Effect of corneal aberrations on intraocular lens power calculations

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PURPOSE: To use ray tracing to determine the influence of corneal aberrations on the prediction of the optimum intraocular lens (IOL) power for implantation in normal eyes and eyes with previous laser in situ keratomileusis (LASIK).

SETTING: Hospital Universitario Virgen de la Arrixaca, Murcia, Spain.

DESIGN: Case series.

METHODS: The optimum IOL power was calculated by ray tracing using a patient-customized eye model in cataract surgery cases. The calculation can be performed with or without inclusion of the patient's corneal aberrations. Standard predictions were also generated using current state-of-the-art IOL power calculation techniques. The results for all predictions were compared with the optimum IOL power after cataract surgery.

RESULTS: For patients without previous LASIK (n = 18), the standard approaches and the ray-tracing procedure gave a similar mean absolute residual error and variance. The incorporation of corneal aberrations did not improve the accuracy of the ray-tracing prediction in these cases. For post-LASIK patients (n = 10), the ray-tracing prediction incorporating corneal aberrations generated the most accurate results. The difference between the prediction with and without considering corneal aberrations correlated with the amount of corneal spherical aberration ($r^2 = 0.82$), resulting in a difference of up to 3.00 diopters in IOL power in some cases.

CONCLUSIONS: Ray tracing using patient-customized eye models was a robust procedure for IOL power calculation. The incorporation of corneal aberrations is crucial in post-LASIK eyes, primarily because of the elevated corneal spherical aberration.

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The aim of cataract surgery is to restore the patient's vision; thus, its success depends on the proper selection of the power of the intraocular lens (IOL) to be implanted. At present, there is no universal method for calculating the power of the IOL to be implanted. The selection of the best formula depends on the individual characteristics of the patient having surgery. Although for normal cataract patients, almost all conventional formulas provide similar power values,[1] the selection of the formula is important for myopic or hyperopic patients.[2,3] It is also well known that standard formulas should be modified for patients who have had laser in situ keratomileusis (LASIK). Thus, several formulas are

available for use depending on the type of surgery the patient receives.[4–8]

Differences between formulas are related to the prediction of the position of the IOL after surgery, the equivalent refractive index used to describe the cornea as 1 refractive surface, and the corneal power correction used when each formula is applied to patients who have had LASIK. On the other hand, most commonly used IOL power calculations are performed with paraxial optical formulas.[9–13] In these approaches, the eye is modeled as a 2-lens system in which the cornea is considered to be a unique surface, being the IOL thickness ignored and whose position is not representative of the real IOL position in the eye.[14]

Thus, the A-constant in these formulas must be adjusted to improve the accuracy in an average population.

Several studies have presented IOL power calculation procedures based on the thick-lens theory.[15,16] Olsen[16] developed a formula based on the paraxial thick-lens theory in which the position of the IOL is estimated using 5 biometric parameters. Still, the paraxial nature of this formula does not consider corneal and IOL aberrations, limiting its accuracy.

Standard LASIK surgery increases corneal aberrations.[17,18] Intraocular lenses have varying amounts of aberrations[19–21]; and in some cases, such as aspheric IOLs, they have elevated spherical aberration.[22] Because the optimum focus depends on the particular aberrations of the optical system, IOL power calculations are affected by the total amount of aberrations in the pseudophakic eye.

Previous studies addressed the impact of aberrations on IOL power calculation. Norrby[23] developed another thick-lens ray-tracing method that takes spherical aberration into consideration. Preussner et al.[24] propose the use of nonparaxial ray-tracing procedures for IOL power calculations, showing the importance of corneal asphericity. This was confirmed in a large-population study[25] in which the mean anterior corneal eccentricity values were used. In a further step in this direction, personalized corneal eccentricities, calculated from the anterior corneal topography, were introduced into the nonparaxial ray-tracing

procedure,[26] showing their influence in the calculation, especially in post-LASIK eyes. The effect of the rest of the anterior corneal aberrations was not considered in the calculation, although a visual impression was generated to subjectively judge their impact.

In this study, we evaluated the effect of corneal aberrations on IOL power calculations in normal eyes (eyes with no previous surgery) and post-LASIK eyes. We did this using exact ray tracing through customized models that reproduced optically, as accurately as possible, each patient's eye. The calculations were performed in white light to ensure the most realistic conditions. In real eyes, we evaluated the impact of taking aberrations into consideration to determine the optimum IOL for implantation.

PATIENTS AND METHODS

Normal eyes (eyes with no previous LASIK) and post-LASIK eyes were examined before and after cataract surgery between 2007 and 2010. Except for cataract, all eyes were healthy. The research followed the tenets of the Declaration of Helsinki, and all patients provided written consent.

Preoperative Assessment

Corneal topography and biometry measurements (axial length [AL] and anterior chamber depth [ACD]) were performed before cataract surgery. The instruments used were a Placido-based corneal topographer (Atlas, Carl Zeiss Meditec AG), an optical biometer (IOLMaster, Carl Zeiss Meditec AG), and a conventional ultrasound system (Ocuscan RxP, Alcon Laboratories, Inc.). Because of the degree of the cataract in some patients, biometric optical measurements were not possible; in these cases, the AL used for the IOL calculation was that measured with the ultrasound device.

Surgical Technique

The same surgeon (J.M.M.) performed all cataract surgeries using a small-incision technique. All eyes had implantation of an aspheric monofocal IOL (Tecnis ZA9003, Abbott Medical Optics, Inc.). The surgeon selected the IOL power according to his standard practice.

Postoperative Assessment

Postoperative measurements were taken at 1 month. In addition to the measurements taken preoperatively, an accurate subjective refraction based on objective measurements was performed postoperatively. First, the wavefront aberrations in each eye were measured using a purpose-designed Hartmann-Shack sensor.[27] From the mean of 3 measurements of each patient, the objective refraction (sphere and astigmatism) was determined. These values were used as the starting point for the final subjective refraction. The spherical equivalent (SE) was calculated and translated optically to the IOL plane. In each case, this value was added to the power of the IOL that was implanted, leading to the determination of the optimum IOL power for each patient.

From Laboratorio de Óptica (Canovas, Alcon, Villegas, Artal), Centro de Investigacion en Optica y Nanofisica, Universidad de Murcia, Campus de Espinardo, and Servicio de Oftalmología (Abenza and Marin), Hospital Virgen de la Arrixaca, Murcia, Spain; Abbott Medical Optics (Canovas), Groningen, The Netherlands.

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Ray-Tracing Procedure

Figure 1 is a diagram of the ray-tracing procedure used, which was described in detail elsewhere.[28] For each eye, a complete custom eye model was built.[29] The surfaces considered were retrieved from the clinical measurements in each patient's eye. Thus, the cornea was described from the corneal elevations obtained from the corneal topography measurements. These elevations were centered with respect to the eye's pupil using the distance between the pupil center and the corneal apex calculated from the images recorded by the topographer.

The cornea was described using a single refractive surface and an equivalent refractive index that was calculated to reproduce the complete power of the cornea in the Le Grand eye model[30] considering only the anterior surface. The calculated value was 1.33, which is in close agreement with the equivalent refractive index calculated from physiologic data.[31]

As a key element of the ray-tracing procedure,[28] the actual position of the IOL was predicted using a regression ($r^2 = 0.80$) that related the IOL position measured after surgery with an optical coherence tomography system (Visante, Carl Zeiss Meditec AG) (ACD_post) and the ACD estimated from anterior segment slitlamp images (IOLMaster) (ACD_pre), as shown in Figure 2 and described by

$$ACD\_post = 0.88 \times ACD\_pre + 1.63 \qquad (1)$$

Formulas describing the surfaces of the IOL were provided by the manufacturer and were introduced as input into the modeling. To complete the eye model, the retina was placed in a position corresponding to the measured AL.

A computational routine was developed using an optical ray-tracing software package (Zemax Development Corp.). Exact ray tracing was performed through the optical surfaces for a 4.0 mm pupil in white light. The area under the radially averaged polychromatic modulation transfer function (MTF) was calculated for each IOL power introduced into the eye model. Th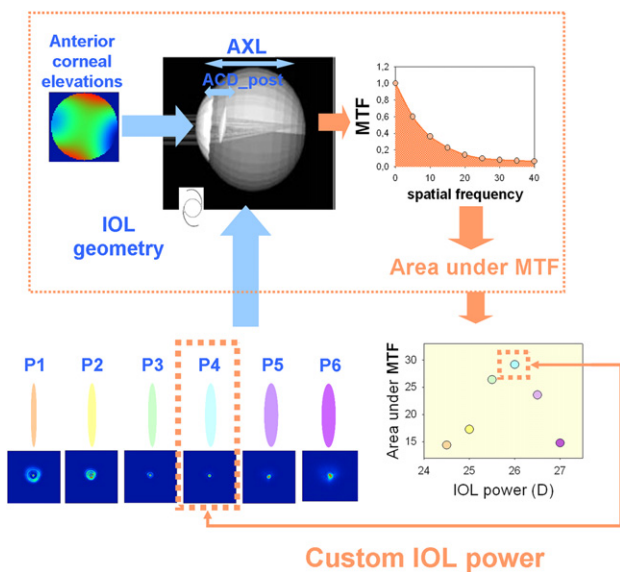e procedure was repeated sequentially for a series of IOL powers in 0.50 diopter (D) steps. The IOL power that maximized the area under the polychromatic MTF, used as an image-quality metric, was chosen as the desired IOL. For each patient, the procedure was repeated 4 times with 4 different measured corneal topographies. The final selected IOL power was the mode of the 4 predictions.

This procedure can be performed with different levels of sophistication. In this study, the calculations were performed with and without the introduction of corneal aberrations. In the first case, the complete set of elevations retrieved by the corneal topographer was introduced into the model. The IOL power calculated using this procedure was called the custom with corneal wavefront aberrations (custom + CWA). In the second case, only the power of the cornea was used as input for the modeling. The result of this prediction was called the custom without corneal wavefront aberrations (custom − CWA).

The optimum IOL power was determined with the ray-tracing procedure in both cases (custom + CWA and custom − CWA) in normal eyes and post-LASIK eyes. The difference between these predictions was called the corneal wavefront aberration influence (CWI). The corneal aberrations were calculated for each topography measurement using ray tracing in a separate model and averaged for each patient. In this case, the focal point was set to minimize the root-mean-square (RMS) spot size at the image plane for a 4.0 mm pupil.

Analysis of Results

In normal eyes, the SRK/T prediction[12] was calculated for comparison. In post-LASIK eyes, the simple SRK/T (referred to as SRK/T in figures) was also used. In addition, the double-K SRK/T method[7] was used for eyes that had myopic LASIK and the SRK/T with Masket method for eyes that had hyperopic LASIK[5] (this combined method referred to as double-K/Masket in the figures). These were selected because they are reported to be the most accurate methods for improving the accuracy of IOL power calculations after refractive surgery using the data that were available in this study.[5,32] To generate the double-K prediction, the corneal power before LASIK surgery was used in all cases in which this value was available. In cases in which it was not, 43.86 D was used as the preoperative corneal power.[32] For myopic eyes, the correction of post-LASIK corneal power was performed as suggested by Savini et al.[33] For eyes that

Figure 1. For every IOL power, an eye model was built from patient's biometric data. From these data, the area under the radial MTF was retrieved and the IOL power that maximized this metric was chosen.
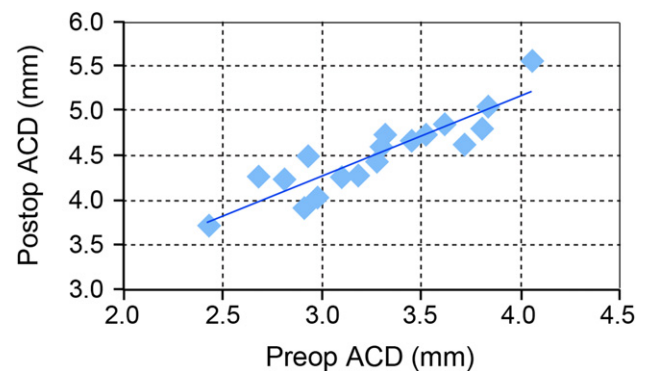

Figure 2. The ACD before surgery as function of the ACD after the surgery. From this result, the predictive model described by equation 1 was extracted (ACD = anterior chamber depth).
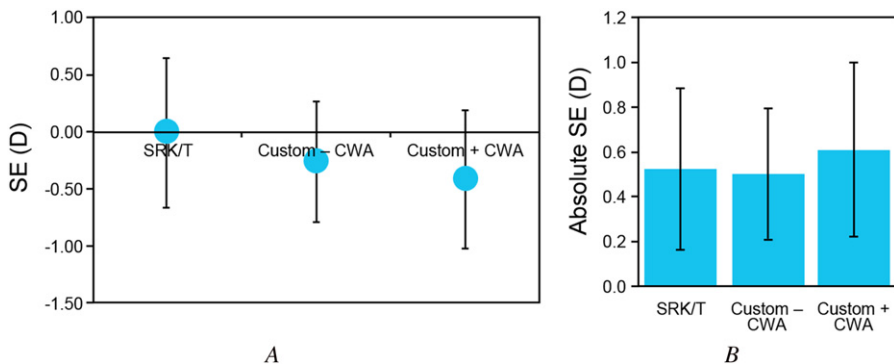
A   *B*

Figure 3. *A*: The mean SE refractive error in eyes without previous LASIK achieved by the SRK/T (0.0 ± 0.7 D), ray tracing with corneal aberrations (Custom + CWA) (−0.4 ± 0.6 D), and ray tracing without corneal aberrations (Custom − CWA) (−0.3 ± 0.5 D). *B*: The mean absolute SE refractive error (0.5 ± 0.4 D, 0.6 ± 0.4 D, and 0.5 ± 0.3 D, respectively) (CWA = corneal wavefront aberration; SE = spherical equivalent).

had hyperopic LASIK, the IOL power was calculated with the SRK/T formula modified by the Masket and Masket method,[5] which considers the surgically induced change in the manifest refraction after LASIK.

All IOL power predictions were subtracted from the optimum IOL power determined after the surgery for each patient. In addition, the difference between IOL powers was transformed back to the spectacle plane to calculate the residual SE error predicted by all procedures.

The Student *t* test was used to evaluate the statistical significance of the difference between the mean and the mean absolute errors, while the consistency in the prediction was tested using the F test for variances. A *P* value less than 0.05 was considered statistically significant. Before significance testing, mean absolute errors underwent cube root transformation to satisfy assumptions of normality.

RESULTS

The study evaluated 18 patients who did not have previous LASIK and 10 patients who had previous LASIK (2 hyperopic, 8 myopic).

Patients with No Previous Laser in Situ Keratomileusis

Figure 3 shows the mean residual SE and mean absolute SE error for the predictions calculated for patients without previous LASIK. Although the mean arithmetic residual SE was statistically significantly different between the SRK/T prediction and both ray-tracing predictions (*P* < .05), the mean absolute error showed no statistical differences (*P* > .05). All procedures showed the same consistency in the calculation because there were no statistically significant differences in variances. Therefore, the accuracy of the SRK/T prediction and both ray-tracing predictions were similar.

Figure 4 shows the difference between ray-tracing predictions caused by corneal aberrations versus the amount of aberration. Corneal aberrations are represented as the RMS of all 3rd-order and above wavefront aberrations. There was a slight correlation between the 2 parameters (r^2 = 0.58). The maximum difference between ray-tracing predictions was 0.50 D, which was also the power increment for the IOL model in this study.

Patients with Previous Laser in Situ Keratomileusis

Figure 5 shows the mean residual SE and the mean SE error for the predictions calculated for patients who had previous LASIK. Although the mean residual error by the double-K/Masket and ray-tracing procedure incorporating corneal aberrations was not statistically significantly different (*P* > .05), the double-K/Masket method showed a larger variance than the complete ray-tracing procedure (*P* < .05). In the case of absolute SE error, the double-K/Masket and ray-tracing procedures without considering corneal aberrations did not give statistically significantly different results. On the other hand, when corneal aberrations were considered in the ray-tracing prediction, the absolute SE error was statistically significantly better than the double-K/Masket (*P* < .05). Therefore, the accuracy of the ray-tracing prediction incorporating corneal aberrations was higher than that of the double-K/Masket method, while the ray-tracing procedure that did not consider aberrations produced results with an accuracy similar to both considered formulas.

Figure 6 shows the impact of corneal aberrations on the ray-tracing prediction versus the amount of corneal aberrations for each patient. In eyes with
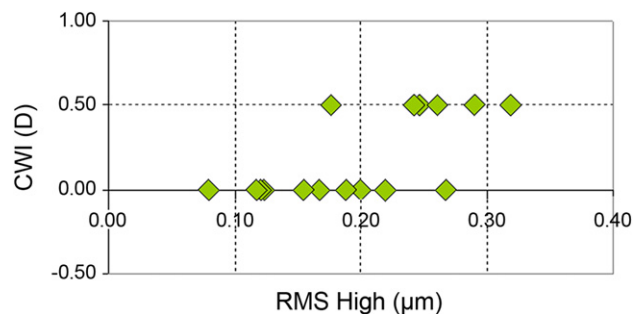

Figure 4. Corneal wavefront aberrations influence in the ray-tracing prediction, defined as the difference between the ray-tracing prediction including corneal aberrations and without them, as a function of the corneal HOAs in eyes without previous LASIK (CWI = corneal wavefront aberration influence; RMS High = root mean square of all 3rd-order and above wavefront aberrations).
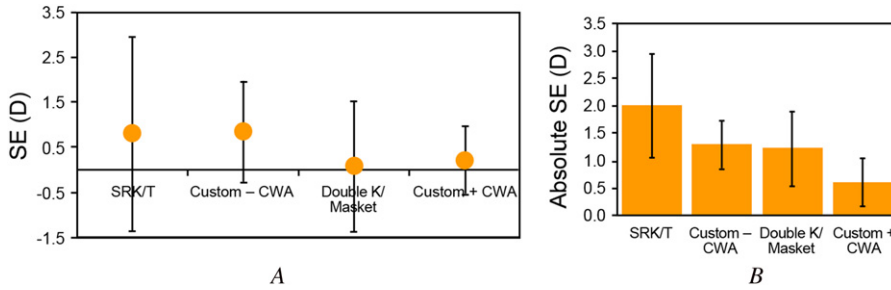
Figure 5. *A*: The mean SE refractive error in eyes with previous LASIK achieved by the SRK/T (0.8 ± 2.2 D), double-K/Masket (0.1 ± 1.5 D), ray tracing with corneal aberrations (Custom + CWA) (0.2 ± 0.8 D), and ray tracing without corneal aberrations (Custom − CWA) (0.8 ± 1.1 D). *B*: The mean absolute SE refractive error (2.0 ± 1.0 D, 1.2 ± 0.7 D, 0.6 ± 0.4 D, and 1.3 ± 0.4 D, respectively) (CWA = corneal wavefront aberration; SE = spherical equivalent).

previous LASIK, the degree to which corneal wavefront aberrations influenced the optimum IOL power depended on the amount of corneal aberrations, reaching up to 3.00 D with a correlation similar to that in eyes without previous LASIK ($r^2 = 0.59$). The amount of corneal aberrations in eyes with previous LASIK was significantly higher than in eyes without previous LASIK. The range of corneal RMS values was approximately double in eyes with previous LASIK. If the amount of aberrations were considered to be the same in post-LASIK eyes and eyes without LASIK (up to 0.3 μm), the differences between the 2 ray-tracing predictions would be similar between the 2 groups of eyes. Thus, the main difference in the impact of corneal aberrations in both populations was the result of the increased amount of aberrations in post-LASIK eyes.

Figure 7 shows the difference between ray-tracing predictions and corneal spherical aberration. Corneal aberrations had a better correlation with corneal spherical aberration ($r^2 = 0.82$) than with the RMS of all corneal higher-order aberrations (HOAs). Therefore, corneal spherical aberration was probably the main reason for the increased accuracy of the ray-tracing procedure over that of the other IOL power predictions.
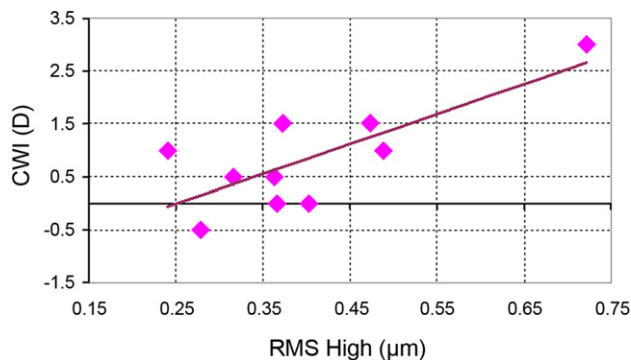
DISCUSSION

Today, the IOL power calculation formula should be selected according to the specific population being evaluated. For example, formulas for post-LASIK patients are not valid for patients who had not had previous refractive surgery.[4–8] We have shown that ray tracing is a robust method for calculating IOL power in eyes that have not had LASIK and in post-LASIK eyes. The custom ray-tracing procedure we used has been described in detail.[28] Furthermore, a comparison between the IOL power calculated using this method and using some current IOL power calculation formulas was performed for 19 young subjects.[28] This comparison showed no difference in the mean IOL power calculated in this population. However, the IOL power calculated by different procedures was larger for higher refractive errors. This comparison was performed as a conceptual exercise to show the possible differences with respect to the current state of art. However, it was not possible to test the validity of the results because that population comprised normal young students who did not have cataract surgery. The impact of corneal aberrations on IOL power calculation using ray tracing was shown by artificially increasing up to 5 times the corneal aberrations in a normal eye because post-LASIK corneal data

Figure 6. Corneal wavefront aberrations influence in the ray-tracing prediction as a function of the corneal HOAs in eyes with previous LASIK (CWI = corneal wavefront aberration influence; RMS High = root mean square of all 3rd-order and above wavefront aberrations).
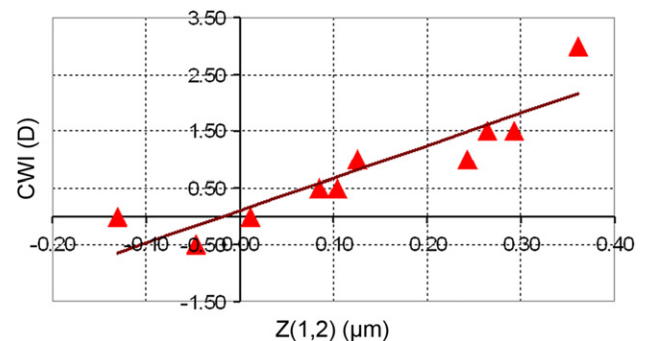

Figure 7. Corneal wavefront aberrations influence in the ray-tracing prediction as a function of the corneal spherical aberration in the post-LASIK population (CWI = corneal wavefront aberration influence; Z(1,2) = 4th-order spherical aberration).

were not available in that study.[28] The present study, however, validates our ray-tracing procedure in a real clinical setting in patients having cataract surgery with no previous LASIK and patients having cataract surgery who had previous LASIK by comparing IOL power predictions and final outcomes.

Our initial goal was to verify that the IOL power can be accurately predicted in eyes without previous refractive surgery. The prediction method's accuracy was similar to that of the SRK/T formula, especially in the mean absolute prediction error and variance. This verifies the accuracy of the procedure because accuracy of the SRK/T formula is similar to that of other paraxial formulas[1] in normal eyes. We classified normal eyes as those having a close to average AL. The mean AL of the normal population in our study was 23.7 mm ± 0.8 (SD). Thus, their classification as normal eyes is justified.

The ray-tracing prediction is based on only the optical treatment of patients' data. Paraxial formulas optimize the A-constant to keep the mean prediction error close to zero, as can be seen in Figure 3, A, for the SRK/T formula. The lack of an A-constant in the ray-tracing approach could make it more sensitive to measurement errors.[34] With the ray-tracing procedure, the mean residual error was statistically significantly different than that with the SRK/T formula; however, there were no differences in the mean absolute error or the variance. The reason that the mean SE error was larger with the ray-tracing procedure might be the optimization of the A-constant used in the SRK/T prediction. Our ray-tracing procedure has no fudged parameters[34] that can compensate for experimental errors. On the other hand, the consistency of the 2 procedures was similar given that the variance was not statistically different. Therefore, the similarity in the predictive results with both methods is a validation of the ray-tracing procedure. In other words, ray tracing can be used to calculate the optimum IOL power for a specific IOL and a specific patient.

We found the impact of corneal aberrations on the prediction was limited in normal eyes, primarily because the magnitude of corneal aberrations was small in these cases. The maximum difference between the 2 ray-tracing predictions was 0.50 D, which was the power increment for the IOL model used in the study.

In fact, the ray-tracing prediction incorporating corneal aberrations gave a slightly higher error than the ray-tracing procedure that did not consider corneal aberrations. Because the impact of corneal aberrations on the calculation was small, their consideration introduced noise, reducing in stability of the prediction.

Future studies of normal eyes might incorporate some improvements. One is the approximation related to the equivalent refractive index.[35] Although the value chosen for the model was equivalent to that predicted by physiological measurements,[31] a fully customized model could be used that considers the posterior corneal surface, although the impact of introducing further experimental measurement errors should be evaluated. In addition, IOL placement prediction remains a challenge. Improvements in the accuracy of input into the model will further decrease errors in IOL power prediction. If these inaccuracies are reduced, the impact of corneal aberrations might be more evident in a normal population.

Once the model was validated in a normal population, we applied it to cataract patients who had previous LASIK. In this group, we found that the significant improvement offered by the ray-tracing prediction was the result of taking corneal spherical aberration into consideration. In previous studies,[18,36] patients who had standard myopic LASIK had increased positive spherical aberration values, while those who had hyperopic LASIK had increased amounts of negative corneal spherical aberration. The post-LASIK patients in our study also showed this trend. The patients with negative spherical aberration in Figure 7 were those who had previous LASIK for hyperopia. In contrast, the patients with increased positive corneal spherical aberration were those who had previous LASIK for myopia. It is not surprising that taking into consideration the large values of spherical aberration in these patients improved the IOL power predictions. A combination of nonparaxial optical calculations and consideration of the actual aberrations in the cornea and the IOL produced better results.

Several empirical approaches to improve IOL power prediction in post-LASIK patients have been developed. Masket and Masket[5] presented a method in which the IOL power calculation used for normal eyes is corrected for post-LASIK eyes depending on the refractive error corrected by LASIK. Yoon et al.[36] evaluated the sources of the spherical aberration induced by LASIK. They found that the induction of spherical aberration was directly related to the amount of correction applied. These results are in agreement with our findings. Accordingly, for IOL power calculation, corneal spherical aberration provides a theoretic explanation for the hyperopic shift in patients who had LASIK for myopia. Moreover, custom ray tracing uses only data collected before cataract surgery and does not rely on the patient's history, which is not always available.

The impact of corneal topography on IOL power calculation has been studied. Preussner et al.[26] introduced personalized corneal eccentricities in a nonparaxial ray-tracing procedure, showing the influence on the calculation, especially in post-LASIK eyes. However,

the impact of HOAs was not objectively established because they were not included in the calculation, although a visual impression was generated to subjectively judge their impact. In our procedure, we incorporated anterior corneal aberrations into the calculation. In addition, we considered the impact of corneal HOAs; the improvement in the calculation was the result of the introduction of CWA. At this point, it is interesting to reevaluate normal cataract patients. Although Figure 7 plots the results in post-LASIK eyes, it shows the impact of corneal spherical aberration for a wide range of values. The mean corneal spherical aberration for a 6.0 mm aperture is 0.27 ± 0.02 μm[19]; this rescales to 0.05 μm for a 4.0 mm pupil. According to the regression provided by the results in Figure 7, the impact of considering corneal spherical aberration in IOL power calculation was 0.39 D at the IOL plane, which translates to 0.30 D at the spectacle plane.[37] This value might be easily influenced by errors related to the rest of the input variables because, for example, the refraction process itself has a standard deviation of 0.39 D.[34] As we previously discussed, this difference may be relevant when the errors related to the rest of the biometric input parameters are further reduced. When this is achieved, corneal aberrations will play a role in IOL power calculation, even for lower values.

Although ray-tracing prediction and current state-of-the-art methods in post-LASIK eyes predicted on average a zero SE, the standard deviation was higher for the corrected double-K/Masket method (0.8 D versus 1.5 D), which is reflected by the significantly larger variance (0.6 D versus 2.1 D) ($P < .05$). The difference was also evident for the mean absolute SE error, which was 1.2 ± 0.7 D with the double-K/Masket method and 0.6 ± 0.4 D with the ray-tracing method. It can therefore be concluded that the ray-tracing approach is more accurate and more predictable than current state-of-the-art IOL power calculations. This confirms the validity of ray tracing as a global method that can be used for IOL power calculations in normal eyes and in eyes that have had LASIK for myopia or hyperopia.

With respect to the ray-tracing procedure, the same limitations can be applied for post-LASIK eyes and normal eyes. In fact, the impact of the approximated equivalent refractive index of the cornea should theoretically be larger in post-LASIK eyes because LASIK modifies the ratio between the anterior corneal radius and posterior corneal radius. Pérez-Escudero et al.[38] measured the change in the anterior and posterior corneal radius after LASIK for myopia. The mean equivalent refractive index changed from 1.329 to 1.323, representing a decrease in power of approximately 0.7 D. However, the equivalent refractive index

depends on the characteristics of the LASIK procedure. Indeed, when we considered separately our patients with previous myopic LASIK, we found a mean hyperopic error (0.5 ± 0.5 D). This may suggest the need to change the equivalent refractive index or to take into consideration the posterior corneal surface as a part of a complete characterization of the posterior corneal surface, similar to the procedure used for the anterior cornea in the ray-tracing procedure we describe. Both issues should be evaluated in future studies.

In conclusion, we developed a robust, accurate, and customized ray-tracing method to predict the optimum IOL power for normal eyes and post-LASIK eyes. In addition, we found the incorporation of corneal spherical aberration to be the most important improvement provided by this method, especially in post-LASIK eyes. In both groups, the effectiveness of the procedure depends on the quality of the biometric measurements introduced into the model for each patient.

WHAT WAS KNOWN

- There are several formulas to predict the IOL power that are only partially patient specific because some modifications must be made when patients have had refractive surgery or have extreme eye geometries.

- Most common clinically used IOL power calculation methods are based on a paraxial optics representation of the eye and therefore cannot directly account for corneal or IOL aberrations.

WHAT THIS PAPER ADDS

- An optimized approach based on ray tracing that 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.

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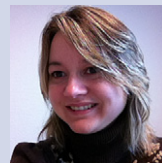
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