Review Article

Five generations of intraocular lens power calculation formulas: A review

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ABSTRACT

Background: The effectiveness of cataract surgery depends on preoperative biometric data, including the axial length (AL), keratometric value (K), anterior chamber depth (ACD), and the accuracy of the intraocular lens power (IOLp) calculation. Five generations of IOLp calculation formulas have been developed. This review summarizes these formulas and focuses on the characteristics, advantages, and disadvantages of each. Moreover, it compares the results of several formulas used in patients with specific characteristics.

Methods: The authors searched PubMed and Google Scholar, using keyword combinations including IOLp, formulas, AL, ACD, K, and diopters (D). Two hundred recent articles that referred to IOLp calculation formulas and their effectiveness when used preoperatively in cataract surgery were retrieved and analyzed.

Results: Each generation has advantages and disadvantages for individual patients, and the selection of the most appropriate IOL differs due to patients' different ALs. The shorter or longer the eye is, the less accurate some formulas become. Formulas such as SRK-T, Holladay, SRK-II, Hoffer, and Binkhorst II seem to have comparable efficacy. However, studies have indicated that Hoffer is superior for short eyes. In contrast, SRK/T appears to be slightly more superior for long eyes. The fifth-generation formulas also appear to be very promising.

Conclusions: Based on the available literature, there is no gold standard as yet that can be used for all patients. Instead, each patient should be managed individually depending on their particular eye characteristics.

KEY WORDS

cataract surgery, intraocular lens power, formulas, axial length, anterior chamber depth, ACD, keratometric value, diopters

INTRODUCTION

Cataract removal and intraocular lens (IOL) implantation are surgical operations characterized by a high success rate [1]. The postoperative patient satisfaction of these procedures depends on accurate biometry and appropriate intraocular lens power (IOLp) formula selection [2]. Corrected visual acuity is the expected outcome of cataract surgery. Patients have high expectations regarding refractive outcomes and generally want to achieve spectacle

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independence [3-6]. The introduction of phacoemulsification is characterized by a small incision and minimizes cylindrical error [7, 8]. Furthermore, improvements in biometry and IOL calculation formulas have made these expectations realizable, with only minor spherical errors expected following surgery [9].

The high demand for spectacle independence after cataract surgery has promoted the development and evolution of several new IOLp calculation formulas [10-20]. Continuous curvilinear capsulorhexis (CCC) is safe. Thus, capsular IOL implantation has become a widely used procedure [21]. This technique allows for the implantation of the IOL into the bag, reducing IOL subluxation after surgery [21, 22]. The following markers are usually used to assess the quality of biometry: a) the percentage of eyes that achieve spherical equivalent (SE) within 0.5 D and 1.0 D of that estimated, and b) the estimated postoperative refractive error [23]. The 2004 RCOphth guidelines reported that 72%-97% of patients might achieve SE within 1.0 D of the predicted value [24-26]. Although it was previously suggested [23, 27-30] that 85-90% of patients with cataracts should achieve SE refraction within 1.0 D of that estimated, the 2004 RCOphth guidelines reported that approximately 97% of patients with cataracts should achieve a predicted SE refraction of 1.0 D [24].

The present review aimed to summarize the main formulas used to date, focusing on the characteristics, advantages, and disadvantages of each. Moreover, it compares the results of several formulas used in patients with specific characteristics.

METHODS

We screened the PubMed/MEDLINE and Google Scholar databases for articles referring to IOLp calculation formulas and the effectiveness of each formula when used preoperatively in cataract surgery. The present review includes articles written in English, mostly in the last two decades. The keyword combinations used for this research included IOLp, formulas, axial length (AL), anterior chamber depth (ACD), keratometric value (K), and diopters (D).

RESULTS

In total, 200 articles were retrieved and analyzed, emphasizing the most recent literature. Based on the reviewed studies, we attempted to present and categorize the formulas used for the IOLp calculation. In addition, we analyzed the differences between the formulas and compared the results of different formulas in the IOLp calculation. We found that each generation has advantages and disadvantages for individual patients, and the selection of the most appropriate IOL differs due to patients' different ALs. The shorter or longer the eye is, the less accurate some formulas become. Formulas such as SRK-T, Holladay, SRK-II, Hoffer, and Binkhorst II seem to have comparable efficacy. However, studies have indicated that Hoffer is superior for short eyes. In contrast, SRK/T appears to be slightly more superior for long eyes. The fifth-generation formulas also appear to be very promising.

Table 1 provides a summary of the advantages and disadvantages of the main five-generation formulas. Table 2 provides a summary of the most suggested formulas for short, medium, and long eyes. Table 3 provides a summary of all abbreviations used in this review.

DISCUSSION

Multifocal IOLs were developed in the early 1990s to improve vision following cataract surgery [31]. However, multifocal IOLs can have some adverse visual outcomes which may dissatisfy patients [32]. They may not achieve good visual outcomes in cases with preexisting eccentric fixation due to macular lesion [33], clinical characteristics associated with dry eye [34], and in the presence of astigmatism [35]. In addition, low contrast sensitivity, halos, and glare restrict the use of multifocal IOLs [32]. However, newer generations of multifocal IOLs claim to be able to achieve spectacle independence [36].

Quadrifocal IOLs were comparable to trifocal IOLs in terms of safety, while they gave promising results in terms of near, far, and medium distance vision expressed in uncorrected visual acuity. The findings of Kohnen et al. [37] were also in agreement with the results mentioned above. The efficacy of IOL implantation depends on the accuracy of ocular biometric measurements and IOLp calculation formulas [38, 39]. Moreover, the selection of appropriate patients is important [40]. The subjective vision of females seems to be worse than that of males, both pre- and postoperatively [41]. The power calculation formulas may differ in terms of accuracy when applied to different types of IOLs [42]. Therefore, new types of IOLs need to be developed [43], and formulas for the IOLp calculation should also be optimized [44]. Encouraging results for trifocal IOLs in terms of visual acuity after implantation [45, 46] have led to them being more frequently used.

Pseudophakic monovision is a broadly used approach in which an IOL is implanted in one eye intended to be emmetropic, while myopic overcorrection is performed on the other eye, thereby providing good visual results at all distances [47-49]. High rates of patient satisfaction (92%) have been reported using this approach [49]. Pseudophakic monovision has been compared to multifocal IOLs in clinical trials. These have reported similar results between the two approaches in terms of visual acuity at all distances as well as for spectacle independence [47]. The amount of anisometropia that ideally needs to be achieved is controversial, but current evidence suggests that the refraction difference between eyes must be approximately 1.5 D. Greater amounts of anisometropia after the operation may lead to loss of stereopsis [50].

Intraocular lens power prediction

Three primary factors can impact the accuracy of IOLp predictions. The first factor is the accuracy of the AL and K readings. Second, the accuracy of the manufacturers' quality-control techniques of IOLp labeling is of paramount importance, while the accuracy of the IOLp formulas needs to be ensured [23, 38, 39, 51-53]. Developments in IOLp formulas [9, 54], together with the development of better surgical techniques [55-60] and careful measurements that precede the operation [28, 51, 53, 58, 59, 61, 62], have led to significant postoperative improvement in refractive results [2, 27-29, 38, 41, 51, 53, 56-59, 62-74].

Despite IOLp calculation refinement, inherent issues remain, including that individual biometry values can vary significantly and that the final position of the IOL needs to be predicted [53, 62, 75-80].

While most studies have focused on improving the accuracy of the formulas used, between 43% and 67% of large refractive differences (> 2.0 D) are actually due to inaccurate preoperative measurements [61].

Partial coherence interferometry (PCI) has led to significant improvements in the field of biometry. However, debate regarding the optimal IOL formula continues [2, 81]. The main sources of postoperative refractive errors include the measurement, IOL calculation formula, IOL insertion process, and lens constant errors [6, 51, 53, 62, 82-84].

In contrast to the physics and technology efforts that have attempted to standardize biometry, many have proposed the individualization of formula parameters [39, 56, 79, 85]. Thus, several authors have focused on adjusting factors in the IOL calculation formulas, such as the surgeon factor [53, 62, 66, 86-88] or retinal thickness [62, 76]. Other factors related to less predictable outcomes include low preoperative visual acuity [72], ocular comorbidity [72], astigmatism [41], and high ametropia. It has been reported that many formulas ignore the different possible shapes of lenses and do not provide adjustment for IOLs with low or negative power [89].

Fyodorov first reported Gaussian optics-based IOL calculations [90]. The model reported by Fyodorov was first produced in 1967 [90] to be used with iris-clip type IOLs. The corneal dome height was used as a geometric landmark for the effective lens position (ELP). Corneal height is very useful for anterior chamber IOLs [91], but not for IOLs of the posterior chamber. Similar approaches with minor differences have also been described in other studies [4].

The most accurate classification of IOL calculation formulas is based on the category of functions and biometric variables used for IOLp. Vergence, ray tracing, and artificial intelligence (AI)-based formulas assess the estimated ELP. Furthermore, some AI-based formulas choose the IOLp to bypass the ELP assessment. Biometric data collected before the operation (AL, ACD, and K) and the accuracy of the IOLp calculation formulas are the main factors that determine the accuracy of calculations [52]. Ocular biometric data used in these formulas include AL, corneal power, and ACD [12, 52]. Corneal steepness tends to vary the most between people, while SE and AL show lower variation rates. This is probably because the AL adapts to the power of the cornea during the childhood process of emmetropization [41].

A 1 mm deviation of the corneal diameter (CD), AL, and ACD may lead to 5.7 D, 2.7 D, and 1.5 D of refractive error, respectively [56]. The ACD, AL, and corneal power contribute to refraction at rates of 42%, 36%, and 22%, respectively [92]. In 1981, Hoffer [6] reported that the error was estimated to be within ± 1.0 D in 70% of cases. In 1982, Shammas [93] found the same error in 79% of cases, while Hillman [94] reported it in 60% of cases. Richards et al. [95] reported that the percentage of incidents within ± 1.0 D varied from 55% to 90%, a variation that occurred because of the formula chosen, the surgeon performing the operation, and/or the IOL style. Holladay et al. [53] used a dataset that included a number of different surgeons in their study. They reported an average absolute error of 0.61 D. In another study with very long and very short eyes, Olsen and coauthors [9] reported an error of 0.60 D. Gale and coauthors concluded that after the operation, a SE of ± 0.5 D and ± 1.0 D of the intended target should be reached by 55% and 85% of patients, respectively [96]. Simon et al. reported that SE within ± 0.5 D and SE within ± 1.0 D were reached in 67% and 94% of cases, respectively [97]. Hahn et al. reported that 80% of cases reached refraction within ± 0.5 D of the goal, although the surgeons were highly experienced, and comorbidity factors were excluded [98]. Sheard suggested that following the operation, an SE of ± 0.5 D and ± 1.0 D of the intended target should be reached in 60% and 90% of patients, respectively [99]. Moreover, it was proposed that machine measurements play a crucial role in the variability of results between the IOL formulas [100]. Olsen analyzed how AL, corneal power, and estimation of the postoperative IOL position affect the refractive outcome of cataract surgery accompanied with IOL implantation by conducting a Gaussian error-propagation analysis [38]. Generally, negative probable errors (PEs) show a tendency for myopic refractive outcomes, while positive PE is associated with hyperopic refractive outcomes [29]. As no particular formula is completely accurate and eyes have different characteristics, surgeons have tended to change the formula used based on the particular ocular dimensions of the patient undergoing a cataract operation [101]. However, no consensus has been reached on the statistical methods that should be used to compare IOL formulas [101]. Moreover, different numbers of variables have been assessed, ranging from two (Holladay 1, Hoffer Q, SRK/T, T2) to seven (Holladay 2) [73]. The term "mean refractive error" is a factor that shows the extent of hyperopia or myopia that an eye has, compared to the predicted values [74]. Therefore, "mean refractive error" is a term used to describe the accuracy of the lens constants used [102]. The standard deviation (SD), which is independent of optimization, reflects the accuracy of a formula [74].

A review of the accuracy of IOLp calculations showed that when an investigator tests a formula that they have developed, the superiority of their respective formula against any other IOLp calculation formula is always highlighted, independent of whether they are theoretical or regression formulas [77]. Furthermore, reports on formula accuracy from authors who have not developed a formula typically included a combination of theoretical and regression formulas [77]. Lastly, it was reported that the average percentage of patients who had refractive errors greater than 2.0 D after the operation was 10% in studies conducted before 1980 and 5% in those conducted after 1980 [77]. The use of optical biometry in cataract surgery has led to an improvement in refractive results and has shown greater accuracy than applanation ultrasound (US) biometry [96, 103, 104].

IOLMaster

IOLMaster is used for IOLp calculations and considers optical biometry as well as various calculation formulas [103]. IOLMaster uses PCI technology to measure the AL. Furthermore, quick and accurate calculations are possible with the use of automated K and ACD measurements [105]. This makes IOLMaster a convenient device to use [106] and less operator-dependent than applanation US [107]. Intra-examiner and inter-examiner variabilities in the measurement of ACD and AL were lower when the measurement was performed with IOLMaster than with applanation US [107]. The AL and ACD measurements can be reproduced to a great extent [108]. The accuracy of high-resolution PCI with the IOLMaster [52] has been reported to be ten times greater than the accuracy of US [52], while the results of IOLMaster and automatic keratometer seem to be very similar in terms of corneal radius measurements [108].

Lenstar

Lenstar (Haag-Streit AG, Koeniz, Switzerland) uses optical low coherence reflectometry (OLCR) to measure the AL, central corneal thickness, ACD, lens thickness (LT), and retinal thickness [109]. The results of Lenstar are similar to IOLMaster in relation to the accuracy of the biometric measurements [105]. In a study by Hoffer et al., the authors concluded that Lenstar could be more accurate than IOLMaster because of its optical ACD measurements and K, which considers multiple repeated measuring points [109]. The main advantage of Lenstar compared to IOLMaster is that it can measure the parameters required for the newer IOL calculation formulas. For example, the measurement of LT with Lenstar can be easily used in the Olsen, Holladay 2, and Barrett Universal II formulas [109].

IOL SPECIFIC FORMULAS

Binkhorst 1

With the use of the Binkhorst 1 formula (a first-generation theoretic formula), Shammas modified the AL (AL = 0.9 AL + 2.3). This affected the IOLp as much as varying the ACD [51].

Binkhorst 2

The Binkhorst II formula (a first-generation theoretic formula) changed how the ACD constant was expressed, making it a function of AL (AL / 23.45 × ACD) [51].

Ladas Super Formula

The Ladas Super Formula selects the formula that presents the greatest accuracy for the respective combination of AL and K for the prediction of refractive outcomes [110]. The Ladas Super Formula has been assessed in only one study, in which the authors concluded that the respective formula had a higher mean absolute error (MAE) a) for all ALs compared to the Barrett Universal II formula, b) than the Holladay 1 and Barrett Universal II formulas when applied to eyes with short AL, and c) when compared with the SRK/T and Barrett Universal II formulas for eyes with long AL [74].

FIRST-GENERATION FORMULAS

In 1967, Fedorov et al.[111] were the first to describe an equation designed to estimate the appropriate IOLp needed to achieve the desired refractive status after cataract surgery [3]. Since 1967, a number of theoretical and regression formulas for IOL calculations have been used to offer the best possible estimation of IOLp. The first practical regression formulas used a constant, the A-constant, in their calculations. The SRK formula uses the equation: P = A - 2.5AL- 0.9K, where P = IOLp targeting for emmetropia, A represents the A-constant, and K represents the corneal curvature [112]. In addition, the Binkhorst formula uses a constant value for the ACD following the operation [113]. In the original theoretical formula, the ACD depends on the style of the lens and placement in the eye [53]. The authors who investigated the formula concluded that a linear equation should be used. Moreover, this equation should use a constant for each lens style, which is empirically determined, and coefficients for the AL and corneal power that yield the emmetropic IOLp. In earlier years, studies that compared theoretical formulas with ACD and linear regression were split in their conclusions [53].

THEORETICAL FORMULAS

Since theoretical formulas consider physiologic optics, they are potentially more accurate than regression formulas when used past the limits of any given database, for example, in eyes with unusually high or low AL [62]. Theoretical formulas were first developed by Thijssen, Van Der Heijde, and Binkhorst [62]. In theoretical IOLp formulas, the method used to predict pseudophakic ACD is of paramount importance. Pseudophakic ACD variations postoperatively contribute to the total refractive prediction error by 20% to 40%. This percentage varies and depends on the accuracy of the ACD prediction [82].

SRK FORMULA

The SRK and SRK-II formulas use A-constants that were empirically determined by manufacturers and surgeons [62]. The regression formulas of Lloyd/Gills, Sanders/Kraff, and Retzlafflll ultimately led to the creation of the SRK formula, which has been used globally because of its simplicity and the fact that a constant, individual to each style of IOL replaced the ACD [51]. According to two major population-based studies in Iran, the mean ACD in people over 40 years old is less than 3.0 mm. Moreover, for Iranian cataract surgery candidates with normal AL, predictions with SRK-II were found to be as accurate as other formulas [92].

REGRESSION FORMULAS

Regression formulas seem to have a successful record in terms of accuracy [62]. Several investigators have published methods that use linear regression to increase the accuracy of theoretical formulas [53]. Given that their accuracy has already been proven, regression formulas seem easier to derive and manipulate than theoretical ones. The residual error of these formulas, whether due to the technique used by the surgeon or IOL design, is reformatted into a single constant [62].

SRK 1

Because formulas based on Gaussian optics make the elucidation of errors particularly complicated and challenging to avoid, Retzlaff, Sanders, and Kraff introduced an “empirical” approach (i.e., the SRK-I formula) [39].

SECOND-GENERATION FORMULAS

Better results were obtained when the authors investigated polynomial regression formulas [53]. Investigators using a theoretical formula reported better results after correlating the expected ACD postoperatively to the AL and using higher and lower ACDs for longer and shorter eyes, respectively [53].

SRK-II formula

The second-generation formula, SRK-II, expanded upon the SRK and aimed to achieve greater accuracy in long (AL > 26 mm) and short eyes (AL < 22 mm) by incorporating adjustments to the basic formula [28, 114, 115]. Some of the IOLp calculation formulas are based on theoretical optics [87], while others are empirical with no consensus regarding the superiority of either of these formulas [87]. This may be related to the variety of variables associated with the performance characteristics of surgeons, such as the type of keratometer or US used, IOL style, and the surgical approach that each surgeon uses [87]. The SRK formula is the most widely used worldwide [87], while the SRK-II has been reported to be inferior to the other formulas [74, 92]. Sanders et al. reported that 30% and 81% achieved errors of < 0.5 D and < 1.0 D, respectively, when using SRK-II [62]. SRK-II is, for the time being, the most widely used formula. In a European cohorts the mean ACD was reported to be at least 1.0 mm higher than that in Iranian population [92] In contrast, in a Singaporean population, where the mean ACD (3.08 mm) in a Singaporean cohort was reported to be lower than that in European and American cohorts [92]. Moreover, the accuracy of SRK-II in the prediction of refractive results was good [92]. In 1988, the authors of SRK modified the A-constant (SRK-2), which was increased in steps of 1.0 D when the AL was shorter than 22 mm (+ 1 D), 21 mm (+ 2 D), and 20 mm (+ 3 D) and decreased by 0.5 D if it was longer than 24.5 mm [51].

Holladay formula

The Holladay formula is a newer second-generation theoretical formula. This has shown promising results due to it giving a more accurate location of the optical plane of the IOL regarding the vertex of the cornea and fovea [53]. The calculation of ACD can be performed more easily and with better accuracy in aphakic eyes than in phakic eyes because the plane of the iris is dependent on the location of the iris root. In such eyes, the iris plane bows forward after contacting the crystalline lens, whereby it introduces other factors, among which the thickness and position of the crystalline lens are the most important. This is the reason why preoperative and postoperative ACDs correlate poorly, particularly in patients with greater and more variable LT [53]. Holladay combined a personalized ACD factor using the Fyodorov method, taking into account AL and K-reading to predict the corneal height [51].

THIRD-GENERATION FORMULAS

In the early 1990s, third-generation theoretical formulas (e.g., Hoffer Q, Holladay 1, and SRK/T) gained universal acceptance and remained the most frequently used in the United Kingdom [116]. These formulas consider constants associated with the expected position of the IOL. In a study by Holladay, the author defined the "surgeon factor" as the distance from the iris plane to the plane of the IOL. On the other hand, Haigis used three constants for improved ELP prediction, while Hoffer Q considered the ACD constant. Finally, the A-constant is used by SRK/T to calculate the ACD by considering the retinal thickness and corneal refractive index [51, 53, 56, 62, 116-118].

The third-generation theoretical formulas and the improved T2 are formulas that only use AL and K readings to predict the IOL position [51, 53, 62, 119]. Among the third-generation theoretical formulas, Holladay 1 has the greatest accuracy for eyes with an AL < 26.0 mm, while the SRK/T has the greatest accuracy for eyes ≥ 26.0 mm [110].

Although various studies have reported a difference in the predictive accuracy of older formulas for IOLp calculations [51, 120], only a few have been compared with third-generation IOLp formulas. Numerous other comparisons [73, 74] among diverse formulas for IOLp calculations have concluded that third-generation and post-third-generation formulas provide good results.

SRK/T

The SRK/T formula [62] is among the most popular for IOLp prediction for implantation during cataract surgery. Sanders et al. described this formula, which was based on the non-linear terms of the theoretical formulas, and further optimized it using empirical regression techniques [62]. The SRK/T ACD prediction method is less accurate when applied to eyes with a long AL [121], although an overall accuracy of 81% has been reported [62]. It has been reported that its IOLp predictions do not differ significantly from those of other formulas and are therefore used most frequently in clinical practice [24, 54]. However, in specific situations, the so-called "SRK/T cusp phenomenon" can occur [122]. The "SRK/T cusp phenomenon" is a mathematical artifact inherent to the SRK/T calculations and is attributed to the corneal height cusp that may affect a large proportion of eyes. To overcome this problem, Sheard et al. suggested replacing the SRK/T formula for corneal height estimation with an empirical regression formula, the T2 formula [119]. Therefore, the T2 formula is an amendment to the SRK/T whereby the calculation of the corneal height is strengthened to prevent the non-physiological behavior of the SRK/T [73]. Sheard et al. proposed that surgeons switch to the T2 formula to improve the refractive outcomes by 10% [119].

The ACD constant of SRK/T is either provided by the manufacturer or derived from the SRK-II A-constant based on the formula: ACD = [0.62467 × A] – 68.747 [42, 62]. The Hoffer Q, Holladay 1, and SRK/T formulas erroneously assumed that steep-cornea-eyes have deep anterior chambers, while eyes with flatter corneas have shallow anterior chambers [68]. Similar to the Holladay 1 formula, the SRK/T formula is a modified Binkhorst that incorporates the Fyodorov model for ELP assessment [113]. The accuracy of the SRK/T formula should still be confirmed using independent datasets [62]. Findl et al.[116] reported an MAE of 0.44 D after using the SRK/T formula, with the use of PCI for AL assessment. Sanders et al.[62] assessed 990 patients that were operated on by several different surgeons with different IOLs and reported outcomes of 29%, 79%, and 95.3% with the SRK/T formula for 0.5, 1.00, and 2.00 D, respectively. However, few studies have presented refractive results following phacoemulsification using the SRK/T formula. In addition, existing studies have not used strict methodologies to avoid bias [6, 51, 62, 123].

Hoffer Q and Holladay 1

The Holladay 1 formula relies on the corneal height equation of Fyodorov et al. for the postoperative prediction of ACD. In contrast, the Hoffer Q formula uses an independently derived formula that considers the tangent of corneal power [3].

FOURTH-GENERATION FORMULAS

Newer formulas, including Haigis, Holladay, Olsen, and Barrett Universal II, depend on a wide variety of variables and different methodologies for their calculation algorithms [109]. The third and fourth-generation formulas are currently the most widely used IOLp calculation formulas [6, 51, 53, 62, 83, 84, 116]. However, especially in eyes with extremely high AL, the latest formulas (e.g., Holladay 2) do not appear to be better than the third-generation ones [83, 124]. The Holladay 2 and Haigis fourth-generation formulas and the fifth-generation formulas (Barrett Universal II, Olsen) include more parameters. This helps to achieve a more accurate ELP estimation. These parameters are the preoperative ACD and LT in the Haigis formula, while the Holladay 2, Olsen, and Barrett Universal II formulas use the ACD and corneal white-to-white (WTW) [125]. According to the current literature, the newer formulas do not outperform the optimized Hoffer Q for short eyes or SRK/T for long eyes [126].

Holladay 2

The Holladay 2 formula for IOLp determination was introduced in clinical practice in 1996 but has not yet been published [83]. Initially, it was suggested as a possible amendment to the Holladay formula [83]. Holladay 2 performs similarly to Hoffer Q in short eyes, while Holladay 1 and Hoffer Q perform equally well in eyes with normal AL. SRK/T and Holladay 2 do not provide different results in eyes of medium length, but the SRK/T seems to perform better in very long eyes. Holladay et al.[53] used data of 12 different surgeons and reported that the MAE ranged from 0.48 D to 0.81 D for the respective formula.

Haigis

Haigis is a fourth-generation formula that considers the ACD measurements before the operation, in addition to AL, to predict ELP [56]. Haigis differs significantly from formulas that depend on two variables. The Haigis formula calculates IOLp by taking into account three variables (a0, a1, and a2) to determine ELP (d), where d = a0 + (a1 × ACD) + (a2 × AL) [66, 84]. In the study by Haigis et al.,[84] the calculation of PCI was conducted using the Zeiss IOLMaster, while they performed the IOL calculation using the Haigis formula both with and without optimization of the constants. Their predicted outcome following the operation was within ± 1.00 D and ± 2.00 D in 85.7% and 96% of cases, respectively [84]. In a study by MacLaren et al.,[70] the authors reported a significantly lower MAE with the Haigis (0.91 G 0.09 D) formula compared to the Hoffer Q formula (1.13 G 0.09 D). However, it is possible that the Haigis, Holladay 2, and Olsen formulas perform better for eyes across the entire AL spectrum [116]. The Haigis formula performs better only in extremely myopic eyes, where minus-powered IOLs are required [66, 127]. A unique characteristic of the Haigis formula is that it considers ACD without relying on corneal power for its ELP calculations [84].

Hill-radial basis function (RBF)

The Hill-RBF formula has recently been released for clinical use [89]. Existing data suggest that the postoperative refractive accuracy using this formula may be equivalent to or exceed the current industry standard IOLp formulas [89].

FIFTH-GENERATION FORMULAS

Barrett Universal II

For reformulation of the Barrett Universal II formula, data from Acrysof SN60WF IOLs were used, while 62% of the data for the derivation of the T2 formula were from the same IOLs [119]. The Barrett Universal II [128] formula considers the change in the principal planes of IOLs with different powers. To achieve this, it uses AL, K, ACD, LT, and WTW and calculates ELP through the ACD and a lens factor [128-130]. The Barrett Universal II formula can be found online.The Barrett Universal II formula is more accurate than the formulas of previous generations [74]. In two studies by Kane et al., the authors reported that by using Barrett Universal II, they achieved the highest percentage of eyes within ± 0.50 D [73, 110].

Olsen

Newer formulas are now available that are based on ray tracing and thick-lens models. The Olsen formula is available either installed in advance on OLCR devices (OlsenOLCR) or as software that can be purchased (OlsenStandalone). It uses AL, K, ACD, LT, and patient age. Its C-constant function enables ELP calculation according to the ACD and LT [56]. OlsenStandalone performed better than OlsenOLCR in all AL ranges except for long eyes. However, even in such cases, there was no significant difference (MAE difference ~ 0.001 D) between the two [74]. Despite its superior ranking with OLCR data, OlsenStandalone performed the worst of all nine formulas in terms of the PCI measurements [74]. To evaluate the IOL position, the Olsen formula requires the input of the C-constant, which, in turn, requires the measurement of LT [131]. In a study by Cooke and Cooke [74], the authors found that the Olsen OLCR yielded more hyperopic results than OlsenStandalone, which was more evident in eyes with low AL. Table 1 provides a summary of the advantages and disadvantages of the main five-generation formulas.

CONSTANTS/ ELP

According to the study by Cooke et al., the accuracy of the Olsen formula varies between $\text{Olsen}_{\text{OLCR}}$ and $\text{Olsen}_{\text{Standalone}}$, while $\text{Olsen}_{\text{OLCR}}$ appeared to be inferior to Barrett Universal II [74]. Similar differences between the two Olsen versions were reported by Gocke et al. and were more noteworthy in short eyes [136]. A "constant," optimized for the operating surgeon and type of IOL is used in all formulas. The optimization of the constant is based on both the preoperative parameters and outcomes for a large set of patients.

The origin and composition of these sets of patients carry significant weight on the decision of whether a certain IOLp calculation formula is applicable in clinical practice [61]. Some datasets include different surgeons, while others include different styles of IOLs [62]. The ELP can be described as a constant derived by the IOLp calculation formula, which is then calculated to yield the observed outcome according to the actual dataset [131]. The error in ELP estimation is the most limiting factor, as opposed to any AL measurement inconsistencies, as laser biometry is very accurate [38]. Vergence formulas with two variables use the AL and corneal power for ELP calculation. Neural networks have been deployed for ELP prediction, but this approach does not appear to be more accurate than the current formulas [137]. To improve biometry prediction, personalized constants have been used, particularly in eyes with high ametropia [138, 139], although in Haigis' formula, personalized constants did not lead to significant improvement [2]. Most IOLp formulas combine different variables for ELP evaluation, and these include AL, corneal height, the ACD prior to the operation, LT, refraction, age, sex, and race [61, 89, 131, 139, 140]. The IOL constants are reported to vary according to AL [139] and K [141], with both of the variables mentioned above varying between the sexes.

A-constant

The A-constant of the SRK/T formula needs to be adjusted in eyes with steep corneas to avoid myopic error [141]. Hoffer emphasized the importance of optimizing the A-constants [142]. This optimization can be easily performed using several software programs or Zeiss IOLMaster software [143-145]. When using PCI for AL measurements compared to acoustic methods, there may be more than a 1.0 D difference between the customized A-constants [143].

Table 1. Advantages and disadvantages of the main IOLp calculation formulas discussed

IOLp Calculation Formula	Advantages	Short Comes
FIRST-GENERATION FORMULAS		
SRK Formula	Simple to use and individualized to each IOL A-constant replaced ACD [51].	Empirically derived A-constants [62].
SRK1 Formula	Simpler and more accurate than formulas based on Gaussian optics [39].	Empirical approach [39].
SECOND-GENERATION FORMULAS		
SRK-II Formula	Greater accuracy in long (> 26 mm) and short eyes (AL < 22 mm) [28, 115, 116].	30% achieved an error of < 0.5 D and 81% < 1.0 D [62].
Holladay Formula	More accurate in the location of the optical plane of the IOL, considering the vertex of the cornea and fovea [53].	Theoretical formula [53].
THIRD-GENERATION FORMULAS		
SRK/T Formula	Accurate for eyes ≥ 26.0 mm, ACD calculation using A-constant, retinal thickness, and corneal refractive index. Corresponding accuracy of approximately 81% [62].	Empirical regression techniques, less accurate ACD prediction in long eyes [62].
T2 Formula	Improvement of SRK/T with enhanced corneal height calculation preventing non-physiological behavior. Comparing SRK/T, T2 improves refractive outcomes by 10% [73, 120].	-
Hoffer Q and Holladay 1 Formulas	Holladay 1: accurate for eyes with an AL < 26.0 mm. The corneal height equation is taken into account to predict postoperative ACD [3]. Hoffer Q, an independently developed formula, uses the tangent of corneal power and takes the ACD constant into account [3].	Holladay 1 and Hoffer Q perform the same in medium eyes [3].
FOURTH-GENERATION FORMULAS		
Holladay 2	Improvement to the Holladay formula. More accurate estimated postoperative ACD position using preoperative anterior segment biometric data like ACD, LT, CD, patient age, and preoperative refractive error. Satisfactory calculation across the whole AL range [83].	Worse than SRK/T in very long eyes, but the same results in medium-long eyes [83].
Haigis	The Haigis presents significantly lower MAE than the Hoffer Q formula. Satisfactory for the whole AL range and in extremely myopic eyes. Uses three constants for better ELP prediction [66, 127]	Uses ACD but no corneal power to calculate ELP [84].
Hill-RBF	Provides satisfactory postoperative refractive accuracy [89].	
FIFTH-GENERATION FORMULAS		
Barrett Universal II	More accurate compared to previous generation formulas. Uses AL, ACD, K, LT, WTW, ELP. Better results in long eyes [128-130]. The highest percentage of eyes within ± 0.50 D [111].	Not for all cases [128-130].
Olsen	Uses AL, ACD, K, LT, and patient age. Better accuracy in IOLp calculation across the whole AL range [56].	Not for all cases. More hyperopic results, especially in short eyes [74].
IOL SPECIFIC FORMULAS		
Binkhorst 1	With the use of this formula (a first-generation theoretic formula), Shammas modified the AL (AL = 0.9 AL + 2.3). This affected the IOLp as much as varying the ACD [51].	-
Binkhorst 2	The formula (a first-generation theoretic formula)changed how the ACD constant was expressed, making it a function of AL [51].	-
Ladas Super Formula	Uses 1-5 formulas depending on the AL and K and the formulas introduced to be most accurate for these biometry data [111].	-

Abbreviation: IOLp, intraocular lens power; SRK, Sanders Retzlaff-Kraff; ACD, anterior chamber depth; AL, axial length; mm, millimeter; D, diopter; LT, lens thickness, CD, corneal diameter; ELP, effective lens position; K, keratometric value; WTW, white-to-white.

C-constant

The C-constant is used to evaluate the position of the IOL postoperatively, based on the dimensions and positions of the crystalline lens before the operation [131]. After cataract surgery and in the bag implantation, the IOL is located in a defined manner predicted by the formula IOLc = ACDpre + C × LTpre, where IOLc represents the IOL center, ACDpre represents the ACD before the operation (including corneal thickness), LTpre represents the thickness of the crystalline lens before the operation, and C is a constant related to the IOL type determined as the mean value in a respective sample [131].

Table 2. Most suggested IOLp calculation formulas, in short, medium, and long eyes

SHORT EYES	MEDIUM EYES	LONG EYES
Hoffer Q [51, 62, 83, 117, 132]	Third and Fourth-Generation Formulas [62, 83]	SRK/T (better results) [117, 125, 132-134]
Haigis [132, 135]	Holladay [29]	Haigis (better results reported in several articles) [13, 66, 67, 127]
Holladay 1 [73, 132]	Hoffer Q [62, 83]	Barrett Universal II (superior results in recent articles, especially when AL > 30 mm) [89, 135]
Holladay [2, 73, 132]	SRK/T [28, 62, 83]	Olsen (similar results with Barrett Universal II and Haigis reported in several articles, better in eyes with AL 28.0-30.0 mm and 26.0-28.0 mm) [89, 135]
SRK/T [62, 73]	Holladay 1 [28, 62, 83]	Hoffer Q [115, 117, 125, 134]
Barrett Universal II [132]	Olsen [28, 62, 83]	Holladay 1 [117, 125, 133]
T2 Formula [132]	Holladay 2 [62, 83]	Holladay 2 [125, 134]
SRK-II [62]	Haigis [62, 83]	SRK-II [134]
Binkhorst II [62]		Binkhorst II [134]
Hill-RBF [135]		

Abbreviation: IOLp, intraocular lens power; SRK, Sanders Retzlaff-Kraff; AL, axial length; mm, millimeter; RBF, Hill-Radial Basis Function.

Table 3. Abbreviations used in this review paper

Expanded form	Abbreviation
Anterior Chamber Depth	ACD
Artificial Intelligence	AI
Axial Length	AL
Continuous Curvilinear Capsulorhexis	CCC
Corneal Diameter	CD
Diopter	D
Effective Lens Position	ELP
Hill-Radial Basis Function	Hill-RBF
Intraocular Lens	IOL
IOL power	IOLp
Keratometric Value	K
Lens Thickness	LT
Mean Absolute Error	MAE
Millimeter	mm
Optical Low-Coherence Reflectometry	OLCR
Partial Coherence Interferometry	PCI
Probable Error	PE
Sanders Retzlaff-Kraff	SRK
Spherical Equivalent	SE
Standard Deviation	SD
Ultrasound	US
User Group for Laser Interference Biometry	ULIB
White-To-White	WTW

AL MEASUREMENT

Preoperative AL measurement is of paramount importance for increasing the accuracy of IOLp prediction [61, 82, 146]. It has been reported that 54% of the errors in the predicted refraction after cataract surgery are related to AL measurement errors [82]. Since the introduction of IOLMaster (Carl Zeiss Meditec AG, Jena, Germany), optical biometry has become vital for measuring ocular AL because it is significantly more accurate than applanation US [28, 52, 105, 107, 146, 147]. Because of the familiarity of the technique and the relatively low cost, especially in developing countries, US biometry is used more often than optical biometry for AL measurements and IOLp calculations. Other indications include situations where optical biometry cannot be used due to opaque ocular media or the posterior segment, a pathology including vitreous hemorrhage or poor fixation [28, 29, 106, 146, 148]. Measuring AL with immersion US biometry may be more precise than using the contact method. However, this is more critical in eyes with longer AL [146, 149]. Applanation ultrasonic biometry may lead to imprecise AL measurement because of the indentation of the globe and off-axis assessment of AL by the transducer [107, 116, 146]. Immersion US avoids this by measuring AL without indentation of the eyeball, achieving a better refractive outcome than applanation A-scan in IOLp prediction [150]. Dual-beam PCI technology enables the performance of AL measurements [28, 52]. PCI measures the amount of reflected infrared laser light from the internal tissue interfaces [28, 52, 84]. In standard US biometry, AL is measured from the corneal vertex to the internal limiting membrane. The IOLMaster includes formulas designed to convert the optical path length into a geometric distance [84]. Using a fixation beam, IOLMaster performs AL assessment along the visual axis [84]. There is no need for anesthesia, while the risk of corneal trauma or infection is almost absent [52, 151].

A-scans differ systematically as they measure AL [84, 152-154]. Mean ALs of approximately 23.5 mm are commonly reported when A-scan is used [155]. To deal with these systematic differences in the measurement of AL, the authors recommend the personalization of formula constants so that a zero mean error in refractive outcome can be achieved [51, 53, 62]. Olsen et al. reported that up to 58% of IOLp prediction errors depend on the measurement of AL and K [56]. Wang et al. subsequently developed an AL regression equation alongside standard formulas [156]. The expected wide variation in AL and ACD within the patient population is an inherent limitation that commonly results in refractive surprises [157]. An error of 1 mm in the assessment of AL results in a postoperative refractive error of ~2.88 D, or 3.00 to 3.50 D in IOLp calculation (depending on the AL of the eye) while, an error of 1.0 D in K results in an error of 0.9 to 1.00 D in the calculation of IOLp [38, 82, 158].

ACD PREDICTION

ACD can be assessed using optical pachymetry [108]. The use of LT for the estimation of ACD postoperatively was initially introduced by Olsen in 1986 [91] and greatly affected the prediction of ACD in a recent series [159]. Holladay et al. were the first to report a potentially wide variability in ACD for a given AL [160]. For example, a 0.25 mm error in the measurement of postoperative ACD corresponds to a 0.1 D and 0.5 D error in two eyes with AL of 30.0 mm and 20.0 mm, respectively [56]. If "the method of the average ACD" is the only method used for predicting the ACD, then the ACD prediction errors are reported to account for ~40 % of the total refractive prediction error [82]. ACD prediction can be significantly improved using a regression equation that incorporates the AL, preoperative chamber depth, LT, and corneal height. The ACD source is estimated to contribute approximately 20% when the ACD value is assessed based on the above principle [6, 82]. The anterior chamber is usually shallower in females [161], but this factor affects the refractive outcome after cataract surgery to a much lower extent than corneal steepness and AL [162]. Hoffer used an ACD prediction formula for posterior chamber lenses and reported that the measured ACD following the operation was directly proportional to the AL of the eye ($ACD = 0.292\ AL - 2.93$) [163].

COMPARISONS BETWEEN FORMULAS

Some formulas discussed above outperform others because of the ocular characteristics as well as the geometry of the particular lens used [164].

Short Eyes

The current literature defines short eyes as those with an AL shorter than 22.00 mm [51]. ELP calculation errors appear to be AL-dependent, and short eyes appear to be more susceptible to greater errors than long eyes [56]. Despite technological improvements, the IOLp calculation accuracy of formulas is low for short eyes [9, 160]. This might be because, in small eyes, characteristic exaggeration variables need to be considered [165]. An example reflecting the difficulty of IOLp calculation in short eyes is that 80% of these eyes possess crystalline lenses of large dimensions while they have normal anterior chamber dimensions in the pseudophakic state [69]. It has been reported that short eyes tend to lead to myopic predictions [132]. An early study by Olsen estimated the source of IOLp calculation errors to be the result of erroneous measurements of AL in 54% of cases, corneal power in 8%, and incorrect postoperative ACD calculation at 38% [82]. Arguably, prediction errors appear to be greater when using contact US due to involuntary compression of the eye, even by experienced operators [29, 106, 107]. Moreover, formulas with a decent performance in medium and high AL eyes do not appear to perform well in short eyes [74]. Several studies that evaluated the accuracy of different IOLp calculation formulas were based on data from optical biometry measurements in short eyes [116]. Aristodemou et al. reported that the refractive outcomes following cataract operations in eyes with AL < 22 mm could be more easily predicted using the Hoffer Q than the Holladay and SRK/T [116]. This result was confirmed by Gavin and Hammond, who compared Hoffer Q with the SRK/T in eyes shorter than 22 mm [63]. The Hoffer Q seems to generally offer the best results in short eyes [51, 83, 166], even though some authors who performed a comparison of many formulas, including the Hoffer Q, in short eyes reported that none of the compared formulas seemed to outperform others [73, 100, 167]. MacLaren et al. concluded that the theoretical refractive outcomes with Haigis and Hoffer Q were better than those with Holladay 1 and SRK/T in eyes that required IOLp over 30.00 D. However, these results were not subjected to statistical analysis [70]. Sanders et al. [62] investigated a dataset of eyes with AL less than 22.0 mm (n = 99) and found no difference between any of the five formulas (SRK/T, Holladay, SRK-II, Hoffer and Binkhorst II) with errors < 0.5 D, < 1.0 D, or > 2.0 D ($\chi 2$ with Yates correction).

Formula Results: It appears that older formulas tend not to produce very good results in extreme ALs. The SRK-II formula was the only formula with significantly worse results compared to Haigis. In a retrospective study by Rae Roh et al. [2] formulas that use the fixed ACD method (e.g., Binkhorst I) tend to predict long ACDs in short eyes, thus leading to myopic errors [56]. Hoffer Q is regarded as the best formula available for short eyes based on a number of studies [51, 63, 83]. Nevertheless, Hoffer Q calculates the postoperative ELP according to AL and K and does not use an accurate, measured ACD rather than an estimated one [51]. The Haigis formula calculates the ELP via ACD and AL measurements [168]. A direct comparison of Hoffer Q and Haigis in short eyes showed a lower refractive prediction error in Haigis [2]. A 2014 study by Eom et al. further analyzed the accuracy of both formulas and reported increased precision with Haigis in eyes with ACD lower than 2.40 mm compared to Hoffer Q [169]. Shorter eyes tend to have a shallow ACD [135, 170]. In contrast, Mustafa et al. reported that SRK/T outperformed Haigis, Hoffer Q, and Holladay 1 and noted that only the latter seemed to be less affected by shallow ACDs [85]. A retrospective study by Maclaren et al. further supported the superiority of Haigis over Hoffer Q in extreme hyperopia, although Haigis tended to overcorrect myopia. The same study reported a significant difference in the lens design. Haigis gave better results when used for open-loop lenses, whereas Hoffer Q yielded better results when used for plate-haptic lenses [70]. Hoffer [83] examined the MAE in 317 eyes using four formulas. Hoffer Q and Holladay 2 had lower MAE in short eyes (< 22.0 mm). Perhaps the best available evidence on the correct IOL choice for short eyes can be attributed to the meta-analysis by Wang et al., which compared the accuracy of Haigis, Holladay 2, Hoffer Q, Holladay 1, SRK/T, and SRK-II [171]. Their systematic review suggested that Haigis was superior compared to other formulas, although this difference was not significant, at least against the Holladay 1 and 2 formulas. The authors attributed the better performance of Haigis to its use of three constants (a0, a1, and a2) along with ACD and AL measurements in ELP prediction. In conclusion, it appears that most new generation formulas tend to be associated with relatively good results in eyes with AL < 22.0 mm. According to a meta-analysis by Wang et al., Haigis appears to be the most accurate classic formula. The notion that Hoffer Q may perform better in A-scan biometry should be considered. In these cases, the ACD measurement may not be accurate, leading to erroneous results with the Haigis formula. The newer formulas, including Barrett Universal II, Hill-RBF, and Holladay 2, also appear to perform well in these eyes.

Medium AL eyes

In medium AL eyes, the IOLp prediction results seem to depend on the selected formula for the statistical analysis of optical biometry data [28, 29]. No significant differences were reported between Holladay 1, Olsen, and SRK/T in the refractive outcome prediction of 77 eyes [28]. In a study with 100 eyes with an average AL of 22.89 mm, the authors reported that the IOLp calculation, using the Holladay formula, yielded more accurate results than those that used the SRK/T and Hoffer Q formulas [29]. In a study of 8018 eyes, Holladay 1 provided better or equivalent results to Hoffer Q and SRK/T for AL from 22 to 26 mm [116]. Currently, Holladay 1, Hoffer Q, and SRK/T (i.e., third-generation formulas), Holladay 2, Haigis, and Olsen (i.e., fourth-generation formulas), or even newer formulas are the most frequently used in clinical practice because they yield decent results in medium AL eyes, and they all provide equivalent results [6, 51, 53, 62, 83, 84]. Hoffer et al. evaluated the SRK/T formula in 325 eyes with medium AL (from 22.0 to 24.5 mm) and reported a prediction error of ± 1.00 D in 94.5% [51]. Hoffer concluded that the Holladay 1 and Hoffer Q formulas perform better than the other formulas in eyes with ALs between 22.0 mm and 24.5 mm [83]. In a study by Aristodemou et al., the MAE with different formulas was similar for AL of 22.0 to 23.5 mm, while Holladay 1 had slightly better predictions than other formulas for AL (23.5 to 24.5 mm) [116]. Hoffer et al. [51] reported a mean PE within ± 1.00 D in 94.8% of patients when using the Holladay 1 formula, 93.2% for the Hoffer Q formula, and 94.5 % for the SRK/T formula in a study of 325 eyes with medium ALs (from 22.0 to 24.5 mm). Narváez et al. [167] compared the Hoffer Q, Holladay 1, Holladay 2, and SRK/T formulas in 643 eyes with different ALs using immersion US biometry for their assessment. They reported no difference in terms of formula performance between the formulas in the four subgroups of ALs. The MAE they reported, using the SRK/T formula, was 0.52 ± 0.43 D (range 0.00 to 2.49 D) in 437 eyes with medium AL (22.0 to 24.49 mm). Hoffer [83] examined the MAE in 317 eyes using four formulas. Aristodemou et al. [116] performed the largest IOLp calculation formula study reported in the literature to date by comparing the Hoffer Q, Holladay 1, and SRK/T formulas in 8108 eyes and reported that the Holladay 1 tended to outperform the others in eyes from 23.5 mm to 26.0 mm.

Long eyes

Many studies have evaluated different IOLp calculation formulas' performance using optical biometry data from eyes with long AL [64, 66-68, 116, 149]. A study with a sample size greater than 300 long eyes showed that the SRK/T apparently outperforms Holladay 1 and Hoffer Q for eyes with AL longer than 27 mm [116]. Similar to short eyes, the accuracy of IOLp calculation formulas is relatively limited in long eyes (AL > 24 mm), especially in the most commonly used formulas [9, 127].

Potential sources of prediction error are the same as in short eyes, as described by Olsen, AL, corneal power measurement errors, and postoperative ACD prediction errors [38, 56]. A prospective study on extremely myopic eyes reported that when using the Barrett Universal II or Olsen formulas, only AL was associated with prediction errors [89]. Particularly when using A-scan biometry, the lower rigidity of the sclera in longer eyes would increase the possibility of errors due to involuntary corneal indentation with the probe [89]. Additionally, off-axis measurement, particularly in patients with posterior pole staphylomas, may lead to incorrect AL values [107, 124, 146]. Accurate preoperative assessment of AL may be critical in restricting prediction errors [146]. To this end, devices using PCI such as the Zeiss IOLMaster have increased the accuracy of AL measurements [27, 106, 172]. Nonetheless, a retrospective analysis of the results of SRK/T in high myopia patients undergoing cataract surgery using A-scan, B-scan, applanation, and optical biometry reported hyperopic errors with all methods [173]. Another source of prediction errors is that low-powered IOLs designed for highly myopic eyes are available in the 1.0 D steps. This can be somewhat avoided by aiming for myopia, thus limiting postoperative hyperopic surprises that may not be tolerated by previously myopic patients [174]. Even with less extreme IOLp, using standard formulas and IOL constants in myopic eyes frequently leads to postoperative refractive changes toward hyperopia when targeting emmetropia [9, 66, 67, 116, 127]. Many surgeons may target myopia to avoid hyperopic errors. The target refraction for highly myopic patients undergoing cataract surgery usually ranges from -0.5 D to -2.0 D or even up to -3.0 D [124, 175]. More myopic refractive targets are advised as AL increases when using third-generation formulas [176]. A retrospective study by Geggel et al. focused on different target refraction in commonly used formulas for myopic eyes and recommended a target of -1.0 D for Haigis, -1.75 D for Hoffer Q, -1.5 D for Holladay 1, and -1.0 D for SRK/T [174].

Haigis highlighted the use of positive-D IOL constants both in positive- and negative-D IOLS as potential sources of hyperopic error. The lens geometry changes when the power converts from positive to negative. In other words, the principal planes switch sides with respect to the haptic plane. As a countermeasure, Haigis suggested using different A-constants for positive- and negative-powered IOLs [127]. The role of A-constants in hyperopic error may be further supported by its persistence despite the development of more accurate AL measurement devices [149]. Furthermore, it has been reported that ACD calculation errors may not contribute significantly to errors when using low-power IOLs [177]. This may be further supported by reports of hyperopic surprises in eyes with zero-D IOLs, where ACD calculation is irrelevant [173]. Based on the geometric changes of low- and negative power IOLs, Hoffer proposed IOLp ≤ 6.0 D as a cut-off point where IOLp calculation should differ [178]. The decreased prediction error using optimized constants for negative power IOL implantation has been demonstrated in a number of studies [66]. The user group for laser interference biometry (ULIB) offers a list of optimized constants for most IOLs on their website [143].

To decrease the prediction errors, Preussner et al. developed a regression equation adjusting the measured AL: Final AL = 0.9479 × measured AL + 1.0848, where AL was measured using IOLMaster [133]. Wang and Koch hypothesized the presence of a systematic error in AL measurement from optical biometry due to the use of a single refractive index. They reported that this would become more apparent in greater ALs [156]. Combining data from the eyes of two study centers, Wang proposed the following AL adjustments:

Holladay 1 2-center optimized AL = 0.8814 × IOLMaster AL + 2.8701
Haigis 2-center optimized AL = 0.9621 × IOLMaster AL + 0.6763
SRK/T 2-center optimized AL = 0.8981 × IOLMaster AL + 2.5637
Hoffer Q 2-center optimized AL = 0.8776 × IOLMaster AL + 2.9269

An early study suggested that SRK/T provided the best results for myopic eyes among the commonly used formulas. Zaldivar et al. reported similar performance for SRK/T, Hoffer Q, Holladay 1, and Holladay 2 using A-scan biometry, with marginally better results for SRK/T [124]. The long AL subgroups in the studies by Roberts and Hodge, as well as Cooke and Cooke, showed no significant difference between formulas [74, 104]. Similarly, Wang et al. and Narváez et al. reported no significant differences between Holladay 1, Haigis, SRK/T, and Hoffer Q in eyes with AL > 25 mm and 26 mm, respectively [156, 167]. The study by Narváez et al. included Holladay 2 without noting any significant differences [167]. Other study groups concluded that Hoffer Q is more accurate for eyes with AL > 25 mm [114]. Among studies that further divided long AL into subgroups, Kijima et al. reported similar results between Holladay 1 and SRK/T in AL between 24.5 mm and 26.9 mm, while SRK/T appeared to perform better for AL > 27.0 mm [179]. A small retrospective study by Bang et al. [68] found that Haigis was more accurate over SRK/T, Holladay 1 and 2, and Hoffer Q, particularly in eyes with AL > 29.7 mm. Roessler et al. in a study of 37 eyes with AL of > 26.5 mm reported that the Haigis predicted refractive outcome following cataract operation was better than the Holladay 1 and SRK/T outcomes [64]. The Haigis formula has been reported to have the best performance in eyes with extreme myopia [66, 127]. The Haigis performed better than the Hoffer Q, Holladay 2, and SRK/T formulas in 44 eyes with AL > 26 mm that received myopic refractive lens exchange [67]. In a study by Bang et al. that included 53 eyes with AL > 27 mm, the Haigis formula displayed the greatest accuracy regarding the postoperative refractive error prediction, compared to the Hoffer Q, Holladay 1, Holladay 2, and SRK/T formulas [68]. In a study by Wang et al., which included 34 eyes with an AL ≥ 28 mm, the Haigis displayed greater accuracy than the SRK/T [149]. It has been proposed that a modification to the Ladas Super Formula should be made to include SRK/T for long eyes and exclude Holladay 1, given that SRK/T appears to be the most accurate formula and is recommended in three large studies [73]. Adjustment of measured ALs may also be used to correct systemic inaccuracies in long eyes [134]. Considering the high probability of a hyperopic surprise in eyes with ALs greater than 25.0 mm, Wang et al.[156] introduced a method for optimizing AL in IOLp calculation formulas. A study of Chinese patients with long AL (> 25.0 mm) reported that the Hoffer Q formula predicts better than all other formulas, while Holladay 1 and SRK/T were similar in terms of prediction [114]. In a study that included a small number of eyes in the extreme ranges of AL without sufficient statistical power, the authors reported that the SRK/T formula gave the best results for long eyes (AL > 26.0 mm) [166]. In a study by Narváez et al. [167], which included 44 eyes with an AL longer than 26.00 mm, the authors reported similar prediction accuracy of the postoperative refractive outcomes among the optimized Hoffer Q, Holladay 1, SRK/T, and Holladay 2 formulas.

In a study by Wang et al. [149] that included 34 eyes of AL between 25.00 mm and 28.00 mm, the SRK/T and Haigis formulas had similar performances and performed better than the Holladay 1, SRK-II, and Hoffer Q formulas. In eyes with very high AL and predicted IOLp of zero or less, the prediction of refractive outcomes was less accurate, and it was reported that they should use separately optimized IOL constants [66]. In a study by Cooke et al., long eyes resulted in more hyperopic mean prediction errors for all traditional formulas except for the Haigis [74], a result that has also been reported by others [132]. Hoffer found that SRK/T, Holladay, and Hoffer had equal performance rates, while all of them outperformed SRK-II with AL greater than 26.0 mm [51]. Hoffer et al.[51], in a study of 89 eyes with ALs greater than 24.5 mm, concluded that the Holladay 1 formula achieved the lowest MAE of 0.41 D with 0.31 SD compared to the SRK-I, SRK-II, SRK/T, and Hoffer Q formulas. [51] Donoso et al. examined 212 eyes with the SRK-II, Binkhorst II, Hoffer Q, Holladay 2, and SRK/T formulas and inferred that the SRK/T was probably the most accurate for eyes with AL > 28.0 mm [180]. As already mentioned, Hoffer [83] examined the MAE in 317 eyes using four formulas. The SRK/T had the lowest MAE in the medium-long (24.5 to 26.0 mm) and very long (> 26.0 mm) eyes. Aristodemou et al. [116], in a study of 8108 eyes, used the Hoffer Q, Holladay 1, and SRK/T formulas and reported that the SRK/T was the most accurate for long eyes (> 26.0 mm).

In a study by Olsen et al. [131], the Haigis, Hoffer Q, Holladay 1, and SRK/T formulas had similar performance, while the SRK/T formula was the most accurate in eyes with an AL > 27.0 mm.

For IOLp greater than 6.0 D, traditional formulas may also meet the NHS benchmark standards [89]. In IOLp < 6.0 D, AL-adjusted Haigis and Holladay 1 have also been reported with accurate power predictions [176]. However, in studies that included Barrett Universal II, it almost invariably appeared among the most accurate formulas, often with Olsen and Haigis [66, 67, 73, 176]. This is further supported by a systematic review and meta-analysis by Wang et al., who used data from 11 observational studies and reported that Barrett Universal II outperformed the Holladay 2, SRK/T, Hoffer Q, and Holladay 1 formulas. Concurrently, they established no significant differences between Barrett Universal II and Haigis in most AL groups. In the group with AL between 24.5 and 26.0 mm, Barrett Universal II appeared to be more accurate, but this was supported by only one retrospective study [73, 171]. Studies on the Olsen formula have suggested no difference between Haigis and Barrett Universal II [171].

In addition, a prospective study compared Olsen, Haigis, and Barrett Universal II as the three most accurate formulas for eyes with high myopia [89]. This study found better results with Barrett Universal II over Haigis in eyes with AL > 30.0 mm. Both formulas, as well as Olsen, were very accurate in the 28.0 to 30.0 AL group, as well as in controls with 26.0 to 28.0 mm AL [89]. Moreover, the AL measurement and IOL calculation were performed with a new Fourier-domain light-source optical biometer. Thus, the more accurate AL measurements and optimized constants may have also improved the results [89, 178].

Eyes with a long AL can sometimes have postoperative hyperopia if traditional third-generation formulas are used. Improved A-constants and AL adjustment formulas tend to provide more accurate results, particularly in IOLp < 6.0 D. New generation formulas, Olsen (even more so the standalone version), Haigis (and Haigis +/-), and Barrett Universal II have been associated with excellent postoperative refractive results. Nonetheless, especially when using standard formulas, it may be advisable to aim for postoperative myopia. Thus, hyperopic surprises may be avoided, while any residual myopia may be well tolerated by patients with myopia. Table 2 provides a summary of the most suggested formulas for short, medium, and long eyes.

HAIGIS versus SRK/T

A characteristic of the Haigis formula is that a measurement rather than an estimation of ACD is performed, while the SRK/T formula estimates the ACD, which is one of its weak points [28]. In a study that compared the Haigis and SRK/T formulas regarding their use in the correction of corneal astigmatism with toric IOLs, the authors concluded that the Haigis formula was more accurate [181]. In another study by Lundqvist et al., there was an association between the prediction errors of the SRK/T and Haigis formulas with patient sex [182]. In a study by Behndig et al. that assessed the impact of sex as females have a lower ACD and AL than males, the authors reported that Haigis outperforms SRK/T for refraction predictions postoperatively in females. Apart from the biometrical differences between eyes, K is of vital importance in explaining the differences between the two formulas [183].

SRK-II versus SRK/T

SRK-II and SRK/T are derived from empirical and theoretical research, respectively [62]. In a study by Hoffer et al., the authors concluded that SRK-II and SRK/T performed equally well in predicting the outcome. However, no eye had an AL greater than 26.39 mm [51]. In a study by Retzlaff et al., the mean standard error of the SRK/T, SRK/II, and Holladay formulas were 0.86, 0.89, and 0.88, respectively [62].

Haigis versus Hoffer Q

A study that included 76 eyes that underwent cataract surgery and had IOLs ranging in power from 30 to 35 D reported that Haigis was more accurate for open-loop lenses, while Hoffer Q was more suitable for plate-haptic lenses [70]. In a study by Eom et al. [141], MAE predicted by the Hoffer Q and Haigis formulas were compared, and their correlation was evaluated with ACD. They concluded that the MAEs predicted by the Hoffer Q and Haigis formulas were identical (0.40 D) for eyes with ACD ≥ 2.4 mm.

Haigis L versus Holladay 2

In a study by McCarthy et al.[184], the authors reported better performance of the Haigis L and Shammas no-history methods than the Holladay 2 with the clinical history-adjusted K method.

Hoffer Q versus SRK/T

In a study by Gavin and Hammond [63] that included 41 eyes with an AL < 22.00 mm, the Hoffer Q and SRK/T formulas were compared using IOLMaster for biometric assessments and reported better mean errors and MAEs with the Hoffer Q formula than with the SRK/T formula (0.61 D and 0.78 D v 0.87 D and 0.98 D, respectively). However, optimized IOL constants were not used. Many studies have compared third-, fourth-, and fifth-generation IOLp calculation formulas in terms of accuracy in eyes with low AL [2, 63, 67, 70, 74, 83, 100, 103, 116, 141, 167].

COMPARISONS OF MANY FORMULAS

In a study by Retzlaff e t al. [62], data from 1677 cases were used to compare the SRK/T, Holladay, SRK-II, Hoffer, and Binkhorst II formulas. For refractive errors < 0.5 D, the percentages achieved were 50%, 50%, 48%, 42%, and 47%, respectively, with Hoffer being the worst performing formula ($P < 0.001$), while the others had similar accuracy. Regarding refractive errors < 1.0 D, the outcomes were 80%, 80%, 77%, 78%, and 78%, respectively, with SRK-II performing worse than SRK/T and Holladay ($P = 0.03$). For refractive errors > 2.0 D, SRK/T, SRK-II, and Holladay performed significantly better than the Hoffer and Binkhorst formulas ($P = 0.02$). In a study by Aristodemou et al. [116], the authors compared the SRK/T, Holladay, SRK-II, Hoffer, and Binkhorst II formulas and reported that for errors < 0.5 D and < 1.00 D, the outcomes were 50% and 80%, respectively, using the SRK/T formula [116].

In a study that evaluated the accuracy of the Hoffer Q, Holladay 1 and 2, SRK-I and II, and SRK/T formulas, the Holladay 1 and 2, Hoffer Q, and SRK/T formulas substantially outperformed the SRK-I and II formulas [51, 83]. All seven formulas (Barrett Universal II, Haigis, Hoffer Q, Holladay 1, Holladay 2, Olsen, and SRK/T) were found to vary, with 72% to 80% of eyes within ± 0.50 D. This is usually accepted as the value that allows spectacle independence [186].

Studies that evaluated MAEs derived from the Hoffer Q, Haigis, Holladay 1, Holladay 2 and SRK/T formulas did not detect any statistically significant differences [67, 167]. When evaluating eyes with ACD ranging from 3.0 mm to 3.5 mm, the Holladay 1, Hoffer Q, SRK/T, and Haigis formulas have shown similar results [74]. In a study by Olsen et al. [131], the authors detected no statistically significant difference in terms of accuracy between the Haigis, Hoffer Q, Holladay 1, and SRK/T formulas, except for eyes with an AL over 27.0 mm, for which the SRK/T seemed to be the most accurate. In a study by Narváez et al. [167], which included 643 eyes, the Holladay 2, Hoffer Q, Holladay 1, and SRK/T formulas were statistically similar.

The present review was a comprehensive attempt to present IOL calculation formulas for patients with different structural eye characteristics, such as different AL. It has outlined all the basic forms of the IOLp calculation formulas used to date, based on the most recent literature. Moreover, we reviewed the effectiveness of certain forms and different generations of formulas in eyes with short, medium, and long AL and compared the effectiveness of different IOLp formulas for these eyes. However, articles from only two, albeit large, databases were used: PubMed and Google Scholar. Many of the articles in the literature used small samples that exhibit different characteristics. This makes it challenging to arrive at a definitive conclusion. In addition, most articles used different methodologies, and a large number of formulas have been developed. As such, it is difficult to compare all the formulas effectively and determine the superiority of one over another in eyes with specific structural characteristics.

Future research must compare the results of different formulas in eyes with short, medium, or long AL using a much larger sample population. Moreover, formulas of the same generation must be compared using a large sample population of patients with various AL. However, it is crucial to select appropriate samples as far as the differences in IOLp calculations are concerned with eyes that have different structural characteristics. Finally, it is crucial to invest in the development of newer IOLp calculation formulas so that refractive errors can be more efficaciously treated in extremely short or long eyes.

CONCLUSIONS

Cataract surgery with IOL implantation has a high success rate. However, selecting the most appropriate IOLp to achieve the best refractive outcome and postoperative patient satisfaction can be challenging. The development of five-generation formulas allows surgeons to estimate and select the most appropriate one for each patient according to their specific eye characteristics.

The IOL calculation formula, IOL insertion, and potential errors regarding the lens constant are mainly associated with refractive errors caused postoperatively and thus should be considered preoperatively. The IOLp calculation uses several different factors, including the accuracy of biometric data, such as AL, ACD, K, and corneal power. Other important factors are the central corneal thickness, LT, corneal refractive index, and CD. The accuracy of the manufactured IOLp control is also of paramount importance. However, other factors that contribute to IOL calculation and errors include the surgeon factor, retinal thickness, low preoperative visual acuity, ocular comorbidity, astigmatism, and high ametropia.

Two categories of IOL calculation formulas have been reported. Functional formulas and formulas that use biometric values for IOLp calculation. The first directly calculates the ELP, while the second selects IOLp but does not predict ELP. Research has revealed that short eyes appear to be more susceptible to greater errors than long eyes, as they are characterized by large crystalline lenses and normal anterior chamber anatomy. Although most recent studies indicated no significant differences in using formulas such as the SRK-II, SRK-T, Holladay, Hoffer, and Binkhorst II in short eyes, some studies have reported the superiority of the Hoffer formula in some cases. However, most of the existing reports are based on a limited sample population.

Similarly, there are no important differences between the formulas in the IOLp calculation of longer eyes, although it seems that there is a minor superiority of SRK/T in some cases. However, the longer the eye, the less accurate the formulas become. In addition, recent studies have indicated that fifth-generation formulas seem to be promising, as better results have been reported when the Olsen and Barrett Universal II formulas were used. Finally, based on the available literature, there is no gold standard as yet that can be applied to all patients. Instead, each patient should be managed individually depending on their particular eye characteristics.

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