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Analysis of accuracy of twelve intraocular lens power calculation formulas for eyes with axial myopia

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Abstract:

PURPOSE: The aim of this study is to compare twelve intraocular lens power calculation formulas for eyes longer than 25.0 mm in terms of absolute error (AE), the percentage of postoperative emmetropia, and agreement interval in Bland–Altman analysis.

MATERIALS AND METHODS: Data of myopic patients who underwent uneventful phacoemulsification between January 2016 and July 2021 was reviewed. Intraocular lens power was calculated using Holladay 1, SRK/T, Hoffer Q, Holladay 2, Haigis, Barrett Universal II, Hill-RBF, Ladas, Kane, EVO, Pearl-DGS, and K6 formulas. Three months after phacoemulsification, refraction was measured, and mean AE was calculated. The percentage of patients with full visual acuity (VA) without any correction, with ± 0.25D, ±0.5D, ±0.75D, and limits of agreement for each formula were established.

RESULTS: Ninety-one patients, whose ocular axial length ranged between 25.03 mm and 28.91 mm, were included in the study. The Barrett Universal II formula achieved the lowest mean AE of 0.11 ± 0.11 (P < 0.001) just before Kane (0.13 ± 0.09; P < 0.001 except vs. Haigis and Holladay 2) and SRK/T formulas (0.18 ± 0.12). In addition, the Barrett Universal II formula had the highest percentage of patients with full VA without any correction (72.5%) followed by Kane and Holladay 2 formulas (56.0% and 49.5%, respectively). Finally, Barrett Universal II, Kane, and Haigis formulas obtained the lowest agreement interval (0.5725, 0.6088, and 0.8307, respectively).

CONCLUSION: The Barrett Universal II formula is recommended for intraocular lens power calculation for eyeballs with the axial length longer than 25.0 mm. The Kane formula also gives very promising results in regarding the accuracy of intraocular lens power for myopic eyes.

Keywords:

Intraocular lenses, myopia, phacoemulsification

Introduction

Accurate intraocular lens (IOL) power calculation is a very important aspect of phacoemulsification because patients' expectations for perfect vision after cataract surgery are still increasing.[1] Therefore, we have so many different IOL power calculation formulas. Conventionally, we have classified them by generations when all of them have been vergence formulas.[2,3] The new division distinguishes, apart from formulas based on simple vergence (i.e., Hoffer Q, Holladay 2, and Haigis), also such with interactive vergence (Barrett Universal II), ray tracing (Olsen), artificial intelligence (Hill-RBF), or hybrid (Ladas, Kane).[4]

Most of them are exact for eyes with axial length (AL) ranging between 22.0 mm and 25.0 mm.[5] The accuracy of IOL power calculation formulas for eyes shorter than 22.0 mm and longer than 25.0 mm is still questionable.[6-8] So far, the Barrett Universal II formula appeared to be the most accurate in calculating IOL power for myopic eyes.[6,8-14] However, the newly developed methods based on artificial intelligence or

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hybrid also have very promising results.[15-18] The Kane formula stands up among them.[19,20] However, there is still no agreement among cataract surgeons regarding the choice of the formula.

The Kane formula is based on theoretical optics and incorporates both regression and artificial intelligence components to refine prediction. It is a new IOL power formula created using several large data sets from selected high-volume surgeons that uses a combination of theoretical optics, thin lens formulas, and "big data" techniques to make its predictions. It uses AL, keratometry (K), anterior chamber depth (ACD), lens thickness (LT), central corneal thickness, and gender of the patient to make its predictions.[4,20]

The Barrett Universal II recognizes the change in vergence that occurs when the lens changes from a positive lens to a minus lens and as such it does not require additional correction factors such as transformation or unusual constance for patients with high myopia and very long axial lens. It has a unique theoretical model to predict the effective lens position and this differs quite significantly from what has been used previously.[8,21]

Most often the research methodology is based on the calculation of absolute error (AE) using an absolute value of a difference between postoperative and predicted spherical equivalences of refractive error.[1,2,5,9,10,14,18,22-24] Only a few authors have considered the percentage of patients with postoperative full visual acuity (VA) without any correction, as well as the percentage of postoperative hyperopia after phacoemulsification[2,3,9] and even receiver operating characteristic curves method.[8]

This study aimed to compare the IOL power calculation formulas for eyes longer than 25.0 mm in terms of AE and the percentage of patients with full VA without any correction after cataract surgery. In addition, the study tries to confront the accuracy of IOL power calculation formulas using Bland–Altman analysis with particular regard to the limits of the agreement interval. It is pioneering due to its method. Finally, a list of as many as 12 formulas proves the reliability of the study.

Materials and Methods

Data of patients with eyes of AL exceeding 25.0 mm and with Wisconsin Grade 3 or 4 cataract who underwent uneventful sutureless phacoemulsification with monofocal, acrylic, and foldable IOL (AcrySof SA60AT, Alcon Laboratories, Fort Worth, TX, USA) implantation with 2.4 mm clear corneal incision between January 2016 and July 2021 were retrospectively reviewed. Based on Hoffer *et al*.'s recommendations, only one eye per patient was included in the study.[25] Rigorous exclusion criteria were applied such as corneal astigmatism >2.0 D, postoperative best-corrected visual acuity (BCVA) <0.8, the history of other ophthalmic procedures, i.e., vitrectomy, limbal relaxing incisions, and corneal refractive surgery, any intraoperative or postoperative complications, as well as previous corneal diseases.

The study was conducted adhering to the tenets of the Declaration of Helsinki. Each patient signed informed consent for routine cataract surgery. The study is retrospective, based only on available medical records, and as such does not require the approval of the Institutional Review Board.

Preoperative optical biometry was performed with the use of Zeiss IOLMaster 700 (Carl Zeiss Meditec AG, Jena, Germany) obtaining the following data for each patient: AL, K, ACD, LT, and white to white (WTW) as corneal diameter. IOL power was calculated with twelve different formulas (Holladay 1, SRK/T, Hoffer Q, Holladay 2, Haigis, Barrett Universal II, Hill-RBF, Ladas, Kane, EVO, Pearl-DGS, and K6). A keratometric index of 1.3375 was used.

Each cataract surgery was performed by the same eye surgeon. Acrylic foldable intraocular lenses were implanted. Postoperative refraction was measured 3 months after cataract surgery.

Numerical error (NE) was defined as the difference between the real postoperative refractive outcome expressed as spherical equivalent and the refraction predicted by each formula. A positive value indicated a hyperopic error and a negative value referred to myopic error while absolute value means AE. Based on the AE ≤0.12, the percentage of patients with full VA without any correction was established. In addition, the percentage of patients with ± 0.25D correction (0.13≤ AE ≤ 0.37), ±0.5D (0.38≤ AE ≤ 0.62), ±0.75D (0.63≤ AE ≤ 0.87), and ± 1.0D (0.87< AE) was counted.

Besides, the Bland–Altman method comparing NE value of each formula and zero target expected after phacoemulsification was used and Bland–Altman plots with the limits of the agreement interval for each formula were drawn. Proposed in 1983, the Bland-Altman analysis is a simple way to evaluate a bias between the mean differences, and to estimate an agreement interval, within 95% of the differences of the second method, compared to the first one. Data can be analyzed both as unit differences plot and as percentage differences plot.[26,27]

Statistical analysis was performed using the Statistica 13.1 package. $P < 0.05$ was considered statistically significant unless it was necessary to apply Bonferroni corrections for multiple comparisons which reduced the significance level down to even 0.0023. Data distribution for normality was checked using the Shapiro–Wilk test. The nonparametric Kruskal–Wallis test was used to check statistically significant differences between groups. Mann–Whitey U test (for quantitative variables) and the Chi-square test with Yates correction (for qualitative variables) were used for comparison between pair of formula. Systematic error and the degree of agreement were assessed with the Bland–Altman analysis and presented graphically.[28]

Results

Ninety-one patients (43 men and 48 women) with the mean age of 68.7 ± 8.1 years (range: 47-84 years) were included in the study. The AL of the studied eyes ranged between 25.01 mm and 28.57 mm.

Out of the twelve evaluated formulas, the Barrett Universal II achieved the lowest level of mean AE 0.11 ± 0.11 D followed by Kane (0.13 ± 0.09 D) and SRK/T (0.18 ± 0.12 D). Considering them and even applying Bonferroni corrections for multiple comparisons statistically significant differences were found in the following pairs: Barrett Universal II versus all other formulas ($P < 0.001$) and Kane versus other formulas ($P < 0.001$) except Haigis ($P = 0.020$) and Holladay 2 ($P = 0.173$). Detailed results of the calculated AE for each formula were summarized using descriptive statistics – mean, standard deviation (SD), median, and range in Table 1.

In terms of the AE, which indicates the expected correction after cataract surgery, the studied group was divided into five subgroups – with expected emmetropia, ±0.25D, ±0.5D, ±0.75D, ±1.0D and more correction (AE ≤ 0.12, with range 0.13–0.37, 0.38–0.62, 0.63–0.87, and >0.87, respectively). The percentage distribution of the subgroups is presented in Figure 1.

In addition, the Bland–Altman analysis has been performed. The study compared the mean NE of each IOL power calculation formula with zero target expected after cataract surgery. Using NE and ± SD, the limits of the agreement interval were counted. Once the agreement interval is the smallest, the IOL power calculation formula is the most accurate. The calculation results are presented in Table 2 and illustrated graphically in Figures 2 and 3.

Discussion

The exact prediction of IOL power for myopic eyes is still a problem in daily practice for a cataract surgeon. There are many studies looking into this problem[1-3,5-15] and assessing the accuracy of selected formulas based on different parameters, most frequently the AE.[1,2,5,9,10,14,18,22-24]

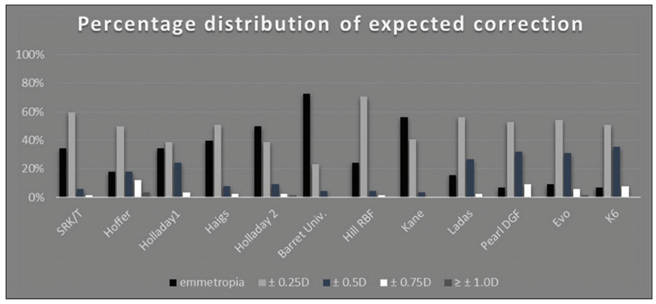

Figure 1: Percentage of eyes with emmetropia, ±0.25D, ±0.5D, ±0.75D and ≥ ±1.0D

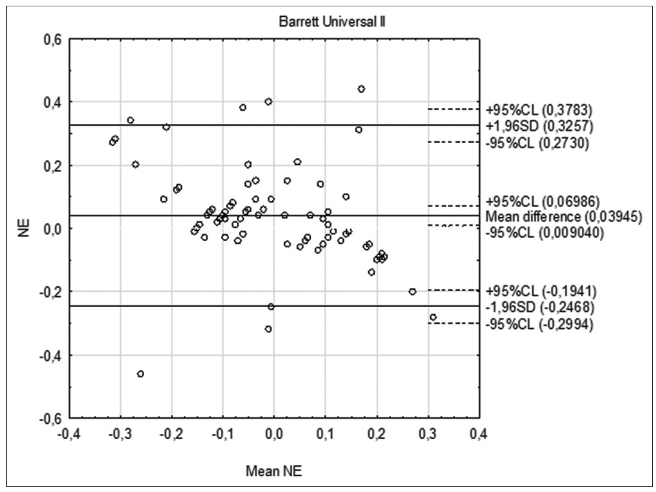

Figure 2: Bland–Altman plot for the Barrett Universal II formula

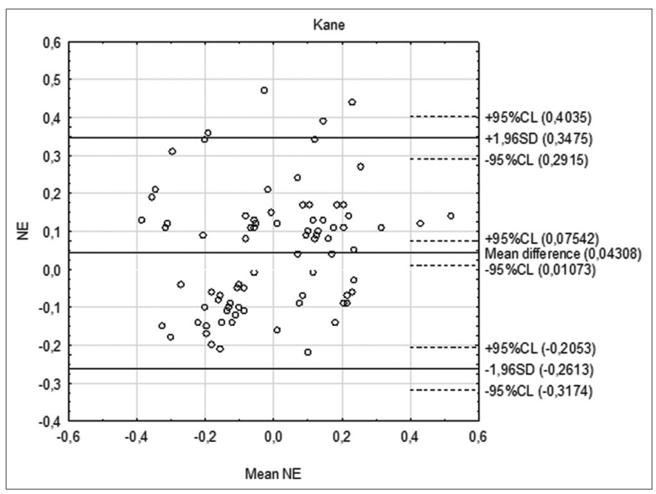

Figure 3: Bland–Altman plot for the Kane formula

The study used three different methods to assess the accuracy of IOL power calculation formulas, i.e., AE, the best percentage vision and Bland–Altman plot. AE is the most frequent method used in such studies.[1,2,5,9,10,14,18,22-24] Based on the absolute value of the results of arithmetic

Table 1: Descriptive statistics of absolute error

	AE		
	Mean±SD	Median	Range
Holladay 1	0.25±0.18	0.20	0.02-0.71
SRK/T	0.18±0.12	0.16	0.00-0.67
Hoffer Q	0.34±0.24	0.29	0.02-0.96
Holladay 2	0.19±0.18	0.13	0.01-1.00
Haigis	0.19±0.14	0.15	0.01-0.67
Barrett Universal II	0.11±0.11	0.06	0.00-0.46
Hill-RBF	0.20±0.11	0.19	0.02-0.67
Ladas	0.28±0.15	0.26	0.01-0.77
Kane	0.13±0.09	0.11	0.01-0.47
EVO	0.35±0.18	0.34	0.02-0.91
Pearl-DGS	0.36±0.16	0.34	0.08-0.73
K6	0.36±0.19	0.33	0.02-0.87

AE: Absolute error, SD: Standard deviation, SRK/T: Sanders Retzlaff Kraff/Theoretical, RBF: Radial basis function, EVO: Emmetropia verifying optical, DGS: Debellemanière Gatinel Saad

Table 2: Data of the Bland-Altman analysis

	NE	SD	NE+1.96SD	NE-1.96SD	Agreement interval
Holladay 1	0.0657	0.2990	0.6517	−0.5203	1.1720
SRK/T	−0.0139	0.2183	0.4140	−0.4417	0.8557
Hoffer Q	0.0430	0.4095	0.8455	−0.7596	1.6051
Holladay 2	0.0413	0.2596	0.5502	−0.4676	1.0178
Haigis	0.0998	0.2119	0.5151	−0.3156	0.8307
Barrett Universal II	0.0395	0.1460	0.3257	−0.2468	0.5725
Hill-RBF	0.0691	0.2171	0.4947	−0.3565	0.8512
Ladas	0.1585	0.2819	0.7109	−0.3940	1.1049
Kane	0.0431	0.1549	0.3475	−0.2613	0.6088
EVO	0.1047	0.3829	0.8552	−0.6457	1.5009
Pearl-DGS	0.1938	0.3423	0.8648	−0.4771	1.3419
K6	0.1473	0.3772	0.8865	−0.5920	1.4785

SD: Standard deviation, NE: Numerical error, SRK/T: Sanders Retzlaff Kraff/Theoretical, RBF: Radial basis function, EVO: Emmetropia verifying optical, DGS: Debellemanière Gatinel Saad

calculation, it simply shows the deviation from the zero target. The method is easy and effective but biased. It is practical to evaluate the percentage of emmetropic patients since the goal of phacoemulsification is to achieve emmetropia. However, it does not show the rest of the outcomes so the spread is unknown, therefore such method is not exact. Finally, agreement interval in Bland-Altman analysis, as the only, considers measurement accuracy error (bias) and precision of differences inclouding SD. However, this method is difficult and is not popular in such studies. Furthermore, Bland–Altman plot method only defines agreement intervals but it does not say whether those limits are acceptable or not.[26,27] Nevertheless, the Bland–Altman method is unique in that it provides a simple way to evaluate a bias, and therefore it is superior to other methods.

This study demonstrated that the Barrett Universal II formula achieved the lowest AE (0.11 ± 0.11 D) and the highest percentage of emmetropic patients (72.5%). In addition, the Barrett Universal II formula obtained the lowest agreement interval by Bland–Altman analysis (0.5725). It is therefore recommended for IOL power calculation for eyes with AL exceeding 25.0 mm. However, the Kane formula also performed very well, only slightly worse than Barrett Universal II (AE of 0.13 ± 0.09 D; agreement interval of 0.6088).

Based on eleven observational studies involving 4047 eyes, a meta-analysis in 2018 proved the superiority of Barrett Universal II over Holladay 1, Hoffer Q, SRK/T, and Holladay 2 in predicting IOL power in long eyes, although there was no statistical difference in the comparison between Barrett Universal II and Haigis as well as between Barrett Universal II and Olsen.[6] However, the meta-analysis did not consider the latest IOL power calculation formulas such as Hill-RBF, Kane, EVO, Ladas, or K6. On the other hand, Kane *et al*. concluded in their 2017 study that new methods (Ladas, Hill-RBF, and FullMonte) for predicting the postoperative refraction had failed to yield more accurate results than the current formulas (Barrett Universal II, Holladay 1). That study comprised 3122 eyes which was enough group to reach reliable conclusions.[29] However, they did not include the Kane formula among others which, according to nowadays literature, performs very well.

Hipólito-Fernandes *et al*. proved that new generation formulas, especially Kane, VRF-G, and EVO might help us in achieving better refraction results. Although 828 patients were studied, different AL were considered and therefore the myopic ones were relatively few. Nevertheless, using the Kane formula, the highest percentage of patients with refraction ± 0.25 and ± 0.75 was obtained (47.0% and 97.7%, respectively).[20] In our study, the percentage was similar, being 40.7% and 100.0%, respectively. In turn, Connell and Kane considering the accuracy of 9 formulas (Hill-RBF, Kane, Holladay 2, Barrett Universal II, Olsen, Haigis, Hoffer Q, Holladay1, and SRK/T) counted that the Kane formula had the lowest mean absolute prediction error ($P < 0.001$ for all formulas). Although they involved 846 patients, there were not enough eyes of short or long AL to adequately power statistical comparisons within these AL subgroups.[19] The Kane formula in comparison to Barrett Universal II could obtain better outcomes in short eyes. It may be related to the fact that effective lens position calculation errors are AL-dependent and short eyes seem to be more susceptible to greater errors than long eyes. The Kane formula, as a hybrid based on theoretical optics and artificial intelligence, has more important adjustment in short eyes.

The Kane formula gives promising results; however, the publications on its use are not common. Meanwhile, we have much more studies showing that the Barrett Universal II formula is more accurate compared to the other methods. Abulafia *et al*. divided 106 studied eyes with an axial length exceeding 26 mm into two subgroups depending on IOL power. They demonstrated that the SRK/T, Barrett Universal II, Holladay 2, and Olsen formulas had the best refraction prediction results for IOL power 6.0 D or higher, while only the Barrett Universal II formula had the best refraction prediction results for IOL power less than 6.0 D.[14]

According to the European Registry of Quality Outcomes, the percentage of the prediction error within ± 0.5D after cataract surgery is 73.7%.[18] By following this parameter, Nemeth and Modis in their study on 186 eyes proved the superiority of Hill-RBF and Barrett Universal II over the SRK/T formula (83.62%, 79.66%, and 74.01%, respectively).[18] In our study, in this terms, the Barrett Universal II formula achieved only slightly better results than Hill-RBF (95.6% and 94.5%). The higher percentage in our study was due to more rigorous inclusion criteria (postoperative BCVA ≥0.8). In turn, Zhou *et al*. found in their 2019 study involving 98 patients that both mean NE and mean AE (0.35 ± 0.30 D) were the lowest for the Barrett Universal II formula. In our study adequate AE is 0.11±0.11 D; nevertheless the study conducted by Zhou *et al*. concerned patients with high myopia (AL of 29.63 ± 2.35 mm; range 24.61-33.28 mm) and in our study AL was ranged between 25.01 mm and 28.57 mm.[11]

Most of the studies evaluating the accuracy of IOL power calculating formulas would be based on the assessment of AE,[1,2,5,9,10,14,18,22-24] while only a few have proposed other criteria for assessing the effectiveness of IOL power calculation formulas.[2,3,9] In a Polish study in 2021 involving 81 eyes a receiver operating characteristic curves methodology with counting area under the curve (AUC) was used.[8] Considering AUC, the greatest accuracy of Barrett Universal II just before Holladay 1 was shown (0.764 and 0.718, respectively) but the Kane formula was not studied.[8]

Bland and Altman established a method to quantify the agreement between two quantitative measurements by constructing limits of agreement interval. These statistical limits are calculated using the mean and the SD of the differences between two measurements. To check the assumptions of normality of differences and other characteristics, they used a graphical approach. The resulting graph is a scatter plot, in which the Y-axis shows the difference between the two paired measurements (A-B) and the X-axis represents the mean of these measures (A/2 + B/2). An ideal model would claim that the measurements obtained by one method or another gave exactly the same results. Hence, all differences would be equal to zero.[26,28] In practice, we construct an agreement interval – the smaller the agreement interval, the more precise the method. In the study NE of each formula was compared to refraction equal to zero. Considering the limits of the agreement interval, the greatest accuracy goes to the Barrett Universal II formula, followed by Kane and Haigis (0.5725, 0.6088, and 0.8307, respectively).

In addition, considering the NE, we can estimate whether the formula produces myopic or hyperopic results. In the study, only SRK/T induced myopic outcomes while all other formulas targeted hyperopia. Tsang *et al*. in their study involving 125 eyes observed hyperopic prediction error after phacoemulsification. They demonstrated that the Hoffer Q formula obtained the lowest mean hyperopic error of 0.36 D while Holladay 1 and SRK/T caused a slightly larger hyperopic shift, with outcomes of 0.53 D and 0.74 D, respectively.[2] However, in this 2003 study, they used A-scan ultrasonography method, which is less accurate than partial coherence interferometry to measure AL.

There are several limitations to the study. All patients had implanted the same model of IOL, so these results may not be generalizable to IOL models of a different design. The IOLs evaluated in the study were of anterior asymmetric biconvex and many other IOL designs such as equi-biconvex were also common. The differences in IOL shape could affect prediction errors and change the relative performance of the formula tested. Similarly, one eye surgeon is a limitation in generalization. In addition, pupil dilatation was not considered in the study. There are reports on the influence of pupil dilation on the accuracy of IOL power calculation formulas.[30] Finally, parameters such as K, ACD, and LT were not considered in terms of the accuracy of IOL power calculation formulas in the study. On the other hand, some authors found notable biases in the prediction errors of most of the formulas when plotted versus not only AL but also K, ACD, and LT.[13]

The relatively narrow range of the eyeballs’ length (25.01–28.57 mm) is a limitation of this study also. In some studies, myopic patients were divided into subgroups in terms of AL, for example, 24.5–27 mm, 27–30 mm, and >30 mm.[11] However, the differences in these subgroups were not significant; the Barrett Universal II formula obtained the smallest AE in all subgroups. In a Chinese study, two subgroups were distinguished (25–28 mm and >28 mm) and also the results in both subgroups were similar.[2] Therefore, it can be concluded that AL range adopted in this study is sufficiently representative for all myopic eyes. Yet extremely high myopia, which is defined by some authors as an AL of >27 mm and refractive power of >10.0 D, is rare in Europe (1.2%).[5] This further supports the fact that eyeballs' AL in this study is good enough.

The lack of the Olsen formula is next limitation of this study. The key feature of the Olsen formula is accurate estimation of the IOL’s physical position using a newly developed concept, the C-constant (a ratio by which the empty capsular bag will encapsulate and fixate an IOL following in-the-bag implantation). This approach predicts the IOL position as a function of preoperative ACD and LT and works independently of traditional factors such as AL, K, WTW, IOL power, age, and gender.[31]

Conclusion

The study shows that the Barrett Universal II formula is recommended for IOL power calculation for eyes with AL longer than 25.0 mm, but the Kane formula is very accurate as well. Both of these formulas achieved the best results both in the terms of AE and using the Bland–Altman methodology with an agreement interval. Although the reliability of the presented results could be limited due to the small number of the studied group, the whole concept of such method seems promising.

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Conflicts of interest
The authors declare that there are no conflicts of interests of this paper.

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