BMC Ophthalmology

RESEARCH

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Studying the effect of keratoconus severity on the accuracy of intraocular lens power calculation using newer keratoconus-specific formulas

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Abstract

Purpose to study the effect of keratoconus severity on the accuracy of intraocular lens power calculation using newer keratoconus (KC) specific formulas.

Methods This was a retrospective case series that included 99 eyes from 99 patients. The included patients were further subdivided into 3 groups according to keratoconus severity. The results of various IOL power calculation formulas were analyzed in this study. Two KC specific formulas were employed: Barrett True K KC and Kane KC. Additionally, the following formulas were utilized: Barrett Universal II (BUII), EVO 2.0, Hoffer QST, Kane, and PEARL-DGS.

Results The Kane KC was the only formula to show a myopic mean prediction error (−0.76 ± 1.06 D). BUII and Barrett True K KC formulas showed the least mean and median absolute errors. The median absolute error (MedAE) for BUII and Barrett True K KC was 0.34 and 0.35 D respectively. BUII and Barrett True K KC formulas had the highest cases within ± 0.25 D of the intended refraction (42.42% and 39.39%, respectively). In severe KC eyes, the MedAE for Barrett True K KC and BUII formulas was 0.56 and 0.46 D respectively. In severe KC eyes, Barrett True K KC and BUII formulas showed the highest cases within ± 0.25 D of the intended refraction (27.27% and 27.27%, respectively).

Conclusion most non KC specific IOL power calculation formulas perform in an acceptable way in mild KC eyes. In moderate and severe KC eyes, the KC specific formulas perform better than the standard formulas. Barrett True K KC formula performed better than Kane KC in moderate and severe KC eyes. BUII formula was the best performing non KC specific formula in moderate and severe KC eyes.

Keywords Biometry, Sum-of-segments, ARGOS, Keratoconus, IOL power calculation, Kane KC, Barrett true K KC

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Introduction

Keratoconus (KC) is a progressive, non-inflammatory condition of the cornea that alters its structure and curvature. In a healthy eye, the cornea maintains a smooth, dome-shaped profile, which is essential for refracting light and directing it onto the retina to achieve clear vision [1–3]. The prevalence of keratoconus in the whole population was 1.38 per 1000 population [95% confidence interval (CI): 1.14–1.62 per 1000] [4].

In individuals diagnosed with keratoconus, the occurrence of cataracts is significantly greater than that observed in the general population. This association is especially pronounced in younger patients, as those with keratoconus tend to experience the onset of cataracts at an earlier age. Among the various types of cataracts, nuclear cataracts are the most frequently observed in this demographic. As these patients progress in age, cataracts can emerge as a primary factor contributing to visual impairment, frequently requiring surgical treatment [5–7].

The calculation of intraocular lens (IOL) power in eyes affected by keratoconus presents significant challenges. This difficulty arises primarily from alterations in the ratio of the anterior to posterior corneal radii, rendering the conventional keratometric refractive index—typically applied to convert the anterior corneal radius of curvature into the equivalent total corneal power—ineffective. Additionally, there are variations in the estimation of the effective lens position. The irregularity of the corneal surface and the non-orthogonal nature of the meridians further complicate the situation. Keratoconus-related dryness and tear film irregularities necessitate repeatability of K values, adding another potential cause of inaccuracy. Lastly, the keratometric readings obtained along the visual axis may not correspond to the measured keratometric values [8–12]. Inaccuracy in measurement of axial length, keratometry and anterior chamber depth can contribute to 36%, 22% and 42% of errors, respectively, in intraocular lens power calculation [13].

The cumulative findings lead to an overestimation of corneal power, an underestimation of the necessary IOL power, and unexpected hyperopic refraction results. In more complex cases, difficulties in acquiring accurate measurements for IOL power calculations may lead to incorrect and unanticipated results. (14–15) Therefore, KC specialized formulas, such as the Kane KC, the Barrett True K KC (with predicted or measured posterior astigmatism), and less commonly the Holladay 2 with KC adjustment formulas, have been developed to improve the accuracy of IOL power calculations in KC patients [16].

In the Kane KC formula, specific modifications are applied to the original Kane formula. To reduce the influence of corneal power on the effective lens position (ELP) calculation, the formula employs a modified corneal power derived from the anterior corneal radius of curvature. This approach provides a more precise representation of the anterior/posterior ratio in eyes affected by keratoconus. (17–18) In the Barrett True K KC formula, the post-refractive Barrett True K formula (which has a double K concept; one for estimating the ELP and the other for use in the vergence formula to calculate the IOL power) is modified using the measured or estimated posterior cornea and central corneal thickness to estimate the total corneal power (TCP) in keratoconus [10, 12, 19]. In the Holladay 2 with KC adjustment formula, the basic ELP algorithm has been modified to accommodate the anomalous link between the axial length (AXL) and anterior chamber depth (ACD) [19, 20].

The aim of this study was to study the effect of keratoconus severity on the accuracy of intraocular lens power calculation using newer keratoconus-specific formulas.

Materials and methods

This was a retrospective case series that included 99 eyes from 99 patients. The included patients were older than 18 years of age, phakic patients with diagnosed keratoconus of different severities. The patients included in this study underwent a standard and uneventful phacoemulsification procedure, followed by the implantation of a hydrophilic acrylic aspherical aberration-free intraocular lens (Akreos Adapt AO, Bausch + Lomb, USA), within the capsular bag. Following the established protocol, patients were arranged for a concluding follow-up appointment and were asked to provide their written consent to engage in the research study. The investigation received approval from the local ethics committee at the Faculty of Medicine, Alexandria University, located in Alexandria, Egypt, in alignment with the principles outlined in the Declaration of Helsinki. The study's exclusion criteria encompassed patients who encountered intraoperative complications that could potentially affect postoperative biometric measurements, those with insufficient visual acuity that would hinder accurate postoperative refraction, and individuals with other ocular conditions that could interfere with biometric evaluations, such as corneal scarring or lens dislocation. A comprehensive review of the patients' medical records, covering the period from January 2021 to October 2024, was performed. Demographic data, including age and gender, were recorded, along with biometric parameters such as axial length (AXL), keratometric readings (K), anterior chamber depth (ACD), lens thickness, central corneal thickness, and white-to-white diameter.

The included patients were further subdivided into 3 groups according to keratoconus severity. The classification of keratoconus severity is primarily based on measurements of corneal curvature, specifically the K-values.

These measurements are essential for evaluating the extent of corneal steepening, which is a defining feature of keratoconus. The condition is divided into three distinct stages: mild, moderate, and severe. Mild keratoconus is indicated by a mean K-value of less or equal to 48 diopters (D). Moderate keratoconus is identified by K-values ranging from 48 D to 53 D. Severe keratoconus is marked by K-values that exceed 53 D [17]. This advanced stage is associated with considerable corneal distortion and significant visual impairment, sometimes necessitating more invasive interventions such as corneal transplantation [21].

Preoperative AXL measurements were performed using the ARGOS biometer (Alcon, Inc., Fort Worth, TX), a sophisticated swept-source optical coherence tomography (SS-OCT) device that operates at a wavelength of 1060 nm. This instrument utilizes sum-of-segments biometry in conjunction with a segmental refractive index. The average of three high-quality scans was recorded. All patients underwent standard phacoemulsification without any complications, with a 2.4 mm clear corneal incision at 10 to 11 o clock. This was followed by the implantation of a foldable hydrophilic acrylic IOL, and was subsequently monitored during the postoperative period. Manifest refraction was evaluated 4 to 6 weeks post-surgery. The refractive error was then converted to spherical equivalent (SE) and documented, calculated using the formula SE = spherical power + (cylinder power/2).

The results of various IOL power calculation formulas were analyzed in this study. Two KC specific formulas were employed: Barrett True K KC and Kane KC. Additionally, the following formulas were utilized: Barrett Universal II (BUII), EVO 2.0, Hoffer QST, Kane, and PEARL-DGS, all of which can be accessed through the ESCRS IOL calculator website (https://iolcalculator.escrs.org/). The initial A-constant used was 118.4 for most for mulas. For the BUII formula, the initial Lens Factor (LF) was 1.62. For Hoffer QST formula, the initial pACD was 5.14. These lens constants were updated from the online IOL constants library IOLCon available at https://iolcon.org/index.php, the website of the ESCRS IOL calculato r (https://iolcalculator.escrs.org/), and the online site of "User group for Laser Interference Biometry" (ULIB), available at http://ocusoft.de/ulib/c1.htm.

Refractive prediction error (PE) was evaluated by determining the difference in spherical equivalent between the predicted value from the formula and the actual measurement taken 4 to 6 weeks following surgery. The absolute prediction error (APE) was obtained by expressing the PE as a positive value. Key outcomes measured included the median absolute prediction error (MedAE), the mean absolute prediction error, and the percentage of cases that were within 0.25, 0.5 D, 1 D, and 2 D of the intended refraction.

Data analysis was executed using SPSS Statistics for Windows (version 26.0; SPSS Inc., Chicago, IL, USA). The quantitative data were summarized by their range, median, mean, and standard deviation. The Kolmogorov-Smirnov test was applied to assess the normality of the dataset. Friedman's ANOVA test was used to compare the means of different groups. The Wilcoxon signed-rank test for paired samples was conducted to analyze the medians within the same group. Additionally, the chi-square test was performed to evaluate the distribution of cases within the designated refraction range. Statistical significance was determined with a p-value threshold of less than 0.05.

Results

This study included 99 eyes from 99 patients. The mean age was 43.7 ± 7.2 years (range from 33 to 61years). The study included 55 males and 44 females. Table 1 shows the demographic and biometric data of the whole included patients ($n = 99$) and the subgroups according to KC severity.

Table 2 lists the arithmetic mean prediction errors of the included formulas for the whole cohort. The ANOVA showed that the difference was statistically significant ($p < 0.05$). The Kane KC was the only formula to show a myopic mean prediction error (– 0.76 ± 1.06 D). The Hoffer QST formula showed the highest hyperopic mean prediction error (0.90 ± 0.89 D), followed by Kane, EVO 2.0, and PEARL-DGS formulas. The mean and median absolute errors (MAE and MedAE) for the various formulas are shown in Table 2. Table 2 displays the number of cases within ± 0.25 D, ± 0.5 D, and ± 1.0 D of the target refraction for the whole cohort. The Friedman's ANOVA test showed statistically significant differences ($p < 0.05$). The chi-square test was used to analyze the number of cases falling within the targeted refraction range; the results indicated a statistically significant difference ($p < 0.05$). BUII and Barrett True K KC formulas showed the least mean and median absolute errors. The median absolute error (MedAE) for BUII and Barrett True K KC was 0.34 and 0.35 D respectively.

BUII and Barrett True K KC formulas had the highest cases within ± 0.25 D of the intended refraction (42.42% and 39.39%, respectively). The EVO 2.0 formula had the highest cases within ± 1.00 D of the intended refraction (96.97%). The BUII, PEARL-DGS, and Barrett True K KC formulas had 100% of cases within ± 2.0 D of the intended refraction.

Subgroup analysis of eyes with mild, moderate, and severe KC was done. Table 3 shows the mean and median absolute errors for the included formulas for eyes with mild KC. Table 3 displays the number of cases

Table 1 Demographic and biometric data of the whole included patients ($n = 99$) and the subgroups

	All patients	Mild KC	Moderate KC	Severe KC
	Mean ± SD (range) (n = 99)	**Mean ± SD (range) (n = 33)**	**Mean ± SD (range) (n = 33)**	**Mean ± SD (range) (n = 33)**
Age (years)	43.7 ± 7.2 (33–61)	45.7 ± 8.2 (33–59)	42.5 ± 7.9 (35–61)	46.2 ± 6.2 (39–55)
Sex (Male: Female)	55: 44	17: 14	18: 14	20: 16
Axial length (mm)	23.80 ± 0.30 (23.38–24.35)	23.81 ± 0.41 (23.38–24.20)	23.70 ± 0.40 (23.19–24.35)	23.90 ± 0.29 (23.50–24.20)
Average Keratometry (D)	50.80 ± 4.23 (44.28–58.00)	45.90 ± 1.10 (44.28–47.60)	50.46 ± 1.48 (48.50–50.40)	55.71 ± 1.44 (53.20–57.50)
Anterior chamber depth (mm)	3.15 ± 0.40 (2.60–3.62)	3.10 ± 0.30 (2.72–3.62)	3.19 ± 0.40 (2.60–3.62)	3.15 ± 0.37 (2.70–3.60)
White to white diameter (mm)	11.57 ± 0.40 (11.00–12.10)	11.59 ± 0.38 (11.00–11.90)	11.49 ± 0.38 (11.10–12.10)	11.69 ± 0.28 (11.20–11.99)
Lens thickness (mm)	4.67 ± 0.40 (3.70–5.10)	4.57 ± 0.41 (3.70–4.80)	4.77 ± 0.38 (3.90–5.10)	4.65 ± 0.39 (3.86–5.00)
Central corneal thickness (microns)	505 ± 17.5 (445–555)	525 ± 15.5 (485–555)	500 ± 19.5 (465–535)	485 ± 21.0 (445–515)

Table 2 The outcome of different formulas among all included eyes ($n = 99$)

(n = 99)	**Mean arithmetic error ± SD (range) (D)**	**Mean absolute error ± SD (range) (D)**	**Median absolute error (D)**	**Cases within ± 0.25 D (%ge)**	**Cases within ± 0.5 D (%ge)**	**Cases within ± 1.0 D (%ge)**
Barrett Universal II	0.17 ± 0.62 (-1.38–1.18)	0.46 ± 0.44 (0.01–1.38)	0.34	42.42%	60.61%	84.86%
EVO 2.0	0.67 ± 0.73 (-1.10–2.10)	0.80 ± 0.58 (0.07–2.10)	0.81	36.36%	60.61%	96.97%
Hoffer QST	0.90 ± 0.89 (-0.87–2.88)	0.96 ± 0.82 (0.01–2.88)	0.64	30.30%	39.39%	54.55%
Kane	0.84 ± 0.90 (-0.98–2.66)	0.95 ± 0.78 (0.02–0.66)	0.83	27.27%	39.39%	57.58%
PEARL-DGS	0.67 ± 0.70 (-1.00–1.87)	0.80 ± 0.53 (0.01–1.87)	0.70	12.12%	36.36%	60.61%
Barrett True K KC	0.28 ± 0.65 (-1.16–1.55)	0.54 ± 0.45 (0.03–1.55)	0.35	39.39%	57.58%	78.79%
Kane KC	− 0.76 ± 1.06 (-3.65–1.11)	0.99 ± 0.84 (0.04–3.65)	0.75	27.27%	33.33%	57.58%

within ± 0.25 D, ± 0.5 D, and ± 1.0 D of the target refraction for eyes with mild KC. The Barrett True K KC formula showed the only myopic mean prediction error (− 0.12 ± 0.52 D). The Friedman's ANOVA test showed statistically significant differences ($p < 0.05$). The chi-square test was used to analyze the number of cases falling within the targeted refraction range; the results indicated a statistically significant difference ($p < 0.05$). The BUII formula showed the lowest median absolute errors (0.06 D).

Table 4 shows the refractive outcome of eyes with moderate KC. The Kane KC formula showed the only myopic mean prediction error (− 1.05 ± 1.05 D). Barrett True K KC and BUII formulas showed the least median absolute errors. The MedAE for Barrett True K KC and BUII formulas was 0.32 and 0.33 D respectively. Barrett True K KC and BUII formulas showed the highest cases within ± 0.25 D of the intended refraction (45.45% and 36.36%, respectively).

Table 5 shows the refractive outcome of eyes with severe KC. The Kane KC formula showed the only myopic mean prediction error (− 1.50 ± 0.60 D). Barrett True K KC and BUII formulas showed the least median absolute errors. The MedAE for Barrett True K KC and BUII formulas was 0.56 and 0.46 D respectively. Barrett True K KC and BUII formulas showed the highest cases within ± 0.25 D of the intended refraction (27.27% and 27.27%, respectively).

Table 3 The outcome of different formulas among the eyes with mild keratoconus (*n* = 33)

(*n* = 33)	Mean arithmetic error ± SD (range) (D)	Mean absolute error ± SD (range) (D)	Median absolute error (D)	Cases within ± 0.25 D (%ge)	Cases within ± 0.5 D (%ge)	Cases within ± 1.0 D (%ge)
Barrett Universal II	0.12 ± 0.57 (-1.10–0.98)	0.35 ± 0.45 (0.01–1.10)	0.06	54.55%	54.55%	81.82%
EVO 2.0	0.28 ± 0.52 (-0.81–1.13)	0.43 ± 0.39 (0.08–1.13)	0.21	54.55%	54.55%	72.73%
Hoffer QST	0.28 ± 0.53 (-0.87–1.13)	0.44 ± 0.40 (0.07–1.13)	0.20	54.55%	54.55%	72.73%
Kane	0.26 ± 0.52 (-0.83–1.11)	0.41 ± 0.40 (0.04–1.11)	0.19	54.55%	54.55%	81.82%
PEARL-DGS	0.33 ± 0.54 (-0.82–1.18)	0.48 ± 0.40 (0.07–1.18)	0.27	27.27%	54.55%	72.73%
Barrett True K KC	− 0.12 ± 0.52 (-1.16–0.78)	0.40 ± 0.33 (0.11–1.16)	0.25	36.36%	63.64%	81.82%
Kane KC	0.26 ± 0.52 (-0.83–1.11)	0.41 ± 0.40 (0.04–1.11)	0.19	54.55%	54.55%	81.82%

Table 4 The outcome of different formulas among the eyes with moderate keratoconus (*n* = 33)

(*n* = 33)	Mean arithmetic error ± SD (range) (D)	Mean absolute error ± SD (range) (D)	Median absolute error (D)	Cases within ± 0.25 D (%ge)	Cases within ± 0.5 D (%ge)	Cases within ± 1.0 D (%ge)
Barrett Universal II	0.17 ± 0.68 (-1.38–1.18)	0.51 ± 0.46 (0.06–1.38)	0.34	36.36%	63.64%	81.82%
EVO 2.0	0.47 ± 0.68 (-1.10–1.47)	0.68 ± 0.45 (0.07–1.47)	0.55	18.18%	45.45%	63.64%
Hoffer QST	0.58 ± 0.53 (-0.20–1.55)	0.61 ± 0.48 (0.01–1.55)	0.51	27.27%	45.45%	72.73%
Kane	0.51 ± 0.67 (-0.98–1.52)	0.69 ± 0.45 (0.02–1.52)	0.56	18.18%	45.45%	72.73%
PEARL-DGS	0.54 ± 0.69 (-1.00–1.58)	0.72 ± 0.48 (0.01–1.58)	0.63	9.09%	36.36%	63.64%
Barrett True K KC	0.28 ± 0.68 (-1.11–1.37)	0.54 ± 0.47 (0.08–1.37)	0.32	45.45%	63.64%	81.82%
Kane KC	− 1.05 ± 1.05 (-3.65– − 0.15)	1.05 ± 1.05 (0.15–3.65)	0.66	18.18%	36.36%	63.64%

Table 5 The outcome of different formulas among the eyes with severe keratoconus (*n* = 33)

(*n* = 33)	Mean arithmetic error ± SD (range) (D)	Mean absolute error ± SD (range) (D)	Median absolute error (D)	Cases within ± 0.25 D (%ge)	Cases within ± 0.5 D (%ge)	Cases within ± 1.0 D (%ge)
Barrett Universal II	0.20 ± 0.66 (-1.33–1.15)	0.53 ± 0.41 (0.04–1.33)	0.46	27.27%	45.45%	72.73%
EVO 2.0	1.26 ± 0.61 (-0.13–2.10)	1.28 ± 0.56 (0.13–2.10)	1.20	9.09%	9.09%	18.18%
Hoffer QST	1.84 ± 0.69 (0.45–2.88)	1.84 ± 0.69 (0.45–2.88)	1.77	0.00%	9.09%	9.09%
Kane	1.74 ± 0.69 (0.27–2.66)	1.74 ± 0.69 (0.27–2.66)	1.90	0.00%	9.09%	9.09%
PEARL-DGS	1.14 ± 0.64 (-0.39–1.87)	1.21 ± 0.48 (0.39–1.87)	1.31	0.00%	9.09%	36.36%
Barrett True K KC	0.68 ± 0.52 (0.03–1.55)	0.68 ± 0.52 (0.03–1.55)	0.56	27.27%	36.36%	54.55%
Kane KC	-1.50 ± 0.60 (-2.67– -0.65)	1.50 ± 0.60 (0.65–2.67)	1.45	0.00%	0.00%	18.18%

Discussion

Keratoconus causes problems in IOL power calculations leading to postoperative hyperopia and unexpected refractive surprises. This problem is more evident with more advanced cases. The current study included relatively large number of advanced cases to verify the effect on different IOL power calculation formulas. We included 2 keratoconus specific formulas: Barrett True K KC and Kane KC. Both formulas, as mentioned above, try to minimize or modify the effect of K readings on the estimation of ELP by modifying their original formulas namely, BUII and Kane formulas which were also included in the current for comparison [10, 12, 17]. We also included 3 other formulas available on the online ESCRS IOL calculation site, the EVO 2.0, Hoffer QST, and PEARL-DGS. Emmetropia Verifying Optical (EVO) 2.0 formula is a thick lens formula based on Gaussian optics principles; it considers the anterior and posterior corneal curvatures, as well as the central corneal thickness. The formula calculates the total corneal power using Gaussian thick lens equations. It uses a fixed corneal thickness of 540 µm assumption when a central corneal thickness (CCT) value is not available; otherwise, the measured CCT value is used [22]. The new Hoffer QST formula is an improved version of the old Hoffer Q formula using artificial intelligence [23]. The PEARL-DGS formula is a thick lens formula that uses artificial intelligence techniques to predict distance between the posterior corneal surface and the anterior IOL surface (theoretical internal lens position). It is a modification based on the Haigis formula which has the advantage of not relying on K reading to estimate the ELP [24, 25]. According to the European Registry of Quality Outcomes, the percentage of patients with prediction error within +/-0.5D is 73.7% [29].

The range of the axial length of the included patients was within the average to focus on the effect of the variation of K readings on the IOL power outcome (range was 23.38 to 24.35 mm). Kane KC formula showed myopic prediction error in the whole cohort and this myopic error was more evident as the KC severity increased. This suggests that the modification done in the Kane KC formula may be overshooting. The original Kane formula and Kane KC formulas performed well in the mild KC eyes with MedAE of 0.19 and 54.55% of cases were within ± 0.25 D of intended refraction. Both formulas showed slightly mean hyperopic error of 0.28 D in mild KC eyes. In moderate KC eyes, Kane Formula showed moderate accuracy with MedAE of 0.56 D and moderate mean hyperopic error of 0.51 D, while the Kane KC formula had MedAE of 0.66 and a notable mean myopic error of– 1.05 D in moderate KC eyes. The performance Kane KC in severe KC cases was less accurate with more mean myopic error of– 1.50 D and MedAE of 1.45 D. The original Kane formula had more mean hyperopic error of 1.74 D in severe KC eyes. This suggests the need for undercorrection of the IOL power when using Kane KC formula in moderate and severe KC eyes and the need for targeting myopia when using the original Kane formula in moderate and severe KC eyes. Vandevenne et al. [19] compared the prediction accuracy of the Barrett true K KC and the Kane KC with standard formulas (SRK/T, BUII, and Kane). The reported similar results of Kane and Kane KC formulas in mild KC eyes which were the same reported in the current study; that in mild KC eyes with K reading less than or equal 48 D, there is no change in the IOL power when using the modification of KC. The difference becomes more evident in moderate and severe cases where the original Kane tends towards hyperopia and the Kane KC tends towards the myopia. Vandevenne et al. [19] reported mean error of Kane and Kane KC formulas of 0.89 D and – 0.15 D in moderate C eyes and 2.04 and– 0.75 D in severe KC eyes. Kane et al. [26] compared the accuracy of Kane KC and Holliday 2 with KC adjustment in comparison to standard formulas (BUII, SRK/T, Haigis, Hoffer Q, Holladay 1, Holladay 2, and Kane). They concluded Kane KC was the most accurate formula in that series with mean absolute error of 0.81 D while Holladay 2 with KC adjustment performed poorly with mean absolute error of 1.32 D. They didn't include Barrett True K KC in the comparison.

The non KC specific formulas showed mean hyperopic error in KC eyes. This error was more evident with more KC severity. The non KC specific formulas performed poorly in severe KC eyes with K readings > 53 D. In mild KC eyes, the non KC specific formulas showed acceptable outcome. Kozhaya et al. [27] assessed the performance of multiple non KC specific formulas in comparison to KC specific formulas. They concluded that non KC specific formulas were less accurate in KC eyes and resulted in hyperopic refractive outcomes that increased with steeper K readings. Kane et al. [26] had the same conclusion in their case series.

The BUII and Barrett True K KC formulas showed the best performance among the whole cohort. They maintained their best performance in moderate and severe KC cases. The MedAE was 0.46 and 0.56 D in severe KC eyes for BUII and Barrett True K KC, respectively. It was interesting in this case series that the original BUII formula performed well in moderate and severe KC eyes. Yokogawa et al. [28] assessed the accuracy of Barrett True K KC in Japanese eyes. They concluded that the Barrett True K KC formula had higher prediction accuracy in severe keratoconus. Vandevenne et al. [19] reported MedAE for Barrett True K KC of 0.39 and 0.56 D. The number of moderate and severe KC cases in their case series was 17 and 4, respectively which was less than the number of included patients in the current study (33 moderate and 33 severe KC eyes were included). Parra-Bernal et al. [29] described the accuracy of IOL power calculation in KC patients using total keratometry (TK) and standard K with conventional and KC modified formulas. They reported that Barrett True K KC with predicted posterior corneal astigmatism (PCA) registered the lowest MAE and MedAE. In the current study, we used only Barrett True K KC with predicted PCA not the measured PCA.

The current study showed some points of strength, including a large proportion of severe KC eyes. A notable aspect of the study is the simultaneous strength and limitation associated with the use of lens constants without additional optimization. The authors emphasized the necessity of reporting actual clinical practice outcomes based on the constants already employed in the ARGOS machine and available on the ULIB website. Another possible limitation identified was the retrospective nature of the study. The current study didn't include the measured PCA version of Barrett True K KC or EVO TK formulas in the comparison.

Conclusions

In conclusion, most non KC specific IOL power calculation formulas perform in an acceptable way in mild KC eyes. In moderate and severe KC eyes, the KC specific formulas perform better than the standard formulas. Barrett True K KC formula performed better than Kane KC in moderate and severe KC eyes. BUII formula was the best performing non KC specific formula in moderate and severe KC eyes.

Abbreviations

ACD	Anterior chamber depth
APE	Absolute prediction error
AXL	Axial length
AXLsos	Sum-of-segments axial length
BUII	Barrett Universal II
CCT	Central corneal thickness
D	Diopter
ESCRS	European Society of Cataract and Refractive Surgery
IOL	Intraocular lens
KC	Keratoconus
LF	Lens factor
MAE	Mean absolute error
MedAE	Median absolute error
PCA	Posterior corneal astigmatism
PE	Prediction error
SE	Spherical equivalent
SS-OCT	Swept-source optical coherence tomography
TCP	Total corneal power
TK	Total keratometry

Acknowledgement
None.

Author contributions
H. A.H.: the idea and concept of the study, shared in writing the manuscript, and collecting and analyzing data. T.M.I.: shared in writing and revising the manuscript, data analysis, and the idea of the study. M.S. H.: shared the idea of the study, wrote the manuscript, and analyzed the data. M.S. E.: shared in the data collection and analysis, shared in writing and revising the manuscript. "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 agree to be accountable for all aspects of the work".

Funding
None.

Data availability
Available upon request from the authors.

Declarations

Ethics approval 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.

Competing interests
The authors declare no competing interests.

Consent to publish
Not applicable.

Received: 9 February 2025 / Accepted: 3 April 2025
Published online: 17 April 2025

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