

# Intraocular Lens Power Calculations after Myopic Laser Refractive Surgery: A Comparison of Methods in 173 Eyes

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**Purpose:** To evaluate and compare published methods of intraocular lens (IOL) power calculation after myopic laser refractive surgery in a large, multi-surgeon study.

**Design:** Retrospective case series.

**Participants:** A total of 173 eyes of 117 patients who had uneventful LASIK (89) or photorefractive keratectomy (84) for myopia and subsequent cataract surgery.

**Methods:** Data were collected from primary sources in patient charts. The Clinical History Method (vertex corrected to the corneal plane), the Aramberri Double-K, the Lasky Flat-K, the Feiz and Mannis, the R-Factor, the Corneal Bypass, the Masket (2006), the Haigis-L, and the Shammas.cd postrefractive adjustment methods were evaluated in conjunction with third- and fourth-generation optical vergence formulas, as appropriate. Intraocular lens power required for emmetropia was back-calculated using stable post-cataract surgery manifest refraction and implanted IOL power, and then formula accuracy was compared.

**Main Outcome Measures:** Prediction error arithmetic mean  $\pm$  standard deviation (SD), range (minimum and maximum), and percent within 0 to  $-1.0$  diopters (D),  $\pm 0.5$  D,  $\pm 1.0$  D, and  $\pm 2.0$  D relative to target refraction.

**Results:** The top 5 corneal power adjustment techniques and formula combinations in terms of mean prediction errors, standard deviations, and minimizing hyperopic "refractive surprises" were the Masket with the Hoffer Q formula, the Shammas.cd with the Shammas-PL formula, the Haigis-L, the Clinical History Method with the Hoffer Q, and the Lasky Flat-K with the SRK/T with mean arithmetic prediction errors and standard deviations of  $-0.18 \pm 0.87$  D,  $-0.10 \pm 1.02$  D,  $-0.26 \pm 1.13$  D,  $-0.27 \pm 1.04$  D, and  $-0.37 \pm 0.91$  D, respectively.

**Conclusions:** By using these methods, 70% to 85% of eyes could achieve visual outcomes within 1.0 D of target refraction. The Shammas and the Haigis-L methods have the advantage of not requiring potentially inaccurate historical information.

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Myopic laser refractive surgery has among the highest satisfaction rate of all elective surgeries.<sup>1</sup> When patients who have had laser refractive surgery later have cataract surgery, they expect similar, excellent uncorrected visual acuity. Meeting these patient demands has been difficult because intraocular lens (IOL) calculations after laser refractive surgery are known to be less predictable than with virgin corneas.<sup>2-6</sup>

The sources of prediction error in IOL calculations after laser refractive surgery have been divided into 3 categories: instrument error, index of refraction error, and formula error.<sup>7,8</sup> A significant source of instrument error occurs because most keratometers measure the central corneal radius of curvature in a 2.5- to 3.2-mm zone and assume a spherocylindrical cornea that is no longer true after myopic laser refractive surgery.<sup>6,9</sup> This overestimates corneal refractive power by 15% to 25% and leads to hyperopic

outcomes.<sup>2,10</sup> Furthermore, when the anterior but not the posterior surface has been modified as after myopic laser refractive surgery, error due to index of refraction occurs because the relationship assumed in keratometers (index  $n = 1.3375$ ) between the 2 surfaces is no longer appropriate.<sup>3,6</sup> It is estimated for every 7.0 diopters (D) of refractive correction, corneal power is overestimated by an extra 1.0 D, adding to hyperopic outcomes.<sup>7</sup> A third source of inaccuracy, formula error, occurs because the widely used third-generation IOL power formulas (Holladay, Hoffer Q, SRK/T) use corneal power to predict the pseudophakic anterior chamber depth. Although the cornea is flattened after myopic laser surgery, the anterior chamber depth remains negligibly altered.<sup>8</sup> Thus, when corneal power is corrected for instrument and index of refraction error, third-generation formulas calculate a falsely shallow pseudophakic anterior chamber depth and generate an inadequate IOL

power prediction.<sup>11</sup> Together, unless corrected, these sources of error culminate in what has been termed the “hyperopic surprise” commonly observed after cataract surgery in post-myopic laser eyes.

Methods to correct or minimize these sources of prediction errors are divided into those requiring information from the prior laser surgery (historical) and those that use only current biometry (no history).<sup>7</sup> The majority of the methods evaluated in our study fall into the historical category and include the gold standard Clinical History Method (vertex corrected to the corneal plane), the Aramberri Double-K, the Lasky Flat-K, the Feiz and Mannis, the R-Factor, the Corneal Bypass, and the Masket (2006).<sup>3,11–16</sup> The no history methods evaluated were the Haigis-L and Shammas.cd.<sup>8,17</sup>

Although numerous methods are available to calculate IOL power after myopic laser refractive surgery, an informed decision remains difficult because there are few independent, comparative publications available. Our large multi-surgeon study evaluates and compares formulas and methods of correcting prediction errors.

## Patients and Methods

This was a retrospective review of the IOL calculations done at the University of British Columbia Department of Ophthalmology and Visual Sciences Anterior Segment Assessment Unit between 2000 and 2008. The study was approved by the University of British Columbia Clinical Research Ethics Board and conducted according to the tenets of the Declaration of Helsinki. Eyes that had LASIK or photorefractive keratectomy (PRK) for myopia and subsequent cataract surgery were eligible for this study. Cataract surgeries were performed by standard phacoemulsification with all lenses placed in the capsular bag. Data were collected from primary sources in patient charts.

Biometry measured on the date closest to cataract surgery was used to calculate IOL power. Immersion ultrasound and partial coherence interferometry (Zeiss IOL Master; Carl Zeiss Meditec, Dublin, CA) measurements were included in the study. If axial length was available from both modalities, partial coherence interferometry was used for calculations. IOL Master keratometry and manual keratometry were included in the study. If both sources of keratometry were available for the same eye, values from the IOL Master were used for calculations. For conversion to corneal radii, the standard 1.3375 index of refraction used in North America was assumed in all cases. Anterior chamber depth, lens thickness, and horizontal white-to-white were collected for use in the fourth-generation Haigis and Holladay II formulas.

Lens constants for IOL calculation were matched according to the biometry method used to measure axial length. IOL Master optimized lens constants were sourced from the User Group for Laser Interference Biometry (available at: <http://www.augenklinik.uni-wuerzburg.de/ulib/c1.htm>, accessed June 1, 2009). Constants for ultrasound measurements were obtained from the Holladay International IOL Registry (available at: <http://www.docholladay.com/>, accessed June 1, 2009). If surgeons provided their own personalized lens constants, they were given preference over generic constants. For use in formulas other than the SRK/T, A-constants were converted using standard relations.

The Holladay I, Hoffer Q, SRK/T, and Shammas-PL optical vergence formulas were programmed into Microsoft Excel 2007 (Microsoft Corp., Redmond, WA) using original publications and erratum's and then validated against the commercially available IOL Master and Holladay IOL Consultant software.<sup>18–22</sup> The

proprietary Holladay II and Haigis formulas are not published and so could not be programmed into our Excel database. The Holladay II formula was used from within the Holladay IOL Consultant Professional Edition (V2008.1101) software and the Haigis formula from the Universitäts-Augenklinik Würzburg (available at: <http://www.augenklinik.uni-wuerzburg.de/index.htm>, accessed August 10, 2009).

In addition, the Clinical History Method (vertex corrected to the corneal plane), the Aramberri Double-K, the Lasky Flat-K, the Feiz and Mannis, the R-Factor, the Corneal Bypass, the Masket (2006), and the Shammas.cd post-refractive adjustment methods were programmed into our Microsoft Excel database and used in conjunction with the optical vergence formulas, as appropriate. The Clinical History Method was calculated with refractions vertex adjusted to the corneal plane according to the original Holladay method.<sup>12</sup> The proprietary Holladay II and Haigis formulas were evaluated only with the Clinical History Method because they could not be programmed into our Microsoft Excel database, and manual input of all methods was not feasible. The Haigis-L no history formula was calculated online using study access provided by Dr. Wolfgang Haigis. Intraocular lens power required for emmetropia was back-calculated using the stable post-cataract surgery manifest refraction and implanted IOL power as discussed by Olsen<sup>23</sup> and Aramberri<sup>11</sup> ( $P_e = P_i + 1.5 * R$ , where  $P_i$  = power of implant,  $R$  = postoperative manifest refraction, and  $P_e$  = power required for emmetropia). For IOL power back-calculations, lensometer or autorefractor values were not accepted in lieu of manifest refractions. In eyes that had lens exchanges, refractions used followed final lens implantation. For single piggyback lenses, the refraction preceded the secondary lens implant. Post-laser refraction was considered appropriate when performed between 3 and 6 months after laser surgery and no lenticular changes were noted in the file. Statistical analysis was performed with SPSS (version 16; SPSS Inc., Chicago, IL). For detailed explanations of the formulas, please refer to the original publications listed in our references.

## Results

### Study Population

A total of 201 eyes were eligible for analysis. Sixteen eyes were excluded because they did not have a manifest refraction after cataract surgery or were missing necessary biometry such as axial length or keratometry. Eight eyes with confounding retinal or corneal disease were excluded. Four eyes were excluded because of complications associated with cataract surgery or because they had a postoperative best-corrected visual acuity (BCVA) <20/50.

In total, 173 eyes of 117 patients were included, of whom 90 (52%) were male and 83 (48%) were female. Seventeen Canadian ophthalmologists contributed between 1 and 45 eyes. Laser refractive surgeries were performed between 1992 and 2006, and the mean patient age at the time of surgery was 49 years (range, 24–67 years). Eighty-nine eyes (51%) had LASIK, and 84 eyes (49%) had PRK. Mean keratometry before laser refractive surgery was  $43.79 \pm 1.58$  D (range, 39.18–48.00 D). Mean spherical equivalent before laser refractive surgery was  $-7.36 \pm 3.57$  D (range, -19.25 to -0.62 D), and mean stable spherical equivalent after laser refractive surgery was  $-0.37 \pm 0.96$  D (range, -6.25 to +2.00 D). Fourteen percent of eyes had 1 or more LASIK/PRK re-treatments.

Mean patient age at the time of cataract surgery was 57 years (range, 35–82 years). Mean years from refractive to cataract surgery was 8 (range, 1–16 years). Before cataract surgery the mean spherical equivalent was  $-1.95 \pm 2.44$  D (range, -13.12 to +2.5 D) with a mean BCVA of 20/40. Fifteen different lens

models were implanted: 82 Alcon SN60WF, 36 Alcon SA60AT, 14 Alcon SN60AT, 12 Advanced Medical Optics ZA9003, 5 Bausch & Lomb LI61AO, 4 Advanced Medical Optics AR40e, 4 Bausch & Lomb LI61U, 4 Alcon SA60D3, 4 Alcon SN60D3, 2 Advanced Medical Optics Z9000, 2 Advanced Medical Optics ZCB00, 1 Bausch & Lomb LI61SE, 1 Alcon MA30BA, 1 Alcon MA60AC, and 1 Advanced Medical Optics Z9002. Mean lens power implanted was  $19.87 \pm 2.36$  D (range, 12–25 D). Ninety lenses (52%) were implanted in the right eye, and 83 lenses (48%) were implanted in the left eye. Eight eyes had a lens exchange, and 1 eye had a piggyback lens implantation. Manifest refractions were taken a mean of 203 days after cataract surgery (range, 1–2996 days) with a mean spherical equivalent of  $-0.43 \pm 0.90$  D (range,  $-2.75$  to  $+2.75$  D) and BCVA of 20/25. A total of 113 IOL calculations used axial lengths from the IOL Master (mean,  $26.90 \pm 1.86$  mm; range, 23.53–32.30 mm), and 60 IOL calculations used immersion ultrasound (mean,  $26.76 \pm 1.88$  mm; range, 23.41–31.90 mm). A total of 108 IOL calculations used IOL Master keratometry (mean,  $38.99 \pm 2.05$  D; range, 33.23–43.48 D), and 65 IOL calculations used manual keratometry (mean,  $39.24 \pm 2.00$  D; range, 31.91–44.69 D). Anterior chamber depth, lens thickness, and horizontal white-to-white had mean values of  $3.37 \pm 0.37$  mm (range, 2.55–4.12 mm),  $4.43 \pm 0.44$  mm (range, 3.11–5.79 mm), and  $12.22 \pm 0.39$  mm (range, 11.30–13.00 mm), respectively.

### Comparison of Formula Accuracy

Nine formulas for estimating corneal power or adjusting IOL power after laser refractive surgery were evaluated in conjunction with the 6 optical vergence formulas. In total, 25 different combinations were compared. Table 1 (available at <http://aaojournal.org>) compares the mean arithmetic and absolute prediction errors, ranges, and standard deviations in diopters spherical equivalent of all formulas. Mean absolute prediction error, although not a statistically functional measure, was included because it has been widely used in other studies and facilitates comparison. The percentages that each formula combination predicted between 0 and  $-1.0$  D,  $\pm 0.5$  D,  $\pm 1.0$  D, and  $\pm 2.0$  D relative to emmetropia are compared in Table 2 (available at <http://aaojournal.org>). There were no statistically significant differences in arithmetic prediction errors in eyes that had LASIK compared with PRK ( $P > 0.05$ , independent samples *t* test).

Formula accuracy as a function of axial length was divided into 2 groups: eyes  $<27$  mm and  $>27$  mm. All vergence formulas with the Clinical History Method had similar prediction errors in eyes  $<27$  mm but had more variable outcomes as axial lengths exceeded 27 mm (differences in arithmetic prediction errors statistically significant at the  $P < 0.01$  level). However, the Hoffer Q differed from the SRK/T and Holladay in that it tended to predict myopic outcomes in eyes  $>27$  mm (mean arithmetic prediction error of  $-0.47$  D), whereas the SRK/T and Holladay tended to predict hyperopic outcomes (mean arithmetic prediction errors of 0.58 D and 0.63 D, respectively).

The third-generation SRK/T, Holladay and Hoffer Q with the Clinical History Method had mean absolute prediction errors of 0.72 D, 0.66 D, and 0.66 D in eyes  $<27$  mm compared with mean absolute prediction errors of 0.99 D, 1.05 D, and 1.04 D in eyes  $>27$  mm, respectively. The fourth-generation Holladay II and Haigis with the Clinical History Method had mean absolute prediction errors of 0.78 D and 0.92 D in eyes  $<27$  mm compared with 1.20 D and 1.17 D in eyes  $>27$  mm, respectively. The no history Shammas.cd with the Shammas-PL, the Haigis-L, and the Masket with the Hoffer Q were less affected by axial length (differences in arithmetic prediction error not significant at the  $P < 0.05$  level) and had superior overall accuracy in both sub-

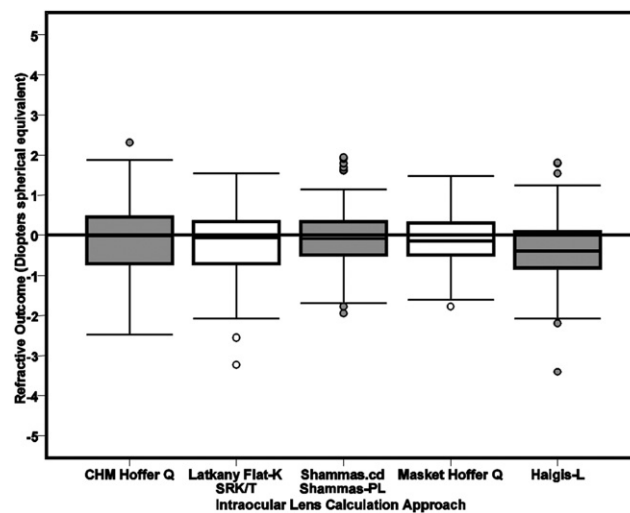


Figure 1. Boxplot of the top 5 intraocular lens (IOL) calculation approaches after myopic laser refractive surgery.

groups when compared with the Clinical History Method with mean absolute errors of 0.61 D, 0.75 D, and 0.48 D in eyes  $<27$  mm compared with 0.76 D, 0.88 D, and 0.73 D in eyes  $>27$  mm, respectively.

Overall, in terms of prediction errors, standard deviations, and minimizing hyperopic “refractive surprises,” the 5 most accurate corneal power adjustment techniques and formula combinations were the Masket with the Hoffer Q formula, the Shammas.cd with the Shammas-PL formula, the Haigis-L, the Clinical History Method with the Hoffer Q, and the Laskany Flat-K with the SRK/T (Fig 1). There were no statistically significant differences in arithmetic prediction errors ( $P > 0.05$ , paired-samples *t* test) between the top formulas and the Clinical History Method with the Hoffer Q (used as a reference standard).

### Clinical Utility of Using Formulas Together to Improve Outcomes

The intuitive conjecture that when more than 1 formula predicts a similar IOL power the calculation is more likely to be accurate was examined. We found that when historical and no history methods predicted IOL powers within 1.0 D of each other, we could be more confident in our calculations. Of the various formula combinations analyzed, the no history Shammas method and the Clinical History Method Hoffer Q had the greatest synergistic benefit. When the formulas had  $<1.0$  D lens power prediction difference ( $N = 88$ ), the percentage of eyes that the Shammas method predicted within  $\pm 0.5$  D of the target refraction increased from 53.8% to 62.5%. The opposite was true when there was a  $>1.0$  D prediction difference ( $N = 81$ ). In those cases the percentage that the Shammas method predicted within  $\pm 0.5$  D decreased from 53.8% to 43.2%.

### Discussion

The accuracy of standard IOL calculations is improving, and with that so are the expectations for accurate post-refractive IOL calculations. Two benchmark standards proposed in 2009 by the British National Health Service (NHS) are that 55% of routine, virgin cornea cataract surgeries should be within 0.5 D and 85% within 1.0 D of the targeted spherical equivalent.<sup>24</sup> In

our evaluation of post-refractive eyes, only the Masket technique (Table 2, available at <http://aaojournal.org>) satisfied the first of the NHS benchmark standards. The Masket technique with the Hoffer Q, Holladay, and SRK/T formulas predicted 58.8%, 55.9%, and 55.3% of eyes within 0.5 D of the target refraction, respectively. Of the other methods, the no history Shamma.cd method with the Shamma-PL formula was closest with 53.8% of eyes within 0.5 D of the target refraction. However, none of the techniques satisfied the second NHS benchmark standard that 85% of eyes be within 1.0 D of the target refraction. The Masket with the SRK/T, Hoffer Q, and Holladay formulas was closest with 84.5%, 83.5%, and 81.2% within 1.0 D of the target refraction, respectively. The no history Shamma.cd with the Shamma-PL formula was again second with 80.9% within 1.0 D of the target refraction.

The Clinical History Method, widely accepted as the gold standard of estimating corneal power after laser refractive surgery, failed to satisfy either of the NHS benchmark standards and was not the most accurate calculation approach in our study. Studies by Geggel<sup>25</sup> and Walter et al<sup>16</sup> report similar findings. The Clinical History Method is inherently problematic because its predictive accuracy is a function of the quality of perioperative laser refractive data.<sup>26</sup> To calculate the Clinical History Method, pre-refractive keratometry readings and pre-refractive and final stable post-refractive manifest refractions are required, which are often from many years ago, of questionable accuracy, or not available at all. Undetected nuclear sclerosis or progressive axial myopia at the time of refractive surgery can make calculation impossible entirely.<sup>26,27</sup> Furthermore, the outcomes of the Clinical History Method differ depending on which vergence formula is used, whether or not refractions are vertex corrected, and if Aramberri Double-K adjustment is applied. This is evidenced by the variable results observed in the literature.<sup>2,11,16,27-29</sup>

Our optimal Clinical History Method combination was with refractions adjusted to the corneal plane, without an Aramberri Double-K adjustment, and when used in conjunction with the Hoffer Q formula. This seems to differ from the standard knowledge for virgin corneas about third-generation formula performance based on the length of the eye where the SRK/T and Holladay formulas are considered more accurate for normal to longer eyes.<sup>19,30</sup> A study by Odenthal et al<sup>29</sup> of 15 eyes found that the Clinical History Method with the Hoffer Q formula predicted more accurate results (70% of eyes within 1.0 D of the target and 70% with <0.5 D of unintended hyperopia) when compared with the SRK/T (50% of eyes within 1.0 D of the target and 20% with <0.5 D of unintended hyperopia) and Holladay I (50% of eyes within 1.0 D of the target and 50% with <0.5 D of unintended hyperopia). Argento et al<sup>31</sup> also found the Clinical History Method with the Hoffer Q formula produced a smaller mean prediction error (mean error  $-0.98 \pm 0.87$  D) when compared with the Holladay II (mean error  $-1.31 \pm 1.35$  D) and SRK/T (mean error  $-2.19 \pm 1.13$  D). These results suggest that knowledge of formula performance in unaltered corneas should be cautiously applied to postrefractive eyes.

In view of the inherent limitations of the Clinical History Method, we were particularly interested in methods that require only current measured values or use limited peri-keratorefractive data, such as the Shamma.cd, Haigis-L, and Masket. Compared with the Clinical History Method combinations, the Shamma.cd, Haigis-L, and Masket methods were less affected by axial length and had superior overall accuracy in both axial length subgroups (<27 and >27 mm). However, the no history Shamma.cd and Haigis-L methods had 4 eyes with prediction errors of >2.0 D spherical equivalent and the Clinical History Method did not. In those eyes, we found that the current measured keratometry readings were very flat (<33.0 D) or very steep (>43.0 D), and on

closer examination of those outlier cases we found that the keratometry was inconsistent with the expected refractive change or the axial length. Re-measurement, using multiple instruments and favoring the historical methods, might reduce the chance of error in such cases.

In conclusion, intraocular lens calculations after myopic laser refractive surgery are improving, but their predictability is still not equivalent to that attained with virgin corneas. Of the 25 formula combinations tested on our dataset of 173 eyes, the 5 most accurate methods (Masket with the Hoffer Q, Shamma.cd with the Shamma-PL formula, Haigis-L, Clinical History Method with the Hoffer Q, and Lankany Flat-K with the SRK/T) predicted between 70% and 85% of eyes within 1.0 D of target refraction. Although the majority of patients can obtain satisfactory visual outcomes using those methods, a significant percentage will still have unacceptable postoperative refractive errors. Warning refractive patients about the increased possibility of postoperative ametropia is important. Particular attention should be given to counseling about the greater likelihood of requiring glasses for both distance and near vision. In circumstances in which there is a wide variability in lens power prediction, it may be prudent to reduce expectations and inform of the options of lens exchange or further laser refractive surgery. Understanding the strengths and limitations of the various calculation approaches will minimize postoperative refractive errors in these eyes.

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