OPTICAL COHERENCE TOMOGRAPHY–BASED CORNEAL POWER MEASUREMENT AND INTRAOCULAR LENS POWER CALCULATION FOLLOWING LASER VISION CORRECTION (AN AMERICAN OPHTHALMOLOGICAL SOCIETY THESIS)

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ABSTRACT

Purpose: To use optical coherence tomography (OCT) to measure corneal power and improve the selection of intraocular lens (IOL) power in cataract surgeries after laser vision correction.

Methods: Patients with previous myopic laser vision corrections were enrolled in this prospective study from two eye centers. Corneal thickness and power were measured by Fourier-domain OCT. Axial length, anterior chamber depth, and automated keratometry were measured by a partial coherence interferometer. An OCT-based IOL formula was developed. The mean absolute error of the OCT-based formula in predicting postoperative refraction was compared to two regression-based IOL formulae for eyes with previous laser vision correction.

Results: Forty-six eyes of 46 patients all had uncomplicated cataract surgery with monofocal IOL implantation. The mean arithmetic prediction error of postoperative refraction was 0.05 ± 0.65 diopter (D) for the OCT formula, 0.14 ± 0.83 D for the Haigis-L formula, and 0.24 ± 0.82 D for the no-history Shammas-PL formula. The mean absolute error was 0.50 D for OCT compared to a mean absolute error of 0.67 D for Haigis-L and 0.67 D for Shammas-PL. The adjusted mean absolute error (average prediction error removed) was 0.49 D for OCT, 0.65 D for Haigis-L (P=.031), and 0.62 D for Shammas-PL (P=.044). For OCT, 61% of the eyes were within 0.5 D of prediction error, whereas 46% were within 0.5 D for both Haigis-L and Shammas-PL (P=.034).

Conclusions: The predictive accuracy of OCT-based IOL power calculation was better than Haigis-L and Shammas-PL formulas in eyes after laser vision correction.

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INTRODUCTION

Laser in situ keratomileusis (LASIK), photorefractive keratectomy (PRK), and other laser vision correction (LVC) procedures are popular surgical options for the correction of myopia, astigmatism, and hyperopia. An unfortunate consequence of LVC is the difficulty in accurately calculating intraocular lens (IOL) power for cataract surgery.[1,2] More and more people who had LVC will face this problem as they age and develop cataracts.

Theoretic formulas, including SRK/T, Holladay II, and Hoffer Q, are the current standard for calculating IOL power. They work well on virgin eyes that have not had LVC procedures. The achieved refractions after cataract surgery are within 1.0 diopter (D) of the target in a great majority of eyes.[3-5] Three biometric parameters are essential in these formulas: axial length, corneal power, and predicted IOL depth (also known as effective lens position, ELP). The IOL depth cannot be known before surgery and is predicted by its statistical association with various preoperative measurements.[6]

Prior LVC introduces error in corneal power measurement. The corneal power is determined by both anterior and posterior corneal surfaces. Conventional instruments for measuring corneal power such as the manual keratometer, automated keratometer, and Placido-ring topography measure only the anterior corneal power and extrapolate the posterior corneal power by assuming a fixed relation between anterior and posterior surface curvatures. This assumption is implicit in the use of a fixed keratometric index (1.3375) to convert anterior corneal curvature to a net (or total) corneal power value.[7] The assumption does not hold in eyes after LVC, which alters the anterior curvature but leaves the posterior surface unchanged.[8-10] Therefore, myopic LVC will lead to overestimation of corneal power by standard keratometry because the negative power of the posterior corneal surface is underestimated, which results in a hyperopic refractive outcome after cataract surgery.[11] Similarly, hyperopic LVC will lead to underestimation of corneal power by standard keratometry and may lead to a myopic outcome.[12] Another source of error in corneal power measurements after LVC is that conventional keratometry measures corneal power at the outside edge of a ring or pattern (about 3.1 mm for Bausch & Lomb manual keratometer[13] and 2.6 mm for IOLMaster automated keratometry[14]), but it does not directly measure the central corneal power. Therefore the spherical aberration induced by LVC could affect the accuracy of keratometry.

CURRENT METHODS FOR IOL CALCULATION AFTER LASER VISION CORRECTION

Many methods have been proposed to improve the accuracy of IOL power selection for post-LVC eyes. Most of these rely on available clinical tests that do not directly measure the posterior corneal curvature and power. They use the following categories of additional information to supplement standard IOL calculations:

1. Pre-LVC keratometry and LVC-induced manifest refraction change. The classic "Clinical History Method"[15] (capitalized to distinguish it from other methods that also use historical data) uses pre-LVC keratometry and LVC-induced refraction change to correct the bias in conventional keratometry. This method subtracts LVC-induced refraction change from the pre-

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LVC keratometry. Another example is the Feiz-Mannis method,[16] where the IOL power is first calculated using the pre-LVC keratometry as if the patient had not undergone LVC. It is then adjusted by adding LVC-induced manifest refraction change divided by 0.7.

2. LVC-induced manifest refraction change. The refraction-derived version of the Shammas method uses the LVC-induced refraction change to modify the keratometry measurement.[17] Some formulas adjust the recommended IOL power based on the magnitude of LVC correction. Some examples are the Masket method[18] and the Latkany method.[19]
3. No prior data (also known as no-history or regression-based methods). The Wang/Koch/Maloney method,[20,21] the no-history version of the Shammas-PL formula,[22] and the Haigis-L formula[23] all estimate the corneal power from standard keratometry using a conversion formula obtained by regression analysis of refractive outcome of cataract surgery after LVC.

Compared to standard IOL formulas, all these post-LVC formulas/methods are partially successful in reducing the unexpected refractive error after cataract surgery. However, methods that rely on clinical history are not always applicable because historical data from the time of LVC are often missing or incomplete. Even if they were available, the historical keratometry and refraction may not account for corneal changes since the initial LVC procedure. The Haigis-L formula,[23] the no-history Shammas-PL formula,[22] and Wang/Koch/Maloney method[20, 21] do not rely on historical data or pre–cataract surgery refraction, and therefore they are always applicable. These regression-based post-LVC IOL formulas have been shown to be superior to some historical methods.[24] The regression-based methods should compensate for the effect of LVC well in average corneas, but could err in eyes with unusually steep or flat posterior corneal surfaces.

Theoretically, the most accurate way to obtain the net corneal power is to measure the posterior surface as well as the anterior surface curvatures in each individual eye. This was pointed out in an editorial in the special issue of the *Journal of Cataract and Refractive Surgery* featuring this subject[25]:

“Resolution of this problem will require a method for accurately measuring posterior corneal power or a technique for adjusting IOL power after implantation. Until then, surgeons are faced with performing multiple calculations to ‘guesstimate’ the correct IOL for patients who, by their original decision to have PRK or LASIK, have demonstrated that they have above-average refractive demands.”

Of course, the success of measuring both corneal surfaces depends on the accuracy of the instrument being used. Since the posterior corneal surface reflection is much weaker than the anterior reflection, tomography systems are required. Slit-scanning tomography (Orbscan II, Bausch & Lomb, Rochester, New York), rotating slit Scheimpflug-camera (Pentacam, Oculus GmbH, Wetzlar, Germany), and dual-Scheimpflug (Galilei, Ziemer Ophthalmic Systems AG, Port, Switzerland) systems have been used for this purpose.[26-30] They have performed better than the Clinical History Method for eyes with prior LVC.[29,30] However to date, no study has shown these methods to provide more accurate IOL power calculation than the newer regression-based post-LVC IOL formulas.

PREVIOUS WORK ON OPTICAL COHERENCE TOMOGRAPHY–BASED INTRAOCULAR LENS POWER CALCULATION

Optical coherence tomography (OCT) can also measure both anterior and posterior corneal powers.[31,32] OCT is a noncontact imaging technology that provides detailed cross-sectional images (tomography) of internal structures in biological tissues.[33] In OCT, a beam of light, typically in the near infrared, is directed at a sample and the delay of reflected light is measured by comparing the sample reflection with a reference reflection in an interferometer. A cross-sectional image is achieved by scanning the probe beam laterally and combining the resulting series of axial scans. A 3-dimensional scan can be obtained by combining a series of cross-sectional scans. The axial resolution of OCT is determined by the coherence length of the light, hence the name “optical coherence tomography.” The broader the spectrum of the light used, the shorter the coherence length and the higher the axial resolution. The axial resolution of OCT is very high, ranging from 1 to 17 μm full-width-half-maximum,[34,35] making it ideal for imaging and measuring thin eye structures such as the retina and cornea. The higher axial resolution of OCT allows for clear delineation of corneal boundaries even in the presence of opacities.[36] This contrasts with slit-scanning technology, which can have problems detecting corneal boundaries in scarred corneas[36] and post-PRK corneas.[37-39] Therefore, from the standpoint of resolution, OCT is an ideal instrument for measuring corneal shape, curvature, and power.

The investigation of OCT corneal power measurement started with the use of time-domain technology by Tang and colleagues.[31] Due to the slow speed (2 kHz axial scan repetition rate) of time-domain OCT, they found direct measurement of anterior and posterior corneal powers to be imprecise. It was necessary to combine OCT pachymetry with Placido-ring topography to obtain acceptable measurement repeatability for net corneal power of 0.23 D pooled standard deviation before LASIK and 0.26 D after LASIK. With the advance from time-domain to Fourier-domain detection, the speed of OCT corneal mapping became much faster. Using a 26 kHz Fourier-domain OCT device, Tang and colleagues were able to directly measure net corneal power with repeatabilities of 0.19 D before LASIK and 0.26 D after LASIK, without any supplemental information from Placido-ring topography.[32] The repeatability of posterior corneal power measurement by Fourier-domain OCT, 0.02 D, was very good both before and after LASIK. That study also showed that OCT anterior corneal power agreed well with conventional automated keratometry in normal eyes, with a mean difference of only -0.04 D (95% limits of agreement of -1.14 to 1.06 D). However, the OCT net corneal power was on average -1.21 D lower than conventional automated keratometry in normal (without LVC) eyes. The main reason for the difference was that the OCT-measured anterior-posterior curvature ratio was 0.836 ± 0.016, much lower than the ratio of 0.883 assumed by the conventional keratometric index of 1.3375.[9] In post-LASIK eyes, OCT net corneal power was 2.89 D lower than automated keratometry. The difference was primarily due to the fact that the anterior-posterior curvature ratio was even lower in postmyopic LASIK eyes—on the average 0.720 as measured by OCT. Fourier-domain OCT showed no significant change in posterior corneal power with LASIK (-6.23 D before and -6.13 D after), which suggested that the corneas remained stable and the OCT measurements were reliable. Thus Fourier-domain OCT measurement of the anterior corneal curvature and power has been validated against conventional keratometry. Fourier-domain OCT measurement of the posterior corneal curvature and power could not be directly validated because of a lack of an accepted standard, but it had excellent repeatability and stability after LASIK. Based on these results for measuring anterior, posterior, and net corneal power, Fourier-domain OCT has the potential for improving IOL power calculation after previous LVC.

Because Fourier-domain OCT-based corneal power measurements were significantly lower than conventional keratometry, it is not appropriate to use these values in standard IOL formulas. Therefore a different formula for OCT-based IOL calculation was developed by Tang and colleagues.[40] As with the theoretic IOL formulas, the OCT-based IOL formula is based on an optical vergence model of the eye (ie, the paraxial approximation of Gaussian optics was used). In a pilot study of routine cataract surgery on virgin eyes (without previous LVC), Tang and colleagues[40] showed that topography-supplemented, time-domain OCT-based IOL power calculation performed as well as the standard theoretic formulas. In another pilot study of postmyopic LVC cataract surgery, Tang and colleagues[41] showed that the Fourier-domain OCT-based IOL power calculation had better predictive accuracy than the Clinical History Method and was equivalent to the Haigis-L formula. In a larger study on post-LVC cataract surgery, Tang and colleagues[42] found that the Fourier-domain OCT-based IOL calculation had a mean absolute error (MAE) of 0.57 in the postmyopic LVC group (N=22 eyes), compared to an MAE of 0.73 for the Haigis-L formula. However, the advantage was not statistically significant (P=.19). In the smaller (N=9 eyes) posthyperopic LVC group, OCT also showed better performance, but the advantage was not statistically significant due to the small number of subjects. Thus these small studies were not definitive in showing the value of OCT-based corneal power measurement and IOL calculation over the regression-based approach.

The purpose of this current study was to refine the OCT-based IOL formula in a larger study of post-LVC cataract surgery, and again compare it with the regression-based formulas, which constitute the current standard of best clinical practice. The hypothesis is that OCT-based IOL formula, by directly measuring both anterior and posterior corneal power, will have a higher predictive accuracy than regression-based formulas for spherical equivalent refractive outcome in post-LVC cataract surgery.

MATERIALS AND METHODS

This prospective observational study was conducted at two academic eye centers (Casey Eye Institute and Cullen Eye Institute). The study protocols were approved by the institutional review boards (IRB) of the two universities (Oregon Health & Science University and Baylor College of Medicine). Written informed consents were obtained from all participants according to the IRB-approved research protocols. The study adhered to the tenets of the Declaration of Helsinki. The study is registered with www.ClinicalTrials.gov (Identifier: NCT00532051).

Participants having uncomplicated cataract surgery following previous LVC for myopia or myopic astigmatism were included in the study. The allowed LVC techniques included LASIK, PRK, and laser subepithelial keratomileusis (LASEK). The cataract surgeries were performed by phacoemulsification. The participants must not have had any vision-limiting eye disease other than cataract. Only eyes that received a monofocal IOL were included. These IOLs included Alcon Acrysof SN60AT, SA60AT, SN60WF, SN6AT3/4 (Alcon Laboratories, Inc, Fort Worth, Texas), and AMO ZA9003 and ZCB00 (Abbott Medical Optics, Inc, Santa Ana, California). All of these IOLs were foldable acrylic lenses. Axial length (AL) and anterior chamber depth (ACD) were measured with a partial coherence interferometer (IOLMaster; Carl Zeiss Meditec, Inc, Dublin, California). The IOLMaster also provided standard automated keratometry. Cataract surgeries were performed by the coauthor surgeons (D.H., R.L.A., D.M.G., and L.H.L. at Casey Eye Institute; and D.D.K. at Cullen Eye Institute) using clear corneal incision and phacoemulsification. Manifest refraction was measured at the 1-month postoperative visit (at least 30 days after cataract surgery).

CORNEAL POWER MEASUREMENT BY OCT

The Fourier-domain OCT system used in this study was the RTVue (Optovue Inc, Fremont, California). It provides an axial resolution of 5 µm and a speed of 26,000 axial scans per second. The precision of corneal thickness mapping[43] and corneal power measurement[32] have been previously described by some of the coauthors of this thesis.

The RTVue OCT system was used to measure anterior, posterior, and net corneal powers, as well as the central corneal thickness (CCT). The system was calibrated once a month using a ceramic ball with a radius of 7.9328 mm to maintain accurate curvature measurement. The cornea was scanned with a mapping pattern (Pachymetry+Power) that consisted of 6-mm lines on eight evenly spaced meridians within an acquisition period of 0.31 second. Each meridional line was composed of 1019 axial scans. The subject 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.

On each meridional cross-sectional OCT image, the software (RTVue Version 6.4) identified the anterior and posterior corneal boundaries. The anterior and posterior curvature along each meridian was calculated by parabolic fitting over the central 3-mm-diameter area (Figure 1). From each image, the anterior corneal power was calculated by $P_A = (n_1 - 1)/R_a$, where n_1 = refractive index of cornea (1.376) and R_a = anterior radius of curvature. The posterior corneal power was $P_P = (n_2 - n_1)/R_p$, where n_2 = refractive index of aqueous (1.333) and R_p = posterior radius of curvature. The net corneal power (NCP) was calculated by $NCP = P_A + P_P - (CCT * P_A * P_P / n_1)$. The overall anterior and posterior and net powers of the cornea were obtained by averaging over the eight meridians. Each scan contained five consecutive measurements (five sets of eight meridional scans) acquired over 1.55 seconds. The measurements with the maximum and minimum NCPs were discarded, and the remaining three measurements were averaged. Three scans were taken at the preoperative visit, and the scan with the median NCP was used for IOL power calculation.

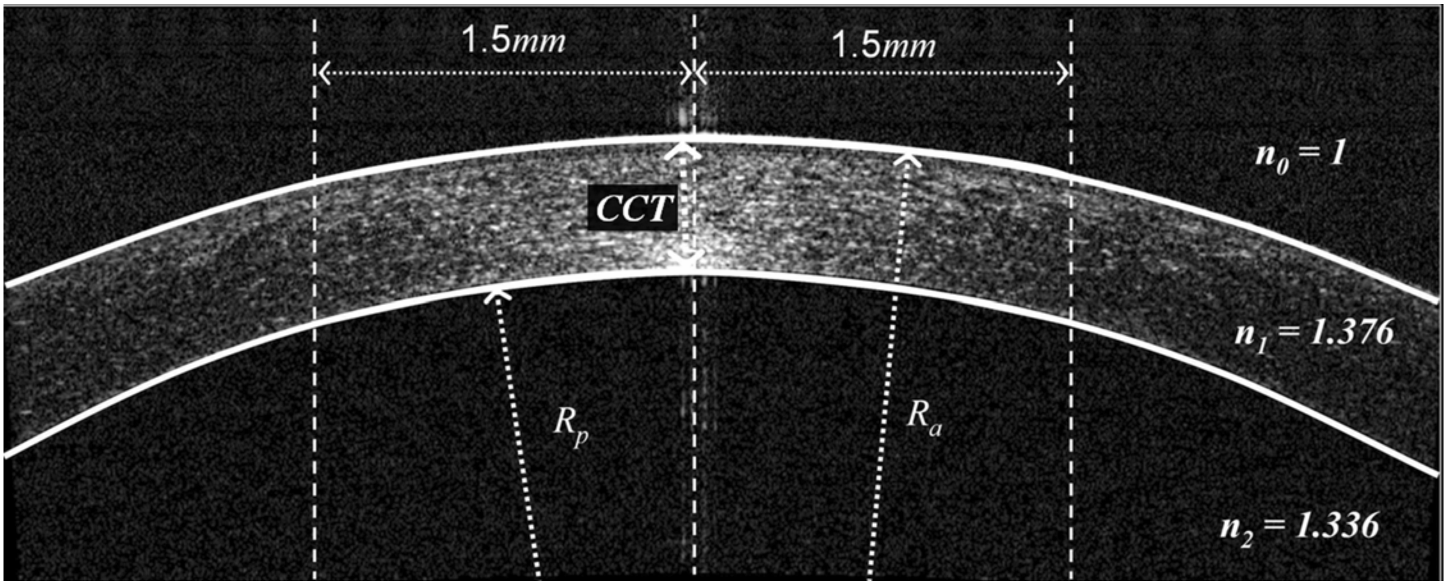

FIGURE 1

The anterior and posterior corneal radii of curvature (R_a and R_p) are calculated by fitting within the central 3-mm-diameter zone. The refractive powers of the anterior and posterior corneal surfaces are then calculated using the known refractive indices of air (n_0), cornea (n_1), and aqueous (n_2). CCT, central corneal thickness.

OCT-BASED INTRAOCULAR LENS FORMULA

The OCT-based IOL formula was based on an eye model consisting of three optical surfaces: cornea, IOL, and retina. The formula has been previously described.[40-42] Both the cornea and the IOL were modeled as thin lenses. Light traveled through the first three surfaces and focused on the retina. Vergence was tracked from the retinal plane to the anterior eye surface.

At the back of the IOL, vergence

$$V_1 = n_2 / l_1 \qquad \text{Eq. 1}$$

In front of the IOL, vergence

$$V_1' = V_1 - P_1 \qquad \text{Eq. 2}$$

At the back of the corneal surface, vergence

$$V_2 = 1 / (1/V_1' + l_2/n_2) \qquad \text{Eq. 3}$$

In front of the corneal surface, vergence

$$V_2' = V_2 - NCP \qquad \text{Eq. 4}$$

Where $n_1 = 1.376$, refractive index of cornea
$n_2 = 1.336$, refractive index of vitreous and aqueous humor
l_1 = vitreous length = $AL - l_2 - CCT$
l_2 = IOL depth (also called effective lens position, see Eq. 6 and Eq. 7)
P_1 = IOL power
NCP = net corneal power by OCT

In the current study, a small optimization factor of ($0.0302*AL$ - 1.739) was added to match the post–cataract surgery refractive outcome. The optimization was based on the series of post-LVC patients presented in this study. The factor is added to the vergence in front of anterior corneal surface V_2'. Therefore, the predicted manifest refraction spherical equivalent (MRSE) at the spectacle plane is:

$$MRSE = 1 / \{1 / (V_2' + 0.0302*AL - 1.739) + vertex\ distance\} \qquad \text{Eq. 5}$$

A vertex distance of 12 mm was assumed in our calculations.

The IOL depth was predicted using a regression-derived formula that is the same as in previous studies[40-42]:

If $AL \leq 24.4$ mm:

$$IOL\ depth = 0.711 * ACD + 0.623 * \sqrt{AL} - 0.25 * P_P + (pACD - 8.11) \qquad \text{Eq. 6}$$

If $AL > 24.4$ mm:

$$IOL\ depth = 0.711 * ACD + 0.623 * \sqrt{[AL + 0.8 * (AL - 24.4)]} - 0.25 * P_P + (pACD - 8.11) \text{ Eq. 7}$$

where $pACD$ is the ACD-constant, P_P is the posterior corneal power by OCT. The ACD-constants were personalized constants for the clinical investigators based on their clinical series with the IOLMaster partial-coherence interferometer in routine cataract surgery.

Surgeon D.D.K. used his own personalized ACD-constants at Cullen Eye Institute, whereas the surgeons at the Casey Eye Institute shared a set of personalized ACD-constants.

Overall, the OCT-based IOL formula took as input five preoperative biometric measurements. The partial coherence interferometer provided *AL* and *ACD*. OCT provided *NCP,* P_P, and *CCT*.

COMPARISON WITH STANDARD REGRESSION-BASED FORMULAS

Two no-history regression-based post-LVC IOL formulas—the Haigis-L and the Shammas-PL—were used for comparison with the OCT-based formula. These regression-based formulas constitute the current standard because they require only standard pre–cataract surgery biometry and have outperformed the Clinical History Method.[24] The Haigis-L calculations were done with the widely used ASCRS IOL Calculator (http://iol.ascrs.org). The personalized Haigis constants were derived from the personalized ACD-constant using the formulas provided by Haigis.[44] A spreadsheet was created to calculate results from the Shammas-PL formula.[22]

The MAE in predicting the postoperative MRSE for each formula was calculated by:

$$\text{MAE} = |\text{ prediction error }| \qquad \text{Eq. 8}$$

where the prediction error is the predicted MRSE minus the actual post–cataract surgery MRSE.

The adjusted MAE was obtained by removing the mean error of the clinical series:

$$\text{Adjusted MAE} = |\text{ prediction error} - \text{mean prediction error }| \qquad \text{Eq. 9}$$

POWER ANALYSIS AND STATISTICAL ANALYSIS

The number of subjects needed to obtain a statistically significant comparison was estimated using the results of our previous pilot study.[41] In that pilot study, the adjusted MAE of refractive prediction for OCT-based post-LVC IOL calculation was 0.50 D compared to 0.78 D for Haigis-L formula (*P*=.26, N=16 eyes). To detect an improvement in MAE from 0.78 D to 0.50 D at the *P*=.05 level with >80% likelihood, statistical power analysis showed that 43 eyes are required, assuming that one eye of each subject is used in statistical analysis to avoid the problem of correlation between the two eyes of the same subject. Thus we aimed to recruit at least 43 subjects for the present study.

Paired *t* tests (two-tailed) were used to compare corneal power measurements using OCT and automated keratometry. Because the MAE and adjusted MAE do not have normal distributions, a nonparametric statistical method was needed. Therefore the Wilcoxon signed-rank test (for paired samples) was used to compare the adjusted MAE between different methods of IOL power calculation. Pearson's chi-square test was used to compare the proportion of eyes within 0.5 D and 1.0 D of predicted refraction. A *P* value of less than .05 was considered statistically significant.

RESULTS

SUBJECT CHARACTERISTICS

Forty-six eyes of 46 cataract surgery patients with previous myopic LASIK or PRK were enrolled. The age was 61.5 ± 8.0 years (mean ± standard deviation; range 42 to 79 years). For 41 of the 46 subjects, the magnitudes of previous myopic correction were not known. The magnitude of previous myopic correction of the other five subjects was -4.66 ± 1.33 D.

CORNEAL POWER MEASUREMENTS

As a preliminary step to validate the OCT anterior corneal curvature measurements, these measurements were compared with conventional keratometry. The anterior power by conventional keratometry was obtained by multiplying the IOLMaster auto-K output by 0.376/0.3375 (recovering the anterior curvature and then computing the power using corneal index instead of keratometric index). For Casey Eye Institute, the anterior corneal power by OCT was 45.33 ± 3.63 D and the automated keratometry was 45.13 ± 3.52 D. The difference was insignificant (*P*=.53). For Cullen Eye Institute, the anterior corneal power by OCT was 45.54 ± 3.07 D and the automated keratometry was 45.70 ± 3.40 D. The difference was also insignificant (*P*=.46). Based on the agreement between OCT-measurement anterior corneal power and automated keratometry at both centers, the Fourier-domain OCT systems at both centers were performing with consistent calibration and reliability. Therefore we pooled the data from the two centers.

After pooling the results from the two clinical centers, the difference between the anterior corneal powers measured by Fourier-domain OCT (45.47 ± 3.22 D) and those measured by automated keratometer (45.52 ± 3.18 D) was not statistically significant (*P*=.52). There was close agreement between OCT and conventional keratometry for anterior corneal curvature measurement.

The average OCT NCP, 39.41 ± 3.11 D, was significantly lower than automated keratometry, 40.86 ± 2.85 D. The average difference was -1.45 D (*P*<.001). The difference was consistent over the range of corneal powers at both clinical centers (Figure 2). The average posterior corneal power measured by OCT was -6.16 ± 0.28 D.

PREDICTIVE ACCURACY OF INTRAOCULAR POWER CALCULATION

The error of predicting the postoperative refraction (predicted - actual MRSE) for OCT-based IOL calculation was compared with the results for two regression-based post-LVC IOL formulas—the Haigis-L and Shammas-PL. The standard deviation of the prediction error was smaller for OCT than the regression-based formulas (Table 1). When the prediction error was plotted against the axial length, there was no trend for any positive or negative slope, showing that all three formulas were well calibrated across the considerable range of axial length (Figures 3). There appeared to be more scatter at longer axial lengths for the Shammas-PL formula

(Figure 3 middle), which was less apparent for the Haigis-L formula. The OCT formula performed approximately equally at all axial lengths (Figure 3, bottom). All three formulas performed similarly at the two clinical centers. There was no significant difference between the two clinical centers in the predictive performance of any of the three formulas.

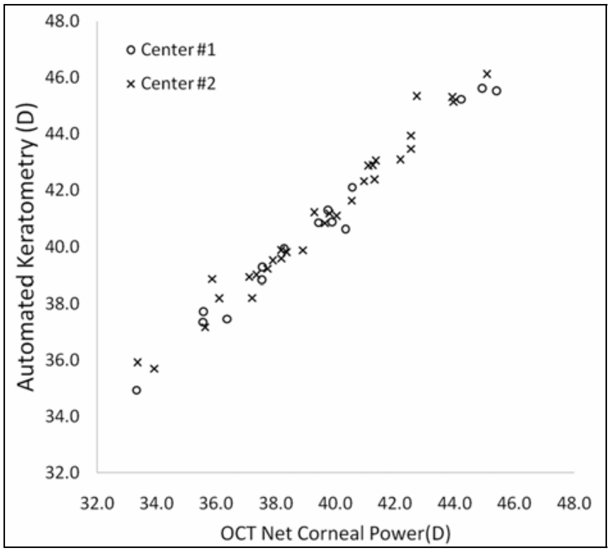

FIGURE 2

IOLMaster automated keratometry is plotted against OCT net corneal power. Center #1, Casey Eye Institute; Center #2, Cullen Eye Institute.

The MAE for OCT-based IOL calculation was lower than for the regression-based formulas (Table 1). However, because the OCT formula used an adjustment factor that was optimized for the current data set (note the average prediction error was near zero), it is not fair to compare this performance measure. The adjusted MAE, which removes the average prediction error for all formulas, is a more meaningful parameter to compare in this situation. The adjusted MAE was 0.49 D for the OCT formula, which was significantly better than the Haigis-L formula (0.65 D, *P*=.031) and the Shammas-PL formula (0.62 D, *P*=.044).

TABLE 1. REFRACTIVE PREDICTION ERROR OF OCT-BASED IOL FORMULA COMPARED WITH REGRESSION-BASED FORMULAS*

IOL FORMULA	MEAN ± SD (D)	RANGE (D)	MAE (D)	ADJUSTED MAE (D)†	WITHIN 0.5 D	WITHIN 1.0 D
OCT	0.05 ± 0.65	-1.63 ~ 1.07	0.50	0.49	59%	89%
Haigis-L	0.14 ± 0.83	-1.65 ~ 1.82	0.67	0.65	46%	78%
Shammas-PL	0.24 ± 0.82	-2.30 ~ 1.76	0.67	0.62	46%	85%

IOL, intraocular lens; MAE, mean absolute error; OCT, optical coherence tomography; SD, standard deviation.
*Prediction error is predicted manifest refraction spherical equivalent (MRSE) – actual postoperative MRSE.
†MAE with mean error removed.

Using the OCT formula, the prediction error was within ±0.5 D MRSE in 27 eyes (59%), compared to 21 eyes (46%, *P*=.034) for both the Haigis-L and Shammas-PL formulas (Table 1). Using the OCT formula, the prediction error was within ±1.0 D in 41 eyes (89%), compared to 36 eyes (78%, *P*=.036) for the Haigis-L formula and 39 eyes (85%, *P*=.40) for the Shammas-PL.

The prediction error of the OCT formula was significantly correlated with both the Haigis-L formula (Figure 4, left) and the Shammas-PL formula (Figure 4, right). These correlations were similar at the two clinical centers.

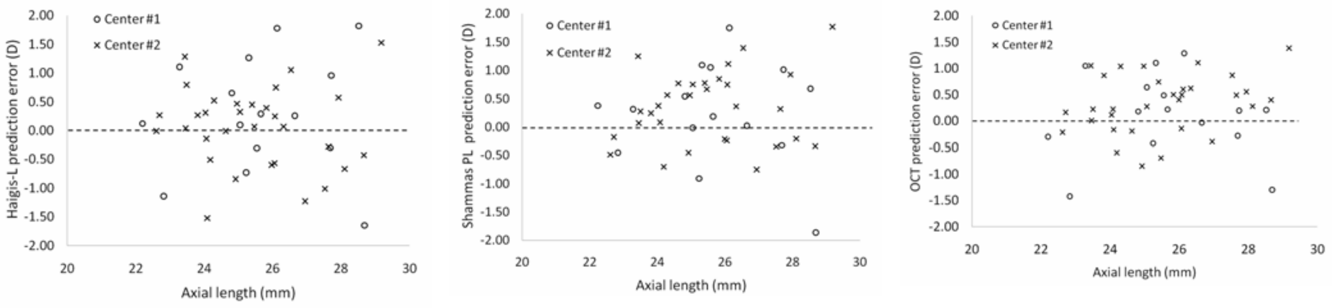

FIGURE 3

Prediction errors for post–cataract surgery spherical equivalent refractive outcome are plotted against axial eye length for the Haigis-L formula (left), the Shammas-PL formula (center), and the OCT-based IOL formula (right). Center #1, Casey Eye Institute; Center #2, Cullen Eye Institute.

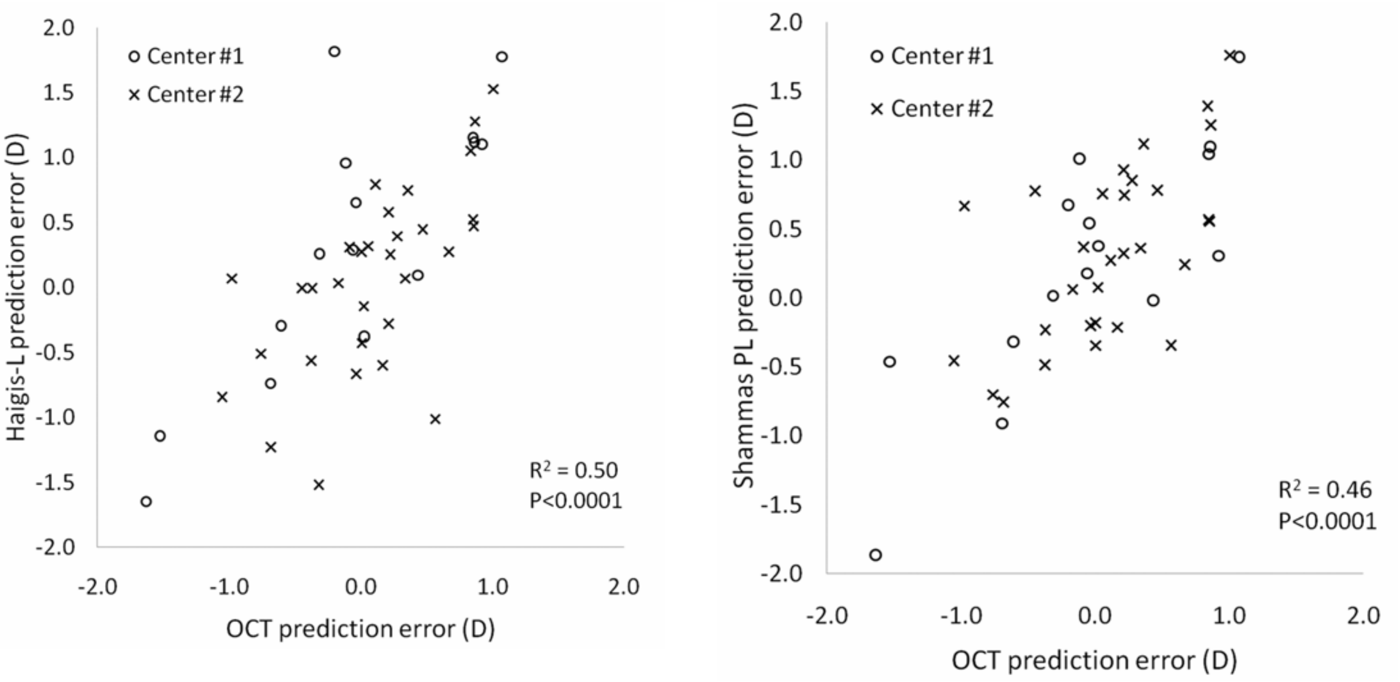

FIGURE 4

The refractive prediction error of the OCT-based IOL formula is correlated with the Haigis-L formula (left) and the Shammas-PL formula (right). Center #1, Casey Eye Institute; Center #2, Cullen Eye Institute.

DISCUSSION

Laser vision correction was introduced in the 1980s.[45,46] By now, many of the early patients have reached an age when cataracts are common,[47-49] and some already have had cataract surgery.[2,12,50] With millions of LVC procedures done each year, the number of cataract patients with previous LVC will eventually reach a similar magnitude. Therefore, an accurate method for selecting IOL power in these patients will be increasingly important. The main challenge in calculating IOL power in these cases is measuring the true posterior corneal power, because the assumption of a fixed relationship between anterior and posterior curvatures no longer applies after LVC. Thus standard keratometry can produce large errors in the corneal power estimate, and conventional IOL formulas can easily lead to significant unintended hyperopic or myopic outcome.

Many methods have been proposed to improve the accuracy of IOL power selection for post-LVC eyes. The classical Clinical History Method[15] is well known because it was introduced early; however, it has obvious limitations. Historical data on keratometry and refraction taken around the time of LVC may not be readily available, and even if they are, they may not account for corneal changes since the initial LVC procedure. In comparative clinical studies, the Clinical History Method generally performed poorly relative to newer methods.[21,24,51,52]

In the absence of a clearly superior method for measuring corneal power and calculating IOL power, a sensible approach is to use a wide variety of methods and derive a consensus value. The American Society of Cataract and Refractive Surgery (ASCRS) sponsored a Web site (http://iol.ascrs.org) that makes this ensemble approach easy, using a collection of formulas selected and organized by Drs Warren Hill, Li Wang, and Douglas Koch. In 2010, Wang and colleagues[24] evaluated the results for 72 eyes of 57 patients using the ASCRS postkeratorefractive IOL power calculator (ASCRS IOL Calculator). They found that methods that used historical data on pre-LVC keratometry (Clinical History Method, Feiz/Mannis, and corneal bypass) performed poorly, with absolute IOL prediction errors averaging 1.10 to 1.31 D, and only 37% to 44% of eyes within 0.50 D of refractive prediction error. A possible reason is that corneal power might have continued to change significantly between the time the post-LASIK refraction was taken and the time of cataract surgery. Wang and colleagues also found that methods that used only historical data on LVC-induced refractive change (adjusted EffRP, adjusted Atlas0-3, Masket, and modified Masket) generally performed well, with absolute IOL prediction error averaging 0.64-0.71 D, and 57% to 67% of eyes within 0.50 D of refractive prediction error. Regression-based methods that used no historical data (Wang/Koch/Maloney, no-history Shammas-PL, Haigis-L) also performed well, with absolute IOL prediction error averaging 0.65 to 0.69 D, and 58% to 60% of eyes within 0.50 D of refractive prediction error. There was no significant difference between and among the "refractive history" methods and the "no history" methods. However, clearly it is easier to use the no-history methods because reliable historical data are not always available and retrieving them can involve significant delays. The best "no-history" method in the 2010 comparison by Wang and colleagues was the Haigis-L method, with an absolute IOL prediction error of 0.65 D. However, the consensus output of the ASCRS calculator, which averaged the predictions of the ensemble of formulas, performed better than any individual formula, yielding an absolute IOL prediction error of 0.57 D. In another large study of 173 eyes of 117 patients, McCarthy and colleagues[52] studied nine different methods of post-LVC corneal power correction or IOL power adjustment, in conjunction with six optical vergence formulas. The top five combinations were the Clinical History Method with the Hoffer Q formula, the Latkany Flat-K method with the SRK/T formula, the Shammas.cd (no history) method with the Shammas-PL formula, the Masket method with the Hoffer Q formula, and the Haigis-L method/formula. Although the Clinical History Method did surprisingly well in conjunction with the Hoffer Q formula in the McCarthy study and was not significantly worse than the other top combinations, it was nevertheless the worst one of the top five.

For our current study, we wanted to compare the OCT-based IOL calculation with the best of current standards. We chose from the ASCRS IOL Calculator because it is commonly accessible to cataract surgeons and is sponsored by a major professional organization. The Haigis-L was a clear choice because it is available on both the ASCRS IOL Calculator and the IOLMaster software, performed well in both the Wang and McCarthy studies, and was already being used by the coauthors clinically. The no-history Shammas-PL formula was chosen because it also performed well in both studies and is publicly available. The Wang/Koch/Maloney method was not used in our current study because it required central corneal power readings from the Atlas topographer, which was not available to all of the clinical investigators. Because of the difficulty of obtaining clinical history data and prior reports that show they do not provide results superior to no-history methods, we did not include in our study any of the methods that require these data. A clinical study by Tang and colleagues[41] had already shown that OCT-based IOL power calculation was significantly better than the Clinical History Method. This is another reason these methods were not studied again here.

Fourier-domain OCT is a promising method for measuring NCP and improving IOL calculation. Its high axial resolution enables precise measurements of both anterior and poster corneal surface contours, curvatures, and powers. Good repeatabilities for anterior, posterior, and net corneal power measurements have been established in a previous study, and the accuracy of the anterior curvature and power measurements has been validated against standard automated keratometry.[32] In the current study, we again found that OCT anterior corneal power was equivalent to automated keratometry, but the NCP was 1.45 D lower than automated keratometry. This difference could be attributed to two factors. First, the keratometric power was defined for the back vertex of the cornea, whereas we chose to define OCT NCP at the corneal principal plane, which is slightly anterior to the front vertex. Second, the conventional keratometric index of 1.3375 was too high. The keratometric index was based on the Gullstrand No. 1 schematic eye, which assumed a ratio of posterior/anterior radii of curvature of 6.8/7.7 (0.883), significantly higher than the actual ratio of 0.836 ± 0.016 in normal eyes as measured by OCT.[32] Applying the keratometric assumption to the current data would yield extrapolated posterior corneal powers of -5.48 ± 0.38 D, which is 0.68 D less negative than the OCT posterior corneal power of -6.16 ± 0.28 D.

In this study, we found that OCT-based IOL calculation had significantly better refractive predictive accuracy than both the Haigis-L and Shammas-PL formulas. This suggests that the OCT-based approach has the potential for improving IOL calculation for post-LASIK cataract patients. However, this conclusion must be tempered by some of the limitations of our study. The major limitation of the current study design was that the adjustment factor in the OCT-based IOL formula was optimized for the current data. So only the adjusted MAE, which removes the mean arithmetic error from all formulas, could be fairly compared. OCT did perform significantly better than Haigis-L and Shammas-PL formulas in terms of adjusted MAE. Nevertheless, a more definitive evaluation of the OCT formula requires an independent study.

The performance of the Haigis-L and Shammas-PL formulas in the present study was better than in the McCarthy study[52] but worse than in the Wang study.[24] In the Wang study, the refractive prediction errors were presented in the form of percentage within ± 0.50 and ± 1.00 D. The investigators found that Haigis-L and Shammas-PL had 58% to 60% of eyes within ± 0.50 D and 90% to 96% within ± 1.00 D of refractive prediction error. In our current study, Haigis-L and Shammas-PL had only 46% of eyes within 0.50 D and 78% to 85% within 1.00 D of refractive prediction error. In the McCarthy study, the prediction error was -0.26 ± 1.13 D with the Haigis-L formula and -0.10 ± 1.02 D with the Shammas-PL formula. In our study, the refractive prediction error was 0.14 ± 0.83 D with the Haigis-L formula and 0.24 ± 0.82 D with the Shammas-PL formula. Thus the standard deviation was narrower in our study.

One possible explanation for the differences between the three studies is the numbers of operative variables. The Wang study was performed in a single center with two surgeons and one IOL model. Our study involved two centers, five surgeons, and six IOL models. The McCarthy study involved 14 surgeons and 15 IOL models. Furthermore, because the McCarthy study was an 8-year retrospective review, the biometry methods were less well controlled. For example, both manual and automated keratometry and both partial coherence interferometry and immersion ultrasound were used. These trends suggest that real-world results of OCT-based IOL power calculation are likely to be worse than the results presented here as the ranges of operative variables become greater. An advantage for having two clinical centers and multiple IOL models in our present study is that it demonstrates, to a limited extent, the robustness of the OCT-based IOL calculation method. The performance of the OCT formula was similar at the two separate clinical centers (Figures 3 and 4). In our previous study of OCT IOL power calculation in postmyopic LASIK eyes,[41] the MAE was 0.50 D, the same as for the present study. Since our previous study had an entirely different data set and involved yet a third eye center (Doheny Eye Institute) and OCT machine, this suggests that the OCT-based IOL calculation method can be generalized to work in multiple clinics employing separate OCT machines, as long as they employ the same software and calibration method.

In normal eyes, benchmark standards for refractive outcomes after cataract surgery have been established in the National Health Service of the United Kingdom.[53] These standards are 55% of eyes within ± 0.5 D of the predicted refraction and 85% of eyes within ± 1.0 D of the predicted refraction. In our study, the OCT-based IOL calculation achieved refractive prediction error within ± 0.50 D in 59% of eyes, and within ± 1.00 D in 89% of eyes, exceeding those benchmark standards. Whether these standards can be met in real-world applications of the OCT-based IOL formula requires further multicenter studies.

The OCT-based IOL formula provides information from an independent measurement of corneal power and therefore may be complementary to other types of post-LVC IOL formulas. Wang and colleagues[24] found that the average prediction of the 10 IOL formulas in the ASCRS IOL Calculator provided better predictive accuracy than any single formula, but the advantage was not statistically significant. McCarthy and colleagues[52] explored various formula combinations and concluded that synergistic effects were found when a historical method was combined with a no-history method, but only when their predictions differed by less than 1.0 D. Our data (Figure 4) indicate that the prediction error of the OCT formula was moderately correlated with both the Haigis-L formula (R^2=0.50) and the Shammas-PL formula (R^2=0.50). Thus there may be a modest benefit in combining the predictions from the formulas. This can be explored more easily and in a more systematic fashion by incorporating the OCT-based IOL formula into the ASCRS IOL Calculator. This step is being explored. In the meantime, the OCT-based IOL formula is freely shared as a downloadable spreadsheet on the website www.COOLLab.net.

A limitation of the present study is that we were not able to compare OCT with slit-scanning and Scheimpflug instruments such as the Orbscan II, Pentacam, and Galilei. These instruments are also able to detect the posterior corneal surface and measure its optical power. Compared to OCT, slit-scanning has a relatively poor axial resolution, which 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 for the Orbscan II.[36-39] Pentacam and Galilei use the Scheimpflug principle to extend the depth of focus and rotational scanning to simplify corneal power measurement. Thus they could theoretically outperform the Orbscan II. Although these instruments have been shown to perform better than the Clinical History Method,[29,30] comparisons with newer and higher performance post-LVC IOL formulas are lacking in the published literature. Further studies are needed to compare these instruments with OCT for post-LVC IOL power calculation.

Optical coherence tomography is a rapidly evolving technology, and thus the current study only captures a snapshot of its early potential. The present study used a Fourier-domain OCT system with a speed of 26 kHz axial scan repetition rate, and an axial resolution of 5 μm. Future studies will likely use anterior segment OCT systems with even higher performance. Scanning speeds of 300,000 to 400,000 axial scans per second[54,55] and axial resolution of 1.3 μm[56] have been demonstrated in the laboratory. Because there is a trade-off between speed and resolution, it is useful to know which is more important in future anterior segment OCT systems. A recent study by Tang and colleagues[32] on OCT corneal power measurement offered some clues on whether the precision was limited by speed or resolution. Speed is more important if the measurement error is dominated by corneal movement during the scan. In this case, since the anterior and posterior cornea move together, the resulting error would have opposite signs and partially cancel one another. Therefore the NCP should have less variability than the anterior corneal power. On the other hand, if the precision is limited by resolution, then the measurement error should be dominated by errors in the delineation of anterior and posterior corneal boundaries, and the variances should be independent and additive. In this case the variability of the NCP should be greater than both that of the anterior and posterior corneal powers. The study results showed that the variability of NCP measurement was less than that of the anterior power, and therefore suggests that motion is the dominant source of error. Thus, for the purpose of more precise corneal power measurement, the development of future anterior segment OCT systems should focus on further improving speed and reducing motion error. Faster Fourier-domain OCT technology has been demonstrated,[54,55] which might further improve the precision of corneal measurements in the future.

OCT corneal power measurement could also be improved by better scanning depth and improved pupil centration. The Fourier-domain OCT system used in the current study had a relatively shallow scan depth and therefore could not image the cornea and iris in the same frames. Pupil centration was performed by the operator at the time of the scan using the real-time video display and could be affected by operator error and subject motion. Ideally, an OCT system with a deeper scan range could be used to capture the pupil position so the corneal power measurement could be precisely centered over the entrance pupil. Furthermore, a deeper OCT scan could be used to measure the crystalline lens position and thickness, which are useful in improving the prediction of the IOL depth.[40]

Another limitation of the current OCT technology is the algorithm for measuring the power of corneal surfaces. The algorithm used in the current study simply fits parabolic curves to meridional profiles of the corneal surfaces, thus ignoring the effect of higher-order aberrations. The algorithm could potentially be improved by measuring the spherical aberration with higher-order curve fits, or using ray tracing to account for the effect of aberrations.[57-59] Because post-LVC eyes generally have higher optical aberrations,[60,61] these approaches could improve the accuracy of corneal power measurement and IOL calculation. Also missing from the current algorithm is the measurement of posterior corneal astigmatism, which may not parallel that of the anterior cornea in some normal[62] and post-LVC eyes. The measurements of these higher-order optical terms are more susceptible to motion error and are likely to work better with the next generation of higher-speed anterior segment OCT systems.

In summary, we have shown that OCT-based IOL calculation performed better than regression-optimized post-LVC IOL formulas (Haigis-L and Shammas-PL). However, independent clinical studies will be needed to confirm these results. Because OCT is a relatively new technology, many improvements in hardware and software in the near future can be anticipated to further improve corneal power measurement and IOL power selection. This is a promising technology that could eventually become the best way to calculate IOL power for post-LVC cataract surgery.

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