

Intraocular Lens Power Calculation by Ray-Tracing after Myopic Excimer Laser Surgery

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- **PURPOSE:** To investigate the refractive outcomes of intraocular lens (IOL) power calculation by ray-tracing after myopic excimer laser surgery.
- **DESIGN:** Prospective, interventional case series.
- **METHODS:** SETTING: Multicenter study. PARTICIPANTS: Twenty-one eyes of 21 patients undergoing phacoemulsification and IOL implantation after myopic laser in situ keratomileusis or photorefractive keratectomy were enrolled. INTERVENTION: IOL power calculation was performed using internal software of a Scheimpflug camera combined with a Placido disc corneal topographer (Sirius; CSO). Exact ray-tracing was carried out after the axial length (measured either by immersion ultrasound biometry or partial coherence interferometry), target refraction, and pupil size had been entered. MAIN OUTCOME MEASURES: Median absolute error, mean absolute error, and mean arithmetic error in refraction prediction, that is, the difference between the expected refraction (as calculated by the software) and the actual refraction 1 month after surgery.
- **RESULTS:** The mean postoperative refraction was -0.43 ± 1.08 diopters (D), with a range between -1.28 and 0.85 D. The mean arithmetic error was -0.13 ± 0.49 D. The median and mean absolute errors were $+0.25$ D and 0.36 D, respectively. Also, 71.4% of the eyes were within ± 0.50 D of the predicted refraction, 85.7% were within ± 1.00 D, and 100% within ± 1.50 D.
- **CONCLUSIONS:** Ray-tracing can calculate IOL power accurately in eyes with prior myopic laser in situ keratomileusis and photorefractive keratectomy, with no need for preoperative data. (Am J Ophthalmol 2013; ■: ■–■. © 2013 by Elsevier Inc. All rights reserved.)

INTRAOCULAR LENS (IOL) POWER CALCULATION AFTER corneal refractive surgery continues to be challenging. More than 30 methods have been proposed as possible solutions to this problem. Some of them have been shown

to lead to good refractive outcomes, similar to those achieved in unoperated eyes.^{1,2} However, such calculations require much more time than those carried out in virgin eyes and still depend on the expertise of the ophthalmologist who has to choose the IOL power. The difficulties derive from several factors, such as the necessity of selecting the result from one of the several formulas presently available, which often produce a wide range of IOL powers; the need to enter all the formulae in calculation spreadsheets, which may be subject to errors; the risk of measuring a wrong corneal radius if the optical zone is small, because the instrument readings may be taken outside the treated area (so-called *radius error*); the lack of methods to calculate corneal power reliably when the optic zone is decentered or when multiple treatments have been carried out (eg, excimer laser surgery after radial keratotomy). Two solutions have been offered to help surgeons make accurate calculations and correct decisions. The first consists of an Excel spreadsheet (Hoffer-Savini LASIK IOL Power Tool)³ released by Hoffer and Savini in 2007. The second is an Internet-based IOL power calculator developed by the American Society of Cataract and Refractive Surgery.⁴ With both tools, however, surgeons still have to decide which formula should be used. Moreover, they cannot be used for cases with decentered optical zones or multiple treatments. Lastly, the American Society of Cataract and Refractive Surgery calculator does not allow the operator to enter manual or simulated keratometry values and does not include several excellent published formulas.

Theoretically, a better solution is represented by optical ray-tracing based on the Snell law. This method is not subject to the 3 problems that make IOL power calculation inaccurate after corneal refractive surgery⁵: the keratometric index problem, because ray-tracing does not rely on any fictitious index to calculate the corneal power; the radius problem or instrument error, because ray-tracing can be performed over any corneal diameter; and the formula error, because the IOL position can be calculated without relying on the anterior corneal curvature (unlike in the case of third-generation theoretical formulas, such as the Hoffer Q, Holladay 1, and SRK/T).^{6–8} In addition, ray-tracing does not require any historical data and can incorporate corneal aberrations in IOL power calculation.⁹ Previous studies have shown encouraging results with this approach.^{10–12} The purpose of this study was to evaluate the preliminary results of ray-tracing, as performed by a rotating Scheimpflug camera combined with a Placido disc corneal topographer, in a series of eyes undergoing

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phacoemulsification and IOL implantation after previous excimer laser surgery.

METHODS

THIS WAS A PROSPECTIVE, INTERVENTIONAL CASE SERIES carried out between December 2010 and December 2012. Before being included in the study, the subjects were informed of the study's purpose and they gave their written informed consent. The study methods adhered to the tenets of the Declaration of Helsinki for the use of human participants in biomedical research. The study was approved by the Giovanni Battista Bietti Foundation Institutional Review Board. All patients undergoing phacoemulsification and IOL implantation after myopic laser in situ keratomileusis (LASIK) or photorefractive keratectomy (PRK) were enrolled. If both eyes underwent surgery, only the first eye was evaluated.

Before surgery, all patients underwent anterior segment imaging by a Scheimpflug camera combined with a Placido disc corneal topographer (Sirius, software version 2.5; CSO, Florence, Italy), which provides repeatable measurements of corneal power, corneal thickness, and aqueous depth.^{13,14} Axial length was measured either by immersion ultrasound biometry (Ocuscan; Alcon Laboratories, Fort Worth, Texas, USA) or partial coherence interferometry (IOLMaster; Carl Zeiss, Jena, Germany).

• **RAY-TRACING PROCEDURE:** After the anterior segment of the eye was imaged and the scan was processed, the Sirius internal software calculated the IOL power. Four parameters had to be entered manually: the axial length, the target refraction, the pupil diameter (which was set to 3 mm in all patients), and the labeled A-constant of the IOL. The latter was required because most IOL manufacturers do not provide the curvature and thickness values of their IOLs, which are required for exact ray-tracing. The actual position of the IOL was predicted using a proprietary algorithm, which is based on several measured parameters of the anterior segment of the eye and the A-constant of the IOL.

For ray-tracing to be performed, a bundle of rays parallel to the instrument axis and passing within the entrance pupil of the eye was traced through the anterior and posterior corneal surfaces (as measured by the Scheimpflug and Placido technologies) using the Snell law. For each incoming ray, its intersection with the anterior corneal surface and its angle of incidence relative to the anterior surface normal were calculated. The ray refracted by the anterior surface was obtained using the Snell law, with $n_{\text{air}} = 1.0$ and $n_{\text{stroma}} = 1.376$. This ray then was considered as an incoming ray for the posterior corneal surface and the same procedure as above was applied to calculate the ray refracted by this surface using the Snell law, with $n_{\text{stroma}} = 1.376$ and $n_{\text{aqueous}} = 1.336$. The ray coming from the aqueous humor then was traced through the IOL surface and the vitreous ($n_{\text{vitreous}} = 1.336$) until the

retina. The intersections of rays with the retina created the retinal spot, whose shape and density depended on the aberrations of the optical system. All rays traced until the retina were used to calculate the wavefront error, that is, the difference between the measured wavefront and an ideal spherical wavefront. From this calculation, the refractive outcome associated with a given IOL was estimated by means of the proprietary algorithm.

A final evaluation was performed by assessing the subjective manifest refractive outcomes at 1 month after surgery, which is when refractive stability can be expected with small-incision clear cornea surgery.¹⁵⁻¹⁷ To calculate the mean arithmetic error in the prediction of refractive outcome, the measured manifest refractive spherical equivalent was subtracted from the predicted refraction (based on the IOL actually implanted) provided by the IOL power software of Sirius. The median and mean absolute errors also were calculated.

RESULTS

TWENTY-ONE EYES OF 21 PATIENTS (12 WOMEN; MEAN AGE, 62.4 ± 8.6 years), operated on by 11 different surgeons, were enrolled and completed the follow-up. Ten had undergone myopic LASIK and 11 had undergone myopic PRK. The mean axial length was 27.35 ± 2.16 mm (range, 23.2 to 32.6 mm); the mean power of the implanted IOL was 17.81 ± 3.69 diopters (D; range, 6.0 to 22.5 D), and the mean expected refraction was -0.61 ± 1.38 D. A decentered optical zone was detected in 3 eyes, and central corneal haze was detected in 1 eye.

The following models of IOL were implanted: the AcrySof SA60AT (Alcon Laboratories; $n = 9$), the AcrySof MA60AC (Alcon Laboratories; $n = 5$), the AcrySof SN60WF (Alcon Laboratories; $n = 4$), the MI60 (Bausch & Lomb; $n = 1$), the Envista (Bausch & Lomb, Rochester, New York, USA; $n = 1$), and the LS-313 (Oculentis, Eerbeek, the Netherlands; $n = 1$).

The mean postoperative refraction was -0.43 ± 1.08 D (range, -1.28 to 0.85 D). The median absolute error was $+0.25$ D and the mean absolute error was 0.36 D, whereas 71.4% of the eyes were within ± 0.50 D of the predicted refraction, 85.7% were within ± 1.00 D, and 100% within ± 1.50 D. The mean arithmetic error was -0.13 ± 0.49 D (constant optimization could not be carried out because different IOLs were used in this study). Regarding the 3 eyes with a decentered optical zone, the median and mean absolute errors were 0.33 and 0.32 D, respectively.

DISCUSSION

OUR DATA DEMONSTRATED THAT RAY-TRACING MAY BE AN accurate method to calculate IOL power after corneal

refractive surgery. The IOL power predicted by the software of the Scheimpflug camera combined with Placido disc corneal topographer enabled us to obtain a reliable refractive outcome, because the median and mean absolute errors are close to those reported for unoperated eyes.¹⁸ The reasons for the good results can be ascribed to the fact that ray-tracing is not affected by the 3 errors influencing third-generation theoretical formulas after corneal refractive surgery, as mentioned above, and takes into account spherical aberration, which is significantly changed after myopic PRK and LASIK.^{19,20}

The accuracy of ray-tracing for IOL power calculation in normal eyes has been reported already by other authors.^{9,10,12} However, only a few studies have investigated the potential advantages of ray-tracing versus theoretical thin formulas in eyes that previously underwent corneal excimer laser surgery. Rabsilber and associates used commercially available software (OKULIX; Ingenieurbüro der Leu, Hillerse, Germany) to analyze the corneal curvature data from a Placido disc corneal topographer and to calculate IOL power.¹¹ In their series, the mean absolute error was 0.74 D, an outcome twice as high as ours (0.36 D). The difference may be related to the fact that standard corneal topography does not measure corneal thickness and posterior corneal curvature, as is done with Scheimpflug imaging. The same group later reported an mean absolute error ranging between 0.59 and 0.66 D (depending on the method used to predict the position of the IOL) in a sample of eyes that had undergone refractive surgery and whose IOL power was calculated by means of another optical software program (Zemax-EE Optical Design Program; Radiant Zemax, Redmond, Washington, USA), after corneal curvature was measured by a rotating Scheimpflug camera (Pentacam, Oculus Optikgeräte GmbH, Wetzlar, Germany).¹² Canovas and associates found an mean absolute error of 0.60 D after measuring only the anterior corneal curvature and calculating the IOL power by Zemax in a sample of 10 patients who had undergone previous LASIK.⁹ Compared with these studies, our data suggest that the Sirius internal software offers higher accuracy in eyes that have undergone refractive surgery. This improvement may be related either to more accurate measurements of the anterior segment of the eye or to a more accurate prediction of the IOL position.

Recently, another commercially available technology has been used to calculate IOL power after corneal refractive surgery. The RTVue (Optovue, Inc, Fremont, California, USA), which is based on spectral-domain optical coherence tomography, can measure the curvature of both corneal surfaces and can calculate the total corneal power using the Gaussian optics formula.²¹ Previous studies from the same group led to the development of a ray-tracing IOL power calculation formula (the so called OCT-based IOL power formula), where the IOL position is predicted by means of a 3-variable regression formula using the anterior chamber depth, lens thickness, and axial length as the independent variables.²² This method has 2 disadvantages: first, the IOL is still considered to be

a thin IOL, and second, it can perform ray-tracing calculation only in the paraxial limit because of motion artifacts.²² However, the results reported were reasonably good: Tang and associates achieved an mean absolute error of 0.50 D in 16 eyes that had undergone previous myopic LASIK.²³ Hence, it will be interesting to compare the results of Sirius and RTVue in the same set of patients.

The results of the present study are similar to those obtained using other methods (based on theoretical thin lens formulas) for calculating IOL power after refractive surgery. For example, the Haigis-L formula was reported to lead to a median absolute error of 0.37 D (vs 0.25 D in our sample).²⁴ Shammas and Shammas, using the no-history method, reported 93% of cases within 1.00 D of target (vs 85.7% in our sample).²⁵ In a study comparing different methods to calculate the IOL power after myopic laser refractive surgery, the lowest mean absolute error was achieved by the Masket method combined with the Hoffer Q formula (0.59 D vs 0.36 D in our sample), which also led to a refractive outcome within ± 0.50 D and ± 1.00 D of target in 58.8% and 83.5% of cases, respectively (vs 71.4% and 85.7%, respectively, in our sample).²⁶ Better results were reported by Masket and Masket in their original paper; their patients were within ± 0.50 D of target in 93% of cases (vs 71.4% in our sample).²⁷ However, it should be highlighted that our sample included 3 eyes with decentered ablation, for which the above-mentioned methods would have produced erroneous results because of the so-called radius error. In corneas with decentered myopic ablation, the corneal radius is measured in part on the flat treated area and in part on the transition zone or completely outside the treated area, so that curvature readings can hardly be considered reliable and standard methods to calculate IOL power after excimer laser surgery cannot be applied.

This study has some limitations, and further investigation is warranted. First, in most patients, the refractive change and the preoperative corneal power were unknown, so that we could not compare the results of ray-tracing with those of the many methods requiring perioperative data to calculate the IOL power in eyes after corneal refractive surgery. Second, the ray-tracing software used to calculate IOL power in our sample, although commercially available, is still under development, and further improvements can be expected. After IOL manufacturers provide the curvature and thickness data of each IOL, these could be used in the calculation and the A-constant no longer would be necessary. Third, different IOL models were used, because the patients had been operated on by different surgeons. This was necessary to obtain a relatively large sample, but precluded the calculation of a zero mean arithmetic error in prediction of refractive error, which can be done only if 1 IOL model is selected. Future studies using only 1 IOL model will address this issue. Finally, we did not investigate eyes with prior hyperopic LASIK, so that our results can be applied only to patients who underwent myopic correction by excimer laser surgery.

In conclusion, IOL power calculation by ray-tracing, as performed by the Sirius internal software, enables accurate

refractive outcomes to be achieved in eyes with prior myopic LASIK and PRK.

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Biosketch

Giacomo Savini, MD, completed his Medical School and Residence Program at the University of Bologna, Italy. As an anterior segment surgeon, he focused his research on intraocular lens power calculation. In 2007 he was invited by Kenneth J Hoffer, MD, FACS, to enter the IOL Power Club. In 2009 he has joined the G.B. Bietti Foundation in Rome. Currently he is involved in many scientific projects in cataract and refractive surgery.