentage of eyes with an IOL power prediction error within ±0.5 diopter (D), ±1.0 D, ±1.5 D, and ±2.0 D was also calculated for the IOL power calculation procedures included in the study.

Statistical Analysis

The Wilcoxon test was used to determine whether the mean arithmetic IOL prediction errors produced by various methods were significantly different from zero because some of the data were not normally distributed as determined by the Kolmogorov-Smirnov test. The consistency in the prediction was tested using the Levene test for variances. The percentages of eyes within certain IOL power prediction errors were compared using the chi-square test. Bonferroni correction was applied to account for multiple comparisons.

RESULTS

The study comprised 25 eyes of 25 patients. The mean patient age was 59 years ± 10 (SD) (range 44 to 77 years), and the mean myopic correction before LASIK was −5.70 ± 2.83 (range −12.00 to −2.00 D).

Equivalent Refractive Index

The 2 procedures used to calculate the ERI resulted in nearly identical ERI values (Table 1). Figure 3 shows the individual ERI values determined by both procedures as a function of the spherical correction applied during the corneal refractive procedure. The refraction change after the LASIK procedure was linearly related to the custom ERI values, independently of whether they were calculated from pre-LASIK or post-LASIK data. The r^2 values were 0.69 and 0.50, respectively.

Based on the similarity of the average ERI values shown in Table 1, only the average calculated from the post-LASIK data was included in the custom ray-tracing procedure to evaluate the IOL power using an average ERI. For the custom calculations using pre-LASIK or post-LASIK data, the corresponding ERIs were used.

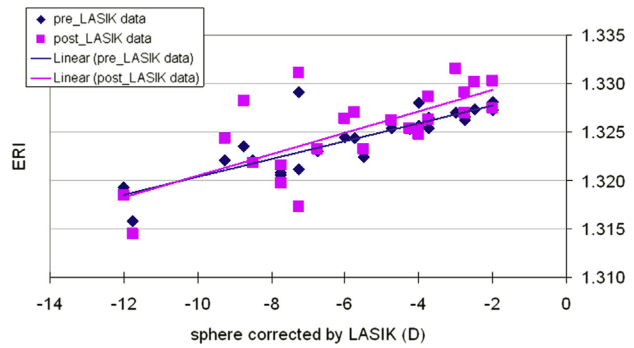

Figure 3. Custom ERI calculated with pre-LASIK data and post-LASIK data and a fixed posterior corneal radius versus the spherical correction applied by LASIK (ERI = equivalent refractive index; LASIK = laser in situ keratomileusis).

Mean Residual Errors

The MRE and MARE for the predictions of the 4 investigated procedures, as well as those of the Haigis-L, are shown in Figure 4, *A* and *B*. Table 2 shows the data corresponding to these plots. The ray-tracing prediction that incorporates the ERI for normal eyes gave an MRE of 0.66 D, which was statistically significantly different from zero ($P<.05$ with Bonferroni correction). All other ray-tracing methods using the recalculated ERI for post-LASIK patients, as well as the Haigis-L, had an MRE close to zero, ranging from −0.24 to −0.08 D. None of them was significantly different from zero. Because of its large MRE, the approach using the ERI for normal eyes was not included in the further analysis.

The variance in the MRE was the smallest for the ray-tracing procedure, incorporating an average ERI calculated from the post-LASIK data, 0.65 D^2. The other 2 ray-tracing procedures that made use of the customized ERI, calculated from pre-LASIK or post-LASIK data, had variances of 0.86 D^2 and 0.97 D^2, respectively, whereas the Haigis-L had a variance of 1.27 D^2. However, none of the ray tracing–based methods differed significantly in variance from that of the Haigis-L.

Mean Absolute Residual Errors

The ray-tracing prediction using an average ERI calculated from post-LASIK data had an MARE of 0.52 D. The ray tracing–based method using an ERI customized using pre-LASIK data had an MARE of 0.56 D whereas that based on post-LASIK data had an MARE of 0.72 D. These were lower than the values from the Haigis-L, which had an MARE of 0.80 D. The percentage of eyes with an IOL power prediction error within ±0.5 D, ±1.0 D, ±1.5 D, and ±2.0 D for each IOL power calculation procedure is shown in Table 3

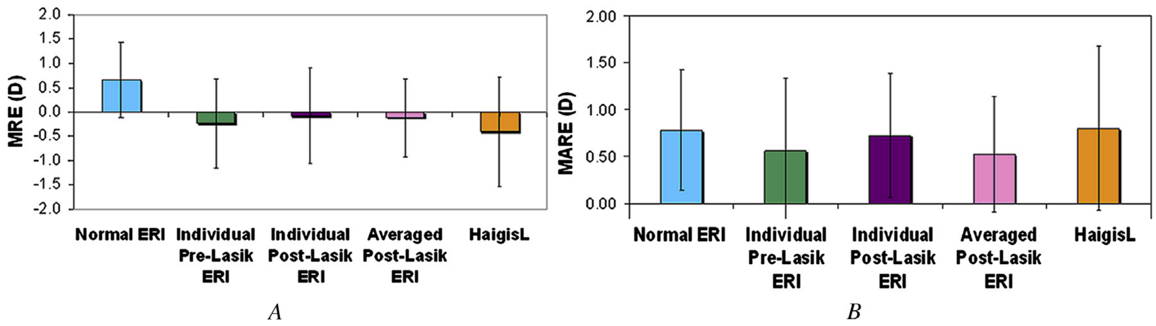

Figure 4. *A*: Mean residual error (MRE) defined as IOL power difference between the optimum IOL power and the different predictions. *B*: Mean absolute residual error (MARE). Error bars represent 1 SD (ERI = equivalent refractive index; LASIK = laser in situ keratomileusis).

and Figure 5. Compared with the Haigis-L errors, the ray-tracing procedure, including the custom ERI with pre-LASIK or post-LASIK data, gave results that were not significantly different. However, the results from the ray-tracing procedure including the average ERI calculated from post-LASIK data differed significantly from the Haigis-L ($P<.05$ with Bonferroni correction). This ray-tracing prediction resulted in 84% and 96% of eyes within ±0.5 D and ±1.0 D IOL power prediction error in the spectacle plane, respectively, while the Haigis-L formula gave a 52% and 84% for the same intervals.

DISCUSSION

Although the predictability of ray tracing for IOL power calculations for post-LASIK patients has been shown in the past,[8,9] this study shows that its accuracy in post-LASIK patients can be further improved by including a modified ERI.

The first objective of this paper was to demonstrate that the ERI was responsible for the small hyperopic average error in myopic post-LASIK patients. Figure 4, *A*, shows this average hyperopic shift when an ERI for normal corneas is used. Statistical analysis shows that the MRE differed from zero ($P<.05$ with Bonferroni correction). Figure 4, *A*, also shows that this hyperopic MRE is eliminated in all the calculation procedures used in this paper to determine IOL power when the ERI is modified for post-LASIK patients. That the small residual average MREs did not differ significantly from zero reinforces that statement.

The methods presented here are not similar to the IOL constant optimization procedure that is recommended by many authors of modern IOL formulas.[1] Intraocular lens constant optimization is based on iterative variations of the IOL constant until the difference between the predicted SE and the actual SE of the postoperative subjective refraction is zero.[21] In the present study, we did not incorporate the postoperative refraction into the ERI calculation. The modification of the ERI with respect to that calculated for the normal population is due to the LASIK procedure, and all approaches contained in this study are based on actual or physiologic corneal data as well as the lack of long-term changes at the posterior cornea due to refractive surgery. Pérez-Escudero et al.[17] measured corneal geometry before and after a myopic LASIK procedure using a single Scheimpflug device that was previously validated with a hybrid model eye. They found statistically significant changes from the preoperative state only for measurements performed 1 day after surgery. Using dual Scheimpflug technology, Smadja et al.[22] also studied the effect of the myopic LASIK procedure on the posterior corneal

Table 2. Mean residual error and MARE.

	IOL Power Prediction Error (D)*	
Method	MRE ± SD	MARE ± SD
Normal ERI	0.66† ± 0.77	0.78 ± 0.65
Individual pre-LASIK ERI	−0.24 ± 0.93	0.56 ± 0.77
Individual post-LASIK ERI	−0.08 ± 0.99	0.72 ± 0.66
Averaged post-LASIK ERI	−0.12 ± 0.81	0.52 ± 0.62
Haigis-L	−0.40 ± 1.13	0.80 ± 0.88

ERI = equivalent refractive index; IOL = intraocular lens; LASIK = laser in situ keratomileusis; MARE = mean absolute residual error; MRE = mean residual error
*Defined as the difference between the optimum IOL power and those calculated with the different approaches used in the study.
†Significantly different from zero ($P<.05$ with Bonferroni correction)

Table 3. Percentage of eyes within a certain IOL power prediction error.

Method	±0.5 D	±1.0 D	±1.5 D	±2.0 D
Individual pre-LASIK ERI	68	80	96	96
Individual post-LASIK ERI	56	84	92	96
Averaged post-LASIK ERI*	84	84	96	96
Haigis-L	52	80	84	96

ERI = equivalent refractive index, LASIK = laser in situ keratomileusis
*Significantly different distribution than the Haigis-L ($P<.05$ with Bonferroni correction)

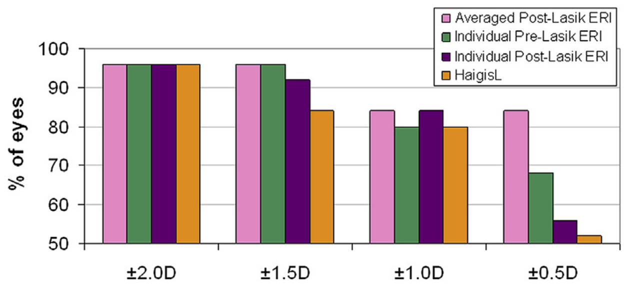

Figure 5. Percentage of eyes within certain IOL power prediction error (ERI = equivalent refractive index; LASIK = laser in situ keratomileusis).

surface. They found steepening of the posterior surface that returned to its original shape after 1 month. Therefore, based on these results, the posterior cornea can be considered unaffected by LASIK surgery because any measurable modification has been shown to revert to the preoperative level in a shorter time than that related to the time between the refractive surgery and the cataract surgery.

Various studies have described this change in the ERI due to refractive surgery. For example, the ERI changed due to the LASIK procedure from 1.329 to 1.323, based on the average data measured by Pérez-Escudero et al.[17] That change led to a decrease in corneal power of approximately 0.7 D. The average post-LASIK ERI found in the Pérez-Escudero et al.[17] study agrees well with the average found in this study determined by both methods for calculating the ERI. However, the change in the ERI depends on the characteristics of the LASIK procedure and the cornea to which it has been applied.[23]

Savini et al.[13] found a correlation between the calculated ERI and the applied correction by the refractive procedure. Figure 3 shows the same analysis in our population for both custom methods; that is, the individual ERI calculated from pre-LASIK data or from post-LASIK data and a fixed posterior corneal radius. In both cases, there is a relationship between the spherical correction applied and the ERI, although not as strong as that found in Savini et al.[13] The r^2 for the ERI calculated with pre-LASIK values was 0.69, while it was 0.50 for the custom ERI using only post-LASIK parameters and a fixed posterior corneal radius. The higher correlation coefficient between the custom ERI values indicates that it varies in the population studied. It is important to determine whether this change increases the accuracy and predictability of the ray-tracing procedure or whether it leads to a similar or higher prediction error due to error propagation.

Our results did not show an improvement in the IOL power prediction with respect to the current state of the art when incorporating a custom ERI (ie, calculated from pre-LASIK or post-LASIK data). The percentages of eyes within different IOL power prediction errors were not significantly better than the percentages given by the Haigis-L formula. Therefore, although the method of using a custom ERI eliminates the MRE, it does not increase the accuracy of the prediction with respect to the current state of the art. The individual ERI calculation is based on published anatomic data and on certain assumptions. These assumptions might induce some errors that could mask the impact of the ERI customization. However, once an average value is incorporated into the ray-tracing procedure, it provides an accuracy that is better than the current state of the art for this type of patient.

The better predictability of the ray-tracing procedure, including the average ERI calculated from post-LASIK data, can be seen in Table 3. This method differed significantly from the outcomes of the Haigis-L ($P < .05$ with Bonferroni correction). This shows that determining the average ERI from actual data is a simple procedure that improves ray tracing to a level that makes it is more predictable than the current state of art for IOL power calculations represented by the Haigis-L.[20]

The data in Table 3 refer to the IOL plane. Assuming that 1.0 D of IOL prediction error produces 0.7 D of refractive error at the spectacle plane,[20] 1.5 D of IOL power error can be translated to 1.0 D of refractive error. Therefore, with the Haigis-L formula, 84% of eyes were within $\pm$1.0 D of the refractive error at the spectacle plane, while the ray-tracing prediction with an average ERI resulted in 96% of the eyes being within that refractive error. One benchmark standard for refractive outcomes after cataract surgery in normal eyes has been set at 85% of patients achieving a final SE within $\pm$1.0 D refractive error.[24] Naturally following this, the Haigis-L formula just meets this standard, while the ray-tracing prediction provided approximately 11% more eyes within that refractive error. We recognize this standard is relatively modest and that the expectation of post-refractive surgery patients is a much higher level of accuracy.

In a comparison study between different IOL power calculation formulas included in the American Society of Cataract and Refractive Surgery calculator, Wang et al.[20] showed that methods that include only post-LASIK data were more accurate than those that include pre-LASIK data. Our results are in agreement with that statement because the introduction of pre-LASIK data did not result in a better prediction. Therefore, the use of pre-LASIK data is not needed in this procedure when actual patient physiologic data are input for the custom ray-tracing procedure.

In a ray-tracing procedure, there are no "fudge" parameters that are optimized to improve average outcomes. Because of this, all distances included in the model are realistic.[25] This means that the accuracy of measurements is critical and can limit the benefit of the exact calculation or the introduction of a custom ERI. It is possible that when the errors related to different biometric inputs are further reduced, the introduction of a custom ERI might provide a further increase in the accuracy of post-LASIK IOL power calculations.

In addition to the improvement we present here, the use of measured data for the posterior cornea in the determination of the custom ERI or the direct incorporation of those measured data might further increase the accuracy of this ray-tracing procedure. Further research is needed to determine the impact of the posterior cornea on error propagation.

In conclusion, this study found that a ray-tracing procedure including anterior corneal data and an ERI calculated using paraxial optics improved the accuracy and predictability of IOL power calculation in myopic post-LASIK eyes. Introduction of a custom ERI calculated from pre-LASIK or post-LASIK data resulted in IOL power calculations that had accuracy comparable to that of the current average state of the art. Ray tracing of IOL power with an averaged ERI gave a high percentage of eyes with low IOL power prediction errors that were significantly better than the current state of art in IOL power calculations for myopic post-LASIK patients and exceeded the current standards for normal eyes.

WHAT WAS KNOWN

- Ray tracing through custom models can be used in eyes with no previous LASIK and in post-LASIK eyes, leading to a robust IOL power calculation method.
- The incorporation of corneal spherical aberration is crucial for the accurate prediction of the IOL power in eyes that have had refractive surgery.

WHAT THIS PAPER ADDS

- A further improvement in the predictability of the ray-tracing procedure for post-LASIK eyes involved the use of a modified ERI based on post-LASIK data and physiologic parameters.
- With this modified ERI, personalized ray-tracing models for IOL power calculations in myopic post-LASIK patients exceeded the current standards for normal eyes.

REFERENCES

1. Holladay JT, Prager TC, Chandler TY, Musgrove KH, Lewis JW, Ruiz RS. A three-part system for refining intraocular lens power calculations. J Cataract Refract Surg 1988; 14:17–24
2. Holladay JT. Cataract surgery in patients with previous keratorefractive surgery (RK, PRK, and LASIK). Ophthalmic Pract 1997; 15:238–244
3. Aramberri J. Intraocular lens power calculation after corneal refractive surgery: double-K method. J Cataract Refract Surg 2003; 29:2063–2068
4. Moreno-Barriuso E, Merayo Lloves J, Marcos S, Navarro R, Llorente L, Barbero S. Ocular aberrations before and after myopic corneal refractive surgery: LASIK-induced changes measured with laser ray tracing. Invest Ophthalmol Vis Sci 2001; 42:1396–1403. Available at: http://www.iovs.org/cgi/reprint/42/6/1396.pdf. Accessed December 25, 2014
5. Benito A, Redondo M, Artal P. Laser in situ keratomileusis disrupts the aberration compensation mechanism of the human eye. Am J Ophthalmol 2009; 147:424–431
6. Kohnen T, Mahmoud K, Bühren J. Comparison of corneal higher-order aberrations induced by myopic and hyperopic LASIK. Ophthalmology 2005; 112:1692–1698
7. Mrochen M, Kaemmerer M, Mierdel P, Seiler T. Increased higher-order optical aberrations after laser refractive surgery; a problem of subclinical decentration. J Cataract Refract Surg 2001; 27:362–369
8. Preussner P-R, Wahl J, Weitzel D. Topography-based intraocular lens power selection. J. Cataract. Refract Surg 2005; 31:525–533
9. Canovas C, Abenza S, Alcon A, Villegas EA, Marin JM, Artal P. Effect of corneal aberrations on intraocular lens power calculation. J Cataract Refract Surg 2012; 38:1325–1332
10. Canovas C, Artal P. Customized eye models for determining optimized intraocular lenses power. Biomed Opt Express 2011; 2:1649–1662. Available at: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3114231/pdf/1649.pdf. Accessed December 25, 2014
11. Olsen T. On the calculation of power from curvature of the cornea. Br J Ophthalmol 1986; 70:152–154. Available at: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1040942/pdf/brjopthal00624-0073.pdf. Accessed December 25, 2014
12. Dubbelman M, Sicam VADP, van der Heijde GL. The shape of the anterior and posterior surface of the aging human cornea. Vision Res 2006; 46:993–1001
13. Savini G, Barboni P, Zanini M. Correlation between attempted correction and keratometric refractive index of the cornea after myopic excimer laser surgery. J Refract Surg 2007; 23:461–466
14. Hamed AM, Wang L, Misra M, Koch DD. A comparative analysis of five methods of determining corneal refractive power in eyes that have undergone myopic laser in situ keratomileusis. Ophthalmology 2002; 109:651–658
15. Masket S, Masket SE. Simple regression formula for intraocular lens power adjustment in eyes requiring cataract surgery after excimer laser photoablation. J Cataract Refract Surg 2006; 32:430–434
16. Zhang L, Wang Y. The shape of posterior corneal surface in normal, post-LASIK, and post-epi-LASIK eyes. Invest Ophthalmol Vis Sci 2010; 51:3468–3475. Available at: http://www.iovs.org/content/51/7/3468.full.pdf. Accessed December 25, 2014
17. Pérez-Escudero A, Dorronsoro C, Sawides L, Remón L, Merayo-Lloves J, Marcos S. Minor influence of myopic laser in situ keratomileusis on the posterior corneal surface. Invest Ophthalmol Vis Sci 2009; 50:4146–4154. Available at: http://www.iovs.org/content/50/9/4146.full.pdf. Accessed December 25, 2014
18. Munnerlyn CR, Koons SJ, Marshall J. Photorefractive keratectomy: a technique for laser refractive surgery. J Cataract Refract Surg 1988; 14:46–52

19. Haigis W. Intraocular lens calculation after refractive surgery for myopia: Haigis-L formula. J Cataract Refract Surg 2008; 34:1658–1663
20. Wang L, Hill WE, Koch DD. Evaluation of intraocular lens power prediction methods using the American Society of Cataract and Refractive Surgeons post-keratorefractive intraocular lens power calculator. J Cataract Refract Surg 2010; 36: 1466–1473
21. Aristodemou P, Knox Cartwright NE, Sparrow JM, Johnston RL. Intraocular lens formula constant optimization and partial coherence interferometry biometry: refractive outcomes in 8108 eyes after cataract surgery. J Cataract Refract Surg 2011; 37:50–62
22. Smadja D, Santhiago MR, Mello GR, Roberts CJ, Dupps WJ Jr, Krueger RR. Response of the posterior corneal surface to myopic laser in situ keratomileusis with different ablation depths. J Cataract Refract Surg 2012; 38:1222–1231
23. Wang L, Mahmoud AM, Anderson BL, Koch DD, Roberts CJ. Total corneal power estimation: ray tracing method versus Gaussian optics formula. Invest Ophthalmol Vis Sci 2011; 52:1716–1722. Available at: http://www.iovs.org/content/52/3/1716.full.pdf. Accessed December 25, 2014
24. Gale RP, Saldana M, Johnston RL, Zuberbuhler B, McKibbin M. Benchmark standards for refractive outcomes after NHS cataract surgery. Eye 2009; 23:149–152. Available at: http://www.nature.com/eye/journal/v23/n1/pdf/6702954a.pdf. Accessed December 25, 2014
25. Norrby S. Sources of error in intraocular lens power calculation. J Cataract Refract Surg 2008; 34:368–376

First author:
Carmen Canovas, PhD

AMO Groningen B.V.,
Van Groningen, the Netherlands