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Research and Application Progress of Intraocular Lens Power Calculation Formulas in the Era of Refractive Cataract Surgery

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Abstract

As cataract surgery progresses from “restoration of sight” to “refractive correction”, precise prediction of intraocular lens (IOL) power is critical for enhancing postoperative visual quality in patients. IOL power calculation methods have evolved and innovated throughout time, from early theoretical and regression formulas to nonlinear formulas for estimating effective lens position (ELP), multivariable formulas, and innovative formulas that use optical principles and AI-based online formulas. This paper thoroughly discusses the development and iteration of traditional IOL calculation formulas, the emergence of new IOL calculation formulas, and the selection of IOL calculation formulas for different patients in the era of refractive cataract surgery, serving as a reference for “personalized” IOL implantation in clinical practice.

Keywords

Cataract Surgery, Intraocular Lens Power Calculation Formula, Refractive Cataract, Lens Power Calculation

1. Introduction

Cataract, the leading cause of blindness worldwide, is reported to be responsible for over 47% of all cases of blindness [1]. The most common cause of cataracts is closely related to age, and China is currently experiencing a stage of social aging. According to statistics from the International Agency for the Prevention of Blindness in 2020, there are more than 78 million people aged 50 and above globally who suffer from vision impairment or loss due to cataract, with China accounting

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for one-fifth of the global total and over 400,000 new cases occurring annually [2]. Currently, cataract extraction combined with intraocular lens (IOL) implantation remains the only effective treatment. With the maturity of cataract surgery techniques and the widespread use of functional IOLs, patients have higher expectations for postoperative visual quality. Cataract surgery has entered the era of precise refraction. To achieve optimal postoperative outcomes, accurate IOL power calculation is essential.

Since the 1970s, researchers have presented a variety of formulas for calculating IOL power, ranging from early theoretical and regression formulas to fourth- and fifth-generation formulas, as well as unique IOL calculation formulas based on AI technology. This review examines the development and implementation of several IOL calculation formulas in the context of refractive cataract surgery.

2. Development and Iteration of Intraocular Lens Power Calculation Formulas

2.1. First-Generation Theoretical Formulas

The power of the first-generation IOL was estimated using geometric optics theory, based on axial length (AL), corneal curvature (K), and postoperative anterior chamber depth (ACD). Stepwise regression analysis was utilized in conjunction with preoperative and postoperative patient data to create a mathematical model that relates corneal curvature, axial length, and IOL power [3]. Representative formulas include Fyodorov, Binkhorst, and the linear regression formula SRK-I. Due to the use of a fixed constant for ACD in calculations, the accuracy of IOL prediction for patients with abnormal axial lengths was not high [4]. It is no longer used clinically at present.

2.2. Second-Generation Regression Formulas

The first-generation theoretical formulas were revised and combined with empirical methods to yield the second-generation formulas. A representative formula is the SRK-II formula, designed by Sanders *et al.* [5] as a revision of the SRK-I formula. The SRK-I formula introduced the A-constant, which is primarily related to the type and manufacturer of the IOL. As the SRK-I formula had low prediction accuracy for patients with abnormal axial lengths, Sanders *et al.* optimized the A-constant, allowing it to be adjusted based on the patient's AL. The SRK-II formula significantly improved the accuracy of IOL prediction compared to its predecessor. Due to the limited reference variables and insufficient accuracy of the second-generation formulas, they are currently rarely used in clinical practice.

2.3. Third-Generation Intraocular Lens Power Calculation Formulas

The third-generation IOL power calculation formulas introduced the concept of the effective lens position (ELP) after surgery, enabling better prediction of IOL power for patients with long or short axial lengths. Representative formulas include Holladay I, SRK-T, and Hoffer Q. Holladay [6] first proposed the Holladay I nonlinear formula; subsequently, Sanders *et al.* [7] developed the SRK-T formula based on the first-generation theoretical formula; and Hoffer [8] created the Hoffer Q formula, which introduced a "correction factor" to improve the accuracy of measured axial length (AL) and thus enhance the accuracy of IOL power calculation. Some studies [9] have shown that the Hoffer Q formulas exhibit good predictability in patients with short axial lengths and still hold clinical application value.

2.4. Fourth-Generation Intraocular Lens Power Calculation Formulas

As third-generation formulas were mostly derived based on normal model eye parameters, they still had errors in predicting IOL power for patients with abnormal axial lengths. Therefore, the Haigis W [10] formula calculates IOL power based on preoperative axial length (AL) and anterior chamber depth (ACD) and introduces three constants (a0, a1, a2) to improve the accuracy of predicting the postoperative effective lens position (ELP). The HolladayII formula, an improvement over the Holladay I formula, predicts ELP based on seven variables (axial length, corneal curvature, white-to-white distance, anterior chamber depth, lens thickness, preoperative refractive status, and age). As the fourth-generation formulas incorporate more measurement parameters, their accuracy has been improved, and they are still widely used in clinical practice.

2.5. Fifth-Generation Intraocular Lens Power Calculation Formulas

Relatively consistent prediction results for individuals with normal axial lengths have been obtained after multiple iterations of the IOL power calculation methods. Through the efforts of numerous researchers, the fifth-generation IOL power calculation formulae were created in order to significantly increase the accuracy of IOL prediction and its use in patients with unique axial lengths. The Barrett Universal II (BUII) formula is an improvement on the Barrett Universal formula, which measures ocular structures using optical coherence tomography (OCT) technology and analyzes ocular biometric data thoroughly using big data and machine learning algorithms to predict the postoperative effective lens position (ELP) and IOL power. The BUII formula [11] [12] also considers the A-constant and lens factor in its calculations, achieving high prediction accuracy across different axial length ranges and is widely used.

Another representative of the fifth-generation formulas is the Olsen formula, which has undergone multiple improvements since its inception. The Olsen formula [13] introduces new ocular biometric measurement parameters, such as corneal curvature radius and lens thickness, and uses a more complex mathematical model to predict ELP, improving the accuracy of IOL power prediction.

The fifth-generation formulas exhibit high predictive accuracy across patients with different axial lengths, holding broad prospects for clinical application.

2.6. Novel Intraocular Lens Power Calculation Formulas

2.6.1. Ladas Super Formula

Ladas developed a new formula that integrates multiple IOL formulas, combining the ideal aspects of the Hoffer Q, Holladay I, optimized Holladay I, Haigis, and SRK/T formulas. It automatically selects the optimal prediction path based on different ocular parameters and surgical conditions, thereby improving the accuracy of ELP and IOL power prediction.

2.6.2. Hill-RBF Formula (Hill-Radial Basis Function)

The Hill-RBF formula is an IOL power calculation formula based on artificial intelligence. Through regression analysis of a large amount of real postoperative refractive outcome data, it leverages the advantages of the Radial Basis Function (RBF) network to efficiently process complex, nonlinear ocular biometric data. This formula predicts postoperative refraction using three variables (AL, K, ACD). Currently, Hill has updated the Hill-RBF formula to Hill-RBF 3.0, an online formula widely used in clinical practice. As Hill-RBF is entirely data-driven, it needs to be continuously improved through the expansion of the database.

2.6.3. EVO Formula (Emmetropia Verifying Optical Formula)

The EVO formula [14], proposed by Yeo Tun Kuan, is an IOL calculation formula based on the convergence of thick lenses. It has been updated to the EVO 2.0 formula, which comprehensively considers the anterior and posterior surfaces of the cornea and IOL and calculates the "emmetropia factor" for each eye using six variables (AL, K, ACD, LT, central corneal thickness (CCT), and posterior corneal surface refractive power (PK)), improving the accuracy of IOL prediction.

2.6.4. Kane Formula

The Kane formula is a comprehensive combined formula that integrates artificial intelligence, theoretical optics, and the thin lens equation, using six key variables (AL, K, ACD, LT, CCT, and gender) to accurately calculate the refractive power of the intraocular lens (IOL). Similar to the Hill-RBF formula, the Kane formula does not rely on traditional methods for calculating the effective lens position (ELP) but instead uses multiple biometric parameters to predict the postoperative refractive status. Notably, this formula considers the influence of gender on IOL calculations, further enhancing prediction accuracy. It has demonstrated high measurement accuracy in multiple studies and holds broad application prospects.

2.7. Intraocular Lens Power Calculation Formulas for Post-LASIK Patients

LASIK surgery has been available for 30 years, and an increasing number of patients who have undergone LASIK are now facing the challenge of cataracts. As LASIK surgery alters the refractive status of the cornea, traditional IOL calculation formulas often fail to accurately predict postoperative refractive outcomes. Applying IOL calculation methods for normal patients may result in varying degrees of refractive errors in postoperative patients [15]. A number of IOL calculation methods appropriate for cataract patients who have had LASIK have been proposed by domestic and international scientists in response to this problem. The Haigis-L formula, the Shammas-PL formula, and the Barrett True-K formula are currently popular formulas. These formulas usually make use of more intricate mathematical models, taking into account both the biological characteristics of each patient and the effect of corneal refractive surgery on corneal refractive power.

3. Application of Intraocular Lens (IOL) Calculation Formulas

Several key factors influence the calculation of intraocular lens power, including axial length (AL), anterior chamber depth (ACD), corneal curvature (K), lens thickness (LT), white-to-white distance (WTW), central corneal thickness (CCT), posterior corneal curvature (PK), and prediction of postoperative effective lens position (ELP). Throughout the development of IOL calculation formulas, accurate prediction of AL and ELP is crucial.

AL influences not only change in postoperative ACD but also has an important role in predicting postoperative ELP. Olsen [4] found that a 1mm change in AL results in approximately a 3D shift in refraction, while a 1mm change in postoperative ACD produces at least a 0.32D shift in refraction.

Patients with normal axial lengths experience less postoperative refractive shift, whereas those with long or short axial lengths may develop some degree of refractive error [16]. Therefore, it is essential to select appropriate IOL calculation formulas based on axial length.

For short axial lengths (<22.0 mm), accurate assessment of ELP before surgery is challenging, increasing the likelihood of IOL prediction errors. Gavin [17] suggested that compared to the SRK/T formula, the Hoffer Q formula results in a more hyperopic postoperative refractive state, and the Hoffer Q formula demonstrates better predictive stability for AL < 22.0 mm. However, Wang Qi [18] and colleagues discovered that the Hoffer Q formula might be prone to myopic drift when comparing the SRK/T, Haigis, and Hoffer Q formulas for estimating IOL power in patients with short axial lengths. Oleksiy V. Voytsekhivskyy [19] and colleagues compared 18 calculation formulas for axial lengths < 22.0 mm and concluded that the K6, Kane, Naeser2, Olsen, and VRF-G formulas exhibit superior accuracy. Yang Zhi *et al.* [20] found that the BUII formula provides the best stability for predicting IOL power in cataract patients with short axial lengths.

High myopic eyes may develop a number of problems that decrease postoperative predictability and increase the chance of postoperative refractive shift and errors, which can impair visual quality. High myopia is defined as an axial length > 26.0 mm or a refractive error > 600 diopters [21].

Yildz [22] found that for cataract patients with axial lengths > 26 mm, among the Haigis, SRK-T, Hoffer Q, and HolladayII formulas, the Haigis formula had the smallest mean arithmetic error. A comprehensive investigation [23] evaluating the accuracy of seven calculation formulas (BUII, Haigis, Hoffer Q, Holladay I, HolladayII, SRK/T, and T2) in 77 eyes with long axial lengths was carried out by Kane and associates. According to the findings, the BUII formula was the most accurate, followed by Hoffer Q, SRK/T, Haigis, and HolladayII. Yang Zhi [24] and colleagues compared the absolute refractive errors of six formulas in postoperative high myopia patients and found that the Kane, BUII, and Hoffer QST (an improvement upon the Hoffer Q formula) formulas had the smallest absolute refractive errors but still exhibited a tendency towards hyperopic drift, suggesting the need to reserve a certain degree of myopia based on axial length. The EVO formula showed better stability than the BUII formula in a predictive analysis of postoperative refractive power in patients with long axial lengths [25]. This could be because the EVO formula takes into account the patient's optical dimensions and the geometric features of the IOL, which are more in line with the patient's actual needs.

For extremely long axial lengths (≥28.0 mm), a study [26] found that compared to the SRK/T and Haigis formulas, the axially optimized SRK/T, BUII, and Hill-RBF3.0 formulas showed the smallest increase in error with axial length. Darcy *et al.* [27] analyzed data from 10,930 eyes and found that the Kane formula had the smallest mean absolute error across various axial length ranges, with slightly higher predictive accuracy than the BUII, Hill-RBF2.0, and HolladayII formulas.

For patients who have undergone laser-assisted in situ keratomileusis (LASIK), using IOL calculation methods for normal patients may result in varying degrees of postoperative refractive error, possibly due to changes in the anterior and posterior corneal surface curvatures after LASIK. The HolladayII formula is currently recognized as a superior method [28]. Additionally, some new formulas provide good refractive predictions. Chen *et al.* [29] demonstrated that the Shammas-PL formula outperforms the Haigis-L formula in the absence of pre-refractive surgery data. Abulafia [30] compared the Barrett True-K and ASCRS online formulas and found that the Barrett True-K formula had higher predictive accuracy. Therefore, the Barrett True-K formula may be a more reliable choice for cataract patients who have undergone LASIK.

The onset of the refractive era in cataract surgery is strongly associated with the development of intraocular lens (IOL) calculation methods. Due to ongoing improvement and modifications, traditional formulas still have a big impact. As artificial intelligence technology has advanced in recent years, it has become more capable of analyzing large amounts of data and learning on its own. Measurement findings have improved in the area of physiological measurements, including axial length, anterior chamber depth, corneal curvature radius, steep axis, flat axis, and average curvature, providing encouraging opportunities for use. Moreover, the number of cataract patients who have had excimer laser surgery is increasing in tandem with the sharp growth in the number of myopia patients worldwide. For this subset of patients, new options are available for accurate prediction of IOL implantation. A detailed comparison of study findings from diverse literature sources is shown in **Table 1**, which may provide a reference for the implementation of several typical new IOL calculation algorithms.

Table 1. Comparison of reference variables, applicable populations, and prediction accuracy of new IOL power calculation formulas.

	Reference Variables	Applicable Populations	Prediction Accuracy
Olsen	AL, K, ACD, LT, CCT, AGE	Full axial length	Proportion of postoperative refractive error within ±0.5D > 90%
BUII	AL, K, ACD, LT, WTW	Full axial length	Proportion of postoperative refractive error within ±0.5D > 90%
Barrett True-K	AL, K, ACD, LT, WTW, TK	Post-corneal refractive surgery	Proportion of postoperative refractive error within ±0.5D > 70%
Ladas SF	AL, K, ACD	Currently rarely used	Postoperative refractive error tends to be high
Hill-RBF 3.0	AL, K, ACD, LT, CCT, WTW, Sexual Distinction	Full axial length	Proportion of postoperative refractive error within ±0.5D > 90%
EVO	AL, K, ACD, LT, CCT, PK	Full axial length	Proportion of postoperative refractive error within ±0.5D > 90%
Kane	AL, K, ACD, LT, CCT, Sexual Distinction	Full axial length	Proportion of postoperative refractive error within ±0.5D > 90%
Haigis-L	AL、K、ACD、TK	Post-corneal refractive surgery	Proportion of postoperative refractive error within ±0.5D > 60%

4. Summary and Outlook

In summary, the creation and refinement of intraocular lens computation formulae constitutes an ongoing process of advancement and creativity. The idea of accurate refraction has grown in popularity as cataract surgery ushers in a new era of refractive surgery, and visual quality has emerged as a crucial postoperative evaluation metric. An essential step in this procedure is determining the intraocular lens power. In order to provide references and guidance for "tailored" intraocular lens implantation and, ultimately, improve patients' postoperative visual experience, ophthalmologists must constantly compile their expertise and improve intraocular lens calculating techniques.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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