37 Barrett Formulas: Strategies to Improve IOL Power Prediction

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The search for improvements for more accurate methods to improve refractive outcomes began after Harold Ridley's implantation of the first intraocular lens implant (IOL) in 1949 [1]. There were many aspects of Ridley's intraocular lens that were appropriate, including the choice of polymethylmethacrylate (PMMA) as a lens material, placement in the posterior chamber, and even the method of storage with 10% sodium hydroxide for sterilization neutralized prior to implantation. The post-op refraction, however, was −24.00/+6.00 × 30^0 as the calculation of the required IOL power based on the curvature of the implant did not fully consider the refractive index of the IOL and needed significant refinement.

Biometry at this stage was also rudimentary. The corneal curvature could be measured by keratometers based on the Javal–Schiotz keratometer introduced in 1880 [2], but measurement of the axial length (AL) by A scan ultrasound was only introduced commercially in 1970 (Kretztechnik AG) [3]. Optical biometry greatly enhanced the ability to measure AL with greater precision with partial coherence interferometry (PCI) available with the first IOLMaster introduced in 1999 [4].

Automated keratometers based on LEDs were integrated with optical biometers so that the measurement of corneal curvature was now less dependent on the skill of the user and more repeatable. Optical biometers based on swept-source ocular coherence tomography (SS-OCT) [5] such as the IOLMaster 700 introduced in 2014 further improved the accuracy of AL measurements with a reduction in the standard deviation from 25μm to 8 μm. Modern biometers can measure additional parameters such as central corneal thickness (CCT), lens thickness (LT), and corneal diameter (CD) measurements of the corneal limbus more accurately, in addition to the anterior chamber depth (ACD), available with earlier technology.

Improvements in technology have played a key role, but equally important to refractive outcomes, are the formulas required to predict the required IOL for individual patients with the available information from modern biometers.

It was not common in the early decades of IOL implantation to use a standard IOL power, e.g., 18.0 D, or adjust this power by adding the preop refraction multiplied by a factor of 1.25D. The first formula was derived by Fyodorov [6] in 1967 based on Gaussian optics/vergence calculation and was followed by formulas developed by CD Binkhorst (1972) [7], Colenbrander (1973) [8], Hoffer (1974, publ 1981) [9], Thijssen (1975) [10], Van der Heijde (1975) [11], and the regression-based SRK (1981) [12], which introduced the A-constant. These are considered first-generation formulas where the calculated ACD in

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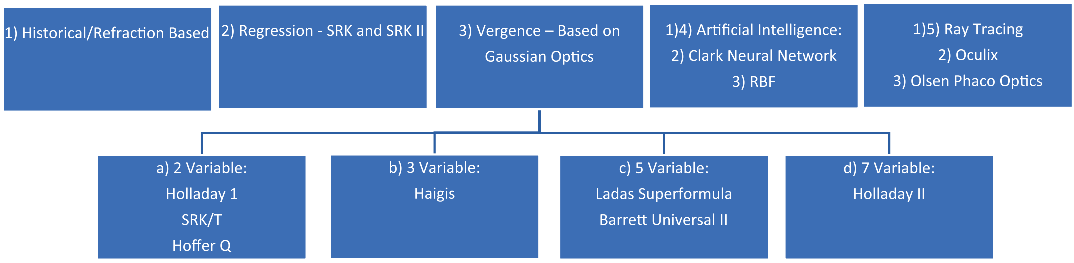

Fig. 37.1 Chart to display the classification of formulas based on the method of prediction

the vergence calculation was not adjusted by any other parameter.

Second-generation formulas were introduced by Hoffer (1982) using the AL to predict the ACD, which was soon followed by R Binkhorst and the SRK II [13] formula. Soon these were followed by the third-generation theoretical formulas using the Al and the K for ACD prediction; the Hoffer Q [14] (1993), Holladay I [15] (1988), and SRK/T [16] (1990).

These formulas were the mainstay of formula prediction for about 25 years until recently when fourth-generation formulas that considered additional parameters such as pre-op ACD and LT were introduced including Barrett Universal (1987) [17, 18], Olsen (1987) [19], Haigis (1990) [20], and Holladay II (1996) [21].

More recent formulas could be considered fifth-generation formulas as they incorporate additional calculation methods including ray tracing and artificial intelligence. These included formulas such as Okulix (2005) [22], Barrett Universal II (2014) [23], Olsen C (2014) [24], Evo (2016), Hill RBF (2016) [25], Pearl DGS (2020) [26], Kane (2019) [27], and Hoffer QST (2020) [28]. The latter list is not exhaustive, and many new formulas have been published in recent years.

Classifying formulas into generations is always controversial as the distinction is somewhat arbitrary, and the date of introduction and grouping is not always sequential. A more logical classification was suggested by an editorial in the *Journal of Cataract and Refractive Surgery* in June 2017 based on the method of prediction [29]. The formulas classified according to the method of prediction are displayed in a chart in Fig. 37.1.

Unfortunately, even this classification has limitations as formulae based on vergence calculations or even ray tracing require a data-driven element to refine the effective lens position (ELP). This component can incorporate artificial intelligence as a strategy to refine the ELP and are therefore, hybrid in nature.

Furthermore, a formula, such as Barrett Universal II, which is a theoretical formula incorporating paraxial ray tracing for the cornea and IOL, uses third-order polynomial regression to refine data-driven refinement of the ELP. The essence of AI whether based on neural networks or similar algorithms relies on the ability of computers to recognize patterns or dependencies, which are not always evident to the individual observer. Some authorities, however, believe that the outcome of AI analysis of large datasets is not distinctive from this statistical method using smaller datasets [30].

Barrett Universal II (BUII)

The reason that the Barrett Universal formula is based on paraxial ray tracing is that this allows the input of custom parameters for refractive index and radii of curvature. This allowed me to calculate the required IOL power for the hydrophilic acrylic IOL I first implanted in August 1983, which was a one-piece foldable lens with an asymmetrical optic and different radii of curvature to conventional PMMA IOLs available at the time [31]. The prediction of the lens position is based on a theoretical model eye I conceived where the ciliary plane is determined as the intersection of an anterior sphere—related to the radius of the cornea—and a posterior sphere—related to the radius of the globe. The lens factor (LF) is the lens constant that indicates the distance from the ciliary plane to the location of the IOL and varies with the lens model characteristics. A relationship between the LF and an equivalent a constant was derived as surgeons are more familiar with the latter value for different IOLs. The radius of the globe (RG) is a difficult parameter to measure, and initially, this was determined empirically and later from actual clinical data using polynomial regression in BUII.

The Barrett Universal II is the core of the Barrett toric calculator [32–34], which incorporates a theoretical model to explain the observed behavior of the posterior cornea based on the ellipticity of the corneal limbus. As such, it differs from a population-based method to derive the posterior cornea, and a unique posterior cornea is calculated for each eye according to the measured parameters.

Similarly, the Barrett True K is based on the BUII with an additional theoretical model to account for the disrupted relationship of the anterior and posterior cornea in eyes that had undergone myopic [35] or hyperopic [36] refractive surgery including RK [37]. Keratoconus is another example where the relationship of the posterior and anterior radii is altered, and more recently, a solution for this condition has been added to the online True K available at apacrs.org [38].

A formula based on paraxial ray tracing treats the IOL as a thick lens, unlike many formulas where the optic is regarded as a thin lens. The BUII calculates the first and second principal planes for the predicted IOL power for an individual eye, which requires relatively complex calculations and iterative solutions. Traditional formulas can typically be condensed to a single line in a spreadsheet, but the BUII requires 750 lines of code in its simplest form and up to 3000 lines of code in the more complex formulas incorporating toric and post-refractive predictions.

Several published studies have compared the BUII to other formulas, and it has been shown to perform well and be equivalent to other top-ranking formulas [39, 40] when targeting emmetropia as well as ametropia in the context of modest monovision [41].

Future strategies to improve IOL power prediction that is worthy of consideration include modifications to biometry, measurements, and the inclusion of additional parameters with existing formulas.

Classical vs. Segmental AL

Traditional pathways to improve ELP power prediction include collecting large datasets and different methods of interpreting the relationship within them. In addition, using the outcome of the first eye undergoing cataract surgery has also proved helpful in refining the outcome of the second eye undergoing cataract surgery [42].

Recent papers have demonstrated that using different refractive indices for each ocular segment as opposed to using a single refractive index can improve the accuracy of traditional formulas such as Holladay 1 or SRK/T. Traditional formulas tend to have a myopic prediction error for short eyes and a hyperopic prediction error for long eyes [43, 44]..

An optical biometer provides an optical path length (OPL) which needs to be transformed into a geometrical path length (GPL) for use in formulas. The average refractive index was derived from the refractive indices of the different segments and then weighted in proportion to the segmented ALs in the Gullstrand model eye.

$$\text{GPL} = \text{OPL} / 1.3549$$

The Classical Axial Length (CAL), as listed in the Partial Coherence Interferometer (PCI) IOLMaster, is adjusted from the GPL calculated with the group refractive index such that it remains compatible with immersion ultrasound.

$$\text{CAL} = \text{GPL} - 1.3033 / 0.957$$

The measured optical path length was transformed by Haigis [45] by the regression equation to be compatible with the AL measured by immersion ultrasound. As the latter is in essence a segmental calculation, the derived geometrical path length (Classical Axial Length) can also be regarded as segmental in nature despite using a group refractive index to measure the optical path length.

The Segmented Axial Length (SAL) is the sum of the GPL of the individual segments calculated using their respective refractive indices:

$$SAL = CCT_{GPL} + AQD_{GPL} + LT_{GPL} + VD_{GPL}$$

Where CCT = Central Corneal Thickness, AQD = Aqueous Depth, LT = Lens Thickness, and VD = Vitreous Depth.

A geometrical path length whether derived from optical biometry in the fashion described above by Haigis for the original IOLMaster and subsequent biometers (CAL), or by considering the individual refractive indices (SAL), relies on assumptions. An empirical adjustment will be impacted by the nature of the original dataset used for this purpose, and the individual refractive indices of the media are assumed values and may vary with the density of a cataract as well as the wavelength of a biometer. Despite these limitations, however, it appears logical for a formula to be optimized according to the method used to derive the AL from the measured optical path length.

The Argos biometer uses segmented AL. Arthur Cummings (Dublin, Ireland) collected a dataset with AL measured by the Lenstar (CAL) and the Argos Biometer (SAL). Using these data, I determined a linear relationship between the two methods of AL measurement:

$$AL_{SAL} = AL_{CAL}{}^{*}0.96 - LT^{*}0.014 + 1.04$$

This is similar but not identical to the modified AL determined by Cooke—CMAL.

$$CMAL = 1.23853 + 0.95855^{*}\,\text{Traditional AL} - 0.05467^{*}\,LT$$

The refractive indices used by the Lenstar are not identical to those utilized by the Argos device, which could explain the differences. Unlike the Lenstar, the Argos biometer uses Gullstrand refractive indices, developed for white light (˜550 nm), and does not scale the refractive indices to the wavelength of the instrument (1060 nm).

The AL calculated using a global refractive index (CAL) is similar to that calculated with segmental AL (SAL) for average eyes but tends to be longer for short eyes and shorter for long eyes [32].

I used the regression formula I derived from Arthur Cummings' data to transform the AL measured by the Lenstar in a series of 5000 eyes to compare the prediction accuracy using CAL or SAL with Holladay 1 representing traditional formulas and BUII. The lens constant was first optimized for both formulas such that the mean error (ME) was zero.

CAL vs. SAL Holladay 1

The MAE for Holladay 1 using CAL was 0.37, and MedAE was 0.287. The percentage of cases predicted within ±0.50 D was 74.8%.

A trend line in a scatter plot graph of the prediction error versus AL showed a left-leaning downward slope with a myopic prediction error for short eyes and a hyperopic error for long eyes.

Using SAL, the MAE and MedAE reduced to 0.35 and 0.276, respectively, and the prediction error within ±0.50 D improved to 75.9%. The trend line in the scatter plot graph of prediction error versus AL was now quite flat.

CAL vs. SAL BUII

The MAE for BUII using CAL was 0.32, and MedAE was 0.25. The percentage of cases predicted within ±0.50 D was 80.2%.

A trend line in a scatter plot graph of the prediction error versus AL showed a relatively flat curve. Using SAL, the MAE was not altered (remaining 0.32) but the MedAE increased slightly to 0.26. The prediction error within ±0.50 D declined to 78.9%. The trend line in the scatter plot graph of prediction error versus AL sloped downward to the right indicating a trend to hyperopic outcomes for short eyes and myopic outcomes for long eyes.

The comparison confirmed, the previously published data by Cooke et al. and Li Wang et al., that while the use of SAL improved the prediction error and removed AL prediction bias for traditional formulas, it actually diminished the prediction accuracy for more modern formulas such as BUII and Olsen This is because the modern formula that performs well has been optimized for CAL and the algorithms correct for AL bias.

This poses a quandary for a surgeon's selection of formulas when using a biometer such as Argos, which utilizes SAL. I, therefore, derived a version of BUII optimized for this Sum of Segments method.

The EyeSuite software on the Lenstar OLCR machine has research export file capabilities, which can provide the optical path length for the segments as an "air" value. The formula was derived from 17,000 eyes with this data, and the segmented AL was calculated from the optical path length using the same refractive indices as the Argos device. In order to maintain consistency with conventional IOL constants, the SAL AL was offset so the average SAL and CAL were equal—the difference in short and long ALs between SAL and CAL was preserved by this strategy. The optimization was derived using the actual radii of the single model SN60WF IOL, but the derived formula is intended to be used with the default biconvex model used in the existing BUII formula.

Validation of BUII SAL (Barrett True AL Formula)

The new formula based on SAL (Barrett True AL) was validated in a dataset of 595 eyes who had biometry performed with the Argos biometer shared by John Shammas. The Shammas validation dataset was not used in any fashion in the derivation or optimization of the Barrett True AL formula.

1. The standard BUII formula based on CAL was compared to four traditional formulas—Haigis, Hoffer Q, Holladay 1, and SRK/T.
2. The standard BUII formula based on CAL was then compared to the new Barrett True AL Formula based on SAL including subgroup analysis of short (<= 22.5 mm) and long eyes (> = 25.5 mm).

The IOL implanted in all cases was the Alcon SN60WF. An optimized constant was calculated for each formula such that the ME was 0.00 D. IOL constants for all formulas were optimized in this analysis. The constant for this dataset is somewhat higher for all formulas, e.g., the optimized a constant for SRK/T was 119.24. This may indicate a shorter refracting lane than 6.0 m, which is not common in the USA, but the refraction was not adjusted in this analysis.

The error in prediction for each formula was calculated, and the ME, SD, MAE, MedAE, as well as the percentage of cases within ±0.25 D, ±0.50 D, ±0.75 D, and ± 1.00 D determined using an excel spreadsheet. The results are listed in Tables 37.1, 37.2, 37.3, 37.4, and 37.5 for BUII (CAL), Haigis, Hoffer Q, Holladay 1, and SRK/T formulas, respectively.

A scatter plot of prediction error vs. AL was constructed for each formula with a linear trend line to evaluate whether significant bias existed

Table 37.1 ME = mean error, SD = standard deviation, MAE = mean absolute error, MedAE = median absolute error, and percentage of cases within intervals for BUII (CAL) formula

BUII (CAL)	% within D	ME	SD	MAE	MedAE
<±0.25 D	47.90%	0.0	0.376	0.310	0.260
<±0.50 D	80.54%				
<±0.75 D	96.98%				
<±1.00 D	99.50%				

Table 37.2 ME = mean error, SD = standard deviation, MAE = mean absolute error, MedAE = median absolute error, and percentage of cases within intervals for Haigis formula

Haigis (CAL)	% within D	ME	SD	MAE	MedAE
<±0.25 D	42.86%	0.0	0.408	0.330	0.298
<±0.50 D	77.82%				
<±0.75 D	93.45%				
<±1.00 D	99.16%				

Table 37.3 ME = mean error, SD = standard deviation, MAE = mean absolute error, MedAE = median absolute error, and percentage of cases within intervals for Hoffer Q formula

Hoffer Q (CAL)	% within D	ME	SD	MAE	MedAE
<±0.25 D	46.05%	0.0	0.410	0.333	0.287
<±0.50 D	74.79%				
<±0.75 D	93.11%				
<±1.00 D	99.33%				

Table 37.4 ME = mean error, SD = standard deviation, MAE = mean absolute error, MedAE = median absolute error, and percentage of cases within intervals for Holladay 1 formula

Holladay 1 (CAL)	% within D	ME	SD	MAE	MedAE
<±0.25 D	45.04%	0.0	0.388	0.322	0.281
<±0.50 D	77.98%				
<±0.75 D	96.30%				
<±1.00 D	99.83%				

Table 37.5 ME = mean error, SD = standard deviation, MAE = mean absolute error, MedAE = median absolute error, and percentage of cases within intervals for SRK/T formula

SRK/T (CAL)	% within D	ME	SD	MAE	MedAE
<±0.25 D	43.03%	0.0	±0.408	0.337	0.297
<±0.50 D	75.13%				
<±0.75 D	94.79%				
<±1.00 D	99.66%				

between these parameters The graphs are displayed in Figs. 37.2, 37.3, 37.4, 37.5, and 37.6 for BUII (CAL), Haigis, Hoffer Q, Holladay 1, and SRK/T formulas, respectively.

Comparison of Standard BUII Formula Based on CAL to Haigis, Hoffer Q, Holladay 1, and SRK/T

BUII has the lowest error in prediction in terms of MAE and MedAE as well as the percentage of cases with a prediction error within ±0.50 D. The trend line, however, for the scatter plot graph of prediction error versus AK slopes downwards to the right indicating a significant relationship which is atypical for this formula when analyzing datasets based on CAL.

The scatter plot is similar to the Haigis formula. The trend line for prediction error vs. AL is typically flatter with the Haigis formula than Hoffer Q, Holladay, and SRK/T formulas when comparing formulas in a dataset based on CAL.

Comparison of Standard BUII Formula Based on CAL to the New Barrett True AL Formula Based on SAL

The prediction accuracy for BUII (SAL) listed in Tables 37.6 and 37.7 is maintained for long eyes and improves for short eyes compared to BUII (CAL) in Tables 37.6 and 37.7—the most impressive feature is the flat trend line in Fig. 37.7, which suggests the potential for improved accuracy with larger datasets.

Classical formulas with only basic optimization such as Holladay 1 improved their prediction with SAL as compared to CAL as demonstrated previously with flattening of the curve in prediction error vs. AL with SAL.

Using a biometer based on SAL, however, could potentially have an adverse impact on more sophisticated formulas as they already have a relatively flat curve of prediction error vs. AL over the range of ALs encountered clinically.

This is evident in a comparison of the outcomes in the Shammas dataset comprising eyes measured with the Argos device. The formulas can be refined in the future with actual Argos data, but the present derivation appears to resolve the issues of using formulas optimized for classical ALs with a sum of segments-based AL such as the Argos device.

The trend line of the Barrett True AL formula based on SAL (Fig. 37.7) is flat unlike the bias evident using the BUII formula based on CAL (fig. 37.2).

The optimized constant for the true AL formula (SAL) was LF = 1.972 versus LF = 1.99 for the standard BUII (CAL), indicating that no change in the IOL constant is required when using the new formula.

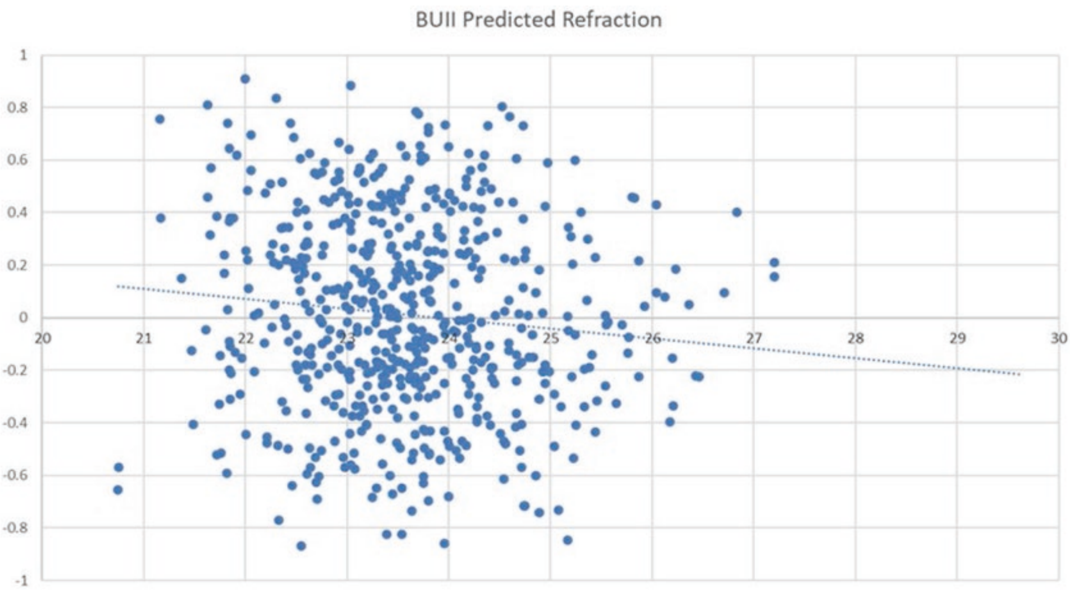

Fig. 37.2 Scatter plot of prediction error vs. AL for BUII (CAL) formula

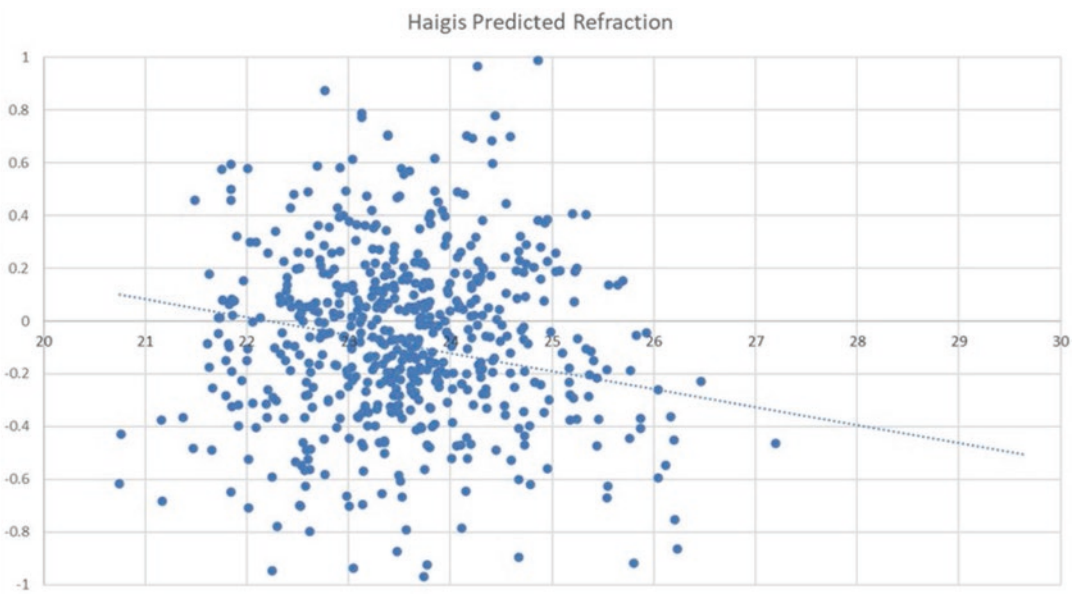

Fig. 37.3 Scatter plot of prediction error vs. AL for Haigis formula

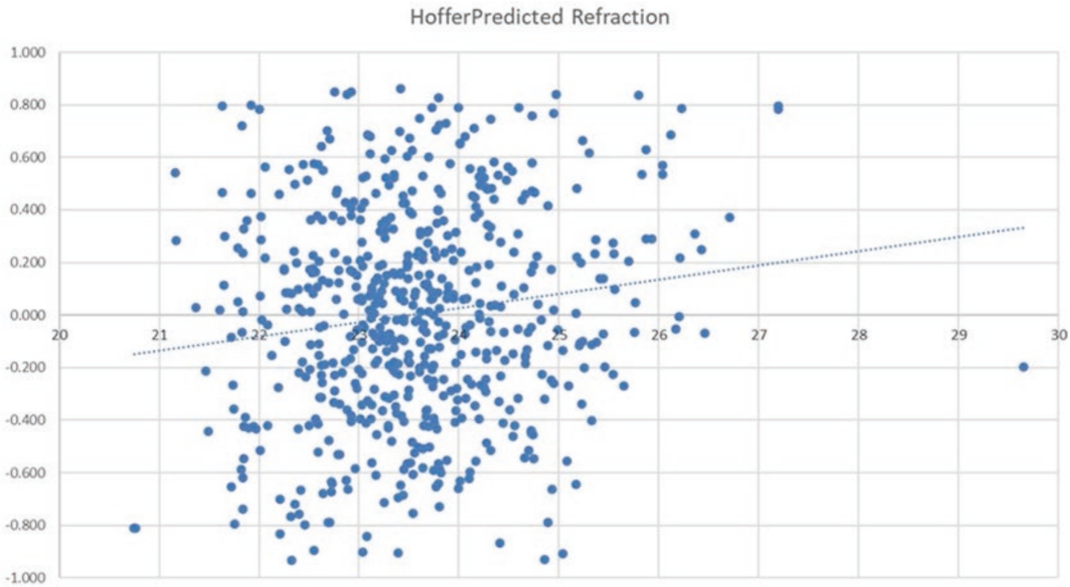

Fig. 37.4 Scatter plot of prediction error vs. AL for Hoffer Q formula

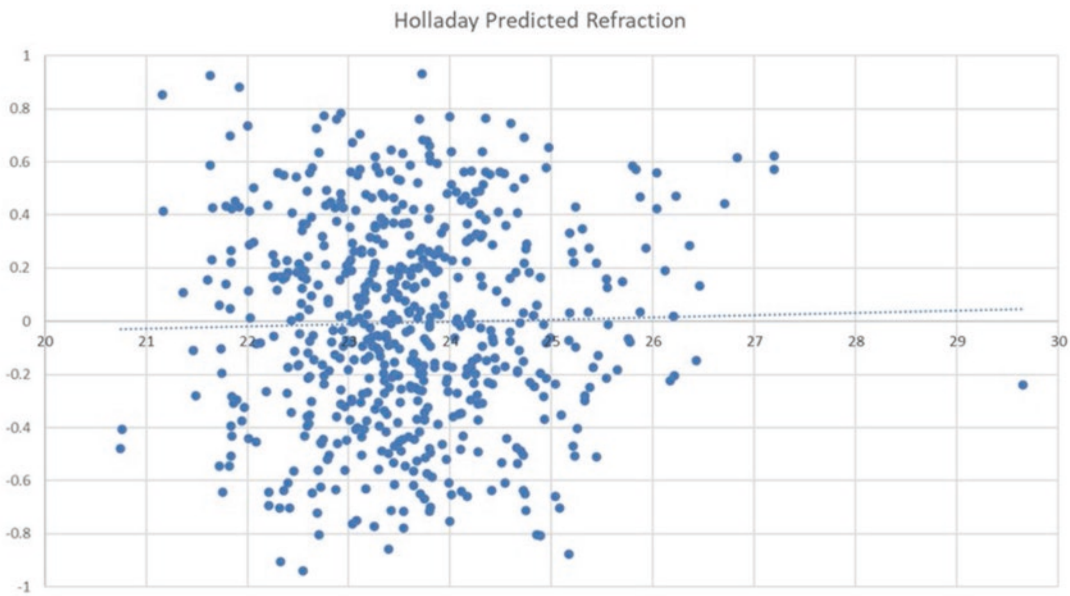

Fig. 37.5 Scatter plot of prediction error vs. AL for Holladay 1 formula

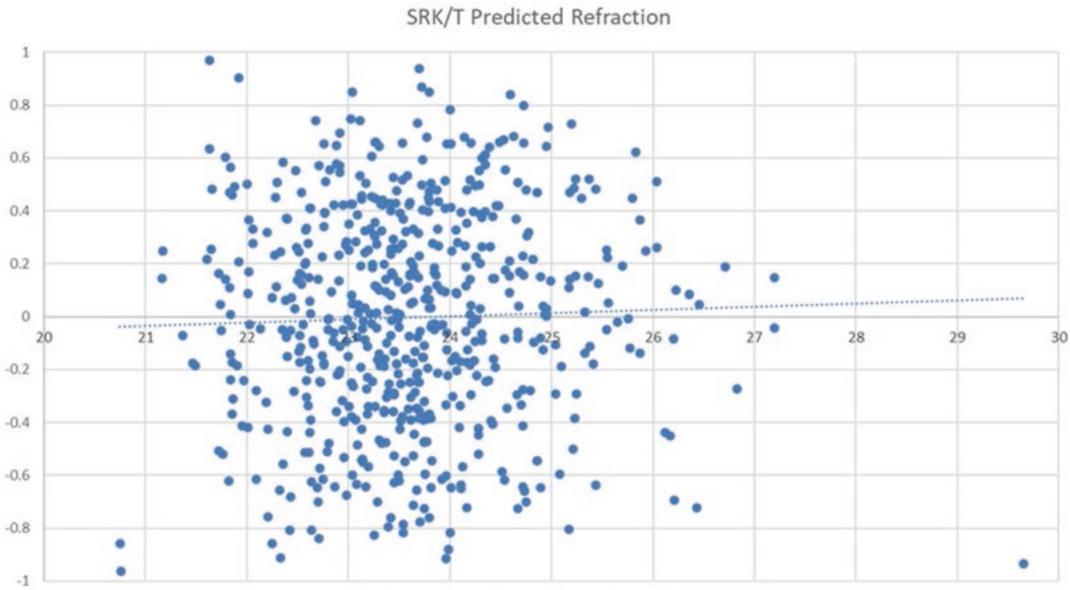

Fig. 37.6 Scatter plot of prediction error vs. AL for SRK/T formula

Table 37.6 ME, SD, MAE, Med.AE, and percentage of cases within intervals for BUII (CAL) formula grouped according to axial length

BUII (CAL) No of eyes 595 Lens factor = 1.972	All eyes (*n* = 595)	Short eyes <= 22 mm (*n* = 43)	Average eyes > = 22 mm < = 25 mm (*n* = 495)	Long eyes > 25 mm (*n* = 57)
Mean prediction error	0.01	0.12	0.01	−0.067
Standard deviation	0.380	0.440	0.371	0.341
Mean absolute prediction error	0.310	0.391	0.306	0.275
Median absolute error	0.260	0.380	0.255	0.225
Maximum absolute error	1.135	1.040	1.135	1.090
% < =0.25 D	47.90%	34.88%	48.08%	56.14%
% < =0.50 D	80.50%	67.44%	80.61%	89.47%
% < =0.75 D	96.98%	90.70%	97.58%	96.49%
% < =1.00 D	99.50%	97.64%	99.80%	98.25%

Table 37.7 ME, SD, MAE, Med.AE, and percentage of cases within intervals for BUII (SAL) formula grouped according to axial length

Barrett true axial length (SAL) No. of eyes 595 Lens factor = 1.972	All eyes (*n* = 595)	Short eyes <= 22 mm (*n* = 43)	Average eyes > = 22 mm < = 25 mm (*n* = 495)	Long eyes > 25 mm (*n* = 57)
Mean prediction error	−0.008	−0.077	0.002	−0.048
Standard deviation	0.37	0.41	0.37	0.32
Mean absolute prediction error	0.305	0.361	0.305	0.264
Median absolute error	0.264	0.317	0.261	0.224
Maximum absolute error	0.996	0.863	0.996	0.857
% < =0.25 D	48.40%	37.21%	48.89%	52.63%
% < =0.50 D	80.34%	72.09%	80.00%	89.47%
% < =0.75 D	96.97%	95.35%	97.17%	96.49%
% < =1.00 D	100.0%	100.0%	100.0%	100.0%

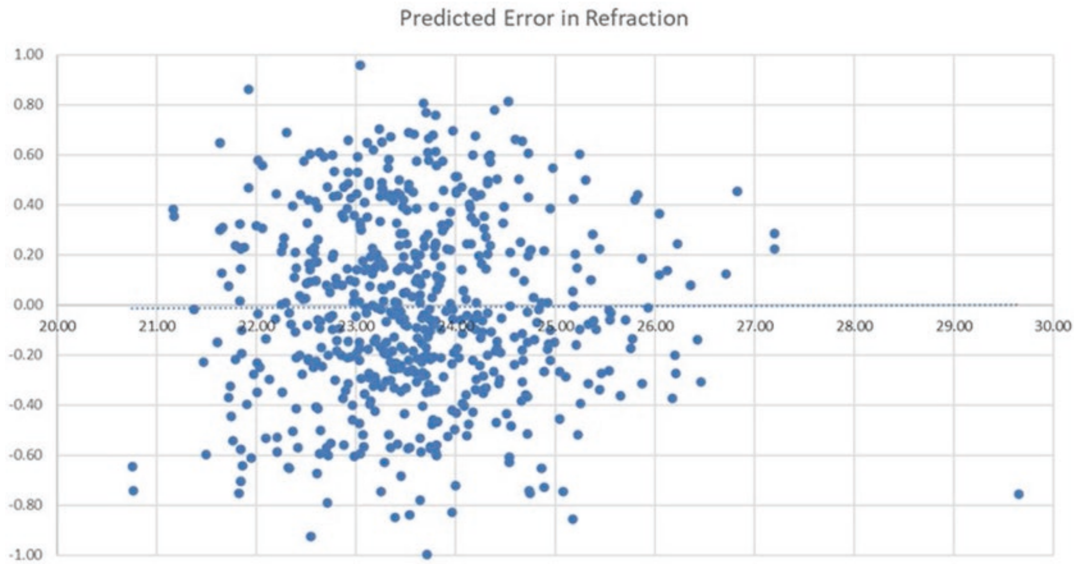

Fig. 37.7 Scatter plot of prediction error vs. AL for BUII (CAL) formula

Summary

The prediction accuracy is maintained for long eyes and improves for short—the most impressive feature is the flat trend line, which suggests improved accuracy with larger datasets.

Classical formulas with only basic optimization such as Holladay improved their prediction with SAL as compared to CAL as demonstrated previously with flattening of the curve in prediction error vs. AL with SAL.

Using a biometer based on SAL, however, could potentially have an adverse impact on more sophisticated formulas as they already have a relatively flat curve of prediction error vs. AL over the range of ALs encountered clinically.

This is evident in a comparison of the outcomes in the Shammas dataset comprising eyes measured with the Argos device. The formulas can be refined in the future with actual Argos data but the present derivation appears to resolve the issues of using formulas optimized for classical ALs with a sum of segments-based AL such as the Argos device.

Measurements

In 2008, Sverker Norrby [46] identified postoperative intraocular lens (IOL) position, postoperative refraction determination, and preoperative AL as the major sources of error contributing to errors in prediction after cataract surgery.

Improvements in the accuracy of optical biometry more recently with swept-source OCT and improved formulas have reduced the impact of these factors although subjective postoperative refraction remains a confounding factor in comparing outcomes. Variability in keratometry remains an important source of error in predicting spherical outcomes, particularly astigmatism, following cataract surgery, and arguably now should be listed as the most important factor.

I compared the repeatability of measuring AL, corneal power, and astigmatism on two separate biometers on the same visit in 144 consecutive eyes during routine pre-op biometry on the same day.

The axial difference in mm was converted to diopters by multiplying by 2.5 to facilitate a comparison of the impact compared to keratometry measured in diopters. The mean difference in AL between the two devices was −0.02 D with a SD of ±0.05 while the MAE was 0.038 and MedAE was 0.025 D. A scatter radar plot superimposed on a target is a useful method to demonstrate the repeatability of measurements and shows how consistent AL measurements have become when measured by two different modern biometers.

The mean difference in keratometry between the two devices was −0.01 D with an SD of ±0.15 while the MAE was 0.10 and MedAE was 0.07 D. The standard deviation of the measurements is greater than AL measurements, but the radar scatter graph demonstrates that the difference in mean Ks is within ±0.25 D for the majority of eyes.

The mean vector difference in magnitude of the cylinder between the two devices was −0.56 D with an SD of ±0.57 while the MAE difference magnitude of the cylinder was 0.55 D and MedAE was 0.41 D. The centroid difference in the measured astigmatism between the two devices was −0.10 D @ 79.2°. The difference between the x and y values of each vector displayed in a double-angle plot demonstrates that the differences in corneal astigmatism vary more widely than the mean K or AL between different devices.

Measures such as using Warren Hill's validation criteria are helpful and are optimizing the corneal surface, but measuring corneal astigmatism is not always repeatable. I have developed a K calculator, which is an integral part of the online Barrett toric calculator for deriving a vector mean or median K when measuring corneal astigmatism from different devices for toric IOL calculations. In a study of 128 patients, the median K of three devices provided the most accurate prediction as it de-emphasizes outliers. The improvement for spherical prediction was modest but the improvement in predicting post-op residual astigmatism was up to 10% and clinically significant [47, 48]. This is why I use the K calculator within the online Barrett toric calculator using three different devices, IOLMaster, Lenstar, and Pentacam to select the sphere and toric cylinder recommendation in all cases.

Additional Parameters

Originally formulas utilized AL and K as the primary measured ocular parameters to predict intraocular lens power. These remain the most important parameters whether the formula is based on vergence calculations, data-driven regression, or artificial intelligence. Pre-op phakic ACD measured from the corneal vertex (epithelium) to the anterior surface of the lens is also correlated to determine the effective lens position of an IOL and was included in the Haigis formulas and most recent formulas. The so-called aqueous depth (AQD) does not include the corneal thickness and is equally useful as a measured parameter to improve outcome prediction. The contribution of different factors can be identified using statistical correlation and preoperative LT, horizontal CD, and CCT all show a relationship to prediction error. These parameters can be included in a formula and the Holladay II uses up to 7 parameters. The BUII can utilize up to 5 parameters including pre-op ACD, LT, and horizontal CD but can also be used with only AL and K [49].

The utility of the additional parameters is evident in the analysis of 287 consecutive eyes by considering the MAE and MedAE as well as the percentage of eyes with a predicted outcome within ±0.50 D.

The error in prediction reduces with the inclusion of additional parameters. A graph of the percentage of eyes with a prediction error within ±0.50 D vs. the number of parameters demonstrates improved prediction accuracy with ACD and LT as additional parameters but the trend line plateaus indicate less impact with the addition of horizontal CD.

Gender, ethnicity, age, and pre-op refraction are other demographic factors that are correlated with the prediction of refractive outcomes that can be considered for inclusion to improve the prediction of formulas. Gender appears to be the most relevant as female eyes tend to have a more myopic prediction error than male eyes for short ALs and a hyperopic outcome for long eyes compared to male eyes is evident in the analysis of large datasets [50]. Even if the data used for formula refinement is not considered separately, a gender bias may still be evident as the representation of gender is unequal in the age group undergoing cataract surgery due to factors such as the longevity of females over males. Deriving separate data-driven algorithms for male and female eyes is likely to improve outcomes.

Many formulas use a thin lens model and do not take into account the change in the principle plane that occurs with different IOL powers. Ray tracing including paraxial ray tracing such as BUII uses a thick lens model and allows the lens parameters to be calculated for each lens power predicted. Ideally, this calculation could include the actual lens parameters such as the radii of curvature or asphericity as these vary with different manufacturers. The impact of individual IOL parameters will have a greater impact on shorter eyes and using actual radii should improve prediction accuracy in this context. Specific IOL parameters are proprietary and are not generally known so assumptions such as an equi-biconvex model can be utilized. In addition, IOL-specific regression such as the Haigis triple optimization is another route to address this aspect of IOL prediction.

New Parameters

Improvements in technology have enabled us to measure anatomical parameters that were not feasible with earlier optical biometers and ultrasound. Scheimpflug tomographers have been able to measure the posterior cornea as have more recent optical biometers based on a swept-source OCT. Direct measurement of the posterior cornea rather than using an estimate based on an assumed value of the keratometer index or even the Gullstrand ratio in the paraxial equation for corneal power may potentially improve spherical and astigmatic refractive outcomes following cataract surgery.

Typically, a new total corneal power is provided by devices or biometers that measure the corneal power such as "True Net Corneal Power" or "Total Keratometry." These measurements may not be equivalent as there is no standard with regard to values such as the refractive index of the cornea or aqueous that may be used in these equations. Furthermore, unless the measurement is adjusted to be compatible with the traditional Gullstrand ratio, the lens constants that users have been accustomed may not be appropriate. Formulas utilize corneal power in a variety of ways including the actual vergence calculation as well as the prediction of the actual IOL position. A customized formula is required to utilize the new parameter, and the issue is accounted for within the online Barrett formulas in that it allows the user to enter the measured posterior cornea rather than the total corneal power. The formula is incorporated into biometers such as the IOLMaster 700 where it is referred to as the Barrett TK. If the measured PCA option is selected, then the posterior cornea values PK1 and PK2 from the IOLMaster or the equivalent posterior cornea values from the Pentacam can be entered. The measured posterior corneal power will then be used for the sphere and toric prediction, which is equivalent to the Barrett TK on the IOLMaster 700. The online formulas require a user to select the instrument by which the posterior cornea has been measured, and the algorithm is adjusted accordingly. In addition, the formulas recognize that not all unexplained astigmatism after cataract surgery is due to the posterior cornea and contains additional algorithms to compensate for factors such as lens tilt. For unusual corneas such as keratoconus or post-refractive cases, the improvement in prediction is significant.

Post-Refractive Formulas

I developed the True K formula, which is based on BUII in order to improve outcome prediction in eyes that have had previous refractive surgery. The formula utilizes the history of the refractive change due to the procedure but can also be used if this information is not available. Compensation for the double K issue where a different K is required for the vergence calculation than that for the prediction of the IOL position is incorporated within the formula. An algorithm for the change in corneal thickness that may occur in certain refractive procedures is also included within the formula. The True K has proved to be effective for patients who have undergone myopic LASIK when the refractive history is known and when no history is available as published in 2016. In a publication in the JCRS in 2018, the True K formula proved to be accurate for patients who had undergone laser correction for hyperopia, and the True K has been shown to be accurate when compared to other methods for RK as published in ophthalmology in 2019. The online True K has a distinctive feature that allows the user to enter the most recent pre-cataract surgery refraction, which has not been impacted by nuclear sclerosis-induced myopia without the preop refraction. This is different than PRK or LASIK where both the pre- and post-refractive procedure refraction is required for the entered refractive history to be taken into consideration. This improves the accuracy in prediction for post-RK eyes as the progressive hyperopia, which may be considerable, is taken into account in the prediction of the IOL power required post-RK.

More recently in version 2.5, a solution for keratoconus is provided within the True K of the online True K formula on the APACRS website. The cornea is steep and irregular within the keratoconus, which is one of the reasons for imprecise measurements particularly in relation to the pupil and visual axis. The most important reason for poor prediction in keratoconus, however, is the altered relationship between the posterior and anterior cornea not dissimilar to post-refractive surgery but in its own unique fashion. This latter relationship is addressed in the True K option for keratoconus by a predictive algorithm or direct measurements of the posterior cornea.

The most accurate method of prediction within the True K formula appears to be a recent modification that allows the True K to incorporate the measured posterior cornea, the so-called True K TK. Similar to the toric, when the measured posterior cornea option is selected, a new page appears where you select the device used and enter the measured posterior cornea values listed within the IOLMaster 700 as the PK1 and PK2 values or corresponding values from other devices such as Scheimpflug devices that are also able to measure the posterior corneal power or radius.

Lawless and co-workers published a relatively large series of their patients consisting of 72 eyes that had undergone previous myopic or hyperopic refractive surgery. Their results confirmed that the True K with the inclusion of the posterior cornea provided the most accurate and repeatable option in both myopic and hyperopic patients undergoing cataract surgery without prior refractive information [51].

An important issue that is not widely appreciated is the need for a custom toric calculator when selecting a Toric IOL in an eye that has undergone previous refractive surgery. The theoretical assumptions within standard toric calculators to predict the posterior cornea or population-based regression methods are no longer valid in the context of toric IOL prediction after cataract surgery.

The True K Toric Calculator was designed specifically for toric prediction post-refractive surgery and, in version 2.0, can now be used with the predicted posterior cornea or a measured option for posterior corneal astigmatism (PCA). In addition, the True K Toric calculator now includes the K calculator, which allows the user to enter up to three different values for the anterior cornea and then calculates a new integrated K or median vector, which is used for the calculation. This is particularly helpful when the Ks of different devices vary, which is not unusual in eyes that have undergone refractive surgery.

The default mode for the True K Toric is the theoretical PCA but I have found that utilizing the measured posterior cornea from SS-OCT provides greater accuracy not only for spherical prediction as previously mentioned but also for toric prediction particularly when no refractive history is available.

In a small series of 28 eyes from my own patients, the method that provided the greatest percentage predicted within ±0.50 D was the True K Toric calculator utilizing the measured posterior cornea from an SS-OCT device.

Formula for Unexpected Refractive Outcome

Managing an unexpected refractive outcome after cataract surgery can be daunting. Corneal refractive surgery or a lens-based solution can be considered whether by exchanging the implanted lens, adding a piggyback, or rotating an existing toric IOL. There are several formulas that can provide some of the required calculations such as the rule of thumb for spherical power, Holladay R for Lens exchange, Astigmatism Fix or Assort for lens rotation, and the vergence formula for the required piggyback IOL but sourcing these different formulas can be confusing.

I, therefore, developed the Barrett Rx (Asia-Pacific Association of Cataract and Refractive Surgeons (APACRS)), which can be used to provide a solution for each of these scenarios in a single formula. The default mode for the Rx is the ELP mode. Here, the actual effective lens position or ELP is calculated from the post-op refraction and used as the basis for the vergence calculation. Alternatively, the IOL mode can be selected, and here, the IOL constant for the implanted lens model is used to determine the ELP. The latter is preferred when the problem is not the ELP prediction but rather due to an abnormal cornea, for example, post-refractive surgery, or a suspected case of lens power mislabeling.

The implanted IOL power and post-op refractions need to be entered including the actual alignment if this is a toric IOL. The lens constant of the implanted lens and that of the planned IOL exchange are also required. It is important to note that the optical ACD and lens thickness are the phakic preop parameters and not the post-op measurements.

Once the data are entered, select calculate and then Rx exchange IOL to display the recommended spherical IOL, toric cylinder, and alignment required for an IOL exchange targeting the desired post-op refraction.

Selecting Rx piggyback on the top menu to display the alternative piggyback IOL, once again both spherical, toric power, and alignment.

Finally look at either the bottom of the IOL exchange or piggyback page, and the Rx formula will display a graph and let you know where to rotate the existing lens for the minimum residual astigmatism.

The Rx is a comprehensive formula that provides the required calculations to manage an unexpected refractive outcome in terms of IOL Exchange, piggyback lens implantation, or toric IOL rotation with both an ELP and IOL option to determine the expected ELP [52].

There are many studies comparing the prediction accuracy of different formulas. One of the most recent comparing 13 formulas was published by Savini et al.,

this year in the BJO [53]. All the modern formulas performed well, and the standard deviation was lowest with BUII. There was certainly no discernible difference in the accuracy of formulas and the method of derivation whether by Gaussian optics or artificial intelligence.

Isaac Newton in his famous book on natural philosophy and mathematics noted that what we know is a drop and what we do not know is an ocean. I would add that when it comes to modern IOL calculations, we should use every drop of knowledge available.

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