ARTICLE

Intraocular lens calculation for aspheric intraocular lenses

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PURPOSE: To evaluate the possible benefits of biometry and ray-tracing intraocular lens (IOL) calculation for aspheric aberration-correcting IOLs.

SETTING: Private eye clinic in Germany.

DESIGN: Retrospective consecutive case series.

METHODS: Eyes with 3 different aberration-correcting IOLs were reviewed. Before surgery, the axial length, corneal thickness, anterior chamber depth, crystalline lens thickness, and corneal radii were measured with the Lenstar biometer. Subjective refraction was taken 1 month after surgery. Okulix ray-tracing software (version 8.79) and the Hoffer Q, Holladay, and SRK/T formulas were used to calculate a prediction error based on preoperative biometry data, the given IOL, and the manifest refraction.

RESULTS: The study evaluated 308 eyes of 185 patients. The median absolute error was 0.28 diopters (D) for the Hoffer Q, 0.27 D for the Holladay, 0.28 D for the SRK/T, and 0.24 D for ray-tracing calculation. Using ray-tracing calculation, 95% of eyes were within $\pm$0.71 D of the predicted refraction as opposed to $\pm$0.85 D with the Hoffer Q, $\pm$0.82 D with the Holladay, and $\pm$0.84 D with the SRK/T.

CONCLUSIONS: Ray tracing based on biometry data improved IOL prediction accuracy over conventional formulas in normal eyes implanted with aberration-correcting IOLs. The number of outliers can also be reduced significantly.

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In modern cataract surgery, aspheric intraocular lenses (IOLs) have become increasingly popular. Optics with a conic shape have the potential to significantly reduce the amount of spherical aberration in the eye, allowing higher contrast and acuity, especially under low light conditions.[1–3] However, the improved optical properties lead to less pseudoaccommodation and therefore increase the influence of defocus. It is therefore mandatory to predict the IOL power as precisely as possible.

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Intraocular lens calculations with optical biometry and conventional formulas[4–6] yield very good results. However, all these formulas use calculations based on the Gullstrand eye model. This assumes a fixed ratio of anterior corneal curvature and posterior corneal curvature. The cornea is treated as a thin lens with a composite index of 1.3375 (or 1.3315 in the case of the Haigis formula). Systematic deviations are compensated for by so-called IOL constants that essentially modify the effective lens position (ELP). Although this leads to a correct result on average, it can deliver less precise results under certain conditions.

Newer eye models, such as that of Liou and Brennan,[7] describe the eye more accurately on average. Using ray-tracing technology, it is possible to work with the physical properties of the IOL and to take full advantage of crystalline lens data delivered by the Lenstar optical biometer (Haag-Streit) to improve prediction accuracy.[8,9]

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The goal of this study was to evaluate whether ray-tracing calculation based on Lenstar measurements improve prediction accuracy in aspheric aberration-correcting IOLs compared with traditional formulas that are currently the gold standards of IOL calculation.

PATIENTS AND METHODS

Eyes that had implantation of premium aspheric IOLs based on Lenstar optical biometry between January 2011 and June 2012 were reviewed retrospectively. All had routine cataract surgery without complications. Eyes with macular disease (eg, neovascular age-dependent maculopathy, macular hole, geographic atrophy, macular edema) and eyes with keratoconus, corneal grafts, corneal scars, or edema were excluded.

All surgical procedures were performed by 2 experienced surgeons using coaxial microphacoemulsification with 2.2 mm (P.C.H.) or 2.5 mm (C.R.L.) posterior limbal incisions placed temporally that were astigmatically neutral or near neutral as previously described.[10]

Preoperative diagnostics and IOL calculation were performed with the optical biometer software (version 3) as well as TMS5 tomography (Tomey) of both corneal surfaces. For comparison with traditional formulas, only biometer data were used as an input into the ray-tracing software (Okulix version 8.79, Tedics). A Lenstar data set includes the following information: axial length (AL), corneal thickness, internal anterior chamber depth (ACD), lens thickness, depth of vitreous cavity, retinal thickness, and corneal radii in the steepest and flattest meridians.

The principles and development of the ray-tracing software have been described.[11–13] The software can be used with the same input data as conventional formulas; however, additional information can be used to refine the model. This includes Lenstar optical path data of the anterior segment as well as corneal tomography with different devices (Placido, Scheimpflug, anterior segment optical coherence tomography [AS-OCT]).

The following aspheric aberration-correcting (as opposed to aberration-neutral) IOLs were implanted: iMics1 (Hoya), Acrysof IQ (Alcon), Tecnis 1-piece (Abbott Medical Optics). Although the exact physical properties of the IOLs are not disclosed by the manufacturers, it is known that the Tecnis IOL has the strongest negative spherical aberration followed by the Acrysof IQ and the iMics1.

The measure of success was the prediction error, defined as the difference between achieved and predicted spherical equivalent (SE) manifest refraction. The manifest refraction was obtained by subjective refraction 1 month after surgery according to DIN 58220.[14] The distance from the patient's head to the acuity chart was 6 m (20 ft).

The subjective refraction was performed as follows: First, the uncorrected acuity was taken. Second, the patient was refracted with spherical lenses until the best spherical glass was found and acuity could not be improved. Third, a cross cylinder ($\pm$0.5 D or $\pm$1.0 D depending on acuity) was applied at 0 degree, 90 degrees, 45 degrees, and 135 degrees. If there was subjective improvement in any of these axes, the patient was offered 2 choices by flipping the cross cylinder along its handle and adjusting the axis in decreasing steps. After the cross-cylinder examination, a final spherical adjustment was performed with the help of a red–green balance chart. Final refraction was reached when there was red–green balance or slight green overweight. All refractions were performed by 1 of 4 experienced ophthalmologists.

The difference between the SE of this refraction and the SE as predicted by the formula or the ray-tracing software was defined as the prediction error. The median, mean, and standard deviation were calculated. The median and mean absolute error were also evaluated after adjusting offsets and constants to a mean prediction error of zero.

The Hoffer Q,[15] Holladay,[16] and SRK/T[17] formulas were used for comparison. For each type of IOL, the specific formula constants were optimized to obtain a mean prediction error of 0.0 D.

The ray-tracing software was set up to import a Lenstar data set. Posterior curvature was configured according to the model of Liou and Brennan,[7] the asphericity Q was set to -0.16 (-0.18 in the Liou and Brennan model), and the pupil was assumed to be 3.0 mm in diameter in the iris plane. All calculations were performed for the best focus, which was defined according to the International Organization for Standardization (ISO 11979-2)[18] for each meridian by the ray that intersects the pupil plane at a distance of

$$d = 0.5 \times \sqrt{2} \times p$$

where p is the pupil diameter. The postoperative IOL position was estimated by averaging 2 algorithms based on (1) AL only and (2) ACD and crystalline lens thickness biometry data, which have been described in detail.[8,19]

To evaluate statistical significance, the Wilcoxon parameter-free matched-pair test and Prism 5.0b software (Graphpad Software) were used.

The various formulas were used with the actual constants recommended in the User Group for Laser Interference Biometry database[A] and the Okulix version 8.79 software out of the box. Because there was a systematic offset for all IOLs in all formulas and all but 1 IOL in the ray-tracing software, the offset for each IOL was adjusted to 0.0 D so as not to compare constants but rather the real potential of the algorithms.

RESULTS

The study reviewed 308 eyes of 185 patients; 117 patients (63.2%) were women. The median age of the patients was 73 years (range 39 to 87 years). The mean corrected distance visual acuity was 0.04 $\pm$ 0.10 logMAR (SD) (range 0.3 to -0.2 logMAR).

The mean implanted IOL power was 21.06 $\pm$ 3.80 D (range 8.0 to 31.5 D). The iMics1 IOL was implanted in 67 eyes, the Acrysof IQ IOL in 82 eyes, and the Tecnis IOL in 159 eyes.

Table 1 shows the overall results. Systematic offsets were corrected for all formulas and the ray-tracing calculation. When using the ray-tracing software and Lenstar crystalline lens data, the median absolute prediction error improved by 9% to 14% depending on the formula. Furthermore, the number of eyes with prediction outside the $\pm$1.00 D boundaries was from 7 (2.3%) to 1 (0.3%). No eye had an absolute prediction error of more than 1.50 D.

The differences in absolute error were highly significant between the ray-tracing software and the SRK/T

Table 1. Prediction error based solely on biometry data (308 eyes).

						% Within Predicted Refraction		
Formula*	Mean [D]	SD [D]	Range [D]	MAE [D]	MEE [D]	±0.25 D	±0.50 D	±1.00 D
HofferQ optimized	0.00	0.41	−1.40, +1.02	0.32	0.28	44.6	76.6	98.4
Holladay optimized	0.00	0.41	−1.13, +1.40	0.31	0.26	48.5	79.2	97.4
SRK/T optimized	0.00	0.43	−1.39, 1.43	0.34	0.28	44.6	78.8	98.1
AL selected optimized	0.00	0.41	−1.40, +1.21	0.31	0.26	48.2	79.8	97.7
Ray tracing offset corrected	0.00	0.37	−1.01, +0.89	0.30	0.24	52.8	81.1	99.7
Ray tracing out of the box	0.04	0.41	−1.01, +1.08	0.34	0.30	42.7	76.2	99.4

AL selected formula = the Hoffer Q result was used for short eyes (<22.0 mm), the SRK/T for long eyes (>26.0) mm, and the Holladay for all other eyes; MAE = mean absolute error, MEE = median absolute error

*Optimized constants are A = 118.90, SF = 1.67, pACD = 5.44 for iMics1; A = 119.27, SF = 1.90, pACD = 5.77 for Acrysof IQ; and A = 119.53, SF = 2.04, pACD = 5.82 for Tecnis. User Group for Laser Interference Biometry constants are A = 118.70, SF = 1.66, pACD = 5.46 for iMics1; A = 119.0, SF = 1.85, pACD = 5.64 for Acrysof IQ; and A = 119.3, SF = 2.00, pACD = 5.78 for Tecnis

and Hoffer Q formulas with and without offset correction ($P<.01$, Wilcoxon matched-pairs signed-rank test). For the Holladay and AL selected formulas, a trend was observed (see median error); however, the Wilcoxon test failed the significance criterion ($P>.05$). When all second-eye procedures were excluded to avoid partial correlation in fellow eyes, significance levels remained almost the same.

Table 2 shows the subgroup analysis for the 3 IOL models. The prediction error for specific IOL types varied a little depending on the formulas used. The number of individuals in each subgroup was too small to reach statistical significance with the exception of SRK/T versus ray tracing in the Tecnis subgroup ($P<.01$, Wilcoxon test). The number of outliers was lowest in the ray-tracing groups.

The classic formulas seemed to favor some IOL models over others. For example, the Hoffer Q formula delivered best results with the iMics1 IOL, the Holladay formula with the Acrysof IQ and Tecnis IOLs, and the SRK/T with the Acrysof IQ IOL. This was not observed with the ray-tracing calculations. The said differences for 1 formula and 3 IOL models were not statistically significant ($P>.05$, Kruskal-Wallis test).

Table 3 shows the outliers in detail. In all but 1 case, the sign of the prediction error calculated with the formulas and ray tracing was identical, but the amount of error was higher with the formulas. Figure 1 shows the absolute prediction errors over AL. The performance of the classic formulas deteriorated toward short eyes and long eyes, although few extreme eyes were present in this patient group.

With AL selected classic formulas, 7 eyes (2.3%) would be outside the ±1.00 D limit. With the ray-tracing formulas, 1 eye (0.3%) would be outside that limit.

Two hundred ninety-three eyes (95%) would have an absolute prediction error of 0.71 D or less using ray tracing including optical lens thickness data, 0.85 D using Hoffer Q, 0.82 D using Holladay, and 0.84 using SRK/T.

DISCUSSION

Aspheric aberration-correcting IOLs have the potential to deliver better visual acuity and contrast than spherical IOLs. To take full advantage of their properties, defocus should be kept to a minimum because it is

Table 2. Subgroup analysis for different IOLs.

	iMics1 IOL Mean AL = 24.04 ± 1.59 mm			Acrysof IQ IOL Mean AL = 24.18 ± 1.64 mm			Tecnis Mean AL = 23.57 ± 1.09 mm		
Formula*	MAE [D]	MEE [D]	Out	MAE [D]	MEE [D]	Out	MAE [D]	MEE [D]	Out
Hoffer Q optimized	0.31	0.27	0	0.35	0.29	2	0.32	0.28	3
Holladay optimized	0.34	0.30	3	0.31	0.25	3	0.31	0.26	3
SRK/T optimized	0.35	0.26	3	0.32	0.26	2	0.35	0.26	2
AL selected optimized	0.33	0.28	2	0.31	0.26	2	0.31	0.26	3
Ray tracing offset corrected	0.30	0.28	0	0.30	0.23	0	0.29	0.24	1
Ray tracing out of the box	0.40	0.37	1	0.30	0.24	0	0.34	0.31	1

MAE = mean absolute error; MEE = median absolute error; Out = outlier, defined as an absolute prediction error of more than 1.00 D

*See Table 1 for constants

Table 3. Outliers with absolute prediction error >1.00 D.

Case	IOL Implanted	Power (D)	AL (mm)	R (mm)	AD (mm)	LT (mm)	Prediction Error: AL Selected Formula (D)	Prediction Error: Ray Tracing (D)
59*	iMics1	15.0	25.05	7.23	2.56	4.64	−1.11	−0.46
61*	iMics1	15.0	25.00	7.19	2.54	4.68	−1.12	−0.32
118	Acrysof IQ	17.5	26.39	7.90	3.05	4.19	1.06	0.68
131	Acrysof IQ	10.5	29.25	8.41	3.82	3.92	1.04	0.41
155	Tecnis	24.5	23.78	8.18	2.57	4.69	1.21	0.75
162	Tecnis	29.0	20.81	7.31	2.35	4.11	−1.40	−0.66
274	Tecnis	24.5	22.59	7.71	2.35	4.59	−1.01	−1.01

AD = internal anterior chamber depth; AL = axial length; IOL = intraocular lens; LT = lens thickness; R = anterior corneal radius
*Fellow eyes of the same patient

the dominant aberration in most pseudophakic eyes in real-life conditions. For this reason, precise preoperative diagnostics and IOL calculation are mandatory.

Intraocular lens calculation with third-generation thin-lens formulas[15,16,20,21] is the gold standard today, has served us well for more than 20 years, and yields satisfying results for the majority of eyes implanted with conventional spherical IOLs.[4–6,22] Calculation accuracy is limited by several factors, such as subjective refraction, pupil width, determination of the final IOL position, decentration of the IOL, corneal asphericity, problems with underlying eye models, and IOL labeling and manufacturing tolerances.[19,23,24]

Ray-tracing calculation based on IOLMaster (Zeiss) input does not offer better predictive precision in normal eyes but has distinctive advantages in eyes with extreme ALs and corneal conditions because model errors and limitations of Gaussian optics are avoided.[25]

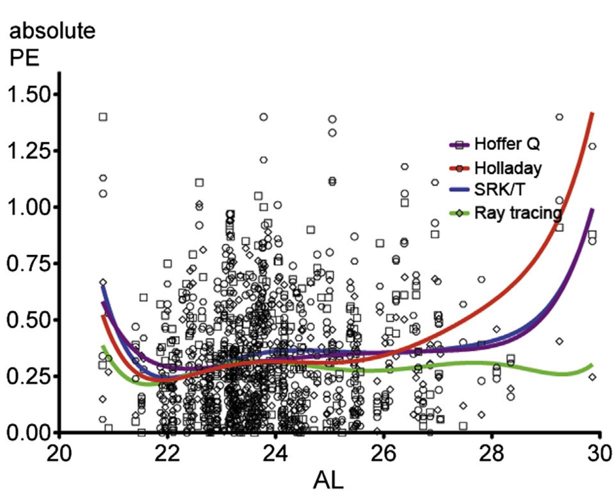

Figure 1. Absolute prediction error over AL scatterplot. Formula, as well as the ray-tracing calculation, systematic offsets are corrected for each type of IOL. A 6th-order polynomial regression line has been added for Hoffer Q, Holladay, SRK/T, and ray-tracing results (AL = axial length; PE = prediction error).

With an improved algorithm for the prediction of axial IOL position, the Okulix package has the potential to outperform formulas based on Gaussian optics, even in normal eyes.

Olsen's PhacoOptics package also offers ray tracing[9] and delivers similar results in terms of IOL power prediction with spherical IOLs (data on file) but does not take corneal or IOL aberrations into account due to its paraxial approach.

Canovas et al.[26] developed a robust, full-aperture ray-tracing model based on the Zemax software (Radiant Zemax) that yielded good results in normal and highly aberrated eyes. The Lenstar optical biometer provides the data needed for the classic IOL formulas, comparable to the IOLMaster,[27,28] but delivers additional information that can be used to improve prediction of the axial IOL position.[8,29,B] Because ray tracing does not use a fictitious but rather the true geometric position of the IOL, it can take full advantage of the optically measured data. The IOL position remains one of the most important sources of error and therefore has a high potential for improving the overall result.[23,30]

The IOLMaster A-constants can be used for the Lenstar device without change, as we have shown in pilot studies.

Because aspheric IOLs significantly reduce the influence of pupil size and also lower the recognition threshold for defocus, subjective refraction becomes more precise and repeatable. Thus, one of the most substantial error contributions is also scaled down significantly. For this reason, IOL prediction with any calculation method will improve in an eye with an aspheric IOL.

As the noise of measuring errors decreases, the true potential of IOL calculation methods becomes visible more clearly. Ray tracing does not have to "fudge" the IOL position to compensate for systematic errors but uses the assumed geometric position instead. For example, the hydrophobic spherical +22.0 D Sensar-1 IOL (Abbott Laboratories) will be assumed to get into the same haptic-plane position as the aspheric +22.0 D Tecnis-1, whereas classic formulas will compensate for the Tecnis' asphericity by modifying its ELP (SRK/T's A-constant increases from 118.8 to 119.5), which does not make sense from a physical viewpoint.

It is therefore not surprising that ray-tracing prediction of the postoperative refraction performed better in our series of eyes with an aspheric IOL. Nevertheless, the classic formulas also delivered results that are considerably better than those described in the literature for standard IOLs and optical biometry.[4–6,31] The most probable reasons are better quality of refraction, independence of pupil size, and possibly very consistent surgery with post-limbal microincisions. Ray tracing achieved a median absolute error of 0.24 D, a considerable improvement of 9% to 14% over already excellent results obtained with classic formulas. The advantage of ray tracing and optical lens-thickness data regarding absolute prediction error has been statistically significant over the SRK/T and Hoffer Q formulas but not the Holladay formula. Our dataset of 308 eyes did not contain enough "odd" eyes to prove this point.

Perhaps more important, the number of outliers is considerably smaller when ray tracing is applied. The 95th percentile of absolute prediction error can be lowered from 0.82 to 0.84 D (formulas) to 0.71 D (ray tracing). Furthermore, the number of eyes exceeding 1.00 D of prediction error could be reduced from 7 of 308 to 1 of 308.

Also not statistically significant, each classic formula seemed to work slightly better with some specific IOL models than with others. This behavior could not be observed for the ray-tracing calculation, which does not rely on axial IOL position adjustment ("constants") but uses the physical data of the given IOL model instead.

In this series, only anterior keratometric radii were used and the posterior curvature was derived theoretically from the anterior one (1:0.83 ratio). If corneal eccentricity and posterior curvature had been included, the median absolute error results might have been better; however, pilot studies in our clinic showed an increased number of outliers due to measuring errors of the topography. In the near future, AS-OCT data exported into the ray-tracing package may improve this problem, as has been described.[32]

In our patient series, few extreme ALs or extreme IOL powers were present. However, even here, systematic errors toward the hyperopic and especially myopic end could be observed with the classic formulas but not with the ray-tracing software.

The slight systematic offsets we observed with both calculation methods for some IOL types may be surprising. They have several components. Refraction distance, ambient light, acuity charts, and refraction strategy may play a role, as may the slightly different labeling of the manufacturers. However, all offsets are well inside the allowed tolerances of ISO 11979.[18]

It would be a great advantage to have IOLs available that are labeled according to a compulsory standard, have discrete steps smaller than 0.5 D, and disclose their manufacturing tolerance. Recently, a significant reduction in prediction error has been shown for IOLs with labeled tolerances.[24]

In conclusion, we believe that in today's demanding cataract surgery involving IOLs with complex aberration-correcting properties, IOL calculation relying on physical data as much as possible is preferable to the classic formulas that have served us so well for more than 2 decades. Ray tracing overcomes some systematic errors and limitations of Gaussian optics, whereas Lenstar anterior chamber and lens thickness data simultaneously allow improved prediction accuracy of the AL position, one of the single largest errors remaining in IOL calculation.

WHAT WAS KNOWN

- Third-generation IOL formulas based on Gaussian optics provide excellent results in normal eyes but suffer from systematic errors in cases of unusual anatomy. Full-aperture ray-tracing IOL calculation does not offer significantly better prediction accuracy than third-generation formulas in normal eyes with spherical IOLs but have been shown to be superior in odd eyes.
- Axial IOL position and subjective refraction are the largest contributions to IOL prediction error.

WHAT THIS PAPER ADDS

- Ray-tracing IOL calculation using Lenstar ACD and crystalline lens thickness data improved prediction error, reduced the number of outliers, and showed less systematic errors than the classic formulas.

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