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An Intraocular Lens Power Calculation Formula Based on Optical Coherence Tomography: A Pilot Study

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Abstract

PURPOSE—To develop an intraocular lens (IOL) power calculation formula based on optical coherence tomography (OCT) that would not be biased by previous laser vision correction.

METHODS—Twenty-seven eyes of 27 cataract patients without prior laser vision correction who underwent phacoemulsification were included in the study. An optical coherence biometer (IOLMaster, Carl Zeiss Meditec) measured anterior corneal curvature and axial eye length. A high-speed (2000 Hz) anterior segment OCT prototype mapped corneal thickness and measured anterior chamber depth and crystalline lens thickness. Posterior corneal curvature was computed by combining IOLMaster keratometry with OCT corneal thickness mapping. A new IOL formula was developed based on these parameters. One month after phacoemulsification, the manifest refraction spherical equivalent (MRSE) was measured. The prediction error in postoperative MRSE of the OCT-based IOL formula was compared with that of three theoretic formulae: SRK/T, Hoffer Q, and Holladay II.

RESULTS—The mean prediction error in postoperative MRSE of the OCT-based formula was 0.04 ± 0.44 diopters (D). The SRK/T was the best of the theoretic formulae, and its prediction error was -0.35 ± 0.42 D. Twenty-one (78%) eyes were within 0.50 D using the OCT formula compared to 18 (67%) eyes using the SRK/T. No statistically significant differences were noted among the formulae.

CONCLUSIONS—For cataract patients without prior laser vision correction, the OCT-based IOL formula was as accurate as the current theoretic formulae. This new formula is based on direct OCT assessment of the posterior curvature and avoids the calculation errors inherent in conventional IOL formulae.

Laser in situ keratomileusis (LASIK) and other laser vision correction procedures are popular surgical options for the correction of myopia, astigmatism, and hyperopia. An unfortunate consequence of laser vision correction is the difficulty it creates for accurately calculating intraocular lens (IOL) power for cataract surgery.^{1,2} Increasingly, people who have had laser vision correction will face this problem as they age and develop cataracts.

Theoretic formulae, including SRK/T, Hoffer Q, and Holladay II, are the current standards for calculating IOL power, and each works well on eyes that have not had keratorefractive surgery. The achieved refractions after cataract surgery are mostly within 0.50 diopters (D)

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AUTHOR CONTRIBUTIONS

Study concept and design (M.T., Y.L., D.H.); data collection (M.T., Y.L., D.H.); analysis and interpretation of data (M.T., Y.L., D.H.); drafting of the manuscript (M.T., Y.L.); critical revision of the manuscript (D.H.); statistical expertise (M.T., Y.L.); obtained funding (D.H.)

of the target refraction.^{3–5} Three biometric parameters are essential in these formulae: axial length, corneal power, and IOL depth (or effective lens position [ELP]). The IOL depth cannot be known before surgery and is predicted by its statistical association with other biometric parameters.⁶

Prior laser vision correction introduces error in corneal power measurement. The corneal power is determined by both anterior and posterior corneal surfaces. However, conventional methods for measuring corneal power, such as manual keratometry, automated keratometry, and Placido-ring topography, measure only the anterior surface. The posterior corneal power is extrapolated by assuming a fixed relationship between the anterior and posterior curvatures. This assumption is implicit in the use of a fixed keratometric index to convert anterior corneal curvature to a dioptric corneal power value.⁷ The assumption does not hold in eyes after laser vision correction, which alters the anterior curvature but leaves the posterior surface unchanged.^{8–10} After myopic laser vision correction, conventional keratometry overestimates corneal power, which could lead to a biased IOL calculation and a hyperopic outcome after cataract surgery.^{11,12} The trend is opposite for patients with prior hyperopic laser vision correction.¹³

Corneal tomography systems can measure the posterior corneal power. Both slit-scanning tomography and rotating Scheimpflug-camera imaging have been used for this purpose.^{14–19} These devices provide convenient alternative methods to calculate IOL power for eyes with prior laser vision correction. These alternatives are particularly valuable when preoperative refractive surgery data are not available. In addition to these devices, optical coherence tomography (OCT) can also be used to measure posterior corneal power. Tang et al.²⁰ recently reported good repeatability and accuracy when using OCT to measure total corneal power. Compared to other types of corneal tomography, OCT has higher axial resolution and better accuracy in corneal measurement in the presence of opacities.²¹ In this article, we report the development of an OCT-based IOL formula and study its accuracy in a series of cataract surgery patients without prior laser vision correction.

PATIENTS AND METHODS

This prospective observational study was conducted at Doheny Eye Institute, Los Angeles, California. The Institution Review Board of University of Southern California approved the study. Informed consents were obtained from all patients and treatment of patients was in accordance with the tenets of the Declaration of Helsinki. The study included 27 eyes from 27 cataract patients (12 men, 13 women), who had no prior laser vision correction. Mean patient age was 70.3 ± 9.4 years (range: 52 to 84 years). All patients underwent uneventful cataract surgery from April 27, 2005 to May 1, 2006, at Doheny Eye Institute.

Patients received AcrySof SN60AT (24 eyes) or SA60AT (3 eyes) (Alcon Laboratories Inc, Ft Worth, Tex) IOLs. Anterior corneal power and axial length of each eye were measured with an optical coherence biometer (IOLMaster; Carl Zeiss Meditec Inc, Dublin, Calif).

OCT Parameters

A high-speed (2000 Hz) anterior segment OCT system (prototype 4B, Carl Zeiss Meditec Inc) was used to measure the anterior chamber depth and crystalline lens thickness and to map corneal thickness. The corneal thickness map was obtained by a corneal mapping pattern that consisted of 10-mm lines (4-mm depth) on 8 meridians centered on the vertex reflection (Fig 1A). Each meridional line comprised 128 axial scans. The entire scan pattern consisted of 1024 axial scans and was completed within 0.5 seconds. An automated computer algorithm was developed to detect the corneal surface boundaries from the meridional cross-sectional image (Fig 1B). The anterior corneal power was obtained by

adjusting the average K-readings from the IOLMaster (multiplied by 0.376/0.3375, ie, the difference between the refractive index of cornea and the keratometric index). The posterior corneal power was calculated by the radius of best-fit sphere over the central 3 mm of the posterior corneal surface, which was reconstructed by combining the corneal elevation map from Placido-ring topography and the pachymetry map from OCT. The details of calculating posterior corneal power using this method were described in a previous article from our group.²⁰ A horizontal OCT line scan of 16-mm length and 8-mm depth, centered on the corneal vertex, measured the anterior chamber depth and crystalline lens thickness (Fig 2A). One month after cataract surgery, the same line scan pattern was used to measure the actual IOL depth (Fig 2B). The manifest refraction spherical equivalent (MRSE) was measured at the same visit.

OCT-based IOL Formula

The OCT-based IOL formula used an eye model consisting of four optical surfaces: anterior corneal surface, posterior corneal surface, IOL, and retina. The IOL was modeled as a thin lens. Light traveled through the first three surfaces and focused on the retina. The IOL depth was predicted based on a three-variable regression formula with axial length, anterior chamber depth, and crystalline lens thickness as independent variables. Subtracting the IOL depth from the axial eye length resulted in the position of IOL relative to the retina. This calculated position is equivalent to the length of the vitreous cavity. The vergence of the light beam traveling through the eye was tracked, starting from the retinal plane to the anterior eye surface (Fig 3).

At the back of IOL, vergence

$$Z_1 = n_2 / l_1 \quad (1)$$

In front of IOL, vergence

$$Z_1' = Z_1 - P_1 \quad (2)$$

At the back of posterior corneal surface, vergence

$$Z_2 = n_2 / (n_2 / Z_1' + l_2) \quad (3)$$

In front of posterior corneal surface, vergence

$$Z_2' = Z_2 - P_2 \quad (4)$$

At the back of anterior corneal surface, vergence

$$Z_3 = n_1 / (n_1 / Z_2' + l_3) \quad (5)$$

In front of anterior corneal surface, vergence

$$Z_3' = Z_3 - P_3 \quad (6)$$

where

n_1 = refractive index of cornea (1.376)

n_2 = refractive index of aqueous and vitreous (1.336)

l_1 = vitreous length (m) = AL - CCT - IOL depth (m, derived by regression formula Eq[8])

l_2 = IOL depth (m, derived by regression formula Eq. [8])

l_3 = CCT (m)

P_1 = IOL power implanted (D)

P_2 = posterior corneal power (D)

P_3 = anterior corneal power (D)

The vergence in front of the anterior corneal surface Z_3' is the refractive error at the corneal plane. Manifest refraction spherical equivalent can then be derived by:

$$\text{MRSE} = 1 / (1/Z_3' + \text{vertex distance}) \quad (7)$$

The vertex distance is 12 mm. Overall, this formula requires six preoperative biometry measurements, including axial length, anterior chamber depth, crystalline lens thickness, central corneal thickness, anterior corneal power, and posterior corneal power. The OCT-based IOL formula has been put into an Excel spreadsheet (see Appendix). A clinical example is also presented.

Standard IOL Formulae

For comparison with the OCT-based IOL formula, we used the three theoretic IOL formulae that were available as part of the Holladay IOL consultant program (version 6.10.2006.0528; Holladay Consulting Inc, Bellaire, Tex). They were the SRK/T, Hoffer Q, and Holladay II formulae.

RESULTS

The average postoperative IOL depth was 4.323 ± 0.295 mm. We investigated multiple variables to predict IOL depth including axial length, anterior chamber depth, lens thickness, anterior chamber width, corneal vault, corneal diameter, anterior corneal power, and posterior corneal power. The best three-term regression formula for predicting IOL depth was

$$\text{IOL depth} = 0.754\text{ACD} + 0.204\text{LT} + 0.045\text{AL} \quad (8)$$

where all measurements were in millimeters.

The R^2 for this model was 0.81, and the P values for anterior chamber depth, lens thickness, and axial length were .000, .004, and .042, respectively. Figure 4 shows the agreement between predicted IOL depth and the actual value. The mean absolute prediction error was

0.097 ± 0.090 mm, which was equivalent to an approximate 0.20-D error in refraction for the average eye.²²

The average vitreous cavity length was 16.08 ± 1.58 mm before phacoemulsification and increased to 19.40 ± 1.35 mm postoperatively. The average increase was 3.32 ± 0.37 mm ($P < .0001$). The increase in vitreous cavity length was negatively correlated with axial eye length ($P = .017$) (Fig 5).

The average MRSE prediction errors 1 month after cataract surgery were tabulated in the Table. The MRSE prediction error was -0.35 ± 0.42 D for the SRK/T and 0.04 ± 0.44 D for the OCT formula. Eighteen (67%) eyes were within 0.50 D of the predicted MRSE using the SRK/T formula whereas 21 (78%) eyes were within 0.50 D using the OCT formula (Fig 6). The Hoffer Q and Holladay II formulae provided similar results, and no differences between formulae were statistically significant.

DISCUSSION

Laser vision correction was introduced in the 1980s.^{23–25} By now, many of the early patients have reached an age when cataracts are common,^{26–28} and some have already had cataract surgery.^{2,13,29–31} With millions of laser vision correction procedures performed each year, the number of cataract patients with previous laser vision correction will eventually increase. Therefore, a method to select IOL power that is not biased by previous laser vision correction is essential. The main challenge in calculating IOL power for cataract patients with previous laser vision correction is measuring the true posterior corneal power because the assumption about the fixed relationship between anterior and posterior curvatures no longer applies. This also leads to biased IOL depth prediction, which further compounds the problem.

Many methods have been proposed to improve the accuracy of IOL power selection for eyes that have undergone laser vision correction. These methods fall into two major categories. The first includes procedures that estimate corneal power.^{30,32–37} Some use historic information such as preoperative keratometry and laser vision correction–induced refractive change to correct the bias in conventional keratometry.³² Some use rigid gas permeable (RGP) contact lens over-refraction to estimate corneal power and bypass conventional keratometry.^{33,34} Others alter the calculation of corneal power from conventional keratometry by assuming a fixed posterior corneal curvature rather than a fixed keratometric index. This ensures that surgical alteration of the anterior curvature does not get propagated into an error in the estimation of posterior curvature (Koch method).³⁰ The second category of methods that improve the accuracy of IOL power selection make direct adjustment to the IOL power.^{31,38–40} These techniques adjust the recommended IOL power using historical information such as laser vision correction–induced refractive change and include the methods proposed by Masker,³⁸ Feiz,^{39,40} and Latkany et al.³¹

These approaches are partially successful in reducing the unexpected refractive error after cataract surgery, but they are not always applicable or successful. Historical data are often missing or incomplete. Because the RGP contact lens over-refraction method relies on clinical refraction, it is not reliable in cases of denser cataracts when the vision is poor and the visual endpoint for clinical refraction is vague.⁴¹ Because of these limitations, poor cataract surgery outcome in postoperative laser vision correction patients is still a growing problem waiting for a solution after years of active research.²⁶

Optical coherence tomography corneal mapping provides a reproducible estimate of the posterior corneal power. We reported the reproducibility to be within 0.10 D.²⁰ The new OCT-based IOL formula combines OCT corneal mapping, OCT biometry, and IOLMaster

measurements to accurately predict postoperative cataract surgery refraction. The early results indicate that the new formula performs as well as the standard theoretic IOL formula in eyes without previous laser vision correction. The OCT formula actually has smaller mean error in the predicted refractive outcome. This is probably because we based our IOL depth formula on the same experimental data, whereas the theoretic formulae used A-constants based on previous data. The standard deviation for the OCT formula predictive error is similar to those of the theoretic formulae. Thus, the OCT formula can be as predictive and precise as the current best practice.

Optical coherence tomography may also provide more accurate biometry inputs for theoretical ray-tracing formulae for IOL power calculations.^{42,43} In those methods, the surface data are necessary to trace rays from object to retina or vice versa based on Snell's law (in paraxial limit, vergence tracing is equivalent to ray tracing). Optical coherence tomography is able to map both surfaces of the cornea, crystalline lens, and IOL with high resolution. The system used in this study is not suitable for this purpose because of motion artifact. Nevertheless, with the increasing scanning speed of Fourier domain OCT technology,⁴⁴ motion artifacts can be reduced and accurate, reproducible ocular surface data may be obtained by OCT.

Although the sample size in the current study is relatively small, the results validate the accuracy and predictability of the new IOL formula in cataract patients without prior laser vision correction. The new OCT-based IOL formula might be a promising solution for cataract patients with prior laser vision correction because OCT measures the actual posterior corneal curvature instead of assuming a fixed value or a fixed relationship with the anterior curvature. It does not require the use of clinical history, which can be easily lost and forgotten in the intervening decades between laser vision correction and cataract surgery. It does not rely on subjective measurements such as RGP contact lens over-refraction. In the next step of development, we are conducting a prospective clinical study of the OCT-based IOL formula on cataract surgery patients who underwent laser vision correction. The IOL depth formula may be subject to revision after more cases are collected because currently it is based on a small sample. Future studies that compare the OCT-based formula with other tomography-based formulae (Orbscan [Bausch & Lomb, Rochester, NY], Pentacam [Oculus Optikgeräte GmbH, Wetzlar, Germany], and others) are necessary to ensure the most accurate procedure.

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APPENDIX

Table 1 is the spreadsheet form of the OCT-based IOL formula. All inputs are put in the middle column (Cell D2-D8, denoted by “X”). The intermediate results are located in the right column (Cell F2, F5-F10). The final output is predicted manifest refraction spherical equivalent (MRSE) (Cell F12). After all inputs have been filled out, different IOL power (Cell D6) can be tested to achieve target refraction outcome.

Table 2 presents an example of a cataract case without prior laser correction. The middle column shows the biometry measurements before cataract surgery. The target refraction was plano. The OCT-based IOL formula recommended an IOL power of 23.50 D (Cell D6). One month after a 23.50-D Alcon SN60AT lens (Alcon Laboratories Inc, Ft Worth, Tex) was implanted, the patient’s refraction was $-0.50 +0.25 \times 35^\circ$.

Figure 1.

A) Optical coherence tomography scan pattern for corneal mapping. **B)** Image overlaid with corneal boundaries located by the automated image processing program.

Figure 2.

A) Preoperative horizontal optical coherence tomography (OCT) cross-section of the anterior segment showing the measurements of anterior chamber depth and crystalline lens thickness. **B)** Postoperative OCT cross-section showing the measurement of IOL depth 1 month after surgery.

Figure 3.

Optical model from which the OCT-based IOL formula was derived. The three refractive surfaces are denoted by P_1 , the IOL; P_2 , the posterior corneal surface; and P_3 , the anterior corneal surface. The distances between adjacent surfaces are denoted by l_1 , l_2 , and l_3 , and the vergences at the two sides of the refractive surfaces are denoted by z_1, z_1', z_2, z_2' , and z_3, z_3' .

Figure 4. Predicted IOL depth based on preoperative measurements of axial length, anterior chamber depth, and crystalline lens thickness was plotted against the actual IOL depth measured postoperatively.

Figure 5. Correlation between axial eye length and the increase in vitreous cavity length after cataract surgery. The increase in vitreous cavity length was generally smaller in eyes with greater axial lengths.

Figure 6.

Error in the predicted spherical equivalent refractive outcome compared to postoperative manifest refraction (MRSE) for the OCT-based IOL formula and the three standard theoretic IOL formulae. Eighteen (67%) eyes were within 0.50 D of the predicted MRSE using the the SRK/T formula whereas 21 (78%) eyes were within 0.50 D using the OCT formula.

TABLE

Error in the Predicted Spherical Equivalent Refractive Outcome Relative to Postoperative Manifest Refraction

	Error (D)			
	OCT	SRK/T	Hoffer Q	Holladay II
Mean	0.04	-0.35	-0.32	-0.32
SD	0.44	0.42	0.50	0.45
MAE	0.36	0.32	0.41	0.36

SD = standard deviation, MAE = mean absolute error after constant optimization

TABLE 1

OCT-based IOL Formula Spreadsheet

A	B	C	D	E	F
1	CONSTANT	INPUT		IOL DEPTH	
2	n1	ACD (mm)	X	IOL DEPTH (mm)	$0.754 \cdot D2 + 0.204 \cdot D3 + 0.045 \cdot D5$
3	n2	LT (mm)	X		
4	Vertex distance (mm)	CCT (mm)	X	VERGENCE (D)	
5		AL (mm)	X	Z1: IOL back surface	$B3 / (D5 \cdot F2 \cdot D4) \cdot 1000$
6		IOL power (D)	X	Z1': IOL front surface	F5-D6
7		Anterior Corneal power (D)	X	Z2: Posterior corneal back	$B3 / (B3 / F6 + F2 / 1000)$
8		Posterior Corneal power (D)	X	Z2': Posterior corneal front	F7-D8
9				Z3: Anterior corneal back	$B2 / (B2 / F8 + D4 / 1000)$
10				Z3': Anterior corneal front	F9-D7
11					
12				Predicted MRSE (D)	$1 / (1 / F10 + B4 / 1000)$

n1 = refractive index of cornea, n2 = refractive index of aqueous and vitreous, ACD = anterior chamber depth, LT = crystalline lens thickness, CCT = central corneal thickness, AL = axial length, X = input of the formula, MRSE = manifest refraction spherical equivalent

TABLE 2

Case Example of the OCT-based IOL Formula

A	B	C	D	E	F
1	CONSTANT	INPUT		IOL DEPTH	
2	n1	ACD (mm)	2.092	IOL DEPTH (mm)	3.57
3	n2	LT (mm)	4.670		
4	Vertex distance (mm)	CCT (mm)	0.525	VERGENCE (D)	
5		AL (mm)	23.00	Z1: IOL back surface	70.65
6		IOL power (D)	23.50	Z1': IOL front surface	47.10
7		Anterior Corneal power (D)	47.21	Z2: Posterior corneal back	41.88
8		Posterior Corneal power (D)	-6.17	Z2': Posterior corneal front	48.05
9				Z3: Anterior corneal back	47.19
10				Z3': Anterior corneal front	-0.02
11					
12				Predicted MRSE (D)	-0.02

n1 = refractive index of cornea, n2 = refractive index of aqueous and vitreous, ACD = anterior chamber depth, LT = crystalline lens thickness, CCT = central corneal thickness, AL = axial length, MRSE = manifest refraction spherical equivalent