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A New Intraocular Lens Power Formula Integrating an Artificial Intelligence–Powered Estimation for Effective Lens Position Based on Chinese Eyes

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Purpose: To develop and evaluate a new intraocular lens (IOL) formula based on Chinese eyes.

Methods: A training dataset of 709 eyes undergoing uneventful cataract surgery was used to train the algorithm for effective lens position estimation. The algorithm was then integrated with Gaussian optics to develop the new IOL formula (Jin-AI). From the same center, 177 eyes served as an internal test dataset. An independent dataset of 557 eyes served as an external test dataset. The standard deviation (SD) of prediction errors was compared among the Jin-AI formula, traditional third-generation formulas (SRK/T, Holladay 1, Hoffer Q), and newer generation formulas (Kane, Barrett Universal II [BUII], Hill–radial basis function [RBF] 3.0, and PEARL–DGS).

Results: In the internal test dataset, the Jin-AI formula showed the lowest SD (0.25 D), followed by the BUII (0.31 D), Kane (0.33 D), and PEARL–DGS (0.33 D) formulas. In the external test dataset, the Jin-AI, Kane, and PEARL–DGS formulas had the lowest SD (0.38 D), followed by the BUII (0.39 D), Hill–RBF 3.0 (0.39 D), SRK/T (0.45 D), Holladay 1 (0.48 D), and Hoffer Q (0.48 D) formulas. The SD of the Jin-AI formula was significantly lower than the third-generation formulas and comparable to the four newer generation formulas. Predictive accuracy of the Jin-AI formula was similar to the newer generation formulas across all axial length, keratometry, and anterior chamber depth ranges.

Conclusions: The new formula has exhibited good performance in predicting postoperative refractions. Its overall predictive accuracy was better than the third-generation formulas and comparable to the newer generation ones.

Translational Relevance: The Jin-AI formula could be a reliable alternative for IOL power calculation in Chinese.

Introduction

Patient demand for refractive correction has promoted the development of refractive cataract surgery techniques. Careful consideration of surgical techniques, biometric measurements, and intraocular lens (IOL) power calculations is necessary to attain this objective.[1–3] Improvements in surgical techniques that have occurred include small incisions with in-the-bag IOL placement, and more accurate biometric measurements have occurred due to the use of optical biometry. It is believed that erroneous estimation of effective lens position (ELP) is the major source of errors in current IOL power calculations.[2,4]

First-generation formulas utilized a constant to denote the lens position because the postoperative ELP cannot be directly measured before surgery. Later third-generation formulas (SRK/T, Holladay 1, and Hoffer Q) incorporated keratometry (K) and axial

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length (AL) and used regression-based methods for predicting ELP. In 2000, Haigis et al.,[5] included preoperative anterior chamber depth (ACD) in his formula to enhance the quality of postoperative ELP prediction. In addition to incorporating supplementary ocular parameters, newer formulas have applied a variety of sophisticated computational methodologies to improve refractive outcomes.[1–3] Examples include the use of thick lens formulas to obtain a more accurate estimation of the total corneal power from the anterior radius and consideration of the geometric particularities of certain IOL models (such as meniscus geometries).[6,7] Furthermore, artificial intelligence (AI) has been used widely in medical practice since the introduction of the third wave of AI techniques.[8] In the field of ophthalmology, AI has been employed to predict glaucomatous optic neuropathy, to screen retinopathy of prematurity, to detect referable diabetic retinopathy, and to perform IOL power calculation.[9,10] The combination of theoretical optics principles with AI components is another factor contributing greatly to the enhanced refractive outcomes of more recent formulas.[2,6,11] These newer formulas have outperformed traditional formulas in routine cataract surgery.[1–3,11–14]

Regardless of the underlying principles of a formula, however, biometric parameters are essential for IOL power calculations. Currently, widely used IOL formulas are based on data from Caucasian eyes, but few incorporate biometric data from Chinese populations in their algorithm construction or theoretical derivation.[15,16] Previous studies have demonstrated differences in ocular dimensions between Chinese and Caucasians.[17–20] Jin et al.[17] found differences in the corneal keratometric index between Chinese eyes and German eyes, Hickson-Curran et al.[20] observed that the Chinese population had significantly steeper horizontal K than the Caucasians, and Wang et al.[18] reported shallower ACD in Chinese compared to Caucasian eyes. Furthermore, the Chinese have a higher rate of myopia and longer AL.[19,21] Given China's large population base and the high number of cataract surgeries, it is essential to use data from Chinese populations to construct appropriate algorithms. This study aimed to develop a new algorithm for ELP estimation based on Chinese eyes and to assess the accuracy of a new AI-powered IOL power calculation formula incorporating this new algorithm.

Methods

This was a retrospective study based on data received from two centers. The study was conducted in accordance with the tenets of the Declaration of Helsinki. Written informed consent was obtained from all patients for use of the clinical data. The internal dataset was collected from the Department of Ophthalmology, Shanghai East Hospital, Tongji University, Shanghai, China, by one of the authors (HJ). The external test dataset was collected from the Zhongshan Ophthalmic Center, Sun Yat-Sen University, Guangzhou, China, by another author (MW). In total, the internal and external datasets included 886 eyes of 886 patients and 557 eyes of 557 patients, respectively. In the internal dataset, the implanted IOLs included ZEISS CT ASPHINA 409MP (269 cases; Carl Zeiss Meditec, Jena, Germany), Alcon SN60WF (67 cases; Alcon Labs, Fort Worth, TX), TECNIS ZCB00 (203 cases; Abbott Medical Optics, Santa Ana, CA), TECNIS ZA9003 (172 cases; Abbott Medical Optics), and Akreos Adapt AO (175 cases; Bausch & Lomb, Bridgewater, NJ). In the external test dataset, the implanted IOL model was the Alcon SN60WF (557 cases).

All eyes underwent uneventful cataract surgery. Exclusion criteria were the presence of intraoperative or postoperative complications, follow-up of less than 1 month, best-corrected visual acuity of less than 20/40 for any reason, and missing biometry. Patients with corneal scarring, keratoconus, prior refractive surgery, keratoplasty, intraocular surgery history, and incomplete documentation were also excluded. Data from only the first operated eye were included for patients undergoing bilateral surgery.

The ocular biometry of all patients was measured using the ZEISS IOLMaster 700 (Carl Zeiss Meditec). Preoperative AL, K, ACD (epithelium to the lens), and lens thickness (LT) were collected. The measurements were carried out by experienced technicians. The actual powers of the implanted IOLs were obtained from medical records. Experienced optometrists conducted the standard postoperative refraction measurements using a 5-meter refractive lane. The refractions were then adjusted to a 6-meter distance.[22]

Modeling of the Jin-AI Formula

The internal dataset was randomly split into a training dataset (709 cases) and an internal test dataset (177 cases) at an 80/20 ratio. The learning features included AL, corneal radius of curve (r), ACD, LT, and A constant. The IOL constant of each IOL type was adopted from the User Group for Laser Interference Biometry (ULIB) website, as advised by Hoffer and Savini.[23]

Misestimation of ELP is the major source of IOL power miscalculation.[4] The back-calculated ELP, determined using the thin lens formula,[24,25] served as

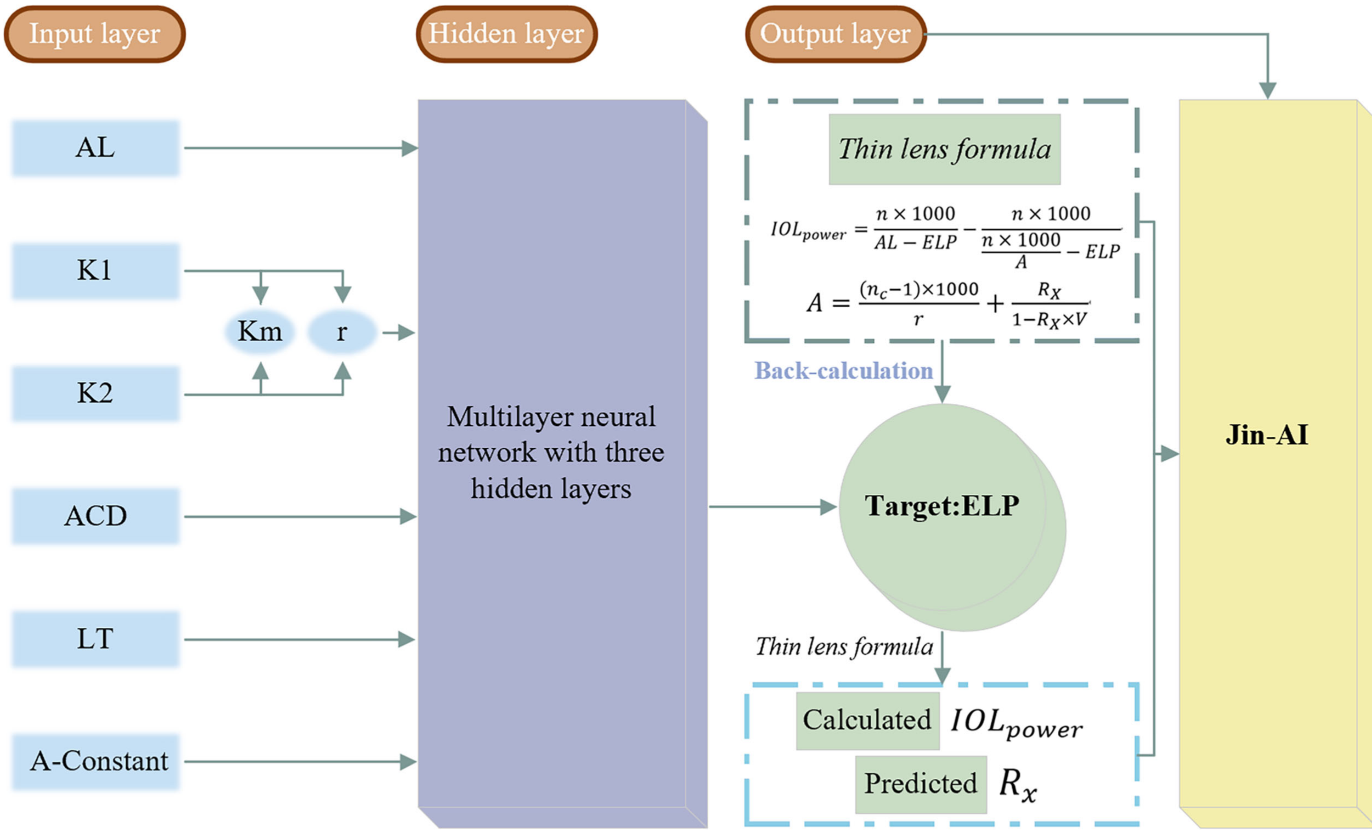

Figure 1. Block diagram of the Jin-AI formula. The calculation processes highlighted by the *dotted green line* were used only during development of the algorithm. AL, axial length (mm); ACD, anterior chamber depth (mm); ELP, effective lens position (mm); IOL_{power}, intraocular lens power (D); n, refractive index of aqueous and vitreous (1.336); n_c, fictitious refractive index of the cornea (1.333); K1, flat keratometry (D); K2, steep keratometry (D); Km, mean keratometry (D); LT, lens thickness (mm); r, corneal radius of curvature (mm); r = 337.5/Km (mm); Rx, postoperative refraction (D); V, vertex distance (12 mm).

the training target (Fig. 1). The equation solved for the back-calculated ELP was as follows:

$$IOL_{power} = \frac{n \times 1000}{AL - ELP} - \frac{n \times 1000}{\frac{n \times 1000}{A} - ELP}$$

$$\mathrm{A} = \frac{(n_c - 1) \times 1000}{r} + \frac{R_x}{1 - R_x \times v}$$

where AL is axial length; ELP is effective lens position; IOL_{power} is the actual implanted intraocular lens power (diopters); n is the the refractive index of aqueous and vitreous (1.336); n_c is the the fictitious refractive index of the cornea (1.333); r is the corneal radius of curvature (mm); R_x is the actual postoperative refraction (diopters); and v is vertex distance (12 mm).

To improve the prediction of postoperative ELP, we constructed a new AI model based on a multilayer neural network. The model was trained on the training dataset using a supervised learning method. The learning features were normalized using z-score. We fine-tuned the AI model through iterative refinement, and the configuration for hidden layers was identified as three layers with 32, 16, and 8 neurons in the first, second, and third layers, respectively. The rectified linear unit (ReLU) activation function was used for all layers of our neural network architecture, combined with an initial learning rate of 0.001, a batch size of 64, a regularization parameter alpha of 0.0001, and a momentum parameter of 0.9. The backpropagation algorithm with the adaptive moment estimation optimizer (ADAM) was selected as the solver to optimize the network parameters. Its $\beta 1$ and $\beta 2$ were set to 0.9 and 0.999, respectively. The model was trained for a total of 300 epochs. Root-mean-square error (RMSE) was used as the loss function. Python 3.7 with the scikit-learn package was employed to train the model. This model was then integrated with Gaussian optics[24] to developed a new AI-powered IOL power formula based on Chinese eyes (Fig. 1), named Jin-AI (Scansys; MediWorks, Shanghai, China). In essence, the Jin-AI formula can be considered to be a combination of AI technique and theoretical optics.

Evaluation of IOL Power Calculation

The accuracy of the Jin-AI formula was compared with that of the SRK/T, Holladay 1, Hoffer Q, Kane, Barrett Universal II (BUII), Hill–radial basis function (RBF) 3.0, and PEARL–DGS in the external test dataset. The open-source SRK/T, Holladay 1, and Hoffer Q formulas were input into an Excel spreadsheet (Microsoft, Redmond, WA), and the three unpublished newer formulas were calculated online (Kane, www.iolformula.com; BUII, calc.apacrs.org/barrett_universal2105; Hill–RBF 3.0, rbfcalculator.com). The PEARL–DGS formula was evaluated with the assistance of Guillaume Debellemanière, MD (Paris, France). For the SRK/T, Holladay 1, and Hoffer Q formulas, constant optimization was performed using the Excel Goal Seek tool. For the Kane, BUII, and Hill–RBF 3.0 formulas, optimization followed the method described by Gatinel et al.[26] The constant optimization for the PEARL–DGS formula was conducted with the help of Guillaume Debellemanière, MD.

The arithmetic prediction error (PE) was calculated by subtracting the predicted outcome obtained by each formula from the postoperative spherical equivalent. The PE standard deviation (SD), mean absolute error (MAE), and median absolute error (MedAE) were calculated. The percentage of cases within ±0.25 diopter (D), ±0.50 D, ±1.00 D, and ±2.00 D was assessed.

Statistical Analysis

Prism 8.0 (GraphPad, Boston, MA), Excel 2019, and R 4.3.0 (R Project for Statistical Computing, Vienna, Austria) were used for statistical analyses. The normality of PEs and MAEs for each formula was assessed using the Kolmogorov–Smirnov test. Multiple performance metrics were evaluated and compared across formulas in the external test dataset, including SDs, MedAEs, MAEs, and the percentage of a PEs within ±0.25 D and ±0.50 D. All aforementioned measures were compared using the heteroscedastic test per recent recommendations by Holladay et al.[27] P values were adjusted for multiple comparisons, and a statistically significant difference was defined as an adjusted $P < 0.05$.

Results

Table 1 shows the characteristics of the study populations. A total of 1443 eyes from 1443 patients were included in the present study, with 709 eyes in the training dataset, 177 eyes in the internal test dataset, and 557 eyes in the external test dataset. In the internal test dataset, the algorithm had an R^2 of 0.94 for ELP prediction with a RMSE of 0.23. Table 2 presents the optimized constant of each model and the SD of each formula in this dataset. In the external test dataset, after constant optimization, the Jin-AI, Kane, and PEARL–DGS formulas had the same SD value of 0.38 D, followed by the BUII and Hill–RBF 3.0 formulas with an SD of 0.39 D. The SD values of the third-generation formulas ranged from 0.45 to 0.48 D (Table 3). The heteroscedastic test revealed that the SD values of the three third-generation formulas were significantly higher than those of the newer ones ($P < 0.001$). In contrast, no significant differences were observed among the SD values of the new-generation formulas (all $P > 0.05$) (Supplementary Table S1).

The lowest MedAE was noted in the Jin-AI, BUII, Hill–RBF 3.0, and PEARL–DGS formulas, with a value of 0.22 D (Table 3; Fig. 2). The MedAE for the Kane formula was 0.23 D, whereas that for the third-generation formulas ranged from 0.27 to 0.29 D. The heteroscedastic test showed that the MedAEs of the third-generation formulas were markedly higher than those of the new-generation formulas (all $P < 0.001$), with no significant differences detected among these new ones (all $P = 0.877$) (Supplementary Table S1).

The results showed that the percentage of eyes with a PE within ±0.25 D ranged from 44.70% (Hoffer Q) to 57.45% (Jin-AI) (Table 3; Fig. 2). The percent-

Table 1. Parameters of Eyes Included in the Study ($N = 1443$)

	Mean ± SD		
Biometric Parameters	Training Dataset ($n = 709$)	Internal Test Dataset ($n = 177$)	External Test Dataset ($n = 557$)
Axial length (mm)	24.08 ± 1.68	24.10 ± 1.57	24.08 ± 1.63
Mean keratometry (D)	44.15 ± 1.39	44.19 ± 1.34	44.13 ± 1.32
Anterior chamber depth (mm)	3.19 ± 0.53	3.22 ± 0.44	3.22 ± 0.47
Lens thickness (mm)	4.49 ± 0.54	4.45 ± 0.44	4.38 ± 0.50

Table 2. SD Matrix of Prediction Errors in the Internal Test Dataset Using the Heteroscedastic Method ($N = 177$)

IOL Formula	Constant After Optimization	SD (D)	SRK/T	Holladay 1	Hoffer Q	Kane	BUII	Hill–RBF 3.0	PEARL–DGS	Jin-AI
SRK/T	409MP: 118.39 SN60WF: 119.03 ZCB00: 119.28 ZA9003: 119.37 Adapt AO: 118.74	0.40	1.000	0.556	0.893	0.000[a]	0.000[a]	0.940	0.011[a]	0.000[a]
Holladay 1	409MP: 1.51 SN60WF: 1.83 ZCB00: 2.05 ZA9003: 2.17 Adapt AO: 1.70	0.43	—	1.000	0.940	0.000[a]	0.000[a]	0.940	0.000[a]	0.000[a]
Hoffer Q	409MP: 5.36 SN60WF: 5.61 ZCB00: 5.89 ZA9003: 5.97 Adapt AO: 5.51	0.43	—	—	1.000	0.000[a]	0.000[a]	0.940	0.000[a]	0.000[a]
Kane	409MP: 118.45 SN60WF: 119.11 ZCB00: 119.31 ZA9003: 119.29 Adapt AO: 118.85	0.33	—	—	—	1.000	0.940	0.940	0.940	0.001[a]
BUII	409MP: 118.43 SN60WF: 119.18 ZCB00: 119.37 ZA9003: 119.41 Adapt AO: 118.82	0.31	—	—	—	—	1.000	0.940	0.940	0.000[a]
Hill–RBF 3.0	409MP: 118.41 SN60WF: 119.03 ZCB00: 119.38 ZA9003: 119.39 Adapt AO: 118.68	0.35	—	—	—	—	—	1.000	0.940	0.043[a]
PEARL–DGS	409MP: 118.62 SN60WF: 119.26 ZCB00: 119.45 ZA9003: 119.41 Adapt AO: 118.97	0.33	—	—	—	—	—	—	1.000	0.000[a]
Jin-AI	409MP: 118.31 SN60WF: 119.01 ZCB00: 119.31 ZA9003: 119.10 Adapt AO: 118.39	0.25	—	—	—	—	—	—	—	1.000

The IOLs included the ZEISS CT ASPHINA 409MP, Alcon SN60WF, TECNIS ZCB00, TECNIS ZA9003, and Bausch & Lomb Akreos Adapt AO.

[a]Statistically significant using the heteroscedastic method.

age of a PE within ±0.25 D was less than 49% for all third-generation formulas, whereas it was greater than 54% for the newer generation formulas. The Jin-AI formula had the highest percentage of PEs within ±0.50 D (84.92%), followed by the BUII (84.56%) and Kane (84.02%) formulas; the third-generation formulas produced a percentage lower than 79%, and the newer generation ones yielded a percentage greater than 82%. The Jin-AI formula significantly produced more cases with PEs within ±0.25 and ±0.50 D than the third-generation formulas ($P < 0.01$) (Supplementary Table S1).

The accuracy of each formula in different ocular dimensions was assessed. As shown in Figure 3, the third-generation formulas exhibited hyperopic shifts in long AL (AL ≥ 26 mm), whereas the Kane formula had

Table 3. Predictive Outcomes of Eight IOL Formulas in the External Test Dataset ($N = 557$)

	Before Optimization			After Optimization								
IOL Formula	ULIB Constant	PE	SD	Optimized Constant	PE	SD	MedAE	MAE	≤±0.25 D	≤±0.50 D	≤±1.00 D	≤±2.00 D
SRK/T	119.0	0.18	0.44	119.20	0.00	0.45	0.29	0.34	45.24%	78.10%	97.49%	99.82%
Holladay 1	1.84	0.19	0.47	1.96	0.00	0.48	0.27	0.36	48.65%	75.58%	95.87%	99.82%
Hoffer Q	5.64	0.20	0.47	5.77	0.00	0.48	0.29	0.37	44.70%	73.61%	96.41%	99.82%
BUII	119.0	0.22	0.40	119.31	0.00	0.39	0.22	0.28	56.37%	84.56%	98.03%	99.82%
Kane	119.0	0.17	0.38	119.25	0.00	0.38	0.23	0.29	54.58%	84.02%	98.74%	99.82%
Hill–RBF 3.0	119.0	0.18	0.39	119.26	0.00	0.39	0.22	0.28	57.09%	83.66%	98.03%	99.82%
PEARL–DGS	119.0	0.25	0.39	119.30[a]	0.00	0.38	0.22	0.29	55.12%	82.05%	98.74%	99.82%
Jin-AI	119.0	0.22	0.39	119.26	0.00	0.38	0.22	0.28	57.45%	84.92%	98.56%	99.82%

[a]The constant of the PEARL–DGS formula was optimized with the help of Guillaume Debellemanière, MD (Paris, France).

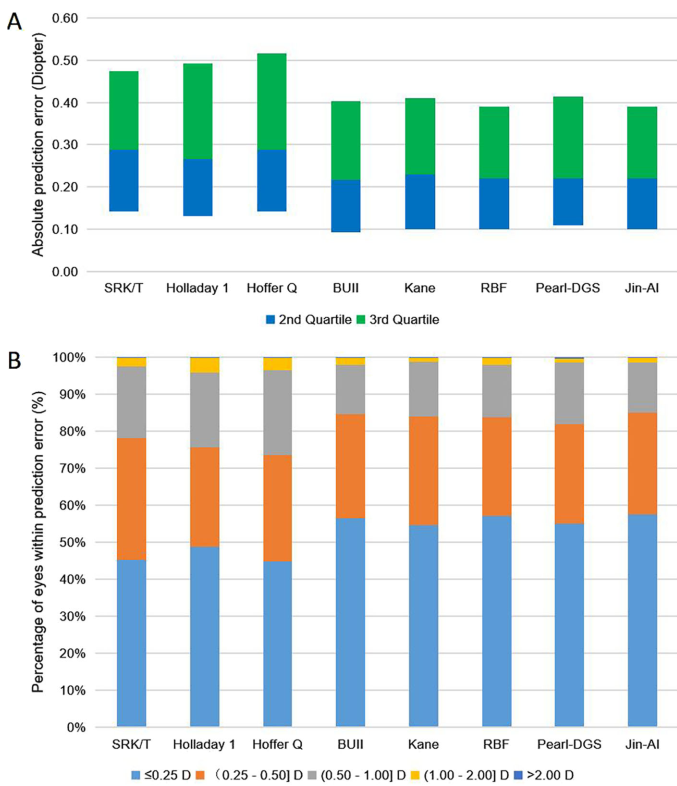

Figure 2. (A) Box plot graph of absolute prediction errors of the eight IOL formulas in total. *Blue boxes* represent the second quartile, and *green boxes* represent the third quartile. (**B**) Stacked histogram comparing the percentage of eyes within prediction error of absolute prediction errors of the eight IOL formulas in total. RBF, Hill–RBF 3.0.

the lowest MedAE in short AL (AL ≤ 22 mm). Overall, the newer generation formulas performed similarly across all AL ranges. Compared to the newer generation formulas, the third-generation formulas were more sensitive to flat (K < 42 D) or steep (K > 46 D) corneas and varying ACD (Fig. 4). In this case, the Jin-AI formula demonstrated a similarly robust performance as the other new formulas.

Discussion

The increasing demand for precise refractive outcomes following cataract surgery has stimulated advancements in IOL formulas. These developments, alongside enhancements in biometric measurements and surgical techniques, have substantially improved the accuracy of refractive outcomes. Formalization of the IOL formula dates back to the 1960s and 1970s. At that time, Fyodorov proposed an early formula that relied on the theoretical principle of refractive vergence to calculate the appropriate IOL power necessary to produce an image on the retina. After that, numerous methods for IOL power calculation have been proposed.[6,11,15,16] The conventional third-generation formulas, including SRK/T, Holladay 1, and Hoffer Q, have demonstrated more predictable refractive outcomes than previous regression and second-generation formulas.[25,28–30] The derivation of these third-generation formulas is all based on thin lens theory, with the use of a regressive method for ELP estimation. However, all of the three conventional formulas are less accurate in eyes with extreme ocular dimensions, which motivates continuous development of ELP prediction in the ophthalmology community.

Because third-generation formulas are widely used in clinical practice, a newly introduced IOL formula is typically compared with these formulas to evaluate performance.[6,11,24] In a study by Melles et al.,[13] the MedAEs of these formulas ranged from 0.287 to 0.303 D. Debellemanière et al.[6] reported MedAE values for the conventional formulas ranging from 0.272 to 0.293 D, whereas Connell and Kane[11] reported similar

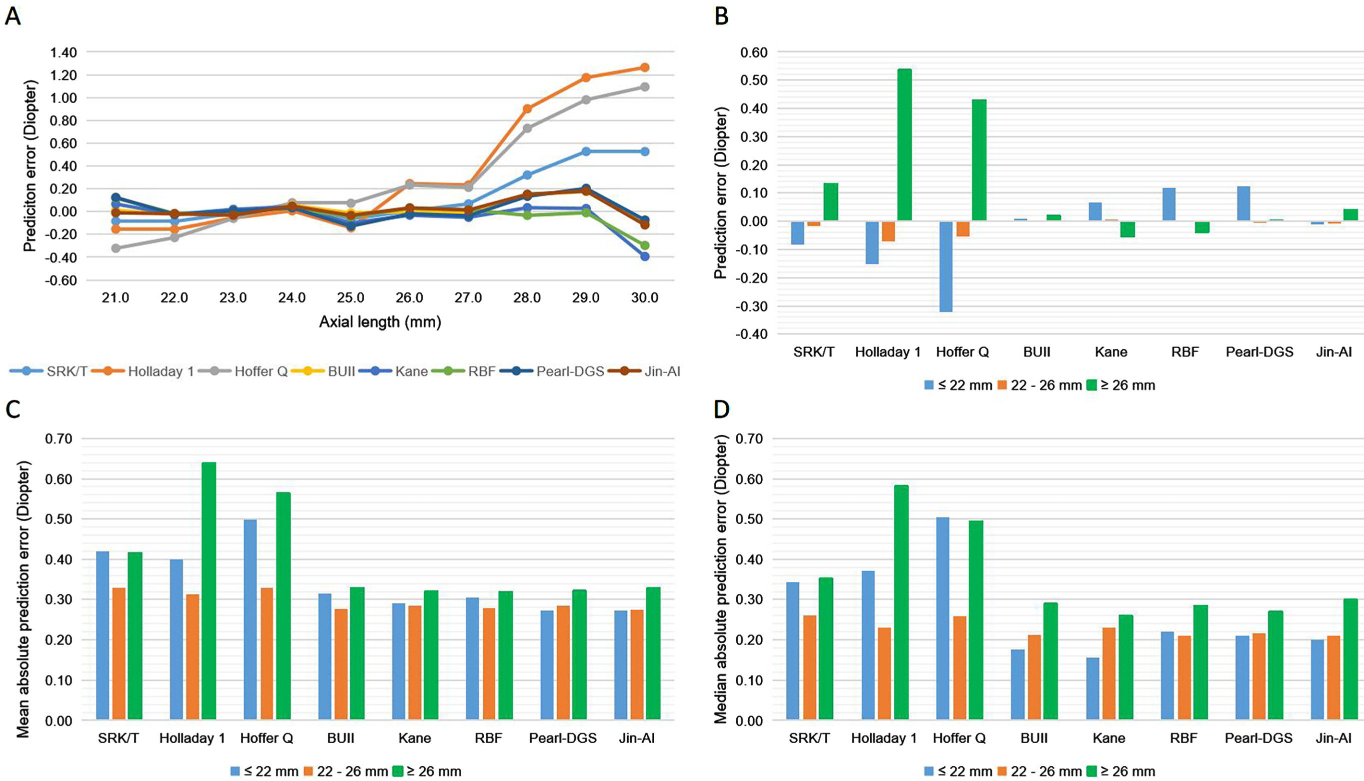

Figure 3. (A) Line graph comparing the prediction error of the eight IOL formulas versus axial length. (**B**–**D**) Prediction error (**B**), mean absolute prediction error (**C**), and median absolute prediction error (**D**) plotted against axial length for the eight IOL formulas.

results. In the external test dataset of the current study, the MedAE values for these formulas were 0.27 to 0.29 D, consistent with previous studies.[6,11,13] This suggests that a comparison of the results from the present study with previously published studies is reasonable. The Jin-AI formula outperformed all three third-generation formulas with a statistically lower SD of 0.38 D. Meanwhile, the Jin-AI formula had a MedAE of 0.22 D, also lower than all three third-generation formulas. The MAE and MedAE are two commonly used metrics to evaluate the performance of IOL formulas. The MedAE measures the central tendency of absolute error and is less influenced by outliers, whereas the MAE considers all errors and may be more sensitive to outliers. However, the MAE represents the true refractive state following cataract surgery because it includes even the most unfavorable outcomes.[31] In this study, the MAE of the Jin-AI formula was 0.28 D, which was also lower than the three conventional formulas.

Accurate refractive prediction in patients with short and long eyes is challenging, as implanting IOLs based on conventional formulas in patients with short AL (≤22 mm) or long AL (≥26 mm) often leads to myopic and hyperopic shifts,[32,33] respectively, which we also observed in our study (Fig. 3). Prior to the development of new formulas, the Hoffer Q for short eyes and the SRK/T for long eyes has been recommended. However, Melles et al.[13] and Kane et al.[34] found that the Hoffer Q formula did not perform best in short AL cases among the three popular third-generation formulas, a finding that aligns with our study. The Jin-AI formula demonstrated consistent accuracy across all AL ranges, as indicated by MedAE values of 0.20 D, 0.21 D, and 0.30 D for eyes with short, medium, and long AL, respectively (Fig. 3). The accuracy of postoperative refractive prediction is also influenced by K.[35] The new formulas still produced more accurate results than the third-generation ones across different K ranges. Figure 4 illustrates that the third-generation formulas exhibited a significant hyperopic shift at mean corneal K values below 42 D and a myopic shift at mean corneal K values above 46 D. Notably, the SRK/T formula produced the largest arithmetic PEs for both flat and steep K, as previously reported by Melles et al.[13] ACD is another critical factor that significantly affects the accuracy of refraction prediction.[13] As shown in Figure 4, the Jin-AI formula maintained its accuracy across a range of ACD values, indicating its suitability for the diverse ocular dimensions in the authors' data.

Misestimation of the postoperative ELP is the primary contributor to inaccurate refractive predictions.[4] The present study demonstrated that the

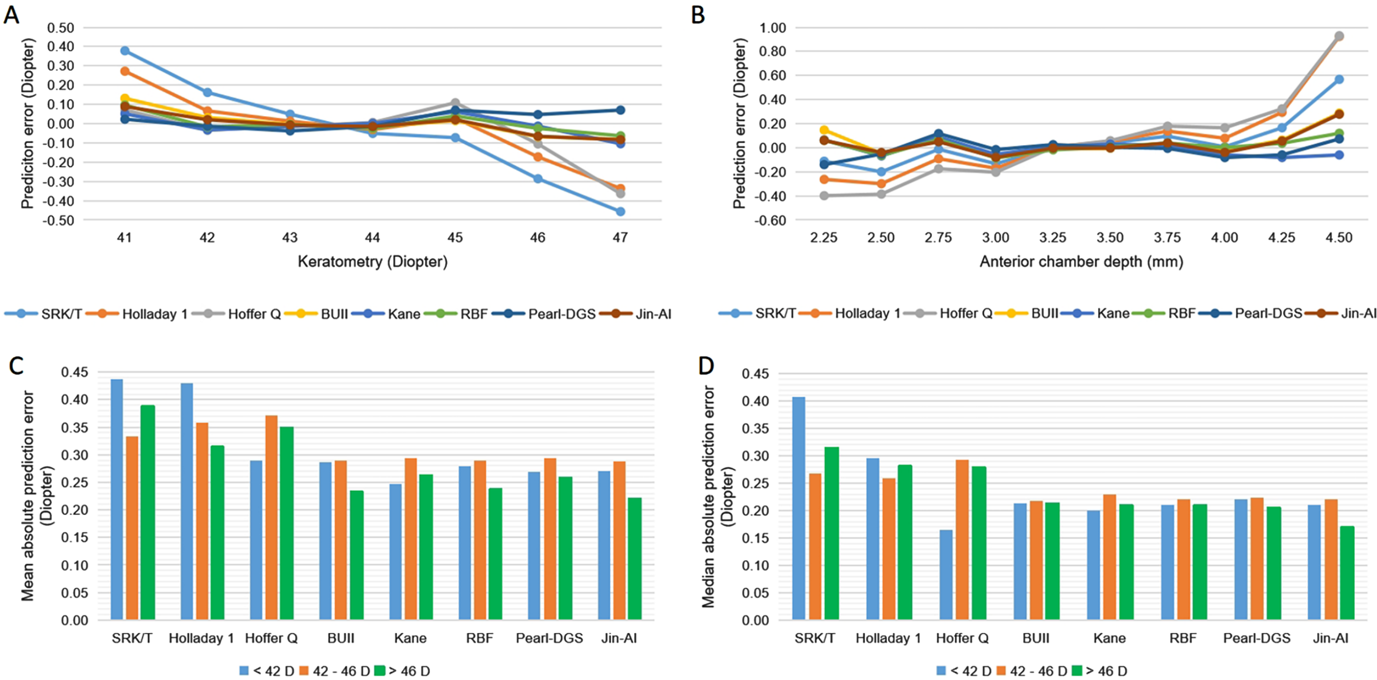

Figure 4. (A, B) Line graphs comparing the prediction error of the eight IOL formulas versus keratometry (**A**) and anterior chamber depth (**B**). (**C, D**) Mean absolute prediction error (**C**) and median absolute prediction error (D) plotted against keratometry for the eight IOL formulas.

accuracy of the third-generation formulas was more influenced by ACD, as these formulas rely solely on two biometric variables (AL and K) to determine postoperative IOL position. To enhance the accuracy of postoperative refraction estimation, newer generation formulas have incorporated preoperative ACD for IOL power calculation. These formulas have exhibited superior performance compared with earlier ones.[1,3,12,13] Among these new solutions, the Kane formula, introduced in 2019, has garnered considerable attention within the field. Extensive studies have endorsed this formula as one of the most accurate formulas currently available.[1,12,36] Comparing the Jin-AI formula with this formula is necessary because it represents the modern paradigm for IOL power calculations. As the Jin-AI formula is AI based, two other popular AI-powered formulas were also evaluated: Hill–RBF 3.0 (using pattern recognition and data interpolation) and PEARL–DGS (utilizing a thick lens equation and machine learning).[6,15] Despite recent studies demonstrating that the EVO, Kane, and PEARL–DGS formulas have outperformed the BUII formula,[1,6,12,36,37] the present study also analyzed the latter due to its popularity among surgeons.

As expected, the five new formulas exhibited similar levels of accuracy in terms of SD, MedAE, and MAE (Table 3). These results agreed with those reported by Savini et al.,[14] who reported that the ranges of SD, MedAE, and MAE for the Kane, BUII, Hill–RBF 3.0, and PEARL–DGS formulas were 0.348 to 0.366 D, 0.214 to 0.238 D, and 0.265 to 0.286 D, respectively. Moreover, the new formulas produced consistent accuracy across various ocular dimensions (Figs. 3, 4), suggesting that these formulas can achieve similar refractive predictions for routine cataract patients with a marginal difference. Following previous protocols, the percentage of eyes with PEs within a certain range was also assessed.[23,31] As shown in Figure 2 and Table 3, most new formulas had remarkably similar percentages of cases within a certain range of PE, and most of them achieved greater accuracy than the conventional formulas in predicting PEs within ±0.25 D and ±0.50 D (Supplementary Table S1). Intriguingly, the Kane and PEARL–DGS formulas did not outperform all three third-generation formulas in such metrics, inconsistent with previous findings.[6,12,13] Possible reasons for this discrepancy include the small sample size of the present study, variations in the studied populations, and differences in statistical analysis methods. Among all studied formulas, the Jin-AI formula had the numerically highest percentage of PE within ±0.25 D, which was significantly higher than the three third-generation formulas. This result indicates that using the Jin-AI formula can produce refractive outcomes closer to the intended refractive error in the authors' data.

We acknowledge three main limitations of the present study. First, only one type of IOL was analyzed in the external testing set; hence, the findings may not be generalizable to all IOL models. Second, as previously mentioned, the algorithm is derived from Chinese individuals, and further study is needed to validate its performance in other populations. Third, although this study involved an independent external test dataset to analyze the new AI-based formula, its real-world accuracy still requires blind evaluation by other Chinese centers.

In summary, the modern heteroscedastic statistical analysis method revealed that the Jin-AI formula, based on Chinese eyes, presents a promising option for calculating IOL power in this particular group. It provides comparable accuracy with the newer IOL formulas while showing better performance in achieving the intended postoperative refraction than the third-generation formulas for the authors' data. Further independent evaluation of the Jin-AI formula is warranted.

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[*] WL and WZ contributed equally to this work.

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