

Intraocular lens power calculation in eyes with previous corneal refractive surgery

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Abstract: Intraocular lens (IOL) power calculation after corneal refractive surgery (CRS) becomes an expanding challenge for ophthalmologists as more and more cataract surgeries after CRS are required. These patients typically also have high expectations as to visual performance. Conventional IOL power calculation schemes frequently provide inaccurate results in these cases. This review aims to summarize and recommend currently available IOL power calculation methods for eyes with the most common CRS methods: radial keratotomy (RK), photorefractive keratectomy (PRK), laser *in situ* keratomileusis (LASIK), and small incision lenticule extraction (SMILE). To this end, biometry measuring methods and IOL formulas will be explained and combinations of both are proposed. In synopsis, it is evident that the latest generation of vergence formulas exhibit favorable IOL power prediction accuracy in post-CRS eyes, even though the predictive precision of methods in eyes without CRS is not attained. Ray tracing computation, intraoperative aberrometry, and machine learning-based formulas hold potential to further improve refractive outcomes in post-CRS eyes.

Keywords: cataract, cataract extraction, corneal surgery, excimer laser, IOL power, IOL power miscalculation, keratometry, LASIK, PRK, refractive surgery, RK, SMILE

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Introduction

The calculation of intraocular lens (IOL) power for patients with prior corneal refractive surgery (CRS) remains a challenging task for ophthalmologists. For the precise prediction of IOL power, generally (1) the axial length of the eye; (2) the corneal refractive power, deduced from its curvature; and (3) the effective lens position (ELP) need to be determined, as the so-called biometry of the eye.¹ This review will describe biometry measuring methods and IOL formulas and will recommend combinations of both, which lead to the precise IOL selection in post-CRS eyes. Furthermore, we will evaluate peer-reviewed literature on the new technology of intraoperative aberrometry (IA).

As described previously, the precise description of corneal refractive power and ELP represent the greatest challenges in post-CRS eyes.² The main

pitfall for the refractive power estimation is the altered relationship between anterior and posterior surfaces of the cornea after CRS, which is not accurately described by the standardized refractive index of a virgin cornea (1.3375). Furthermore, some methods for the measurement of the corneal curvature do not account for the anterior curvature variations within the center area, introduced by CRS.³ Commonly, in myopic post-CRS eyes, these inaccuracies will lead to an overestimation of corneal and to an underestimation of the IOL power to be implanted. To mitigate these errors, practical correction factors and regression formulas for a more precise determination of corneal power have been devised.^{4–6} Furthermore, it is important to understand the evolution of corneal topography measuring methods, which eventually enabled the measurement of the posterior corneal curvature as an essential factor of the total corneal refractive power.

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Commonly, the map, which depicts the corneal curvature, is referred to as corneal topography. A variety of methods have been devised to determine the corneal topography. In keratometry, which was first described more than 100 years ago by von Helmholtz,⁷ the curvature of the anterior corneal surface is measured with four reflected light points, which are oriented on the spherocylindrical corneal surface. Spherocylindricity, however, is only a valid approximation for normal corneas, which limits the use of keratometers in post-CRS eyes.⁸ Photokeratoscopes project a Placido disk to the cornea, and the anterior corneal curvature is calculated from the reflection of the interspaced circles.^{9,10} Photokeratoscopes marketed today include the Atlas 9000 (Carl Zeiss Meditec AG, Jena, Germany). Both keratometry and keratometry only provide information about the anterior corneal surface curvature, which can be converted to total corneal power by using a combined refractive index (1.3375) in normal corneas. In post-CRS eyes, however, additional information about the posterior corneal curvature is essential, since the radii of anterior and posterior curvature do not correspond equally after corneal surgery.^{8,11} Slit-scanning and Scheimpflug imaging represent later innovations, which facilitate the measurement of posterior corneal surface curvatures. In slit-scanning, slit light beams, which are projected through the cornea in defined angles, can yield anterior and posterior curvature as well as corneal thickness after computational analysis.¹² Scheimpflug imaging as implemented in ophthalmic camera systems is based on a rotating camera, which takes images through predefined slits and thereby captures all in-focus images of the anterior segment.¹³ Scheimpflug imaging was demonstrated to have a higher repeatability in measuring the posterior corneal curvature compared with mere slit-scanning.¹⁴ Another imaging technique which has been reported to precisely describe anterior and posterior corneal curvature is optical coherence tomography (OCT), which describes the topography by inferring optical density from the backscatter of emitted infrared light.¹⁵ Finally, IA methods have been developed, which use infrared light and interferometry to measure the optical power of the entire eye during surgery, delivering intraoperative aphakic autorefractive for IOL calculation, which could make preoperative biometry unnecessary.^{16,17}

In classic IOL formulas, the calculation of the ELP, which indicates the position of the IOL

relative to the cornea, is facilitated by utilizing the corneal refractive power. As the corneal refractive power and also anterior chamber depth, however, are altered by CRS,¹⁸ classic IOL formulas lead to inaccurate predictions of the ELP.¹⁹ One way around this pitfall is the use of IOL formulas, which do not utilize corneal power to infer the ELP like the Haigis, Haigis-L, and Shammas.²⁰⁻²² Alternatively, double-K history methods have been developed, in which the corneal power prior to CRS contributes to the ELP prediction and the post-CRS corneal power adds to the IOL power calculation.¹⁹ Moreover, exact measurements of anterior chamber depth are necessary.

As described above, the third essential component for the IOL power calculation is the axial length. In the past, ultrasound biometry, which cannot exactly determine the axial length with reference to the fovea, frequently lead to imprecise IOL power calculations. The advent of optical axial length measurements, applicable on eyes with sufficiently clear natural lens, improved the precision. Such methods are OCT as described above; partial coherence interferometry (PCI), which measures the travel time of infrared light from cornea to retina with interferometry;²³ and optical low-coherence tomography (OLCR), which emits a continuous spectrum of wavelengths and thereby can provide more metrics than PCI.²⁴

Commercialized biometry devices employ different combinations of techniques to measure (a) corneal topography and (b) axial length as evident from the following selection of devices, which are frequently mentioned in this review: IOLMaster 500 (Carl Zeiss Meditec AG, Jena, Germany) (a) automated keratometry and (b) PCI; IOLMaster 700 (Carl Zeiss Meditec AG, Jena, Germany) (a) telecentric keratometry/swept-source (SS)-OCT and (b) SS-OCT; Lenstar (Haag-Streit, Bern, Switzerland) (a) dual-zone keratometry and (b) OLCR; Pentacam (Oculus Optikgeräte GmbH, Wetzlar, Germany) (a) Scheimpflug imaging and (b) PCI.

IOL formulas can be grouped into vergence, ray tracing, and machine learning (ML) formulas. Some formulas have a mixed concept. Vergence formulas like Hoffer Q,²⁵ Holladay,²⁶ Sanders-Retzlaff-Kraff theoretical (SRK/T),²⁷ Haigis,²⁰ Potvin-Hill,²⁸ and Barrett²⁹ use biometry measures in the framework of Gaussian optics to calculate ELP and IOL power. Gaussian optics, however, have been shown to poorly approximate

the optics of the real pseudophakic human eye. In contrast, modern ray tracing methods leverage on the computational power of present computers to exactly calculate the trajectories of all light rays with refractions at each optical surface using Snell's law.³⁰ As it has been reported that the optics of pseudophakic eyes can precisely be measured with ray tracing, novel IOL calculation pipelines based on this technique hold great potential.³¹ One of these pipelines is Okulix (Panopsis GmbH, Mainz, Germany), which can be supplied with input from all common biometry devices (Zeiss, Haag-Streit, Oculus, and others). The Olsen³² formula also uses ray tracing to exactly determine the ELP and to gather information about higher order aberrations in the optical system, which are then integrated with classic biometry measures.

With regard to ML formulas, the Hill radial-basis-function (RBF) formula³³ relies completely on ML, whereas the Kane³⁴ formula features both ML and regression units. Since 2010, the American Society of Cataract and Refractive Surgery (ASCRS) maintains a publicly available online IOL calculator, which features a collection of vergence formulas and which will be referenced in this review (<https://iolcalc.ascrs.org/>).

Radial keratotomy (RK), photorefractive keratectomy (PRK), laser *in situ* keratomileusis (LASIK), and small incision lenticule extraction (SMILE) are the CRS methods, which ophthalmologists will encounter most frequently today and from this time forth, when planning cataract surgery. Therefore, this review highlights IOL power calculation after these CRS procedures. The Medline database was searched electronically using text word synonyms and combinations of 'radial keratotomy', 'photorefractive keratectomy', 'laser in situ keratomileusis', 'small incision lenticule extraction', and 'lens power calculation'. The year of publication was limited to 2010 and onwards. The publication language was limited to English and German. There were 123 articles resulting from our search, which were screened by abstract. In all, 30 articles had relevant information for this article and were evaluated in full-text. Adjunct literature was cited in order to provide background information.

IOL power calculation after RK

RK is a refractive surgery of the cornea for myopia, where radial incisions of the peripheral to

mid-peripheral cornea are performed, which leads to a flattening of the central cornea.³⁵ Early descriptions of the procedure date back to 19th century in Europe; however, it was only widely adopted and refined in the United States and in Europe starting in the 1980s.³⁵ Linear regression analysis showed that there is a significant proportional relationship between the number of incisions and the flattening of both surfaces.³⁶ But anterior and posterior surfaces do not deform in parallel. In fact, flattening is stronger in the posterior than in the anterior corneal curvature, which disqualifies the standard keratometric index for post-RK eyes.³⁶ RK yields acceptable refractive results with 60% of patients within 1 diopter of the intended result.^{35,37} On the other hand, RK can lead to a progressive overcorrection and resulting hypermetropia. As a result of this shortcoming and with the rise of modern laser-based refractive procedures, RK has been used less frequently from the mid-1990s onwards.³⁸ Yet, the patients, who have been operated with RK, will require cataract surgery in the next decades.

In a recent retrospective study, the authors compare the performance of the Haigis with the Barrett True K (no history) formulas in post-RK eyes, and all biometries were measured with the IOLMaster 500 or 700 (Carl Zeiss Meditec AG, Jena, Germany).³⁹ The authors state that the Barrett formula results in a significantly smaller mean arithmetic refractive prediction error (ME) than the Haigis formula (-0.03 ± 0.96 D *versus* -0.29 ± 1.00 D, $p < 0.001$). Yet, there was no significant difference in the mean absolute refractive prediction error (MAE), and the Barrett formula tended to lead to hyperopic results in very flat corneas.³⁹ Another retrospective study comparing different subtypes of the Barrett True K formula with other vergence formulas reported the best results with the Barrett True K (history) formula yielding a median absolute error (MedAE) of 0.275 D.⁴⁰ Of the formulas not requiring pre-RK refraction, the Haigis formula was found to be most accurate (ME = -0.006 D). It was less accuracy reported for the DK-Holladay-IOLM and Potvin-Hill formulas in this study. Corneal topography was determined with a Scheimpflug-imaging Pentacam (Oculus Optikgeräte GmbH, Wetzlar, Germany) and other biometry measures with an IOLMaster 500 (Carl Zeiss Meditec AG, Jena, Germany).⁴⁰ Ma *et al.* not only included a formula purely based on OCT biometry from the RTVue (Optovue, Inc., Fremont, CA, USA), but their study also features accuracy from the

average IOL power on the ASCRS calculator. At 1 month after surgery, comparable MedAEs were reported for DK-Holladay, OCT formula, Barrett True K (no history), and ASCRS average: 0.78 D, 0.74 D, 0.6 D, and 0.59 D. These results point toward the ASCRS average as an accurate calculation method. Biometry for the non-RTVue eyes was determined with the IOLMaster 500 (Carl Zeiss Meditec AG, Jena, Germany).⁴¹ In a similar retrospective study, the authors evaluated the performance of the IOLMaster 700 (Carl Zeiss Meditec AG, Jena, Germany) standard keratometry (K) and total keratometry (TK) methods. In conclusion, they describe no significant difference in MAE between keratometry-based Haigis (0.66 D) and Barrett True K (no history) (0.71 D) versus TK-based Haigis (0.72 D).⁴² Patel *et al.* evaluated the performance of formulas for RK on the ASCRS online calculator, which do not need refraction data prior to RK: DK-Holladay based on IOLMaster (Carl Zeiss Meditec AG, Jena, Germany) biometry (DK-Holladay-IOLM), DK-Holladay based on Atlas (Carl Zeiss Meditec AG, Jena, Germany) biometry (DK-Holladay-Atlas), and Barrett True K (no history) formula. They could report no significant difference for MAE between the methods, respectively (0.95 D, 0.93 D, 0.89 D).⁴³ Potvin and Hill tested an IOL power calculation in post-RK eyes, which is based on Pentacam (Oculus Optikgeräte GmbH, Wetzlar, Germany) Scheimpflug-imaging topography imputed into the DK-Holladay formula. They compared this approach with the performance of Atlas-based biometry and DK-Holladay formula (DK-Holladay-Atlas). They report a MAE 0.7 D of DK-Holladay-Atlas and state no significant difference to the Pentacam method's performance.²⁸ Another study in post-RK eyes compared the new technique of IA with the Optiwave Refractive Analysis (ORA) (Alcon Laboratories, Inc., Fort Worth, TX) system to several vergence formulas, sourcing the biometry data from the IOLMaster 500 (Carl Zeiss Meditec AG, Jena, Germany). The authors report MedAEs as follows, with no statistically significant difference: Barrett True K (no history)=0.34 D, ORA=0.53 D, SRK/T=0.54 D, Hoffer Q=0.51 D, Haigis=0.54 D, and Holladay1=0.44 D. The Barrett True K formula, however, yielded significantly more eyes within ± 0.5 D than SRK/T, Hoffer Q, and Holladay1.⁴⁴ Similarly, Gouvea *et al.* compared the performance of IA measured with the ORA (Alcon Laboratories, Inc., Fort Worth, TX) with the Barrett True K (no history) formula with biometry from IOLMaster 500 or

700 (Carl Zeiss Meditec AG, Jena, Germany). Also, in this retrospective study, no significant difference in MAE could be shown: 0.71 D Barrett True K and 0.89 D IA.⁴⁵

IOL power calculation after PRK and LASIK

Since the advent of excimer laser treatment in refractive surgery in the late 1980s, several distinct procedures employing this technology have been devised. These have predominantly replaced RK as CRS methods.³⁸ The most frequently used procedures have been PRK and LASIK, and therefore, there is an increasing demand for precise IOL power calculations in post-PRK and post-LASIK eyes. In PRK, a mechanical removal of just the corneal epithelium is followed by excimer laser ablation of corneal stroma. In contrast, corneal tissue comprising corneal epithelium and anterior stroma is initially cut and flapped open in LASIK. Subsequently, excimer laser ablation of corneal stroma is performed, and finally, the corneal flap is reinstalled in its initial position.⁴⁶ The mechanism of laser-ablation-induced refractive change is the same in both PRK and LASIK. Myopia correction can be facilitated by central stromal ablation leading to a flattening of the corneal curvature. Hyperopia correction can be accomplished by peripheral stromal ablation resulting in a steeper corneal curvature.³⁸

Wang *et al.* introduced the ASCRS calculator in their 2010 publication and evaluated the predictive precision of the initially included methods. They report that (a) methods using no prior data and (b) methods using the CRS-induced change lead to significantly smaller MAEs than (c) methods incorporating pre-CRS topography and CRS-induced change: (a) Wang/Koch/Maloney=0.66 D, Shammas=0.69 D, Haigis-L=0.65 D, ASCRS mean IOL power=0.57; (b) Adjusted EffRP=0.64 D, Adjusted Atlas 0-3=0.64 D, Masket=0.71 D, Modified Masket=0.62 D; and (c) clinical history=1.1 D, Feiz/Mannis=1.31 D, corneal bypass=1.11 D.⁴⁷ A retrospective study conducted in the same year found the Shammas.cd with Shammas-PL (MAE=0.61 D), the Haigis-L (0.75 D), and the Masket with Hoffer Q (0.48 D) formulas to be least affected by axial length and exhibiting greater accuracy compared to the clinical history method. Furthermore, Shammas and Haigis-L were considered as advantageous as they do not depend upon historical information.⁴⁸ Evaluating a set of eight IOL

power calculation methods, which do not utilize pre-CRS data, Yang *et al.* reported the following MAEs: Holladay 2 FlatK (0.7D), Holladay 2 PCI-K (0.77D), ASCRS-min (0.78D), Wang-Koch-Maloney (0.79D), ASCRS-average (0.84D), Shamma no history (0.85 D), Haigis-L (0.92 D), and ASCRS-max (0.96 D). In this study, biometry data were assembled from the IOLMaster 500 (Carl Zeiss Meditec AG, Jena, Germany), Pentacam (Oculus Optikgeräte GmbH, Wetzlar, Germany), Atlas (Carl Zeiss Meditec AG, Jena, Germany), and Lenstar (Haag-Streit, Bern, Switzerland) and entered into the Holladay IOL Consultant program and the ASCRS calculator. Overall, the authors evaluate the Holladay 2 FlatK method as the most precise IOL calculation method without pre-CRS data. From the ASCRS calculator, the ASCRS-min is described as most accurate.⁴⁹ Another approach is pursued by Rosa *et al.*,⁵⁰ who input correction factor and regression optimized IOLMaster 500 (Carl Zeiss Meditec AG, Jena, Germany) biometry values into the SRK/T formula to achieve a MedAE of 0.55 D. As for RK, Potvin and Hill devised a Pentacam (Oculus Optikgeräte GmbH, Wetzlar, Germany) Scheimpflug-based IOL calculation method for myopic post-PRK and post-LASIK eyes and compared its precision to formulas available on the ASCRS calculator. The biometry data for the ASCRS calculator were gathered by the IOLMaster 500 (Carl Zeiss Meditec AG, Jena, Germany) and the Atlas (Carl Zeiss Meditec AG, Jena, Germany). The Pentacam derived K reading of true net power in the 4.0-mm zone centered on the corneal apex entered into the Shamma no history formula yielded the most precise Pentacam-based output (MAE = 0.63 D), which compared well to the ASCRS-formula-calculated MAEs: Haigis-L = 0.72 D, Shamma = 0.81 D, Modified Masket = 0.83 D, Adjusted Atlas 4.0 mm = 0.78 D, Masket = 0.77 D, Wang-Koch-Maloney = 0.84 D, and History = 1.58 D.⁵¹ In 2015, a study was published, which compared the accuracy of IA ORA (Alcon Laboratories, Inc., Fort Worth, TX) and OCT biometry from the RTVue (Optovue, Inc., Fremont, CA, USA) to the Haigis-L vergence formula in post-excimer laser CRS eyes without historical data. The newer technologies performed similarly to the vergence formula: MAE – 0.34D ORA, 0.39D RTVue, and 0.37D Haigis-L. Biometry data for the Haigis-L formula were collected with the IOLMaster 500 (Carl Zeiss Meditec AG, Jena, Germany).⁵² Also, in 2015, an update to the ASCRS LASIK/PRK calculator was introduced,

newly featuring the Barrett True K (no history) and the OCT-based IOL calculation formula from RTVue (Optovue, Inc., Fremont, CA, USA). This update was triggered by a study, in which the above methods exhibited equal or superior accuracy to other formulas in the ASCRS calculator as reported by MedAE: RTVue = 0.35 D, Barrett True K (no history) = 0.42 D, Wang-Koch-Maloney = 0.51 D, Shamma = 0.48 D, Haigis-L = 0.39 D, and ASCRS-average = 0.35 D. Biometry data other than OCT were assembled with the IOLMaster 500 (Carl Zeiss Meditec AG, Jena, Germany) and the Atlas (Carl Zeiss Meditec AG, Jena, Germany).⁵³ The Barrett True K formula was further validated in myopic post-LASIK/PRK eyes by Abulafia *et al.*, who examined the Barrett True K (history) and (no history) formulas in synopsis with the other formulas on the ASCRS calculator. The Barrett True K (history) formula demonstrated a significantly smaller MedAE than all other formulas with exception of the Masket formula: Barrett True K (history) = 0.33 D, Adjusted Atlas = 0.38 D, Masket = 0.32 D, Modified Masket = 0.48 D, Wang/Koch/Maloney = 0.53 D, Shamma = 0.46 D, Haigis-L = 0.58 D, and ASCRS-average = 0.34 D. In eyes lacking historical data, the Barrett True K (no history) also showed a significantly smaller MedAE (0.41 D) than Shamma (0.53 D) and Haigis-L (0.62 D).²⁹ In the previously cited RK study, comparing the performance of the IOLMaster 700 (Carl Zeiss Meditec AG, Jena, Germany) K and TK methods, also myopic and hyperopic post-LASIK and post-PRK eyes were examined. The following MAEs were reported for myopic (Haigis = 0.72 D, Haigis-L = 0.61 D, Barrett True K = 0.54 D, Haigis-TK = 0.5 D) and hyperopic (Haigis = 0.74 D, Haigis-L = 0.68 D, Barrett True K = 0.71 D, Haigis-TK = 0.7 D) eyes.⁴² Considering that using the ASCRS calculator involves the manual insertion of biometry data into the web-interface, Ferguson *et al.* recently argued that using a biometer-embedded formula, which automatically integrates biometry data and calculates the IOL power, would be advantageous. To this end, they match the accuracy of a biometer-embedded Barrett True K (no history) formula with a multiple formula approach in the ASCRS calculator for post-myopic and post-hyperopic eyes. For post-myopic eyes, the embedded Barrett True K (no history) formula led to the lowest MAE (0.36 D) followed by the Haigis-L formula (0.41 D) from the ASCRS calculator. Likewise, in post-hyperopic eyes, the Barrett True K (no history) formula produced the smallest MAE

(0.41 D), trailed by the ASCRS-average (0.46 D). The authors conclude that the biometer-embedded Barrett True K (no history) method performs equally to the ASCRS multiformula approach, while not involving manual data entry.⁵⁴ In another recent study, the authors used corneal topographies from the Cassini device (i-Optics, The Hague, the Netherlands) plugged into the Haigis formula for IOL power calculations after excimer laser CRS and compared the refractive outcomes with other no history formulas based on IOLMaster 700 topography. They found the following MedAEs for the Cassini Haigis, Barrett True K (no history), and Haigis-L approaches, respectively: 0.34D, 0.34D, and 0.49D.⁵⁵ Gasparian *et al.* investigated the accuracy of the Barrett True K (no history) formula based on IOLMaster 500 or 700 (Carl Zeiss Meditec AG, Jena, Germany) biometry in comparison to IA (ORA Alcon Laboratories, Inc., Fort Worth, TX) in both post-myopic and post-hyperopic LASIK/PRK eyes. The study describes significantly lower MedAE (0.42 versus 0.49 D, $p=0.001$) and MAE (0.51 versus 0.58 D, $p=0.002$) for IA versus Barrett True K (no history). No significant difference, however, for percentage of study eyes achieving a refraction within 0.25 D, 0.5 D, and 0.75 D from the target refraction could be described. Therefore, the authors attribute clinically comparable predictive refractive accuracy to both approaches.⁵⁶

IOL power calculation after SMILE

SMILE as the latest development in the field of laser-ablative CRS has become clinically available in 2011. The technique employs a femtosecond (fs) laser, which in contrast to the excimer laser is capable of dissecting spherocylindrical and aspheric lenticule fragments instead of just planar sections.⁵⁷ In SMILE, the fs laser initially creates a corneal stromal lenticule, without prior flap opening or removal of corneal epithelium. Subsequently, the fs laser introduces a peripheral corneal incision for the extraction of the lenticule, which then is facilitated manually with a forceps. So far, predominantly, myopic patients have been treated with SMILE. Yet, also the potential for correction of hyperopic refraction has been reported.⁵⁷ Compared to LASIK, SMILE mitigates fibrotic response in the corneal stroma⁵⁸ and preserves more of the corneal tissue strength.⁵⁹ Also, SMILE leads to limited damage of corneal nerve fibers and reduced risk of dry eye following CRS.⁶⁰ Given its favorable features, an extensive

application of the technique in the future can be expected, warranting the investigation of post-SMILE IOL calculation.

Luft *et al.* compared the accuracy of formulas listed in the ASCRS calculator to the benchmark of IOL powers calculated with the ray tracing software Okulix (Panopsis GmbH, Mainz, Germany). Biometry for vergence formulas and for the ray tracing software was acquired with a Pentacam HR (Oculus Optikgeräte GmbH, Wetzlar, Germany) and an IOLMaster 500 (Carl Zeiss Meditec AG, Jena, Germany). For history formulas, they report the greatest accuracy for the Masket (MAE = 0.39 D) and Barrett True K (history) (0.44 D) formulas, and for no history formulas, Barrett True K (no history) (0.44 D) and Potvin-Hill (0.42 D) display greatest accuracy, all of which showed no significant difference in accuracy. Significantly worse accuracy was described for Haigis-L (0.58 D), Modified Masket (0.65 D), and Shammas (0.75 D) formulas. The authors recommend the application of the top four formulas together with a ray tracing calculation.⁶¹ In a theoretical prospective study design, IOL power was predicted before and after SMILE with an array of vergence formulas. When the input target refraction is myopic prior to SMILE and emmetropic after SMILE, the predicted IOL powers should be equivalent and can be compared as a measure of prediction stability. In this experimental framework, only the Barrett True K formula demonstrated nonsignificantly different pre and post IOL powers in both eyes with 24–26 mm and >26 mm axial length and was hence described to provide more stable predictions in post-SMILE eyes than the SRK/T, Holladay, and Haigis formulas.⁶² A similar theoretical approach featuring the virtual implantation of the same IOL before and after SMILE was published by Lazaridis *et al.* based on Pentacam HR (Oculus Optikgeräte GmbH, Wetzlar, Germany) and an IOLMaster 500 (Carl Zeiss Meditec AG, Jena, Germany) biometry. The Okulix (Panopsis, Mainz, Germany) ray tracing the software was stated to yield a significantly smaller prediction error compared to Haigis-L, Haigis, Hoffer Q, Holladay 1, and SRK/T formulas.⁶³

Conclusion

In post-RK eyes, for which the pre-RK refraction is known, we would recommend to use the Barrett True K (history) method with biometry provided by IOLMaster 500 or 700 (Carl Zeiss Meditec

AG, Jena, Germany). Yet, since, in many cases, the preoperative refraction values are not at hand, no history formulas have to be considered. In this category, the Barrett True K formula (no history) with biometry provided by IOLMaster 500 or 700 (Carl Zeiss Meditec AG, Jena, Germany) has been shown to more accurately predict IOL power than Potvin-Hill, SRK/T, Hoffer Q, and Holladay formulas. As the Haigis formula with IOLMaster 500 or 700 (Carl Zeiss Meditec AG, Jena, Germany) biometry showed equal accuracy to Barrett True K (no history), these two formulas can be recommended in eyes with no available pre-RK refraction values. New technologies like OCT-based IOL formulas (RTVue Optovue, Inc., Fremont, CA, USA) or IA (ORA Alcon Laboratories, Inc., Fort Worth, TX) have been described to yield neither superior nor inferior results compared to the Barrett True K formula (no history). Also, the ASCRS calculator average has been reported with similar performance to Barrett True K formula (no history). The average value's quality, however, depends on the amount of biometry datapoints provided to the calculator and should therefore be used cautiously.

Similar to post-RK eyes, the Barrett True K (history and no history) with biometry provided by IOLMaster 500 or 700 (Carl Zeiss Meditec AG, Jena, Germany), because of high precision, has evolved to be the standard for IOL power prediction with vergence formulas in post-LASIK and post-PRK eyes during the last few years. This holds true both for post-myopic and post-hyperopic eyes. If Barrett True K is not available, the Haigis-L formula can still be recommended for myopic eyes. Novel advances in technology have made IA (ORA Alcon Laboratories, Inc., Fort Worth, TX) a viable alternative, achieving significantly lower MedAE and MAE than Barrett True K in a recent study. Yet, the required intraoperative technology is expensive. Again, the ASCRS calculator average has been described with similar performance to Barrett True K formula (no history) in post-LASIK and post-PRK eyes, but these results only apply if ample biometry data are collectively inserted into the calculator [e.g. RTVue (Optovue, Inc., Fremont, CA, USA) data plus IOLMaster 500 (Carl Zeiss Meditec AG, Jena, Germany) data plus Atlas (Carl Zeiss Meditec AG, Jena, Germany) data]. As such an aggregate of data will seldomly be available in regular clinic settings, the ASCRS calculator average should be considered with caution on a smaller biometry data basis.

As SMILE has only been employed by clinicians since 2011, sufficient empirical data on IOL power prediction accuracy do not exist. As a broad usage of the technique, however, can be anticipated, the few theoretical studies existent so far are of interest. From these, a favorable accuracy of the Barrett True K (history and no history) and Masket formulas can be inferred. Furthermore, the Okulix (Panopsis, Mainz, Germany) ray tracing software based on Pentacam HR (Oculus Optikgeräte GmbH, Wetzlar, Germany) and an IOLMaster 500 (Carl Zeiss Meditec AG, Jena, Germany) biometry appears to be a precise method to determine IOL power.

In summary, latest generation vergence formulas like the Barrett True K formula have increased the IOL power prediction accuracy in eyes with previous CRS. The predictive precision of eyes without CRS, however, has not yet been reached. Novel techniques like ray tracing computation of biometry data or IA hold the potential to further improve the refractive outcomes in post-CRS eyes. Ultimately, a further implementation of ML-based formulas, which have displayed great accuracy in virgin eyes, appears to be a logical step.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Author contributions

Philipp Anders: Conceptualization; Formal analysis; Methodology; Project administration; Software; Validation; Writing – original draft; Writing – review & editing.

Lisa-Marie Anders: Conceptualization; Formal analysis; Project administration; Validation; Writing – original draft; Writing – review & editing.

Adel Barbara: Conceptualization; Writing – review & editing.

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Achim Langenbacher: Conceptualization; Writing – review & editing.

Zisis Gatzioufas: Data curation; Methodology; Resources; Supervision; Validation; Writing – review & editing.

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