OPEN

Update on Intraocular Lens Formulas and Calculations

Tina Xia, MD, Christine E. Martinez, MD, and Linda M. Tsai, MD

Abstract: Investigators, scientists, and physicians continue to develop new methods of intraocular lens (IOL) calculation to improve the refractive accuracy after cataract surgery. To gain more accurate prediction of IOL power, vergence lens formulas have incorporated additional biometric variables, such as anterior chamber depth, lens thickness, white-to-white measurement, and even age in some algorithms. Newer formulas diverge from their classic regression and vergence-based predecessors and increasingly utilize techniques such as exact ray-tracing data, more modern regression models, and artificial intelligence. This review provides an update on recent literature comparing the commonly used third- and fourth-generation IOL formulas with newer generation formulas. Refractive outcomes with newer formulas are increasingly more and more accurate, so it is important for ophthalmologists to be aware of the various options for choosing IOL power. Historically, refractive outcomes have been especially unpredictable in patients with unusual biometry, corneal ectasia, a history of refractive surgery, and in pediatric patients. Refractive outcomes in these patient populations are improving. Improved biometry technology is also allowing for improved refractive outcomes and surgery planning convenience with the availability of newer formulas on various biometry platforms. It is crucial for surgeons to understand and utilize the most accurate formulas for their patients to provide the highest quality of care.

Key Words: artificial intelligence, biometry, ectasia, ray tracing, vergence formulas

(*Asia Pac J Ophthalmol (Phila)* 2020;9:186–193)

Success of modern-day cataract surgery is increasingly defined by the refractive outcome, and refractive surprises are a common reason for intraocular lens (IOL) exchange. With improving surgical equipment and biometry technology, precise preoperative planning and IOL selection are required and expected.[1–3] The ongoing development in IOL power formulas incorporates new technology and data science to improve the accuracy of IOL selection.

From the John F Hardesty MD Department of Ophthalmology and Visual Sciences, Washington University in St. Louis School of Medicine, St. Louis MO
Submitted March 3, 2020; accepted April 4, 2020.
This work was supported by an unrestricted grant from Research To Prevent Blindness (Ny,NY) to the John F. Hardesty MD Department of Ophthlamology ad Visual Sciences at Washington University.
Correspondence: Linda M. Tsai, John F Hardesty MD Department of Ophthalmology and Visual Sciences, Washington University School of Medicine, 660 S. South Euclid Avenue, Campus Box 8096, St. Louis, MO 63110. E-mail: tsai@wustl.edu.

ISSN: 2162-0989
DOI: 10.1097/APO.0000000000000293

IOL formulas began to be formalized in the 1960s to 1970s. Fyodorov introduced an early formula based on the principles of theoretical refractive vergence to predict the IOL power that would allow the refracted image to fall on the retina.[4] The formula was based on 3 variables that could be extracted from biometry data: axial length (AL), corneal refractive power (K), and the calculated (postoperative) anterior chamber depth (ACD). Even though the Fyodorov formula was used for anterior chamber IOLs, it highlighted a key idea of the need to predict where the IOL will rest after surgery. We see this as a recurrent theme in the subsequent vergence lens formulas, as each new modification aims to better predict the postoperative lens position within the eye, commonly referred to as the effective lens position (ELP).[5–7]

Over time, formulas have changed and evolved. Increasingly the categorization by "generation" is giving way to categorization based on derivation. These derivations fall into the following groups: historical/refraction based, regression, vergence, ray tracing, and artificial intelligence. Historical and regression formulas [first and second generation IOL formulas like Sanders, Retzlaff, Kraff (SRK), Binkhorst, Hoffer and SRKII], with rare exceptions, are mostly considered out of date. Third- and fourth-generation formulas attempt to determine the ELP by taking more biometry factors into account. Ray tracing is a promising option that has proven to be especially accurate in the context of the Olsen formula. IOL formulas derived from artificial intelligence may have an even higher lens power prediction accuracy and are growing in popularity.

This review will briefly summarize the commonly used regression and vergence formulas, and subsequent updates and modifications. Newer approaches to IOL calculations will be discussed and the results of recent studies comparing the refractive outcomes of various lenses in different patient populations.

VERGENCE FORMULAS

Vergence formulas are based on Gaussian optics. In many commonly used vergence formulas, the estimation of ELP is incorporated into the various lens constants used in the calculation.[8] The lens constants vary with each IOL model, depending in part on the lens material, geometry, and its previously observed behavior when implanted into the eye. At the same time, surgeons can, and are encouraged to, optimize these lens constants to control for systematic errors such as small differences in biometry machines, surgical technique, and even patient factors.[3] The intent of optimization is to mathematically mold a specific formula to best predict the correct IOL power for a desired refraction, for a specific eye.

The various vergence formulas take into account up to 6 biometry parameters, and therefore the accuracy of these formulas depend on obtaining accurate preoperative biometry. Many of these biometry measurements can now be obtained in single biometry machines and platforms, which simplifies the IOL calculation and selection process. Furthermore, newer imaging modalities, such as using swept-source optical coherence tomography, improve the repeatability of biometry measurements.[9–11]

Over time, regression-based derivations have been incorporated into each new generation of formulas to better model the refractive behavior and outcomes of IOLs in eyes with a variety of anatomical dimensions.

Third-Generation Formulas

The widely used third-generation equations, SRK/T, Hoffer Q, and Holliday 1, developed from a series of modifications and updates as more knowledge was gained about how IOL power changes with the varying ALs and corneal curvature of the eye. The first generation of IOL formulas relied on a single, fixed constant for ACD based on the IOL type, such as the A-constant in the first SRK formula.[12] Expectedly, this formulation led to large errors in the predicted refraction. Second-generation formulas, such as the SRK II and Hoffer (predecessor to the Hoffer Q), introduced changes to the ACD constant as a function of AL.[13,14] Both of these early-generation formulas were regression-based and are no longer used.

As larger numbers of cataract refractive results were systematically collective and analyzed, third-generations lens equations evolved with more complex theoretical mathematical derivations to incorporate biometry data into predicting the IOL power. The SRK/T equation combined a theoretical mathematical model with empirical regression to optimize the ACD, to modify the retinal thickness and the corneal refractive index.[15] Several studies have shown that the SRK/T formula is more accurate than the other third-generation formulas in longer eyes, generally AL >26.0 mm.[16–20] Personalizing the SRK/T requires optimizing the A-constant of the equation, and Aristodemou et al suggest that about 150 to 250 eyes are needed for optimization.[21]

Holladay 1 and Hoffer Q lens formulas similarly require only the 2 variables of AL and keratometry for IOL power calculation. Both these formulas propose optimization of equation constants for more accurate prediction of ELP. Holladay broke down the ACD into the corneal thickness, distance from corneal endothelium to iris plane, plus distance from iris to IOL position. This latter quantity, not known preoperatively, is termed the "surgeon factor" and is a constant that varies with lens type and requires optimization.[6,12] Hoffer Q introduces another method of calculating ACD and recommend optimization of this personalized ACD.[12] In essence, the third-generation formulas attempted to express mathematically the positive relationship between ACD and AL.

Many studies have compared the different IOL formulas to assess which one is more accurate, and for which eye characteristics. In the medium AL range, the third-generation formulas generally were equally as accurate in their IOL calculations. In an analysis of >13,000 surgeries with SN60WF and SN60AT lens, all formulas, including the third generations, had prediction errors within 0.1D of the predicted refraction when used for medium length eyes (AL 23–25 mm).[18] Moving outside of this range, the prediction errors begin to diverge widely among the formulas. A few other studies demonstrate similar overall mean absolute error for SRK/T, Holladay 1, and Hoffer Q, with a slightly lower absolute error for Holladay 1.[17,22] Segregating by AL, the Hoffer Q is generally more accurate for shorter eyes.[12,16] Although the third-generation formulas are still widely used and referred to during preoperative planning, newer formulas, with improved accuracy, are becoming increasingly more popular.

Fourth-Generation Formulas

Although corneal keratometry and AL are the traditional cornerstone variables for calculating IOL power, there are inherent limitations in using only two anatomic parameters to determine the ELP. Subsequent IOL formula updates incorporated additional patient variables or equation modifications to further decrease the prediction error in the formulas and thus improve refractive outcomes.

The Haigis formula introduced three independent constants, termed a0, a1, and a2, into the equation to mathematically change the IOL power prediction curve, adding more flexibility to the formula.[23] All three of the constants can be optimized via linear regression to increase the prediction accuracy of the function. In the Melles et al's analysis, the Haigis formula demonstrated low variability in prediction error across the range of AL (21–28 mm) and ACD (2.25–4.25 mm) analyzed, suggesting that the Haigis formula may be good for a wide range of eyes.[18] In the same study, prediction error from the Haigis was largely within 0.125D, but tended to be hyperopic errors as the AL moved to the ends of the spectrum.

Regression analysis based on actual postoperative results was also used to derive the T2 formula, which is an update to the SRK/T formula, to decrease systematic error from the estimation of corneal height. In Kane et al's study of 3241 patients, the T2 formula had the lowest absolute error when used for AL 24.5 to 26 mm. T2 also had lower absolute error compared with SRK/T, Hoffer Q, and Holladay 2, whereas another study demonstrated similar results between the T2 and Haigis.[17,24] Although the T2 improved on the SRK/T, the formula still has the limitations of being based on 2 variables.

The Holladay 2 algorithm expanded the number of parameters used in its IOL power calculation to 7 variables: AL, keratometry, ACD, white-to-white measurement, lens thickness (LT), preoperative refraction, and age.[6,22,25] Based on prediction errors, this formulation appears to be most accurate in short to medium length eyes, but may not be a significant improvement from Holladay 1. Hoffer, in a 2000 study of about 300 eyes, showed that Holladay 2 was more accurate than Holladay 1 and equal to Hoffer Q in short eyes <22.0 mm, but not as accurate as Holladay 1 and other formulas in other AL categories.[20] Results from Melles et al also showed very similar absolute error values between Holladay 1 and 2, with a trend toward better accuracy for Holladay 1. This brings to question whether the additional effort of obtaining the added parameters indeed yields more accurate results.

The Barrett Universal II is becoming accepted as one of the most accurate IOL formulas in use today, contributing to its increasing popularity among surgeons. The formula is based on a theoretical model eye and retains the positive correlation of AL and keratometry to ACD.[5] Perhaps what contributes to the accuracy of the Barrett is the incorporation of the principle plane of the IOL into the formula, although the actual derivation of the formula has not been published. In several comparison studies, the Barrett Universal II consistently yielded the most accurate power calculation compared with the SRK/T, Holladay 1, Hoffer Q, T2, Haigis, and Holladay 2.[17,18,24] When compared with its newer-generation peers, the Barrett continues to perform well over a wide range of biometry values.[26] Importantly, the Barrett Universal II is able to maintain its accuracy across a wide range of ALs and ACD, a contrast to earlier formulas. In Melles et al's study, 50% of refractive predictions from the Barrett were within the spherical equivalent of 0.25D from the true refraction; this was the highest percentage compared with other IOL formulas in the study.[18] The Barrett also had the smallest percentage of eyes with >1.00D prediction error. Overall, studies have shown that the Barrett Universal II has the least refractive surprise compared with earlier, established formulas. Of the third- and fourth-generation formulas, the Barrett Universal II may be becoming the modern standard for IOL power calculations. But, as will be discussed in the following section, newer methodologies are being applied to IOL calculation and demonstrate additional opportunities for further improvement in refractive accuracy.

Wang-Koch Adjustment

Very long eyes pose a challenge to accurate IOL calculation. A Wang-Koch (WK) adjustment can be applied to some third- and fourth-generation IOL formulas to optimize the calculation for AL >25 mm.[27] For the Holladay 2 formula, adding AL adjustment can improve the accuracy of the lens calculation. In a recent study of nearly 11,000 eyes, the AL-adjusted Holladay 2 formula achieved the same absolute error as the Barrett Universal II and was better than Holladay 1 and the third-generation formulas; this provides validation for the WK adjustment.[22] When applied to other IOL formulas, the WK adjustment has yielded differing results, improving the accuracy of some formulas while worsening the error in others. The adjustment seems to improve Holladay 1, and shifts the hyperopic errors at longer ALs to more myopic errors, which one can argue is a more desirable outcome of the 2.[18,28] Overall, the effect of the WK adjustment is to shift refractive outcomes in long eyes from hyperopic to myopic, and can be considered as an adjunct to the use of the Holladay 1, Hoffer Q, SRK/T, and Haigis formulas in long eyes. However, the Barrett is still the more accurate formula.

NEWER IOL FORMULAS

Modifications are still being made to vergence-based IOL formulas for improved lens power accuracy. At the same time, newer formulas based on novel derivation methods have been introduced in the last decade with promises of improved accuracy.

Ray Tracing Calculations

As opposed to vergence-based equations, the Olsen formula uses both exact and paraxial ray tracings of optical light through the refractive media in the eye, including the specific optics of a particular IOL, to derive the postoperative position of that lens.[29–31] This principle was simplified into the C constant in the formula, which mathematically relates the center of the IOL to the preoperative ACD and LT. In the Olsen formula, the lens constant is no longer related to AL and corneal power but to the characteristic of the crystalline lens and the dimension of the anterior chamber. Perhaps because ray tracings are more precise and specific than theoretical formulas, Olsen showed that fewer number of surgical cases are needed to validate or optimize the C constant.[7,30] This is certainly an attractive characteristic of the Olsen, allowing surgeons to get to accurate results with fewer number of surgical cases. An earlier 2009 study comparing the Olsen ray tracing formula with Haigis, Hoffer Q, and Norrby formulas showed no significant improvement with the Olsen.[32] However, as will be discussed in the following section, other large-scale studies have supported the accuracy of the Olsen formula compared with other newer-generation calculations.

Artificial Intelligence

The Hill-radial basis function (RBF) calculator is a new method of IOL calculation that uses artificial intelligence and regression analysis of a very large database of actual postsurgical refractive outcomes to predict the IOL power.[33,34] Using the method of pattern recognition, the algorithm may be able to account for undefined factors in IOL power calculation that cannot be modeled with vergence or ray-tracing equations. At the same time, because the Hill-RBF is based mainly on empirical data, its accuracy is limited by the type of data and eye characteristics from which it is derived. For example, if the anatomic characteristics of a particular eye do not match with many of the eyes in the Hill-RBF database, then the IOL prediction will be less accurate, and the calculator will acknowledge this limitation by showing an out-of-bounds notification.[35] Naturally, the algorithm continuously evolves as increasing numbers of surgical results are incorporated into the data set, to improve power prediction for a wider range of eye characteristics. In fact, Hill-RBF 2.0 has been released, which is derived from a larger data-set with expanded "in-bounds" biometry ranges.

The Kane formula is another new IOL formula that incorporates artificial intelligence with theoretical optics for IOL power prediction. The required parameters are AL, corneal power, ACD, sex, and an A-constant.[36] LT and central corneal thickness are optional parameters but can increase the formula accuracy further. Two comparison studies from Kane have shown that the Kane formula has less absolute error compared with the older generation and newer IOL formulas, including Barrett Universal II, Olsen, and Hill-RBF.[22,36] In the 2020 study of 10,930 eyes, the Kane formula was the most accurate formula for all ranges of ALs, with the smallest absolute error for long eyes, AL >26.0 mm.[22]

Results from that same study also showed that the Barrett Universal II had larger overall mean absolute errors compared with the Olsen formula and Hill-RBF (2.0 version) calculator, and was comparable with the AL-adjusted Holladay 2 formula. However, when analyzed by different categories of AL, the Barrett had less error than Olsen and Hill-RBF 2.0 in long eyes (AL >26.0 mm) and is equivalent to the Olsen for medium eyes (22.0–26.0 mm). An earlier study had compared the Barrett Universal II with Hill-RBF version 1.0, and found the Barrett to be overall more accurate, in contrast to the Darcy et al's study.[34] This nicely demonstrates that with expansion of the Hill-RBF database, the calculator can improve its accuracy in IOL power prediction.

The Ladas formula introduces another novel approach to IOL calculation. It is known, from many validated studies, that different IOL formulas perform more accurately for certain eye dimensions. The Ladas formula works by combining the most accurate portions of the IOL formulas to make a "super formula."[37] Depending on the AL or corneal power of the patient, this super formula will choose, among the available formulas, the most ideal one to use. The formulas incorporated into the Ladas are SRK/T, Hoffer Q, Holladay 1, Holladay with WK adjustment, and the

Haigis. For AL <21.49 mm, the Hoffer Q was used. For AL >25 mm, Holladay 1 with WK adjustment was used, and for all other eyes, Holladay 1 was applied. The formula has evolved to be a more accurate with the help of complex deep learning techniques and artificial intelligence. One published study has compared the Ladas formula with the newer IOL formulas.[34] Ladas was less accurate than the Barrett Universal II (except in the short AL group) and Holladay 1, but was more accurate than Hill-RBF v1.0. Since the Ladas formula only helps select the optimal formula to use for a particular eye, it still needs a lens constant, which can be optimized per the surgeon.

IOL formulas are developed to best predict the behavior of IOLs in the eye, chiefly by attempting to predict the ELP. Newer IOL power calculators are applying big-data science and computational methodologies to achieve better IOL power prediction and also hopefully to simplify the IOL selection process.

CHALLENGES FOR IOL CALCULATION FORMULAS

Despite advances in surgical technique, biometry measurements, and IOL calculations, certain clinical cases remain challenges to physicians when choosing the current IOL power. Some of these special circumstances include corneal ectasias, post-refractive eyes, and pediatric eyes. The barriers to consistent and accurate IOL calculation include instability of the eye dimensions, and inaccurate or difficult biometry measurements, especially keratometry. Facing these challenges, investigators have attempted to find the best IOL calculations for these complex clinical cases.

Corneal Ectasias

Patients with corneal ectasias, such as keratoconus, pellucid marginal degeneration, and post-refractive ectasia, are challenging clinical cases not only because of the irregular astigmatism of the cornea, which makes accurate keratometry measurements difficult and less reliable, but also due to the possibility of disease progression and instability of the cornea, which may inevitably increase refractive error. For some patients with severe corneal ectasia, improved refractive outcomes may be best achieved by timing cataract surgery after penetrating keratoplasty. When a patient is deemed to be appropriate for cataract surgery, the challenge in IOL calculation is obtaining accurate and reproducible biometry measurements. Keratometry is likely the source of the biggest error in IOL calculations for corneal ectasia patients.[38] The keratometry is often irregular or high K values, making the estimation for the effective corneal power difficult to calculate.

Among keratometry devices, the reproducibility of measurements in keratoconus is best with the Pentacam because it incorporates posterior corneal curvature.[39] The Pentacam also tends to measure flatter keratometry values when compared with optical biometry and its use therefore may help avoid hyperopic outcomes. When aiming for plano, it is best to choose a myopic refractive target for these patients because essentially all formulas on average result in hyperopic outcomes. It is also important to keep in mind the potential future need for penetrating keratoplasty in eyes with severe keratoconus because choosing a lower power IOL could leave them significantly hyperopic after corneal transplantation.

However, as corneal curvature increases to the extreme, all biometry devices decrease in their reproducibility. Because of decreased predictability in severe keratoconus, one author proposed the use of a standard K value (43.25D) instead of a very high actual K value.[40] For advanced keratoconus (mean central keratometry readings >53.0D), the authors of this review article prefer to utilize standardized K values or utilize the Barrett formula and aim at least 3 diopters more myopic than the actual targeted refractive outcome. There is a tendency for hyperopic errors in keratoconus patients. One can reason that the high K values, especially in severe keratoconus, may overestimate the central effective corneal power, leading to underestimation of IOL power and therefore a more hyperopic error.

There is a lack of extensive studies comparing performance of IOL formulas in corneal ectasias. In one early study from 2007, Thebpatiphat et al[41] compared SRK, SRK II, and SRK/T for calculation of nontoric IOL power in keratoconus patients. SRK II had the least prediction error in IOL power compared with the other 2 methods, for both standard keratometry and topography-derived keratometry. In other studies, the SRK/T was found to have the smallest absolute error when compared with other formulas such as SRK II, Haigis, HofferQ, and Barrett Universal II.[42–44] A more recent article from Wang et al with 73 eyes compared SRK/T, Hoffer Q, Holladay I and II, Haigis, and Barrett Universal II, and demonstrated that for mild and moderate keratoconus, the Barrett Universal II had the smallest prediction error. For severe keratoconus, all formulas performed poorly but Haigis had the smallest error.[45] Overall, all formulas tended to yield hyperopic errors and become increasing unpredictable at higher K values. The differing results from study to study may be due to their small patient numbers because the results can easily be influenced by significant differences in the patient characteristics, such as the average AL of the study population or proportion of patients in each category of keratoconus severity.

Currently, there are no studies on applying the newer artificial intelligence-based algorithms to corneal ectasias. This may be a promising area of further study to increase accuracy of cataract surgery in these patients.

Post-Refractive Surgery Patients

Post-refractive eyes pose a challenge to vergence-based IOL calculations because the anterior corneal power is altered by the procedure. The increased discordance between anterior and posterior corneal curvatures then leads to ELP calculation errors when the measured anterior keratometry values are input into IOL formulas without modification. Hyperopic surprise is the norm in these cases unless accommodations are made to account for the history of refractive surgery. Factors that impact calculations include the type of corneal refractive surgery done, the availability of preoperative keratometry or refractive data, can affect the prediction of the IOL formula, and inclusion of various keratometry measurements, such as simulated-K value (Sim-K), central corneal keratometry, or topography-based corneal keratometry.[46,47] Many different formulas have been proposed to address the varying combinations of the above scenarios.

For radial keratotomy (RK), an incisional refractive surgery, there is no clear consensus on the optimal method of obtaining biometry data or the best IOL formula. It has been suggested that using mainly the central measurements of corneal power (eg, central 3.0 mm) can yield more accurate results than using wider radius measurements.[46,48] This method of estimating postrefractive corneal power resulted in fairly accurate IOL calculation when used with Double-K applied to Holladay 1. In a recent study of 52 post-RK eyes, the accuracy of 7 IOL formulas was compared, including Barrett True K (based on Barrett Universal II) with preoperative history, Barrett True K with partial history, Barrett True K with no history, Double K Holladay 1, Potvin-Hill and Haigis.[47] Of note, the authors specifically used the RK algorithm of the Barrett True K formula. The Barrett True K with preoperative refractive history had the lowest median absolute error. Additionally, if no history was available, the Barrett True K without history still performed better than Double K Holladay, Potvin-Hill, and Haigis.

For laser-assisted in-situ keratomileusis (LASIK)/photorefractive keratectomy (PRK) eyes, several different methods of IOL calculation have been published, differing in the type of biometry data used or the correction factors related to amount of refractive change from the laser procedure. The Masket formula uses SRK/T or Hoffer Q for myopic or hyperopic patients, respectively. Then, the resulting IOL power is adjusted by knowing the surgically induced refractive correction.[49] The Maloney method incorporates the preoperative anterior and posterior, and post-LASIK, or PRK anterior corneal power is added to calculate the adjusted post-refractive corneal power. This method can be used if preoperative information is not available by using a mean posterior corneal power. In one study, the Maloney method had small variance in IOL power prediction but tended to overestimate the lens power.[50] The Shammas formula adjusts the postrefractive corneal power by the postrefractive keratometry and has been shown to yield accurate results even in eyes without historical data.[51–53] The Haigis-L formula is another formula that does not require historical keratometry data, in part because it relies more on the ACD, which should not change with refractive surgery. The Haigis-L does have corrections for whether the refractive surgery was for hyperopic or myopic eyes. The Barrett True K formula can also be used for post-LASIK/PRK and can be used with or without historical keratometry data. A 2016 study demonstrated that the Barrett True K formula had a smaller absolute error and variance in prediction error and was compared with the Shammas, Haigis-L, Maloney, and Masket.[52]

The American Society of Cataract and Refractive Surgery (ASCRS) calculator (https://iolcalc.ascrs.org) has become a valuable resource for suggesting IOL powers based on multiple postrefractive calculations (ie, adjusted Atlas, Masket, modified-Masket, Wang-Koch-Maloney, Shammas, Haigis-L, Galilei) for all postrefractive surgery patients. The typical result is a range of IOL powers. The authors of this review article prefer to choose a higher-power lens from among this range to decrease the likelihood of a hyperopic outcome. There is no clear consensus on the best formula to use for post-RK or post-LASIK/PRK eyes, but the Barrett True K formula holds promise for being a reliable formula. The Asia-Pacific Association for Cataract and Refractive Surgeons (APACRS) website (http://calc.apacrs.org/Barrett_True_K_Universal_2105/) has an online calculator. As larger number of postrefractive patients are studied and newer technology, such as ray-tracing, are incorporated into IOL algorithms, there can be established guidelines on which formulas to use in postrefractive patients to achieve accurate and consistent cataract results.

Pediatric Patients

Pediatric patients undergoing cataract surgery requires careful clinical assessment and planning. Clinicians have to take into account that the pediatric eye will continue growing in size until teenage years, until gradual slowing of the rate of growth. General practice for pediatric cataract surgery is for the patient to be left aphakic if younger than 1 year, with placement of lens at a later time.[54] A randomized, controlled trial in children 1 to 6 months of age comparing lensectomy with contact lens use versus primary IOL insertion did not show differences in visual acuity at 1 year but the IOL group did have more secondary surgeries.[55] When IOL placement is appropriate at time of lensectomy, surgeons purposely choose a hyperopic correction to factor in the growth of the eye with time. Various studies have proposed a scale of undercorrection depending on patient's age at the time of cataract surgery.[56–58]

Studies have compared different IOL formulas for pediatric patients, but have shown different results depending on the study. Even more so than adult eyes, pediatric eyes are prone to large IOL prediction errors because of their very small size and ALs. As discussed in earlier sections, all IOL formulas tend to increase in their margin of error as they are used for ALs at the extremes. The Aphakia Treatment Study group compared Hoffer Q, Holladay1, Holladay 2, SRK II, and SRK/T for pediatric patients.[59] SRK/T had the lowest mean prediction error and also had the highest percentage of eyes within 1.0D of predicted (46%), which was similar to Holladay 1 (44%). In another study, SRK/T and Holladay 2 had the lowest prediction error compared with Holladay 1 and Hoffer Q.[60] At the same time, other studies found no significant differences in performance between SRK II, SRK/T, Holladay, and Hoffer Q in pediatric patients.[61–63] One recent study of 20 Saudi pediatric patients included the Barrett Universal II and Olsen formulas in its comparison with the formulas mentioned above. Both the Barrett and Olsen had larger prediction error compared with all other formulas except for the Haigis; SRK II was most accurate in this study.[64] This study had a small number of patients, but seems to suggest that the newer generations of IOL formulas may not have improved accuracy for pediatric patients. There is room for continued improvement in more reliable IOL prediction for children to improve their quality of life.

DISCUSSION

IOL power calculations continue to improve and evolve at a rate that can seem difficult to keep pace with for the average ophthalmologist. Staying abreast of new formulas is increasingly important in this era of "refractive cataract surgery" involving multifocal, extended depth of focus, and accommodating IOLs. As we employ the latest technology in artificial lenses, biometry, surgical technique, phacoemulsification machines, and operating microscopes, it is also crucial to utilize the most accurate and updated IOL formulas for our patients.

The potential for accurate refractive outcomes within a half-diopter and a diopter of the refractive target has improved from 55% and 85% with SRK/T in 2007 to better than 80% and 95% respectively with newer-generation formulas in recent years.[26,18,65] For example, the SRK/T formula has been popular with many ophthalmologists for >30 years, but performs particularly poorly in eyes with flat or steep keratometry values.[26]

Out of the current third- and fourth-generation formulas, the Barrett Universal II may be becoming the modern standard for vergence IOL power calculations. The Olsen ray tracing formula has been suggested to be more precise than the theoretical based vergence formulas, but seems to be less commonly used. Artificial intelligence-based IOL selection such as the Hill-RBF and the Kane have algorithms that will continuously evolve as increasing data are incorporated. The release of the Hill-RBF 2.0 has shown greater accuracy and expanded ranges for anatomic parameters than its first generation. As ophthalmologists struggle with determining the best method for IOL selection, it would be most reasonable to compare their most accurate, optimized vergence method with $\geq$1 of the newer methods. This is an especially good idea for patients with unusual biometry such as long or short ALs, or flat or steep keratometry.

IOL calculations are also particularly problematic in patients in whom accurate keratometry measurements are difficult to obtain. In corneal ectasia and keratoconus for example, it may be best to use the Pentacam, if available, to obtain the most reproducible corneal measurements and then to aim for a myopic refractive target. Various IOL calculations have been compared without a clear winner, although newer studies suggest the Barrett Universal II to be a strong performer, except in situations of advanced keratoconus, whereas the Haigis formula had the smallest error.[38,44] In patients who have a history of refractive surgery, third-generation formulas are particularly prone to hyperopic outcomes after refractive surgery because they assume a fixed ratio of the anterior and posterior corneal curvatures. The ASCRS online calculator is a helpful and commonly used resource for ophthalmologists performing cataract surgery in post-refractive eyes. There is no clear consensus on the best formula to use for post-RK or post-LASIK/PRK eyes, but the Barrett True K formula found on the APACRS website has been shown to be as accurate, and perhaps more reliable, than the other vergence formulas. Newer formulas such as ray-tracing and artificial intelligence algorithms have great potential to further improve accuracy in this challenging subsection of patients.

Pediatric patients are prone to postsurgical refractive surprises due to their very small ALs. Newer formulas and methods may not be more accurate than older formulas, and there is much room for improving the accuracy of IOL selection. This is a reminder that although refractive outcomes in eyes with, and without, special circumstances continue to improve, it still remains essential to counsel these patients carefully preoperatively.

CONCLUSIONS

IOL selection for cataract surgery is more accurate than ever due to advances in biometric measurements and also in novel methods of IOL power calculation. Additionally, IOL formulas are becoming more accessible to practitioners as more formulas are incorporated into the biometry machines for easier data input. Theoretical formulas can be optimized to achieve very accurate results, but each formula tend to perform better in some eyes compared with others. Newer IOL formulas and IOL updates attempt to generate a single algorithm that would yield accurate results across a large range of eye dimensions. The Barrett Universal II, although based on vergence principles, has achieved consistently accurate results across a wide range of ALs. At the same time, large-scale computational algorithms show promise for further improved accuracy. As IOL formulas continue to evolve and gain validation, ideally, they can also be applied accurately to IOL calculation for diseased eyes and special clinical cases, making good refractive results a possibility for a greater number of patients.

REFERENCES

1. An Y, Kang EK, Kim H, Kang MJ, Byun YS, Joo CK. Accuracy of swept-source optical coherence tomography based biometry for intraocular lens power calculation: a retrospective cross-sectional study. *BMC Ophthalmol*. 2019;19:30.
2. Mylonas G, Sacu S, Buehl W, Ritter M, Georgopoulos M, Schmidt-Erfurth U. Performance of three biometry devices in patients with different grades of age-related cataract. *Acta Ophthalmol*. 2011;89:e237–e241.
3. Sheard R. Optimising biometry for best outcomes in cataract surgery. *Eye (Lond)*. 2014;28:118–125.
4. Fyodorov SN, Galin MA, Linksz A. Calculation of the optical power of intraocular lenses. *Invest Ophthalmol*. 1975;14:625–628.
5. Barrett GD. An improved universal theoretical formula for intraocular lens power prediction. *J Cataract Refract Surg*. 1993;19:713–720.
6. Holladay JT, Gills JP, Leidlein J, Cherchio M. Achieving emmetropia in extremely short eyes with two piggyback posterior chamber intraocular lenses. *Ophthalmology*. 1996;103:1118–1123.
7. Olsen T. Calculation of intraocular lens power: a review. *Acta Ophthalmol Scand*. 2007;85:472–485.
8. Kent C. “Another step closer: lens constant customization”. *Rev Ophthalmol*. 2010. Available at: https://www.reviewofophthalmology.com/article/another-step-closer-lens-constant-customization.
9. Akman A, Asena L, Gungor SG. Evaluation and comparison of the new swept source OCT-based IOLMaster 700 with the IOLMaster 500. *Br J Ophthalmol*. 2016;100:1201–1205.
10. Elbaz U, Barkana Y, Gerber Y, Avni I, Zadok D. Comparison of different techniques of anterior chamber depth and keratometric measurements. *Am J Ophthalmol*. 2007;143:48–53.
11. Kunert KS, Peter M, Blum M, et al. Repeatability and agreement in optical biometry of a new swept-source optical coherence tomography-based biometer versus partial coherence interferometry and optical low-coherence reflectometry. *J Cataract Refract Surg*. 2016;42:76–83.
12. Hoffer KJ. The Hoffer Q formula: a comparison of theoretic and regression formulas. *J Cataract Refract Surg*. 1993;19:700–712.
13. Dang MS, Raj PP. SRK II formula in the calculation of intraocular lens power. *Br J Ophthalmol*. 1989;73:823–826.
14. Yalvac IS, Nurozler A, Unlu N, Cetinkaya F, Kasim R, Duman S. Calculation of intraocular lens power with the SRK II formula for axial high myopia. *Eur J Ophthalmol*. 1996;6:375–378.
15. Retzlaff JA, Sanders DR, Kraff MC. Development of the SRK/T intraocular lens implant power calculation formula. *J Cataract Refract Surg*. 1990;16:333–340.
16. Aristodemou P, Knox Cartwright NE, Sparrow JM, Johnston RL. Formula choice: Hoffer Q, Holladay 1, or SRK/T and refractive outcomes in 8108 eyes after cataract surgery with biometry by partial coherence interferometry. *J Cataract Refract Surg*. 2011;37:63–71.
17. Cooke DL, Cooke TL. Comparison of 9 intraocular lens power calculation formulas. *J Cataract Refract Surg*. 2016;42:1157–1164.
18. Melles RB, Holladay JT, Chang WJ. Accuracy of intraocular lens calculation formulas. *Ophthalmology*. 2018;125:169–178.
19. Narvaez J, Zimmerman G, Stulting RD, Chang DH. Accuracy of intraocular lens power prediction using the Hoffer Q, Holladay 1, Holladay 2, and SRK/T formulas. *J Cataract Refract Surg*. 2006;32:2050–2053.

20. Hoffer KJ. Clinical results using the Holladay 2 intraocular lens power formula. *J Cataract Refract Surg*. 2000;26:1233–1237.
21. Aristodemou P, Knox Cartwright NE, Sparrow JM, Johnston RL. Intraocular lens formula constant optimization and partial coherence interferometry biometry: refractive outcomes in 8108 eyes after cataract surgery. *J Cataract Refract Surg*. 2011;37:50–62.
22. Darcy K, Gunn D, Tavassoli S, Sparrow J, Kane JX. Assessment of the accuracy of new and updated intraocular lens power calculation formulas in 10 930 eyes from the UK National Health Service. *J Cataract Refract Surg*. 2020;46:2–7.
23. Haigis W. Intraocular lens calculation after refractive surgery for myopia: Haigis-L formula. *J Cataract Refract Surg*. 2008;34:1658–1663.
24. Kane JX, Van Heerden A, Atik A, Petsoglou C. Intraocular lens power formula accuracy: comparison of 7 formulas. *J Cataract Refract Surg*. 2016;42:1490–1500.
25. Holladay JT. Refractive power calculations for intraocular lenses in the phakic eye. *Am J Ophthalmol*. 1993;116:63–66.
26. Melles RB, Kane JX, Olsen T, Chang WJ. Update on intraocular lens calculation formulas. *Ophthalmology*. 2019;126:1334–1335.
27. Wang L, Shirayama M, Ma XJ, Kohnen T, Koch DD. Optimizing intraocular lens power calculations in eyes with axial lengths above 25.0 mm. *J Cataract Refract Surg*. 2011;37:2018–2027.
28. Liu J, Wang L, Chai F, et al. Comparison of intraocular lens power calculation formulas in Chinese eyes with axial myopia. *J Cataract Refract Surg*. 2019;45:725–731.
29. Olsen T, Funding M. Ray-tracing analysis of intraocular lens power in situ. *J Cataract Refract Surg*. 2012;38:641–647.
30. Olsen T, Hoffmann P. C constant: new concept for ray tracing-assisted intraocular lens power calculation. *J Cataract Refract Surg*. 2014;40: 764–773.
31. Preussner PR, Wahl J, Lahdo H, Dick B, Findl O. Ray tracing for intraocular lens calculation. *J Cataract Refract Surg*. 2002;28:1412–1419.
32. Jin H, Rabsilber T, Ehmer A, et al. Comparison of ray-tracing method and thin-lens formula in intraocular lens power calculations. *J Cataract Refract Surg*. 2009;35:650–662.
33. Hill W. Hill-RBF Calculator Version 2.0. Available at: https://rbfcalculator.com/index.html. Accessed February 19, 2020.
34. Kane JX, Van Heerden A, Atik A, Petsoglou C. Accuracy of 3 new methods for intraocular lens power selection. *J Cataract Refract Surg*. 2017;43:333–339.
35. Hill W. Hill-RBF Calculator Version 2.0 - IOL Power Calculations for Cataract Surgery. Available at: https://rbfcalculator.com/. Accessed February 22, 2020.
36. Connell BJ, Kane JX. Comparison of the Kane formula with existing formulas for intraocular lens power selection. *BMJ Open Ophthalmol*. 2019;4:e000251.
37. Ladas JG, Siddiqui AA, Devgan U, Jun AS. A 3-D “super surface” combining modern intraocular lens formulas to generate a “super formula” and maximize accuracy. *JAMA Ophthalmol*. 2015;133:1431–1436.
38. Ghiasian L, Abolfathzadeh N, Manafi N, Hadavandkhani A. Intraocular lens power calculation in keratoconus: a review of literature. *J Curr Ophthalmol*. 2019;31:127–134.
39. Hashemi H, Yekta A, Khabazkhoob M. Effect of keratoconus grades on repeatability of keratometry readings: comparison of 5 devices. *J Cataract Refract Surg*. 2015;41:1065–72.
40. Watson MP, Anand S, Bhogal M, et al. Cataract surgery outcome in eyes with keratoconus. *Br J Ophthalmol*. 2014;98:361–364.
41. Thebpatiphat N, Hammersmith KM, Rapuano CJ, Ayres BD, Cohen EJ. Cataract surgery in keratoconus. *Eye Contact Lens*. 2007;33:244–246.
42. Hashemi H, Heidarian S, Seyedian MA, Yekta A, Khabazkhoob M. Evaluation of the results of using toric IOL in the cataract surgery of keratoconus patients. *Eye Contact Lens*. 2015;41:354–358.
43. Alio JL, Peña-García P, Abdulla Guliyeva F, Soria FA, Zein G, Abu-Mustafa SK. MICS with toric intraocular lenses in keratoconus: outcomes and predictability analysis of postoperative refraction. *Br J Ophthalmol*. 2014;98:365–370.
44. Savini G, Abbate R, Hoffer KJ, et al. Intraocular lens power calculation in eyes with keratoconus. *J Cataract Refract Surg*. 2019;45:576–581.
45. Wang KM, Jun AS, Ladas JG, Siddiqui AA, Woreta F, Srikumaran D. Accuracy of intraocular lens formulas in eyes with keratoconus. *Am J Ophthalmol*. 2020;212:26–33.
46. Savini G, Hoffer KJ. Intraocular lens power calculation in eyes with previous corneal refractive surgery. *Eye Vis (Lond)*. 2018;5:18.
47. Turnbull AMJ, Crawford GJ, Barrett GD. Methods for intraocular lens power calculation in cataract surgery after radial keratotomy. *Ophthalmology*. 2020;127:45–51.
48. Awwad ST, Dwarakanathan S, Bowman RW, et al. Intraocular lens power calculation after radial keratotomy: estimating the refractive corneal power. *J Cataract Refract Surg*. 2007;33:1045–50.
49. Masket S, Masket SE. Simple regression formula for intraocular lens power adjustment in eyes requiring cataract surgery after excimer laser photoablation. *J Cataract Refract Surg*. 2006;32:430–434.
50. Wang L, Booth MA, Koch DD. Comparison of intraocular lens power calculation methods in eyes that have undergone LASIK. *Ophthalmology*. 2004;111:1825–1831.
51. Geggel HS. Pachymetric ratio no-history method for intraocular lens power adjustment after excimer laser refractive surgery. *Ophthalmology*. 2009;116:1057–1066.
52. Abulafia A, Hill WE, Koch DD, Wang L, Barrett GD. Accuracy of the Barrett True-K formula for intraocular lens power prediction after laser in situ keratomileusis or photorefractive keratectomy for myopia. *J Cataract Refract Surg*. 2016;42:363–369.
53. Shammas HJ, Shammas MC. No-history method of intraocular lens power calculation for cataract surgery after myopic laser in situ keratomileusis. *J Cataract Refract Surg*. 2007;33:31–36.
54. Mohammadpour M, Shaabani A, Sahraian A, et al. Updates on managements of pediatric cataract. *J Curr Ophthalmol*. 2019;31:118–126.
55. Infant Aphakia Treatment Study Group, Lambert SR, Buckley EJ, Drews-Botsch C, et al. A randomized clinical trial comparing contact lens with intraocular lens correction of monocular aphakia during infancy: grating acuity and adverse events at age 1 year. *Arch Ophthalmol*. 2010;128:810–818.
56. Crouch ER, Crouch ER Jr, Pressman SH. Prospective analysis of pediatric pseudophakia: myopic shift and postoperative outcomes. *J AAPOS*. 2002;6:277–282.
57. Pandey SK, Wilson ME, Trivedi RH, et al. Pediatric cataract surgery and intraocular lens implantation: current techniques, complications, and management. *Int Ophthalmol Clin*. 2001;41:175–196.
58. Plager DA, Kipfer H, Sprunger DT, Sondhi N, Neely DE. Refractive change in pediatric pseudophakia: 6-year follow-up. *J Cataract Refract Surg*. 2002;28:810–815.

59. Vanderveen DK, Trivedi RH, Nizam A, Lynn MJ, Lambert SR, Infant Aphakia Treatment Study Group. Predictability of intraocular lens power calculation formulae in infantile eyes with unilateral congenital cataract: results from the Infant Aphakia Treatment Study. *Am J Ophthalmol*. 2013;156:1252–1260.
60. Vasavada V, Shah SK, Vasavada VA, et al. Comparison of IOL power calculation formulae for pediatric eyes. *Eye (Lond)*. 2016;30:1242–1250.
61. Andreo LK, Wilson ME, Saunders RA. Predictive value of regression and theoretical IOL formulas in pediatric intraocular lens implantation. *J Pediatr Ophthalmol Strabismus*. 1997;34:240–243.
62. Eibschitz-Tsimhoni M, Tsimhoni O, Archer SM, Del Monte MA. Discrepancies between intraocular lens implant power prediction formulas in pediatric patients. *Ophthalmology*. 2007;114:383–386.
63. Neely DE, Plager DA, Borger SM, Golub RL. Accuracy of intraocular lens calculations in infants and children undergoing cataract surgery. *J AAPOS*. 2005;9:160–165.
64. An-Nakhli FR. Accuracy of new and standard intraocular lens power calculations formulae in Saudi pediatric patients. *Taiwan J Ophthalmol*. 2019;9:37–42.
65. Gale RP, Saldana M, Johnston RL, Zuberbuhler B, McKibbin M. Benchmark standards for refractive outcomes after NHS cataract surgery. *Eye (Lond)*. 2009;23:149–152.