Cataract Update

Intraocular lens power calculation after myopic and hyperopic laser vision correction using optical coherence tomography

Maolong Tang, PhDa; Li Wang, MD, PhDb; Douglas D. Koch, MDb; Yan Li, PhDb; David Huang, MD, PhDb

Abstract

Purpose: To use optical coherence tomography (OCT) to measure corneal power and calculate intraocular lens (IOL) power in cataract surgeries after myopic and hyperopic laser vision correction (LVC).

Methods: Patients with previous LVC were enrolled in this prospective study at two centers (Doheny Eye Institute, Los Angeles, CA, USA and Cullen Eye Institute, Houston, TX, USA). Corneal power was measured with a Fourier-domain OCT system. The intra-visit repeatability of OCT corneal power measurement was evaluated by the pooled standard deviation of repeat scans. Axial length, anterior chamber depth, and automated keratometry were measured with the IOLMaster. An OCT-based IOL formula was developed. The mean absolute error (MAE) of refractive prediction for OCT-based IOL formula was calculated. The results were compared with the MAE for Haigis-L formula.

Results: A total of 31 eyes of 24 subjects who had uncomplicated cataract surgery with monofocal IOL implantation were enrolled in the two sites. Twenty-two eyes of 16 subjects had previous myopic LVC ranged from −12.46 D to −0.88 D. Nine eyes of 8 subjects had previous hyperopic LVC ranged from 0.66 D to 5.52 D. The intravisit repeatability of OCT corneal power measurement was 0.24 D. For the myopic LVC group, the OCT formula had a MAE of 0.57 D compared to an MAE of 0.73 D for the Haigis-L formula (p = 0.19). For the hyperopic LVC group, the MAE for OCT and Haigis-L formula was 0.26 D and 0.54 D, respectively (p > 0.05).

Conclusions: Corneal power can be precisely measured with OCT. The predictive accuracy of OCT-based IOL power calculation is equal to current standards for post-LVC eyes.

Keywords: Intraocular lens, Lasik, PRK, Optical coherence tomography

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Introduction

LASIK, 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. More and more people who had LVC will face this problem as they age and develop cataract.

Theoretic formulae, including SRK/T, Hoffer Q and Holladay I, work well on virgin eyes that have not had LVC procedures. The achieved refractions after cataract surgery are within 1.0 D of the target in a great majority of eyes. However, prior LVC introduces error in corneal power measurement which introduces error in IOL power calculation because 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 curvature. 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.6 The
assumption does not hold in eyes after LVC, which alters
the anterior curvature but leaves the posterior surface un-
changed.2,19 Therefore, myopic LVC will lead to overestima-
tion of corneal power by standard keratometry because the
negative power of the posterior corneal surface is underesti-
mated, which results in hyperopic refractive outcome after
cataract surgery.10,11 Similarly, hyperopic LVC will lead to
underestimation of corneal power by standard keratometry
and may lead to myopic outcome.12
Theoretically, the most accurate way to obtain the true
corneal power should be to measure the posterior surface
as well as the anterior surface, in each individual eye. This
was pointed out in an editorial in the special issue of the Jour-
nal of Cataract of Refractive Surgery featuring this subject:13

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

Direct measurement of the posterior corneal power can be
accomplished by several corneal tomography systems. Slit-
scanning tomography (Orbscan II, Bausch & Lomb), rotating
slit Scheimpflug-camera (Pentacam, Oculus GmbH, Wetzlar,
Germany) and dual-Scheimpflug (Galilei, Ziemer Ophthalmic
Systems AG, Port, Switzerland) systems have been used to
for this purpose.14–19 However, the axial (depth) resolutions
of these slit-scanning devices (we use this term to include
Scheimpflug variants) are between 50 and 100 microns 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 the slit-scann-
ing devices.20–23
Optical coherence tomography (OCT) can also measure
both anterior and posterior corneal powers.24,25 The higher
axial resolution of OCT (3–17 microns in commercial instru-
ments) allows for clear delineation of corneal boundaries
even in the presence of opacities.20 With the recent advance
from time-domain to Fourier-domain detection, the speed of
OCT corneal mapping is now faster than slit-scanning de-
vices. Based on these theoretical advantages, we believe
OCT is a promising technology to be developed for measur-
ing corneal power and for IOL power calculations.

Materials and methods

This prospective observational study was conducted at the
Doheny Eye Institute, University of Southern California, Los
Angeles, CA, USA; and Cullen Eye Institute, Baylor College
of Medicine, Houston, Texas, USA. The study protocols were
approved by the institutional review boards of the two uni-
versities. Written informed consents were obtained from all
participants. The study adhered to the tenets of the Declara-
tion of Helsinki.

To be included in the study, the participants must be
scheduled for cataract surgery with a participating surgeon
and have previous LVC. The allowed LVC techniques included
LASIK, photorefractive keratectomy (PRK), and laser subepi-
thelial keratomileusis (LASEK). The participants must not
have any vision limiting eye disease other than cataract.
The preoperative measurements for IOL calculation were
performed at either Doheny or Cullen. Only eyes that re-
ceived a monofocal IOL were included. These IOL’s included
Alcon Acrysof™ SN60AT, SA60AT, SN60WF; and AMO
ZA9003, SN60AT3, and SN60AT4. Axial length (AL) and ante-
rior chamber depth (ACD) were measured with a partial
coherence interferometer (IOLMaster, Carl Zeiss Meditec
Inc.). The IOLMaster also provided standard automated
keratometry. Manifest refraction was measured at the
1-month postoperative visit (at least 30 days after cataract
surgery) by study technicians at Cullen or Doheny.

Corneal power measurement by optical coherence
tomography

Fourier-domain OCT systems (RTVue, Optovue Inc.) were
used to measure anterior, posterior, net corneal powers
and central corneal thickness (CCT) at both Doheny and Cul-
en. The OCT systems were 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 8 evenly-spaced meridians within an acquisi-
tion period of 0.31 s. Each meridional line comprised of
1019 axial scans. The subject was instructed to gaze at an
internal fixation target with the eye being imaged. The oper-
ator centered the scan on the pupil by observing the real-
time video image of the anterior eye during the scan. The
corneal power was calculated by automated software that
was jointly developed by the authors (M.T. and Y.L.) and
Optovue Inc.25 Three OCT scans were taken at the preopera-
tive visit.

IOL power formulae

The OCT-based IOL power formula was previously de-
scribed.26 It used an eye model consisting of four optical sur-
faces: anterior corneal surface, posterior corneal surface, IOL,
and retina. The IOL was modeled as a thin lens.

For eyes after myopic LVC, the OCT net corneal power
was converted to an effective corneal power (ECP) before
insertion into the IOL formula:

$$ECP = 1.0208 \times \text{net corneal power} - 1.6622$$

For eyes after hyperopic LVC, the OCT net corneal power
was converted to an effective corneal power (ECP) before
insertion into the IOL formula:

$$ECP = 1.11 \times \text{net corneal power} - 5.736$$

Eqs. (1) and (2) were based on linear regression of back-cal-
culated ECP against OCT net corneal power. The back-
calculated ECP was from the actual refractive outcome of all
subjects. If both eyes of a subject were included in the study,
only one eye was used to generate back-calculated ECP.

For comparison, we used the ASCRS IOL calculator (http://
iol.ascrs.org) to obtain Haigis-L formula27 results. The mean
absolute errors (MAEs) in predicting the postoperative manifest refraction spherical equivalent (MRSE) for each formula was calculated by:
\[
\text{MAE} = |\text{predicted} - \text{actual MRSE}|
\]  
(3)

**Cataract surgery**

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 coauthors DDK, DH, and others at Cullen and Doheny. The Doheny dataset included two cases performed by two 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 IOL-Master database were used at Doheny.

**Statistical analysis**

The Wilcoxon signed-rank test (for paired samples) was used to compare the MAE between different OCT-based IOL formula and Haigis-L formula. The chi-square test was used to compare the proportion of eyes within 1 D of predicted refraction. A \( p \)-value of less than 0.05 is considered statistically significant. Repeatability was measured by the standard deviation (SD) of repeat measurements.

**Results**

**Subject characteristics**

A total of 31 eyes from 24 cataract surgery patients (13 women, 10 men) with previous LVC were enrolled at the two sites. The age was 58.1 ± 10.7 years (range 34–77 years) at the time of surgery. Twenty-two eyes of 16 subjects had previous myopic LVC with the average magnitude \(-4.97 ± 3.16 \) D and ranged from \(-12.46 \) D to \(-0.88 \) D. Nine eyes of eight subjects had previous hyperopic LVC with the average magnitude \(2.32 ± 2.22 \) D and ranged from \(0.66 \) D to \(5.52 \) D.

**Corneal power measurements**

The intravisit repeatabilities of OCT corneal power measurements were 0.25, 0.04 and 0.24 D anterior, posterior and net corneal power, respectively.

For the myopic LVC group, the net corneal power measured by Fourier-domain OCT \((38.89 ± 4.46 \) D) was significantly lower than standard keratometry \((40.50 ± 3.61 \) D). The average difference was \(-1.61 ± 1.29 \) D \((p < 0.001)\). The differences were more negative for corneas with lower net powers (Fig. 1). For the hyperopic LVC group, the difference between net corneal power measured by Fourier-domain OCT \((45.59 ± 1.18 \) D) and standard keratometry \((45.74 ± 1.31 \) D) was not significant \((p = 0.49)\).

The ECP calculation formulae for the myopic group and hyperopic group are shown in Figs. 2 and 3, respectively. Data from the two sites seemed to follow the same trend lines for both myopic group and hyperopic group.

**Predictive accuracy of intraocular power calculation**

We compared the error of predicting the postoperative refraction (predicted – actual MRSE) for OCT-based IOL formula with the results for the Haigis-L formula (Table 1). For the myopic LVC group, the MAE of OCT-based formula was \(0.57 \) D while the MAE was \(0.73 \) D for Haigis-L \((p = 0.19)\). There was a trend toward fewer large prediction errors using OCT (Fig. 4), with 18 eyes (82%) were within 1 D of actual refractive outcome, compared to 16 eyes (73%) within 1 D for Haigis-L. The difference was not significant. A Bland–Altman plot of prediction errors of OCT and Haigis-L formulas was shown in Fig. 5.

For the hyperopic LVC group, the MAE of OCT-based IOL formula was \(0.26 \) D while the MAE was \(0.54 \) D for Haigis-L \((p > 0.05)\). There was also a trend toward fewer large prediction errors using OCT (Fig. 6), with 9 eyes (100%) were within 1 D of actual refractive outcome, compared to 7 eyes (78%) within 1 D for Haigis-L. The difference was not significant. A
Laser vision correction was introduced in 1980s. By now, many of the early patients have reached an age when cataracts are common, and some already have had cataract surgery. 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 corneal power estimate and conventional IOL formulae can easily lead to significant un-intended hyperopic or myopic outcome.

Many methods have been proposed to improve the accuracy of IOL power selection for post-LVC eyes. The clinical history method and the rigid gas-permeable contact lens over-refraction method are well known because they were introduced early. These methods have obvious limitations. Historical data on keratometry and refraction taken 1 month after surgery; MRSE = manifest refraction spherical equivalent. MAE = mean absolute prediction error in MRSE.

### Discussions

Laser vision correction was introduced in 1980s. By now, many of the early patients have reached an age when cataracts are common, and some already have had cataract surgery. 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 corneal power estimate and conventional IOL formulae can easily lead to significant un-intended hyperopic or myopic outcome.

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### Figures

**Figure 3.** Bland–Altman plot of prediction errors of OCT and Haigis-L formulas was shown in Fig. 7.

**Figure 4.** Distribution of prediction errors in spherical equivalent manifest refraction for Haigis-L and OCT-based IOL formula in eyes after myopic laser vision correction. For OCT formula, 18 out of 22 eyes were within 1 D of actual refractive outcome, compared to 16 eyes within 1 D for Haigis-L formula.

**Figure 5.** Bland–Altman plot assessing the agreement between prediction errors in spherical equivalent manifest refraction for Haigis-L and OCT-based IOL formula in eyes after myopic laser vision correction (n = 22 eyes of 16 subjects).

**Figure 6.** Prediction errors in spherical equivalent manifest refraction for Haigis-L and OCT-based IOL formula in eyes after hyperopic laser vision correction (n = 9 of 8 subjects). For OCT formula, 9 out of 9 eyes were within 1 D of actual refractive outcome, compared to 7 eyes within 1 D for Haigis-L formula.

### Table 1. Accuracy of OCT-based IOL power formula compared with Haigis-L.

<table>
<thead>
<tr>
<th>Keratometry method</th>
<th>Best IOL formula</th>
<th>Prediction error (D)</th>
<th>Range (D)</th>
<th>MAE (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>After myopic LVC (n = 22 eyes)</td>
<td>IOL Master</td>
<td>Haigis-L, myopic</td>
<td>0.35 ± 0.94</td>
<td>(-2.32, 1.30)</td>
</tr>
<tr>
<td></td>
<td>OCT</td>
<td>OCT</td>
<td>0.07 ± 0.80</td>
<td>(-1.24, 2.15)</td>
</tr>
<tr>
<td>After hyperopic LVC (n = 9 eyes)</td>
<td>IOL Master</td>
<td>Haigis-L, hyperopic</td>
<td>0.36 ± 0.72</td>
<td>(-0.61, 1.71)</td>
</tr>
<tr>
<td></td>
<td>OCT</td>
<td>OCT</td>
<td>0.08 ± 0.34</td>
<td>(-0.64, 0.44)</td>
</tr>
</tbody>
</table>

LVC = laser vision correction. Prediction error = predicted MRSE – actual MRSE 1 month after surgery; MRSE = manifest refraction spherical equivalent. MAE = mean absolute prediction error in MRSE.
around the time of LVC may not be readily available, and even if they were, may not account for corneal changes since the initial LVC procedure. Contact lens overrefraction suffers from the relatively inaccurate visual endpoint in cataract patients, who may have significantly decreased vision due to cataract.\textsuperscript{39} Other investigators have also found these two methods to perform poorly relative to newer methods.\textsuperscript{39,40}

Some of the newer methods for post-LVC IOL calculation do not rely on historical data or refraction. One class of methods uses a standard keratometer but calculates the corneal power in alternative fashions more suitable for post-LVC eyes. The Koch method uses standard keratometry to measure the anterior corneal power, and then add a constant posterior corneal power.\textsuperscript{34} The Haigis-L formula uses empirical linear regression analysis of post-LVC cataract surgery results to optimize the estimate of corneal power from standard keratometry.\textsuperscript{27} 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 studied\textsuperscript{27} and is available on the commonly used IOLMaster biomter as well as the ASCRS IOL calculator website (http://iol.ascrs.org). We found that OCT-based IOL calculation had similar predictive accuracy with the Haigis-L formula.

Because the lack of accurate measurement posterior corneal power is the main cause of the error in post-LVC IOL power calculation, direct measurement of posterior corneal power is potentially the optimal solution. OCT as well as slit scanning instruments such as the Orbscan II, Pentacam, and Galilei all have such capability. Theoretically, compared to OCT, slit scanning has a relatively poor axial resolution of 50–100 microns due to the diffraction limit of optical focusing. 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.\textsuperscript{20–23} We will perform the comparison between OCT and slit scanning instruments in other studies.

In summary, we have shown that OCT-based IOL power calculation performs at least as well as a regression-optimized post-LVC IOL formula (Haigis-L). Future improvements in hardware and software of OCT systems 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.

Financial and proprietary interest

Maolong Tang, Yan Li, and David Huang have significant financial interests in Optovue Inc., a company that may have a commercial interest in the results of this research and technology. This potential individual conflict of interest has been reviewed and managed by the Oregon Health & Science University. Li Wang received research support from Ziemer. Douglas D. Koch is a consultant for Alcon Surgical Inc.

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