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Intraocular lens power calculation after previous myopic laser vision correction based on corneal power measured by Fourier-domain optical coherence tomography

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Abstract

PURPOSE—To use Fourier-domain optical coherence tomography (OCT) to measure corneal power and calculate intraocular lens (IOL) power in cataract surgeries after laser vision correction.

SETTING—Doheny Eye Institute, Los Angeles, California, and Cullen Eye Institute, Houston, Texas, USA.

DESIGN—Prospective comparative case series.

METHODS—Patients with previous myopic laser vision correction who had monofocal IOL implantation were enrolled. A Fourier-domain OCT system was used to measure corneal power and pachymetry. Axial length and anterior chamber depth were measured with partial coherence biometry. An OCT-based IOL formula was developed, and the mean absolute error (MAE) of postoperative refraction was compared with that for the Haigis-L formula. At Doheny, corneal power was also measured using the clinical history method, the contact lens overrefraction method, and slit-scanning tomography total optical power.

RESULTS—Sixteen eyes of 16 patients were enrolled at the 2 sites. Previous laser vision correction ranged from -9.81 to -0.88 diopter (D). The MAE was 0.50 D for OCT-based IOL calculation and 0.76 D for the Haigis-L formula ($P = .14$). In the 6 eyes enrolled at Doheny, the MAE of OCT-based IOL calculation was 0.60 D. In comparison, the contact lens overrefraction (MAE = 1.46 D, $P < .05$) and clinical history (MAE = 1.78 D, $P < .05$) methods were worse. Slit-scanning tomography gave an MAE of 1.28 D ($P > .05$).

CONCLUSION—The predictive accuracy of OCT-based IOL power calculation was equal to or better than current standards in post-laser vision correction eyes.

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Direct measurement of the posterior corneal power is a promising solution for calculating intraocular lens (IOL) power after previous laser vision correction, including laser in situ keratomileusis (LASIK) and photorefractive keratectomy. Slit-scanning tomography, rotating-slit Scheimpflug camera, and dual-Scheimpflug systems have been used for this purpose.^{1–6} However, the axial (depth) resolutions of these slit-scanning devices (we use this term to include Scheimpflug variants) are between 50 μm and 100 μm due to the diffraction limit of optical focusing. The relatively poor resolution can lead to large errors in the delineation of the posterior corneal border in the presence of corneal haze or opacity, a problem that is well documented for slit-scanning tomography.^{7–10}

Optical coherence tomography (OCT) can also measure both the anterior and posterior corneal powers.^{11,12} The higher axial resolution of OCT (3 to 17 μm in commercial instruments) allows for clear delineation of corneal boundaries, even in the presence of opacities.⁷ With the recent advance from time-domain to Fourier-domain detection, the speed of OCT corneal mapping is now faster than that of slit-scanning devices. Based on these theoretical advantages, OCT may be a promising technology in this application. This article reports a pilot study of Fourier-domain OCT-based IOL calculation in post-laser vision correction cataract surgery.

PATIENTS AND METHODS

This prospective observational study was performed at Doheny Eye Institute, University of Southern California, Los Angeles, California, and at Cullen Eye Institute, Baylor College of Medicine, Houston, Texas, USA. The study protocols were approved by the institutional review boards of the 2 universities. Written informed consent was obtained from all participants. The study adhered to the tenets of the Declaration of Helsinki.

To be included in the study, the patients must have had previous laser vision correction for myopia or myopic astigmatism. The patients did not have vision-limiting eye disease other than cataract. Only eyes that received monofocal IOLs were included. These IOLs included Acrysof models SN60AT, SA60AT, SN60WF, SN6AT3, and SN6AT4 (Alcon Laboratories, Inc.) and the Tecnis ZA9003 (Abbott Medical Optics). The axial length (AL) and anterior chamber depth (ACD) were measured with a partial coherence interferometer (IOLMaster, Carl Zeiss Meditec, Inc.). Manifest refraction was measured at the 1-month postoperative visit.

At Doheny Eye Institute, participants were also required to have historical data (pre- and post-laser vision correction refraction and pre-laser vision correction keratometry) and corneal power measurements by rigid gas-permeable (RGP) contact lens overrefraction.^{13,14} In addition, slit-scanning tomography measurements were (Orbscan II, Bausch & Lomb) were taken and the total optical power at the 4.0 mm zone diameter was used for IOL calculations.⁶

Optical Coherence Tomography Corneal Power and Pachymetry

Fourier-domain OCT systems (RTVue, Optovue Inc.) were used to measure anterior, posterior, and net corneal powers and central corneal thickness (CCT) at the Doheny and Cullen clinics. The system was calibrated according to the manufacturer's standard procedure.

The cornea was scanned with a mapping pattern (pachymetry + power) that consisted of 6.0 mm lines on 8 evenly spaced meridians within an acquisition period of 0.31 second. Each meridional line comprised 1019 axial scans. Each patient was instructed to gaze at an

internal fixation target with the eye being imaged. The operator centered the scan on the pupil by observing the real-time video image of the anterior eye during the scan.

To decrease motion error, 5 consecutive corneal mapping scans were acquired automatically (1.55 sec) to obtain 1 corneal power measurement. The 2 scans with the maximum and minimum corneal powers were discarded. The anterior, posterior, and net corneal powers from the middle 3 scans were averaged to obtain 1 corneal power output. This selection procedure is now part of the standard RTVue software (version 5.5.0.61). The net corneal power was calculated using a thick-lens formula based on anterior, posterior, corneal powers and CCT assuming Gaussian optics.¹²

Three OCT corneal power outputs were obtained at the pre-cataract surgery visit. The mean of the 3 OCT corneal power outputs was the final corneal power values used in the IOL power calculations.

The OCT-based IOL formula is based on vergence tracing starting from the retinal plane to the anterior corneal surface. The formula was described in a previous study.¹⁵ The OCT net corneal power was converted to an effective corneal power (ECP) before insertion into the IOL formula as follows:

$$\text{ECP} = 1.0208 \times \text{net corneal power} - 1.6622 \quad (1)$$

Equation 1 was based on linear regression of the back-calculated ECP against OCT net corneal power (Figure 1). The back-calculated ECP was back-calculated from the postoperative manifest refraction spherical equivalent (MRSE), preoperative ACD, preoperative AL, preoperative posterior corneal power (from OCT), and preoperative CCT (from OCT) using the OCT-based IOL formula.¹⁵

For comparison with the OCT-based IOL formula, the 3 theoretic IOL formulas that were available as part of the Holladay IOL consultant program (version 6.10.2006.0528, Holladay Consulting, Inc.) were used. They were the double-K versions¹⁶ of SRK/T and Hoffer Q formulas, as well as Holladay II formula. The American Society of Cataract and Refractive Surgery (ASCRS) IOL calculator^A was used to obtain Haigis-L formula¹⁷ results. The corneal power measured by the contact lens overrefraction method, clinical history method, PCI biometry (IOLMaster), and scanning-slit tomography (Orbiscan II) were used in combination with all 4 IOL formulas. The results shown are from the IOL formula that provided the smallest mean absolute error (MAE) of refractive prediction for each method of corneal power measurement. The refractive prediction error equals the predicted MRSE minus the actual MRSE as follows:

$$\text{Prediction error} = \text{predicted MRSE} - \text{actual MRSE} \quad (2)$$

$$\text{MAE} = \text{average} (|\text{prediction error}|) \quad (3)$$

The adjusted MAE was similar to MAE but the mean prediction error was subtracted, which was equivalent to assuming a perfect offset was used in the IOL power calculation; thus the mean prediction error was always zero:

$$\text{Adjusted MAE} = \text{average} (|\text{prediction error} - p_0|) \quad (4)$$

where p_0 is the mean prediction error.

Surgical Technique

Cataract surgery was performed by standard phacoemulsification through corneal tunnel incisions. The foldable IOLs were inserted and positioned in the capsular bag. The surgeons included 2 coauthors (D.D.K., D.H.) and others at Cullen and Doheny. The Doheny dataset included 2 cases performed by 2 referring surgeons outside the Doheny Eye Institute. Personalized IOL constants optimized for the surgeons were used at Cullen based on a broad range of previous IOL cases. The IOL constants in the standard IOLMaster database were used at Doheny.

Statistical Analysis

The Wilcoxon signed-rank test for paired samples was used to compare the MAEs and adjusted MAEs of refractive prediction between different IOL formulas. The Mann-Whitney Test was used to compare the MAEs and adjusted MAEs between the 2 sites. The Fisher exact probability test was used to compare the proportion of eyes within ± 1.0 diopter (D) of predicted refraction. A *P* value less than 0.05 was considered statistically significant.

RESULTS

Sixteen eyes of 16 cataract surgery patients (8 women, 8 men) with previous myopic LASIK were enrolled at the 2 sites. The mean age at the time of surgery was 59.4 ± 11.9 (SD) (range 34 to 77 years). The mean magnitude of previous myopic correction was -4.93 ± 3.45 D (range of -9.81 to -0.88 D). Six patients (4 women, 2 men) were from the Doheny Eye Institute. The mean age was 65.5 ± 4.5 years. Ten patients (4 women, 6 men) were from the Cullen Eye Institute. The mean age was 54.6 ± 11.5 years.

Table 1 compares the error of the predicted MRSE for OCT-based IOL calculation with the results for the Haigis-L formula. There was no statistically significant difference in the MAE between the OCT-based calculation and the Haigis-L formula (*P* = .14). There was a trend toward fewer large prediction errors using OCT (Figure 2), for which 14 out of 16 eyes were within ± 1.0 D of actual refractive outcome, compared with 11 eyes for the Haigis-L formula; the difference was not significant (*P* = .39). Figure 3 shows a Bland-Altman plot comparing the prediction error for Haigis-L and OCT-based methods. The plot suggests that the prediction error of Haigis-L and OCT had no obvious pattern of correlation.

Additional comparisons were possible using data from the Doheny Eye Institute (Table 2). The MAE for OCT-based IOL calculation was smaller than that for contact lens overrefraction and the clinical history methods (both *P* < .05). However, the differences between OCT and Haigis-L and between OCT and slit-scanning tomography methods were not statistically significant. The adjusted MAE for the OCT method was smaller than for the contact lens overrefraction, clinical history, and slit-scanning tomography methods (*P* < .05).

At the Cullen Eye Institute, the MAE for OCT was also lower than the Haigis-L MAE (Table 3); however, the difference was not significant (*P* = .26). Although the prediction errors for both OCT-based calculation and Haigis-L were lower at Cullen than at Doheny (Table 2), the differences in the MAE and adjusted MAE were insignificant.

DISCUSSION

Many methods have been proposed to improve the accuracy of IOL power selection for post-laser vision correction eyes. The clinical history method¹⁸ and the RGP contact lens overrefraction method^{13,14} are well known. Our results showed that these methods are relatively inaccurate and clearly inferior to OCT-based IOL calculations. These methods

have obvious limitations. Historical data on keratometry and refraction taken around the time of laser vision correction may not be readily available. Even if they were, they might not account for corneal changes that occurred since the initial laser vision correction procedure. Contact lens overrefraction suffers from the relatively inaccurate visual endpoint in cataract patients, who may have significantly decreased vision due to the cataract.¹⁹

Some newer methods for post-laser vision correction IOL calculation do not rely on historical data or refraction. The Koch method²⁰ uses standard keratometry to measure the anterior corneal power and then adds a constant posterior corneal power. The Haigis-L method uses empirical linear regression analysis of post-laser vision correction cataract surgery results to optimize the estimate of corneal power from standard keratometry.¹⁷ Theoretically, these methods should work well for eyes with average posterior curvature but could err in eyes that are much steeper or flatter than the average. We included the Haigis-L IOL formula in the current study because it is relatively well studied¹⁷ and is available on the commonly used IOLMaster as well as the ASCRS IOL calculator web site.^A We found that OCT-based IOL calculation had better predictive accuracy than the Haigis-L formula, but the difference was not statistically significant. The MAE of Haigis-L formula (0.76 D) in our study was higher than that of the original Haigis-L study (0.37 D).¹⁷ Therefore, a larger study will be needed to determine whether OCT-based IOL calculation is better than the Haigis-L formula and other formulas in its class.

Theoretically, the best solution for post-laser vision correction corneal power measurement is to accurately measure the curvature of both anterior and posterior corneal surfaces. Although OCT is one such solution, slit-scanning instruments, such as the Orbscan II, Pentacam (Oculus GmbH), and Galilei (Ziemer Ophthalmic Systems AG), also have that capability. Compared with OCT, slit-scanning tomography has a relatively poor axial resolution (50 to 100 μm) due to the diffraction limit of optical focusing (estimated based on the intensity profile of slit images from Orbscan II⁷). The poor resolution can lead to large errors in the detection of the corneal surface boundaries in the presence of corneal haze or opacity, a problem that was well documented in the Orbscan II device.^{7–10} Furthermore, a complete survey of the corneal surface requires 1 to 2 seconds for the slit-scanning devices, which may subject them to significant motion error. We found OCT-based IOL calculation had slightly better predictive accuracy than Orbscan II–based calculations; however, the difference was not statistically significant. Thus, a larger study should be performed to determine whether OCT is better. We were not able to include the Pentacam device or Galilei device in this study because of lack of access to these instruments at Doheny. These 2 instruments use the Scheimpflug principle to extend the depth of focus and use rotational scanning, which simplifies corneal power measurement. Thus, they could theoretically outperform the Orbscan II device. Another drawback of OCT images is under-sampling on the peripheral cornea because of the 8-meridional scan pattern. Further studies are needed to compare these instruments with OCT in this application.

A limitation of the present study is the relatively small size and the mix of data from several surgeons, IOL types, and centers. The OCT IOL calculation result was better at the Cullen Eye Institute than at the Doheny Eye Institute, possibly due to the use of personalized IOL ACD constants at Cullen. This suggests that developing surgeon-specific optimization remains important for the OCT-based IOL formula.

In summary, we have shown that OCT-based IOL calculation outperforms the clinical history method and the contact lens overrefraction method. It performs as well as a slit-scanning corneal tomography system (Orbscan II) and a regression-optimized post-laser vision correction IOL formula (Haigis-L). Larger clinical studies are needed to evaluate the OCT-based formula and other promising new alternatives. Because Fourier-domain OCT is

a relatively new technology, many improvements in hardware and software can be anticipated in the near future to enhance corneal power measurement and IOL power selection. There have also been many recent reports showing that other new methods could obtain lower MAEs.^{21,22} However, until these new methods are thoroughly tested for reliability, the most prudent strategy for the surgeon may be to obtain IOL calculations using several different methods and select the IOL power based on the consensus of multiple methods.²³

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Biography

Figure 1.

Effective corneal power for eyes after myopic laser vision. The squares represent data from Doheny Eye Institute. The triangles represent data from Cullen Eye Institute (ECP = back-calculated effective corneal power [the “true corneal power”]; NCP = optical coherence tomography net corneal power; OCT = optical coherence tomography).

Figure 2.
Distribution of refraction prediction error for Haigis-L formula and OCT-based formulas
(OCT = optical coherence tomography).

Refractive prediction error comparison

Figure 3. Comparison of the refraction prediction error between the Haigis-L formula and OCT-based IOL calculation.

Table 1

Accuracy of OCT-based IOL power calculation compared with the Haigis-L formula (16 eyes of 16 patients).

Keratometry Method	Best IOL Formula	Prediction Error (D)			MAE (D)	Adjusted MAE (D)
		Mean $\pm$ SD	Range			
PCI biometry	Haigis-L	-0.27 ± 0.98	-2.32, 1.30		0.76	0.78
OCT	OCT-based	-0.01 ± 0.67	-1.24, 1.58		0.50	0.50

IOL = intraocular lens; MAE = mean absolute error; OCT = optical coherence tomography; PCI = partial coherence interferometry; Prediction error = actual – predicted manifest refraction spherical equivalent

Accuracy of OCT-based IOL power calculation compared with the Haigis-L formula and other methods at the Doheny Eye Institute (6 eyes of 6 patients). The standard IOL formula that provided the smallest MAE was used for all keratometry methods except OCT.

Table 2

Keratometry Method	Best IOL Formula	Prediction Error (D)			MAE (D)	Adjusted MAE (D)
		Mean $\pm$ SD	Range			
Clinical history	Hoffer-Q	0.31 $\pm$ 2.52	-1.47, 2.09		1.78*	1.78*
CL overrefraction	Holladay 2	0.01 $\pm$ 2.08	-3.09, 3.19		1.46*	1.46*
PCI biometry	Haigis-L	-0.28 $\pm$ 1.19	-2.32, 0.98		0.88	0.88
Slit-scanning tomography	Holladay 2	0.17 $\pm$ 1.61	-2.72, 1.51		1.28	1.22*
OCT	OCT based	0.49 $\pm$ 0.64	-0.33, 1.58		0.60	0.44

CL = contact lens; IOL = intraocular lens; MAE = mean absolute error; OCT = optical coherence tomography; PCI = partial coherence interferometry; Prediction error = actual – predicted manifest refraction spherical equivalent

* $P < .05$ compared with OCT (Wilcoxon signed-rank test)

Table 3

Accuracy of OCT-based IOL power calculation compared with the Haigis-L formula at Cullen Eye Institute (10 eyes of 10 patients).

Keratometry Method	Best IOL Formula	Prediction Error (D)			MAE (D)	Adjusted MAE (D)
		Mean ± SD	Range			
PCI	Haigis-L	-0.27 ± 0.90	-1.46, 1.30		0.69	0.72
	OCT based	-0.31 ± 0.51	-1.24, 0.37		0.44	0.39

IOL = intraocular lens; MAE = mean absolute error; OCT = optical coherence tomography; PCI = partial coherence interferometry; Prediction error = actual – predicted manifest refraction spherical equivalent