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ORIGINAL RESEARCH

Accuracy of Traditional and Modern Formulas for Intraocular Lens Power Calculation After Radial Keratotomy Using Standard Keratometry

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Purpose: To compare the accuracy of multiple traditional and modern intraocular lens (IOL) power calculation formulas in post-radial keratotomy (RK) patients undergoing cataract surgery.

Methods: This retrospective case series included 50 eyes with prior RK who underwent routine phacoemulsification surgery with single-piece acrylic IOL implantation (A constant = 118.8). Outcomes of multiple formulas were calculated. Included formulas were SRK/T, Holladay 1, Holladay 2, Haigis, Barrett True-K, Haigis and Barrett True-K (target refraction of 0.50 D), Barrett Universal II, Kane, PEARL-DGS, Shammas no history, DK SRK/T, DK SRK/T (target refraction of 0.50 D), Double K (DK) Holladay 1, and DK Holladay 1 (target refraction of 0.50 D). Averages of multiple combinations of best-performing single formulas were calculated. Primary outcome is mean absolute error (MAE).

Results: Haigis (with −0.50 D target refraction) and DK SRK/T showed the lowest mean and median absolute errors (MedAE) followed by Haigis, Barrett True-K, and Barrett True-K (with −0.50 D target refraction). Combinations of 3, 4, or 5 of best performing single formulas yielded good results with >60% of cases within +0.50 D of intended refraction and MAE around 0.50 D. The best performing formulas with flatter K readings were PEARL-DGS and Haigis (with additional −0.50 D target refraction) with MAE of 0.72 + 0.71 D and 0.70 + 0.70 D, respectively, followed by Barrett True-K (with intended −0.50 D target refraction) with MAE of 0.75 + 0.63 D.

Conclusion: Using an average of three or more Haigis (with −0.50 D target refraction), the Barrett True-K, DK Holladay 1, and DK SRK/T formulas showed better outcomes than using a single formula for IOLMaster 700 standard K readings. The PEARL-DGS formula showed better accuracy in eyes with flatter K readings (<38 D).

Keywords: radial keratotomy, IOL calculation, PEARL-DGS, Barrett True-K, DK Holladay 1, DK SRK/T

Introduction

Radial keratotomy (RK) is challenging when intraocular lens (IOL) power calculation is required. Patients with prior RK for cataract surgery require special attention regarding perioperative planning, surgical procedures, and postoperative refractive outcomes. The source of error of IOL power calculation after RK was found to be different from that after laser vision correction.[1–3]

Radial keratotomy causes central flattening in a small central optical zone. Measuring keratometry (K) readings should include this small central zone to avoid overestimating corneal power, resulting in undesired postoperative hyperopic error. In addition, RK flattens both the anterior and posterior corneal surfaces with no theoretical change in the effective refractive index used for the calculations. Occasionally, the cornea has irregular astigmatism due to asymmetric incisions. After cataract surgery, central flattening can occur due to corneal edema, which mostly resolves within several months. Sometimes, a residual hyperopic shift can persist for years.[3–7]

Third generation IOL power formulas (Hoffer Q, Holladay 1, and SRK/T formulas) use two variables to estimate effective lens position (ELP): axial length (AL) and K. Flatter K readings lead to errors in the ELP position estimation.

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Flatter K readings led to a shallower expected anterior chamber depth and a more anterior expected ELP. This results in an underestimation of IOL power with postoperative hyperopic errors.[4,8–12]

There are multiple options to choose from when calculating IOL power after a previous RK. This study aims to compare the accuracy of multiple traditional and modern IOL power calculation formulas in post-RK patients undergoing cataract surgery.

Materials and Methods

This is a retrospective case series that included 50 eyes of 50 patients with prior radial keratotomy and had undergone routine phacoemulsification surgery for cataract removal. Patients were recalled for a final follow-up visit and signed an informed consent form in which they agreed to participate in the study. If both eyes of a patient underwent surgery, only the first operated eye was included to exclude second eye refinement (SER) effect. This study was approved by the local ethics committee of the Faculty of Medicine of Alexandria University, Egypt. The ethical code was based on the tenets of the Declaration of Helsinki. Patients were excluded if they had complicated cataract surgery, incomplete data records, or poor postoperative visual acuity (<20/40) leading to inaccurate manifest refraction (which was done subjectively using Landolt C chart on a distance of 20 feet).

Data were collected from the patients' records, including age, sex, type and power of the implanted IOL, axial length, keratometry, anterior chamber depth, white-to-white diameter, lens thickness, and any other relevant data. Postoperative manifest refraction spherical equivalent (MRSE) was recorded from a 3 months postoperative follow-up visit to allow the resolution of corneal edema and postoperative temporary hyperopia. Keratometry readings were obtained using an IOLMaster 700 optical biometer (Carl Zeiss, Meditec, Jena, Germany) version 1.88.1.64861.

Multiple formula outcomes were calculated according to actual postoperative refraction as the target refraction. The included formulas are as follows: SRK/T, Holladay 1, Holladay 2, Haigis, Haigis with additional target refraction – 0.50 D, Barrett Universal II, Barrett True-K, Barrett True-K with additional target refraction – 0.50 D, Kane, PEARL-DGS, Shammas no history, Double K (DK) SRK/T, DK SRK/T with additional target refraction – 0.50 D, DK Holladay 1, and DK Holladay 1 with additional target refraction – 0.50 D. The averages of the multiple combinations of the best-performing single formulas were calculated. For DK formulas, an average preoperative K of 43.86 was used in all cases.[10,13,14]

The updated formula constants installed in the above-mentioned version of the IOLMaster 700 were used for other non-integrated IOL calculation formulas. A hydrophobic single-piece acrylic Alcon AcrySof (model SA60AT) IOL was implanted for all the included cases. The A constant used was 118.8 for most of the formulas. For Haigis formulas, the constants were: A0 = −0.111, A1 = +0.249 and A2 = +0.179. For Barrett formula, the constant was: LF = +1.78. Barrett True-K and DK Holladay 1, available at www.ascrs.org (website of the American Society of Cataract and Refractive Surgery), were used, and the mean of both values was calculated as the ASCRS average IOL power. The ASCRS calculator uses a corneal power of 43.86 D to calculate the effective lens position, and the corneal power measured before cataract surgery for IOL power calculation. The Kane formula is available online at www.iolformula.com. The formula uses regression analysis, and artificial intelligence (AI) was used to improve the results.[15] The PEARL-DGS (Postoperative spherical Equivalent prediction using ARtificial intelligence and Linear algorithms, developed by Debellemanière, Gatinel, and Saad) formula is available online at: www.iolsolver.com with an option to choose post-radial keratotomy.[16] The DK concept was used to modify 3rd generation IOL formulas such as Holladay 1 and SRK/T. It uses the prerefractive K readings to estimate the effective lens position and the current measured post-refractive K readings to calculate IOL power using the vergence formula. The authors used the open-source equations of the DK SRK/T formula published by Aramberri (2003)[13] and the Shammas no history method published by Shammas (2007)[17] in an Excel spreadsheet form to create a simple IOL power calculator.

The prediction error was calculated as the difference between the actual achieved refraction and the predicted refraction using the following formula: The primary outcome included median absolute prediction error, mean absolute prediction error, and percentage of cases within 0.5 D, 1 D and 2 D from the intended refraction. The mean arithmetic prediction error was also calculated to determine whether the formula outcome tended towards hyperopia or myopia.

Data analysis was performed using the Social Sciences SPSS Statistics for Windows (version 26.0; SPSS Inc., Chicago, IL, USA). Quantitative data were described using the range, mean, and standard deviation. Normality of the data was evaluated using the Kolmogorov–Smirnov test. Kruskal Wallis ANOVA test was used to compare different means. A paired sample *t*-test or paired samples Wilcoxon test was used to compare the means of the same group. The chi-square test was used to compare the number of cases within intended target refraction. Differences were considered statistically significant when the associated p-value was less than 0.05.

Results

This study included 50 eyes from 50 patients. The mean age was 59.7 + 10.5 years (range from 33 to 77 years). The study included 22 males and 28 females. Table 1 shows the demographic and biometric data for the included eyes.

Table 2 lists the arithmetic mean prediction errors of the formulas. The ANOVA showed that the difference was statistically significant ($p < 0.05$). The SRK/T formula showed the highest hyperopic mean error, followed by Holladay 1, and Barrett Universal II. The Shammas no-history method had the highest mean error of myopia. Barrett True-K (with an additional −0.50 D target refraction), DK SRK/T, and Haigis (with an additional −0.50 D target refraction) had a mean arithmetic error within 0.25 D from emmetropia.

The mean and median absolute errors of the different formulas are listed in Table 2. A number of cases within +0.50 D, +1.0 D, and +2.0 D of target refraction are also shown in Table 2. The ANOVA test was used to compare means and the chi-square test was used to compare percentages; the difference was statistically significant ($p < 0.05$). Haigis (with an additional −0.50 D target refraction) and DKSRK/T showed the lowest mean and median absolute errors, followed by Haigis, Barrett True-K, and Barrett True-K (with an additional −0.50 D target refraction).

Multiple averages of the best-performing single formulas, namely Haigis (with an additional −0.50 D target refraction), DKSRK/T, Barrett True-K (with/without additional −0.50 D target refraction), and DK Holladay 1 were calculated. All possible combinations of two, three, or all of them were tested, and the best results are listed in Table 3. The average ASCRS represents the average of the DK Holladay 1 and Barrett True-K formulas, as they are the two possible formulas obtained from the ASCRS online IOL power calculator when only IOLMaster K readings were used. The medians of the five best formulae were also calculated (Table 3). Kruskal–Wallis ANOVA and Chi-square tests were used to compare the outcome of using a combination of three, four, or five formulas, and the difference was not statistically significant ($p > 0.05$). All different combinations of 3, 4, or 5 formulas yielded good results with >60% of cases within +0.50 D of intended refraction and mean absolute (MAE) around 0.50 D.

The different possibilities of taking the average of the two formulas were calculated but are not shown for simplicity. Many of them yielded good results with >60% of cases within +0.50 D of intended refraction. The least accurate 2 formula combination was the ASCRS average (DK Holladay 1 + Barrett True-K), with 46% and 76% of cases within +0.50 D and +1.0 D of intended refraction. Adding an additional target refraction of – 0.50 D improved the ASCRS average with 54% and 82% of cases within +0.50 D and +1.0 D of intended refraction. The second least accurate 2 formula combination was Haigis (with additional −0.50 D target refraction) + Barrett True-K (with additional −0.50 D target refraction), with 54% and 92% of cases within +0.50 D and +1.0 D of intended refraction.

Subgroup analysis was performed for 25 eyes with flat average K readings (less than 38 D). The mean axial length was 27.21 + 1.68 (24.33–30.54) mm and the mean average K readings were 34.91 + 2.17 (30.00–37.90) mm. Table 4 shows the outcomes of the different single formulas for this subgroup with flat K-readings. All formulas showed less accurate results, with flatter average

Table 1 Demographic and Biometric Data of the Included Eyes (n = 50)

	Mean + SD (Range) (n = 50)
Age (years)	59.7 + 10.5 (33–77)
Sex (Male: Female)	22: 28
Axial length (mm)	26.38 + 1.82 (23.76–30.54)
Average Keratometry (D)	37.57 + 3.29 (30.00–42.76)
Anterior chamber depth (mm)	3.40 + 0.34 (2.83–4.22)
White to white diameter (mm)	11.97 + 0.42 (11.10–13.10)
Lens thickness (mm)	4.27 + 0.33 (3.69–5.16)

Table 2 Outcome of Different Single Formulas Among the Included Eyes (n = 50)

(n=50)	Mean Arithmetic Error + SD (Range) (D)	Mean Absolute Error + SD (Range) (D)	Median Absolute Error (D)	Cases Within + 0.50 D (%ge)	Cases Within + 1.0 D (%ge)	Cases Within + 2.0 D (%ge)
SRK/T	1.50 + 1.15 (−2.47–4.40)	1.62 + 0.99 (0.13–4.40)	1.49	10%	34%	66%
Holladay 1	1.31 + 1.10 (−2.46–3.78)	1.42 + 0.94 (0.00–3.78)	1.30	20%	40%	74%
Holladay 2	0.98 + 0.97 (−2.58–3.82)	1.13 + 0.79 (0.03–3.82)	0.98	18%	50%	90%
Haigis	0.38 + 0.79 (−2.49–2.58)	0.68 + 0.55 (0.04–2.58)	0.54	42%	80%	96%
Haigis (target −0.50 D)	−0.12 + 0.79 (−2.99–2.08)	0.55 + 0.58 (0.00–2.99)	0.38	56%	86%	96%
Barrett Universal II	1.01 + 0.99 (−1.46–3.59)	1.13 + 0.85 (0.01–3.59)	1.04	30%	46%	88%
Barrett True-K	0.37 + 0.85 (−2.14–3.02)	0.70 + 0.61 (0.01–3.02)	0.56	48%	74%	96%
Barrett True-K (target −0.50 D)	−0.13 + 0.86 (−2.68–2.52)	0.66 + 0.56 (0.02–2.68)	0.54	46%	82%	96%
Kane	0.86 + 0.86 (−0.50–3.64)	0.95 + 0.75 (0.06–3.64)	0.77	36%	58%	90%
PEARL-DGS	−0.28 + 0.97 (−2.35–2.43)	0.82 + 0.58 (0.01–2.43)	0.68	34%	70%	96%
Shammas no history	−1.01 + 0.89 (−2.83–1.36)	1.16 + 0.67 (0.06–2.83)	1.06	18%	44%	90%
DK SRK/T	0.04 + 0.83 (−1.54–2.27)	0.61 + 0.55 (0.01–2.27)	0.46	52%	82%	96%
DK SRK/T (target −0.50 D)	−0.46 + 0.83 (−2.04–1.77)	0.77 + 0.54 (0.01–2.04)	0.64	42%	70%	98%
DK Holladay 1	0.44 + 0.93 (−1.66–3.11)	0.78 + 0.65 (0.03–3.11)	0.58	40%	70%	94%
DK Holladay 1 (target −0.50 D)	−0.06 + 0.93 (−2.16–2.61)	0.72 + 0.58 (0.01–2.61)	0.59	40%	76%	94%

Table 3 Outcome of Different Combinations of the Best Performing Single Formulas Among the Included Eyes (n = 50)

n=50	Mean Arithmetic Error + SD (Range) (D)	Mean Absolute Error + SD (Range) (D)	Median Absolute Error (D)	Cases Within + 0.50 D (%ge)	Cases Within + 1.0 D (%ge)	Cases Within + 2.0 D (%ge)
Median of 5 formulas[a]	0.08 + 0.75 (−2.14–2.52)	0.53 + 0.54 (0.01–2.52)	0.35	64%	82%	96%
Average of 5 formulas[a]	0.12 + 0.73 (−1.95–2.60)	0.53 + 0.52 (0.01–2.60)	0.37	64%	82%	98%
Average of 4 formulas[b]	0.09 + 0.74 (−1.81–2.42)	0.54 + 0.50 (0.01–2.42)	0.34	64%	82%	98%
Haigis (−0.50D) + Barrett True-K + DK SRK/T	0.10 + 0.72 (−2.20–2.46)	0.51 + 0.52 (0.01–2.46)	0.35	66%	84%	96%
Haigis (−0.50D) + DK SRK/T + DK Holladay 1	0.12 + 0.74 (−1.65–2.49)	0.55 + 0.51 (0.01–2.49)	0.35	62%	82%	98%
Haigis (−0.50D) + Barrett True-K + DK Holladay 1	0.14 + 0.72 (−2.15–2.57)	0.51 + 0.52 (0.03–2.57)	0.35	64%	86%	96%
Barrett True-K + DK SRK/T + DK Holladay 1	0.22 + 0.77 (−1.39–2.67)	0.56 + 0.56 (0.01–2.67)	0.41	64%	82%	98%

Notes: [a]DK SRK/T, DK Holladay 1, Barrett True-K (with/without additional −0.50 D target refraction, Haigis (with additional −0.50 D target refraction). [b]DK SRK/T, DK Holladay 1, Barrett True-K, Haigis (with additional −0.50 D target refraction).

K readings, except for the PEARL-DGS formula, which showed an improvement ($p < 0.05$). The best performing formulas with flatter average K readings were PEARL-DGS and Haigis (with additional −0.50 D target refraction) with mean absolute error of 0.72 + 0.71 D and 0.70 + 0.70 D, respectively. The third-best performing formula was Barrett True-K (with an intended additional −0.50 D target refraction), with a mean absolute error of 0.75 + 0.63 D. The percentages of cases within +0.50 D and +1.0 D of intended refraction for the three formulas were 44%, 76%, and 40% versus 44%, 80%, and 80%, respectively. The difference between the two best formulas was not statistically significant ($p > 0.05$).

Table 4 Outcome of Different Formulas in a Subgroup of Flat K Readings (n = 25)

n=25	Mean Arithmetic Error + SD (Range) (D) (n = 25)	Mean Absolute Error + SD (Range) (D) (n = 25)	Median Absolute Error (D) (n = 25)	Cases Within + 0.50 D (%ge)	Cases Within + 1.0 D (%ge)	Cases Within + 2.0 D (%ge)
SRK/T	2.04 + 1.32 (−2.47–4.40)	2.24 + 0.93 (0.56–4.40)	2.27	0%	12%	36%
Holladay 1	1.82 + 1.27 (−2.46–3.78)	2.01 + 0.91 (0.23–3.78)	1.97	8%	12%	52%
Holladay 2	1.31 + 1.18 (−2.58–3.82)	1.53 + 0.88 (0.03–3.82)	1.40	16%	24%	80%
Haigis	0.38 + 0.99 (−2.49–2.58)	0.80 + 0.68 (0.06–2.58)	0.60	36%	72%	92%
Haigis (target −0.50 D)	−0.12 + 0.99 (−2.99–2.08)	0.70 + 0.70 (0.00–2.99)	0.57	44%	80%	92%
Barrett Universal II	1.39 + 1.14 (−1.46–3.59)	1.51 + 0.96 (0.01–3.59)	1.52	20%	24%	76%
Barrett True-K	0.52 + 0.99 (−2.14–3.02)	0.89 + 0.65 (0.03–3.02)	0.76	24%	64%	92%
Barrett True-K (target −0.50 D)	0.03 + 0.99 (−2.68–2.52)	0.75 + 0.63 (0.09–2.68)	0.64	40%	80%	92%
Kane	1.11 + 0.96 (−0.50–3.64)	1.23 + 0.81 (0.17–3.64)	1.20	20%	36%	84%
PEARL-DGS	0.22 + 0.93 (−1.45–2.43)	0.72 + 0.61 (0.01–2.43)	0.61	44%	76%	96%
Shammas no history	−1.30 + 0.95 (−2.83–1.19)	1.40 + 0.77 (0.12–2.83)	1.31	12%	32%	80%
DK SRK/T	−0.16 + 0.91 (−1.54–2.27)	0.73 + 0.55 (0.01–2.27)	0.67	36%	76%	96%
DK SRK/T (target −0.50 D)	−0.66 + 0.91 (−2.04–1.77)	0.94 + 0.61 (0.04–2.27)	0.81	36%	52%	96%
DK Holladay 1	0.52 + 1.16 (−1.66–3.11)	0.98 + 0.78 (0.09–3.11)	0.84	36%	60%	88%
DK Holladay 1 (target −0.50 D)	0.02 + 1.16 (−2.16–2.61)	0.90 + 0.70 (0.05–2.61)	0.74	32%	72%	88%

A combination of best-performing formulas was calculated for the flat K subgroup (Table 5). Many of the combinations of two or three formulas (including DK Holladay 1 and DK SRK/T formulas in addition to the three best performing formulas) yielded good results with approximately 50% and 75 to 80% of the cases within +0.50 D and

Table 5 Outcome of Different Combinations of the Best Performing Single Formulas in a Subgroup of Flat K Readings (n = 25)

n=25	Mean Arithmetic Error + SD (Range) (D)	Mean Absolute Error + SD (Range) (D)	Median Absolute Error (D)	Cases Within + 0.50 D (%ge)	Cases Within + 1.0 D (%ge)	Cases Within + 2.0 D (%ge)
Median of 3 formulas[a]	0.07 + 0.94 (−2.68–2.43)	0.65 + 0.68 (0.00–2.68)	0.57	48%	80%	92%
Average of 3 formulas[a]	0.04 + 0.87 (−2.10–2.34)	0.61 + 0.62 (0.01–2.34)	0.37	52%	80%	92%
PEARL-DGS + Haigis (target −0.50 D)	0.05 + 0.87 (−1.82–2.26)	0.61 + 0.60 (0.01–2.26)	0.47	52%	80%	96%
PEARL-DGS + Barrett True-K (target −0.50 D)	0.12 + 0.89 (−1.66–2.48)	0.67 + 0.58 (0.02–2.48)	0.58	48%	76%	96%
Haigis (target −0.50 D) + Barrett True-K (target −0.50 D)	−0.05 + 0.93 (−2.84–2.30)	0.64 + 0.67 (0.03–2.84)	0.49	52%	84%	92%
Barrett True-K (target −0.50 D) + DK Holladay 1 (target −0.50 D)	0.02 + 0.98 (−1.83–2.57)	0.74 + 0.63 (0.05–2.57)	0.49	52%	72%	96%
Barrett True-K + DK SRK/T + Haigis (target −0.50 D)	0.08 + 0.90 (−2.20–2.46)	0.66 + 0.61 (0.01–2.46)	0.45	56%	76%	92%

Note: [a]Barrett True-K (with additional −0.50 D target refraction), Haigis (with additional −0.50 D target refraction), and PEARL-DGS formulas.

+1.0 D of intended refraction, respectively. The ASCRS average (DK Holladay 1 + Barrett True-K) showed less accurate results, with 28% and 64% of cases within +0.50 D and +1.0 D of intended refraction, respectively. Adding an additional target refraction of – 0.50 D improved the ASCRS average with 52% and 72% of cases within +0.50 D and +1.0 D of intended refraction, respectively (Table 5). A good combination with favorable outcomes was the average of Barrett True-K, DK SRK/T, and Haigis (with an additional target refraction of −0.50 D). This combination yielded an outcome of 56% and 76% of cases within +0.50 D and +1.0 D of intended refraction, respectively.

Discussion

In the current study, the authors showed the outcomes of different traditional and modern formulas in post-RK eyes using only IOLMaster 700 standard K readings. This is a clinical situation in which the operator does not need other machine readings, for example, from corneal tomography or buying a license for Total Keratometry (TK) for IOLMaster 700. The outcomes of different possibilities were shown as to whether the operator used only the optical biometer or had online access to modern IOL calculation formulas. The concept of taking an average of two or more formulas to enhance the outcome was used; it was previously used by the authors in 2011 for post RK eyes[14] and in 2016 for post-myopic laser vision correction eyes.[10]

Older third-generation formulas such as SRK/T and Holladay 1 performed poorly with resultant postoperative clinically significant hyperopia, as they depend on AL and K readings only to estimate the effective lens position (ELP). Holladay 2, despite using more variables to estimate the ELP, did not show much improvement from Holladay 1 results. The Barrett Universal II and Kane formulas, which are used mainly for unoperated virgin eyes with excellent results,[18] showed similar hyperopic postoperative outcomes in post RK eyes. The Shammas no history method[17] was originally described for post-laser vision correction eyes, but the authors used it as an indicator of the upper limit of the IOL power for achieving emmetropia, as it yielded a myopic outcome for most of the cases.

The single formulas that showed better outcomes were the Haigis, Barrett True-K, DK Holladay 1, and DK SRK/T. The Haigis formula does not use K readings to estimate the ELP, which avoids the error caused by flatter K readings in the post RK eyes. The DK modification of the SRK/T and Holladay 1 formulas uses the original pre RK K readings to estimate the ELP instead of the flatter post RK K readings, which are used for the vergence formula to calculate the IOL power for emmetropia.[13] The Barrett True-K formula uses a concept similar to the double-K method to correct ELP estimation errors. Some of the tried formulas, eg, Haigis and Barrett, showed hyperopic mean arithmetic error, so the authors tried targeting −0.50 D and checked the results in a trial to improve the outcome. Targeting a myopic error of 0.50 D improved the accuracy of the Haigis formulas and, to some extent, the Barrett True-K formula, but showed variable outcomes for the DK formulas. Ma et al[19] reported the outcome of the DK Holladay 1 using IOLMaster 500 K readings and Barrett True-K formulas using the ASCRS online calculator. They reported that DK Holladay 1 had median absolute error MedAE 0.78 + 0.76 D and 0.34 + 0.75 D at 1 and >4 months postoperative, respectively. They reported that Barrett True-K had MedAE 0.60 + 0.80 D and 0.69 + 0.67 D at 1 and >4 months postoperative, respectively. In a recent study, Li et al[20] compared the accuracy of Barrett True, Haigis, and DK Holladay 1 in Chinese cataract patients with that of a previous RK using standard K readings obtained from IOLMaster (similar to our study). They reported that the MedAE was lowest for the Barrett True-K formula (0.62), followed by Haigis (0.76), and DK Holladay 1 (1.16). The Barrett True-K formula achieved the highest percentage (46.8%) of eyes with AE within 0.5D (versus 48% in the present study). Haigis achieved the highest percentage (70.21%) of eyes with AE within 1.0 D (versus 80% in the current study). Curado et al[21] showed that the Barrett True-K formula produced significantly more post RK eyes within ±0.50 diopters of intended refraction (63.5%) than the SRK/T, Hoffer Q, and Holladay 1 formulas.

Turnbull et al (including Barrett GD)[22] evaluated 7 IOL calculation formulas: Barrett True-K [History], Barrett True-K [Partial History], Barrett True-K [No History], DK Holladay 1 using IOLMaster K, Potvin-Hill method, Haigis, and Haigis with −0.50 D target refraction. The best results were achieved with the True K [History] (MedAE = 0.275, 76.6% of patients were within ±0.50 D of intended refraction). They stated that of the methods that do not need refractive history, the True K [No History] and unadjusted Haigis were the most accurate (69.2% were within ±0.50 D of intended refraction). They showed that the DK-Holladay using IOLMaster K was less accurate. Their results for Barrett True-K and Haigis were better than the results achieved in the current study and better than those of other reports. This may be due to the different selection of post RK eyes with lower average K readings. Dawson et al[23] reported similar results to the current study, with 51% of post RK eyes with the Barrett True-K, no history was within +0.50 D of intended refraction (versus 48% in the current study) and MedAE of 0.50 D (versus 0.56 D in the current study). The reported outcome of the DK SRK/T formula is not as abundant as that of the DK Holladay 1 formula because the latter is available in the ASCRS online post-refractive surgery IOL calculator. As mentioned above, we used the equations published by Aramberri (2003)[13] to create a simple IOL power calculator using an Excel spreadsheet. Soare et al[11] reported the outcomes of DK SRK/T for post RK eyes. The median prediction error was −0.55 D (versus 0.01 D in the current study), 32.7% of the eyes were within +0.50 D and 52.7% of the eyes were within +1.0 D of intended refraction (versus 2% and 82% in the current study). It should be mentioned here that no axial length Wang-Koch adjustment was done for Holladay 1 and SRK/T formulas in order to avoid extra bias when comparing them to other formulas. However, it is a good idea for another research paper to investigate whether having axial length adjustment would improve the outcome or not with DK modifications.

For better accuracy, an average of three or more formulas is recommended at the time of IOL power calculation (Table 3). The use of a combination of multiple formulas yielded better outcomes, with fewer postoperative hyperopic surprises, than the use of a single formula when standard IOLMaster 700 K readings were used. Despite the close outcome of different combinations, the average of Haigis with a target refraction of - 0.5 D, Barrett True-K, and DK SRK/T showed a slightly better outcome. The use of an average of only 2 formulas is not recommended, as different combinations showed variable results from moderate to good outcomes. It is worth mentioning here that the average of the two formulas available on the ASCRS online post-refractive IOL calculator (Barrett True-K and DK Holladay 1) yielded less accurate outcomes that improved when targeting 0.50 D of myopia but were still less accurate than taking the average of three or more formulas.

Analysis of the outcomes of a subgroup of post RK eyes with flatter K readings (less than 38 D) showed that Haigis, Barrett True-K, DK SRK/T, and DK Holladay 1 eyes had moderate outcomes. Targeting 0.50 of myopia improved the outcome of the Haigis and Barrett True-K formulas and showed variable results with the DK formulas. The Haigis with −0.5 D target refraction and PEARL-DGS formulas had the best outcome, followed by Barrett True-K with −0.50 D target refraction. The PEARL-DGS formula showed significant improvement when used for flatter K readings than the overall included eyes. This formula represents a thick-lens version of the Haigis formula; it uses machine learning using a perfect back-calculated lens position with artificial intelligence and a linear algorithm formula,[16] which explains the better outcome for flatter K readings. To the best of our knowledge, the current study is the first to report the outcomes of the PEARL-DGS formula in post-RK eyes. Calculating the average of 2 or 3 formulas for this subgroup showed improved outcomes when using a single formula. In general, the outcome for post RK eyes with flatter K readings was less than that for all included eyes in the current study. Tavares et al[24] compared Haigis and Barrett True-K in post RK eyes using K readings measured using the IOLMaster. The mean AE was 0.80 ± 0.67 for the Haigis formula and 0.74 ± 0.60 for the Barrett True-K formula. The percentages of eyes within ±0.50 and ±1.00 D of intended refraction were 43.5% and 65.7% for the Haigis formula (versus 42% and 80% in the current study) and 42.6% and 75.9% for the Barrett True-K formula (versus 48% and 74% in the current study), respectively. Their subgroup analysis revealed that for flat corneas (K < 38.00 D), the Barrett True-K formula resulted in more hyperopic results than the Haigis formula (similar to the current study).

Conclusions

In conclusion, using an average of three or more of Haigis (with −0.50 D target refraction), the Barrett True-K, DK Holladay 1, and DK SRK/T formulas showed better outcomes than using a single formula for IOLMaster 700 standard K readings. The PEARL-DGS formula showed better accuracy in eyes with flatter K readings (<38 D).

Abbreviations

RK, radial keratotomy; IOL, intraocular lens; K, keratometry; ELP, effective lens position; AL, axial length; SER, second eye refinement; MRSE, manifest refraction spherical equivalent; DK, double K; MAE, mean absolute error; MedAE, median absolute error.

Data Sharing Statement

Available upon request from the authors.

Ethics and Consent to Participate

This study was approved by the local ethics committee of the Faculty of Medicine, Alexandria University, Egypt. The tenets of the Declaration of Helsinki were followed for this study. All the included patients were recalled for the final follow-up visit and signed an informed consent form.

Author Contributions

Dr. Hany Ahmed Helaly: the idea and concept of the study, shared in writing the manuscript, and collecting and analyzing data. Dr. Amr Mohamed Elhady: shared the idea of the study, wrote the manuscript, and analyzed the data. Dr. Osama Ramadan Elnaggar: shared in writing and revising the manuscript, data analysis, and the idea of the study. "All authors contributed to data analysis, drafting or revising the article, agreed on the journal to which the article was submitted, agreed on all the versions of the article before submission and during revision, gave final approval of the accepted version to be published and any significant changes introduced at the proofing stage, and agreed to be accountable for all aspects of the work".

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