ORIGINAL ARTICLE

Seeking Perfection in the Shortest Eyes: Intraocular Lens Power Calculation in Eyes with Axial Length Inferior to 21 mm

Procura da Perfeição nos Olhos Mais Curtos: Cálculo da Potência da Lente Intraocular em Olhos com Comprimento Axial Inferior a 21 mm

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ABSTRACT

INTRODUCTION: Cataract surgery has evolved towards perfection. However, intraocular lens (IOL) calculation accuracy is diminished in short eyes. The main purpose of this study was to compare the accuracy of 11 IOL calculation formulas in refractive outcomes for uneventful cataract surgery in short eyes with axial length (AL) equal or inferior to 21.0 mm.

METHODS: Retrospective analysis of patients submitted to uneventful phacoemulsification at a tertiary hospital between January 2020 and June 2023. Prediction error (PE) was calculated as the difference between the subjective refraction spherical equivalent (SE) and the targeted SE of each formula. Absolute error (AE) was the absolute value of the PE. For each calculation formula and IOL, PE was zeroed by subtracting the mean PE of each formula. According to IOL power we defined 2 groups: group 1 (IOL power below 30 D) and group 2 (IOL power above 30 D). We analyzed the total of spherical IOLs and the 2 subgroups separately.

RESULTS: We included 87 eyes of 55 patients, with an AL of 20.48 ± 0.55 (range 18.06-21.00) mm. Group 2 included Acrysof® SN60AT IOLs and group 1 included Clareon® CNA0T0 IOLs. Unzeroed mean PE was lowest for Pearl DGS in group 2 (-0.03 ± 0.66 D) and Kane in group 1 (0.05 ± 0.55 D). After zeroing the PE, Pearl DGS was the most accurate (mean AE (MAE) 0.40 D) in all IOLs (as well as in group 2), while Kane exhibited lowest error in group 1. The MAE was significantly higher for Haigis (p=0.045) and Barrett Universal II formulas (p=0.036) in group 2. Although the Hill-RBF showed good results in group 1, it showed disappointing results in group 2 (MAE 0.37 versus MAE 0.56 D, respectively).

CONCLUSION: Pearl DGS showed the lowest error in group 2, while Kane formula showed excellent results in eyes from group 1. Hill-RBF showed good results in IOLs under 30.0 D. Haigis and Barrett Universal II showed disappointing results. The application of modern methods and formulas for IOL calculation will obtain even more accurate results.

KEYWORDS: Axial Length; Eye/anatomy & histology; Lens Implantation, Intraocular; Lenses, Intraocular.

RESUMO

INTRODUÇÃO: A cirurgia de catarata evoluiu na procura da perfeição. Contudo, a eficácia no cálculo da lente intraocular (LIO) é inferior nos olhos curtos. Assim, este estudo pretendeu comparar 11 fórmulas de cálculo de LIO nos *outcomes* refrativos após cirurgia de catarata em olhos com comprimento axial (CA) inferior a 21,0 mm.

MÉTODOS: Análise retrospetiva de doentes submetidos a facoemulsificação de catarata sem complicações num hospital terciário entre Janeiro 2020 e Junho 2023. O erro de predição (EP) foi calculado como a diferença entre o equivalente esférico (ES) da refração subjetiva e o ES alvo para cada fórmula. O erro absoluto (EA) foi o valor absoluto do EP. Para cada fórmula e LIO, o EP foi zerado subtraindo o EP médio de cada fórmula. Foram definidos 2 grupos de acordo com a potência da LIO: grupo 1 (potência inferior a 30,0 D) e grupo 2 (potência superior a 30,0 D). O total de LIOs esféricas e os 2 subgrupos foram analisados separadamente.

RESULTADOS: Foram incluídos 87 olhos de 55 pacientes, com um CA de 20,48 ± 0,55 (intervalo 18,06-21,00) mm. O grupo 2 incluiu Acrysof® SN60AT IOLs e o grupo 1 incluiu Clareon® CNA0T0. O EP não zerado foi menor para a fórmula Pearl DGS no grupo 2 (-0,03 ± 0,66 D) e Kane no grupo 1 (0,05 ± 0,55 D). Após zerar o EP, a Pearl DGS foi a mais fiável (EA médio (EAM) 0,40 D) em todas as LIOs, enquanto Kane demonstrou menor erro no grupo 1. EAM foi significativamente superior nas fórmulas Haigis (p=0,045) e Barrett Universal II (p=0,036) no grupo 2. Apesar da Hill-RBF demonstrar bons resultados no grupo 1, demonstrou resultados insuficientes no grupo 2 (EAM 0,37 *vs* EAM 0,56 D, respetivamente).

CONCLUSÃO: A fórmula Pearl DGS demonstrou menor erro no grupo 2, enquanto a fórmula Kane demonstrou excelentes resultados no grupo 1. Hill-RBF demonstrou bons resultados para LIOs inferiores a 30,0 D. Haigis e Barrett Universal II demonstraram resultados desapontantes. A aplicação de métodos modernos e fórmulas para o cálculo da LIO irá promover resultados ainda mais exatos.

PALAVRAS-CHAVE: Comprimento Axial do Olho; Implante de Lente Intraocular; Lentes Intraoculares; Olho/anatomia e histologia.

INTRODUCTION

Cataract is a leading cause of blindness worldwide, with tremendous social and economic burden for the world's population. Cataract surgery has evolved towards perfection in a quest for emmetropia by surgeons and patients.[1–3] In fact, more than 10 million cataract surgeries are performed worldwide,2 with more than 80% of patients falling within 0.5 diopters (D) and more than 95% within 1.0 D of predicted refraction.[4–6]

However, intraocular lens (IOL) calculation accuracy is diminished for extreme eyes, particularly for the very short.[7–9] Difficulty in predicting the axial plane of the IOL (effective lens position, ELP) is increased in extreme eyes. Additionally, the high IOL power required and short distance between the IOL plane and the retina, magnify the refractive error in the spectacle plane caused by ELP prediction.[10]

On the other hand, it is of uttermost importance to achieve exact measurement of optical structures, since short eyes are subject to systematic errors in axial length (AL) and anterior chamber depth (ACD) measurements.[11] It has been shown that a 0.25 mm measurement error in preoperative ACD corresponds to an error of 0.5 D in an eye with an AL of 20.0 mm (0.1 D in an eye with an AL of 30.0 mm).[12,13]

IOL power estimation is usually made based on Gaussian optics or raytracing. Classical third-generation formulas (SRK/T,[14] Hoffer Q,[15] Holladay 1[16]) have been used for more than three decades and are popularly used in clinical practice: these calculate ELP using only AL and corneal power. Fourth-generation formulas include additional variables: preoperative ACD (Haigis) and additionally corneal white-to-white (WTW) and lens thickness (LT) in the Holladay 2 and Barrett Universal II.

Most recent formulas (such as EVO 2.0, Kane, and Cooke K6) include different methods and variables, namely the process of emmetropization, artificial intelligence base on theorical optics, and AL measurement as a sum-of-segment process.[4,5,17,18]

Therefore, the main purpose of this study was to compare the accuracy of 11 IOL calculation formulas in the refractive outcomes for uneventful cataract surgery in short eyes with AL equal or inferior to 21.0 mm.

METHODS

STUDY DESIGN

We conducted a retrospective chart analysis of patients submitted to uneventful phacoemulsification and in-the-bag IOL implantation by a 2.4 mm clear corneal incision at the Ophthalmology Department of Centro Hospitalar Universitário de Santo António, a tertiary hospital, between January 2020 and June 2023.

The study was approved by our institutional review board and ethics committee - Departamento de Ensino Formação e Investigação, Centro Hospitalar Universitário de Santo António, (2021.037(029-DEFI/030-CE) and conducted accordingly to the principles of the Declaration of Helsinki for the protection of human subjects in medical research.

PARTICIPANTS AND PROTOCOL

Only patients with an AL equal or inferior to 21.0 mm were included. We excluded patients submitted to additional surgical procedures at the time of cataract surgery, previous intraocular surgery, intraoperative complications, and other ocular pathology (namely neovascular age-related macular degeneration, macular edema of any etiology, keratoconus, corneal dystrophy, or scarring), patients with best-corrected visual acuity (BCVA) inferior to 20/40, subjective refraction obtained less than 1 month after surgery, and patients who underwent biometry with other devices than IOL Master® 700 (Zeiss, Germany).

All patients underwent swept-source optical coherence tomography (SS-OCT) biometry with IOL Master® 700 (Zeiss, Germany) to measure AL, anterior corneal curvature in the two principal meridians (K1 and K2), ACD, LT, central corneal thickness (CCT), and WTW. Posterior corneal curvature and total keratometry were not considered in this study. Eyes were excluded from analysis if the device could not obtain any of the measurements.

Subsequently, subjects underwent surgery with standard phacoemulsification techniques using the Centurion® system (Alcon®, USA) through a 2.4 mm clear corneal incision and in-bag intraocular lens (IOL) implantation. The IOL power was chosen by the surgeon without limitation on the formulas used and after discussion of the refractive target with the patient.

Finally, subjective refraction was performed by an experienced ophthalmologist at least 1 month after surgery, aiming for the minimum sphere and cylinder that offered the patient best visual acuity.

OUTCOMES

Target spherical equivalent (SE) was calculated with SRK/T, Haigis, Holladay 1, Hoffer Q and Barrett Universal II using online available IOL calculator (available at iolzero.com). Target SE for Cooke K6, EVO, Hill-RBF, Hoffer® QST, Kane, and Pearl DGS formulas was calculated using the European Society of Cataract and Refractive Surgery (ESCRS) IOL calculator, with the according optimized A constants (available at https://iolcalculator.escrs.org/).

Prediction error (PE) was calculated as the difference between the subjective refraction SE and the targeted SE of each formula. Therefore, a negative PE indicated a myopic error of the formula, and a positive PE indicated a hyperopic error.

For each IOL calculation formula and IOL, PE was zeroed by subtracting the mean PE (ME) of each formula to eliminate the systematic error derived from using non-optimized IOL constants.[19] After adjustment was done to induce a ME of zero, the mean absolute prediction error (MAE) and the median absolute prediction error (MedEA) were calculated. The criteria for classification of the most accurate formula were the MAE, standard-deviation error (SDE), or a combination of both. We also calculated the percentage of eyes within ±0.25, ±0.50, ±0.75 and ±1.00 D of predicted refraction.

According to IOL power we defined 2 groups: group 1 – eyes with IOL power below 30 D and group 2 – eyes with IOL power above 30 D. We analyzed the total of spherical IOLs and the 2 subgroups separately. Each group was divided by IOL due to manufacturer IOL power limitation (maximum power of 30.0 D for Clareon® CNA0T0).

STATISTICAL ANALYSIS

Statistical analysis was performed using the SPSS software (SPSS statistics, version 26.0.0 for Mac OS, IBM, Somers, NY). All measurements are expressed as mean ± standard deviation. The Kolmogorov-Smirnov test was used to assess normality. Comparison between independent continuous variables was evaluated using the Mann-Whitney U test and T-Student test. Fisher's exact test was used for nominal scaled data. Spearman's bivariate correlation test was applied to study correlations. Each formula was compared with the most accurate (lowest MAE and/or SDE) formula using Wilcoxon's test. P values less than 0.05 were considered statistically significant.

RESULTS

We included 87 eyes of 55 patients. Biometric data is shown in Table 1. Mean age of each patient was 64.6 ± 12.5 years. Most patients were women (n=43 [78.0%]) and of white ethnicity (n=55 [100%]). Eight eyes (9.2%) had primary angle-closure glaucoma and three (3.4%) had primary angle-closure. Thirteen (14.9%) eyes underwent prophylactic laser peripheral iridotomy. Mean postoperative SE was -0.25 ± 0.88 D (vs preoperative 4.50 ± 2.54 D, p<0.001) and mean postoperative logarithm of the minimum angle of resolution (logMAR) was 0.10 ± 0.14 (vs preoperative 0.24 ± 0.25, p<0.001).

For refractive purposes, we analyzed only spherical monofocal IOLs, as follows: Acrysof® SN60AT (n=27), Clareon® CNA0T0 (n=25), Acrysof® SN60WF (n=8), CT Asphina® 404 (n=4), Acrysof® MA60AC (n=1) and Acrysof® AU0T00 (n=1).

Table 1. Preoperative biometric data and implanted IOL data.

Variables	Value (range)
Biometry	
Keratometry	
Mean keratometry (D)	45.38 ± 1.86 (45.75-47.54)
K1 (D)	44.76 ± 1.97 (44.95-47.07)
K2 (D)	46.01 ± 1.87 (46.55-48.01)
Axial length (mm)	20.48 ± 0.55 (18.06-21.00)
Anterior chamber depth (mm)	2.49 ± 0.31 (1.83-3.46)
Lens thickness (mm)	4.75 ± 0.32 (4.03-5.33)
Central corneal thickness (μm)	549.8 ± 41.70 (451.0-650.2)
White to white (mm)	11.5 ± 0.46 (10.3-12.8)
IOL Model (n)	
SN60AT	27
CLAREON CNA0T0	25
SN60WF	8
PRECIZON 565	6
ASPHINA 404	4
AT Lisa 838 MP	3
AT Lisa 809 M	3
Tecnis ZLB00	3
CLAREON PanOptix	2
PRECIZON NVA 570	2
AT Lisa 939 MP	1
SN6AT4	1
AU0T00	1
MA60AC	1

SE, spherical equivalent.

Group 2 corresponded to all Acrysof® SN60AT IOLs and in group 1 we only included Clareon® CNA0T0 IOLs for statistical accuracy.

In the group 1 mean IOL power was 28.8 ± 1.24 D (range 26.5-30.0 D) and in the group 2 mean IOL power was 32.6 ± 1.69 D (range 31.0-37.0 D). Mean AL was significantly shorter in group 2 when comparing with group 1 (20.2 ± 0.50 vs 20.8 ± 0.16 mm, $p<0.001$), as well as ACD (2.29 ± 0.23 vs 2.63 ± 0.18 mm, $p<0.001$). Mean CCT was significantly higher in group 2 vs group 1 (556.9 ± 45.9 vs 533.7 ± 35.0 um, $p=0.049$).

Table 2 depicts the mean PE of formula for group 1 (n=25), group 2 (n=27), and for the total of spherical monofocal IOLs (n=66). The formula with the lowest mean PE was the Pearl DGS for group 2, Kane for group 1, and Pearl DGS when considering the total of monofocal IOLs.

After zeroing, we obtained the refractive accuracy for group 1 and group 2, as shown in Tables 3 and 4, as well as for the total of monofocal spherical IOLs, as shown in Table 5. Considering all monofocal spherical IOLs, Pearl DGS was the most accurate (MAE 0.40 D and STDEV 0.57 D, respectively), while Kane exhibited lowest error in the group 1 (MAE 0.37 D and STDEV 0.55 D, respectively). The MAE was significantly higher for the Haigis (0.63 D, respectively, $p=0.045$) and Barrett Universal II formulas (0.69 D, respectively, $p=0.036$) for the group 2, while no significant differences were found for group 1. In group 2, Pearl DGS showed the lowest MAE (0.51 D) and STDEV (0.63 D). Although the Hill-RBF showed good results in group 1, it showed disappointing results in group 2 (MAE 0.37 and STDEV 0.56D versus MAE 0.56 D and STDEV 0.72 D).

Table 1.2. Preoperative and postoperative refractive data.

Variables	Preoperative	Postoperative	*p*-value
Subjective sphere (D)	5.15 ± 2.47	0.19 ± 0.83	**<0.001[1]**
Subjective cylinder (D)	-0.91 ± 0.94	-0.88±0.77	**0.687[1]**
Subjective SE	4.50±2.54	-0.25 ± 0.88	**<0.001[1]**
IOP (mmHg)	15.11 ± 3.97	13.81 ± 2.81	**0.002[1]**
BCVA (logMAR)	0.24 ± 0.25	0.10 ± 0.14	**<0.001[1]**

1-Paired samples t-test; SE, spherical equivalent; IOP, intraocular pressure; BCVA, best-corrected visual acuity.

Table 2. Mean error of each power calculation formula by IOL.

Formula	SN60AT	CNA0T0	All monofocal IOLs
SRK/T	0.59 ± 0.70	0.07 ± 0.63	**0.31 ± 0.77**
Holladay 1	0.20 ± 0.72	0.08 ± 0.60	**0.11 ± 0.68**
Hoffer Q	-0.27 ± 0.72	-0.22 ± 0.60	**-0.32 ± 0.65**
Haigis	-1.25 ± 0.78	-1.08 ± 0.72	**-1.23 ± 0.77**
Barrett Universal II	-0.52 ± 0.86	-0.04 ± 0.56	**-0.35 ± 0.77**
Cooke K6	0.47 ± 0.67	0.14 ± 0.56	**0.32 ± 0.60**
EVO	0.16 ± 0.67	0.06 ± 0.58	**0.17 ± 0.64**
Hill-RBF	-0.40 ± 0.72	0.29 ± 1.06	**-0.09 ± 0.70**
Hoffer QST	0.15 ± 0.71	0.00 ± 0.60	**0.06 ± 0.69**
Kane	0.09 ± 0.68	0.05 ± 0.55	**0.10 ± 0.61**
Pearl DGS	-0.03 ± 0.66	0.07 ± 0.57	**0.07 ± 0.60**

Table 3. Overall accuracy of IOL power calculation formulas for group 2 (N=27).

						% of eyes within PE range				
Formula	**ME**	**STDEV**	**MedE**	**MAE¹**	**MedAE**	**±0.25 D**	**±0.50 D**	**±0.75 D**	**±1.00D**	***p*-value²**
Pearl DGS	0.00	0.63	0.03	0.51	0.48	30.8%	57.7%	73.1%	92.3%	REF
Kane	0.00	0.68	0.07	0.52	0.45	33.3%	51.9%	70.4%	88.9%	0.859
Hoffer Q	0.00	0.72	0.05	0.52	0.38	33.3%	55.6%	74.1%	81.5%	0.657
SRK/T	0.00	0.70	0.04	0.52	0.34	33.3%	59.3%	74.1%	81.5%	0.899
Hoffer QST	0.00	0.71	0.11	0.53	0.36	34.6%	65.4%	73.1%	84.6%	0.990
Cooke K6	0.00	0.67	0.07	0.53	0.41	25.9%	59.3%	74.1%	88.9%	0.524
EVO	0.00	0.67	0.07	0.53	0.48	25.9%	59.3%	74.1%	92.6%	0.718
Hill-RBF	0.00	0.72	0.01	0.56	0.52	30.8%	50.0%	73.1%	84.6%	0.349
Holladay 1	0.00	0.72	-0.05	0.56	0.49	30.8%	50.0%	69.2%	80.8%	0.421
Haigis	0.00	0.78	0.14	0.63	0.59	20.0%	40.0%	68.0%	80.0%	**0.045**
Barrett Universal II	0.00	0.86	0.17	0.69	0.58	22.2%	44.4%	59.3%	74.1%	**0.036**

IOL = intraocular lens; PE = prediction error; ME = mean PE; STDEV = standard deviation of the error; MedE = median PE; MAE = mean absolute PE; MedAE = median absolute PE;
1-Sorted by ascending order of MAE
2-Pearl DGS used as reference for paired comparisons using a Wilcoxon test

Table 4. Overall accuracy of IOL power calculation formulas for group 1 (N=25).

						% of eyes within PE range				
Formula	**ME**	**STDEV**	**MedE**	**MAE¹**	**MedAE**	**±0.25 D**	**±0.50 D**	**±0.75 D**	**±1.00 D**	***p*-value²**
Kane	0.00	0.55	0.11	0.37	0.21	56.0%	72.0%	88.0%	92.0%	REF
Hill-RBF	0.00	0.56	0.02	0.37	0.16	56.0%	72.0%	84.0%	92.0%	0.573
Cooke K6	0.00	0.56	0.11	0.38	0.28	48.0%	80.0%	88.0%	92.0%	0.520
Barrett Universal II	0.00	0.56	-0.05	0.39	0.22	56.0%	76.0%	84.0%	92.0%	0.520
Pearl DGS	0.00	0.57	0.08	0.39	0.27	44.0%	80.0%	88.0%	92.0%	0.324
EVO	0.00	0.58	0.05	0.39	0.27	48.0%	76.0%	88.0%	92.0%	0.614
Hoffer QST	0.00	0.60	-0.03	0.39	0.23	58.3%	75.0%	83.3%	91.7%	0.726
HofferQ	0.00	0.60	-0.03	0.39	0.17	52.0%	76.0%	88.0%	88.0%	0.853
Holladay 1	0.00	0.60	0.00	0.39	0.25	50.0%	75.3%	83.3%	87.5%	0.716
SRK/T	0.00	0.63	-0.04	0.43	0.25	54.2%	75.0%	79.2%	91.7%	0.201
Haigis	0.00	0.72	0.00	0.49	0.32	44.0%	72.0%	84.0%	92.0%	0.166

IOL = intraocular lens; PE = prediction error; ME = mean PE; STDEV = standard deviation of the error; MedE = median PE; MAE = mean absolute PE; MedAE = median absolute PE;
1-Sorted by ascending order of MeanAE
2-Kane used as reference for paired comparisons using a Wilcoxon test

Table 5. Overall accuracy of IOL power calculation formulas for all monofocal spherical IOLs (n=66).

						% of eyes within PE range				
Formula	**ME**	**STDEV**	**MedE**	**MAE¹**	**MedAE**	**±0.25 D**	**±0.50 D**	**±0.75 D**	**±1.00 D**	***p*-value²**
Pearl DGS	0.00	0.57	0.04	0.40	0.29	42.4%	68.2%	80.3%	90.9%	REF
Cooke K6	0.00	0.57	0.07	0.41	0.32	40.9%	71.2%	84.8%	92.4%	0.853
Kane	0.00	0.58	0.06	0.42	0.28	45.5%	65.2%	81.8%	92.4%	0.573
SRK/T	0.00	0.60	0.01	0.42	0.30	47.0%	71.2%	78.8%	87.9%	0.551
Hoffer QST	0.00	0.61	-0.01	0.43	0.29	47.0%	68.2%	78.8%	87.9%	0.568
Hoffer Q	0.00	0.62	0.00	0.43	0.31	42.4%	65.2%	81.8%	87.9%	0.316
EVO	0.00	0.58	0.00	0.43	0.36	39.4%	68.2%	84.8%	93.9%	0.880
Hill-RBF	0.00	0.61	0.00	0.43	0.37	45.5%	63.6%	78.8%	87.9%	0.403
Holladay 1	0.00	0.62	-0.01	0.45	0.39	39.4%	66.7%	78.8%	87.9%	0.168
Barrett Universal II	0.00	0.71	0.00	0.51	0.39	42.4%	60.6%	69.7%	81.8%	**0.049**
Haigis	0.00	0.62	0.00	0.58	0.50	27.3%	48.5%	68.2%	77.3%	**<0.001**

IOL = intraocular lens; PE = prediction error; ME = mean PE; STDEV = standard deviation of the error; MedE = median PE; MAE = mean absolute PE; MedAE = median absolute PE;
1-Sorted by ascending order of MAE
2-Pearl DGS used as reference for paired comparisons using a Wilcoxon test

The percentage of eyes within predicted refraction is shown in Figs. 1, 2, and 3. Considering all monofocal spherical IOLs, EVO, Cooke K6, Pearl DGS and Kane showed more than 90% of eyes with a PE within 1.0 D. In group 1, all formulas showed more than 85% of eyes with a PE within 1.0 D, while in group 2 only Pearl-DGS and EVO 2.0 showed more than 90% of eyes within 1.0 D.

Subgroup analysis of unzeroed PE was performed for eyes with ACD < 2.00 mm, with a significant association only with Barrett Universal II (-1.17±0.86 vs -0.25±0.77 D, p=0.012). A positive correlation was found between ACD and Barrett Universal II PE (r=0.250, p=0.021).

We also calculated the ratio between AL and ACD (AL/ACD) and found a negative correlation with MAE for Cooke K6 (r=-0.215, p=0.045), EVO (r=-0.217, p=0.044), Hoffer QST (r=-0.212, p=0.048), and Pearl DGS (r=-0.219, p=0.042).

We performed subgroup analysis of PE in eyes with shallow anterior chamber (ACD < 2.40 mm) regarding Haigis, Hoffer Q, and Hoffer QST formulas. While the first two are popular third-generation formulas in short eyes, the latter was refined to minimize Hoffer Q's induced error in eyes with extreme ACD and eyes across all AL spectrum. Regarding eyes with ACD <2.40 mm, MAE was lower for Hoffer Q versus Haigis (0.43 vs 0.58 D, respectively, p<0.001) and for Hoffer QST versus Haigis (0.43 vs 0.58 D, respectively, p<0.001). Regarding eyes with ACD >2.40 mm, there were no significant differences between MAE in Hoffer Q/Haigis (0.40 vs 0.52 D, respectively, p=0.081) neither in Hoffer QST/Haigis (0.40 vs 0.52 D, p=0.304). In the shallow anterior chamber group, there was a tendency for a more myopic PE in Hoffer Q vs Hoffer QST (-0.43 vs -0.21 D, respectively), albeit without statistical significance (p=0.671).

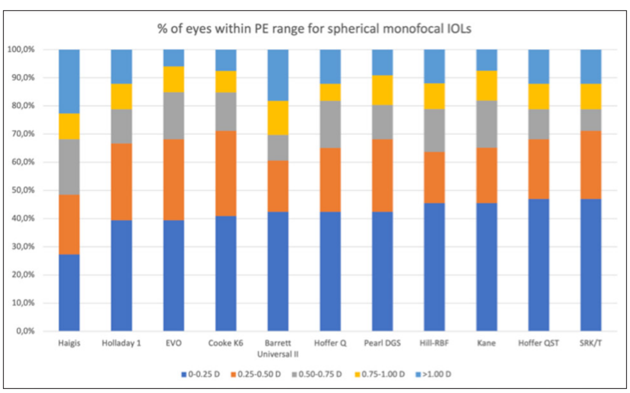

Figure 1. % of eyes within PE range for spherical monofocal IOLs.

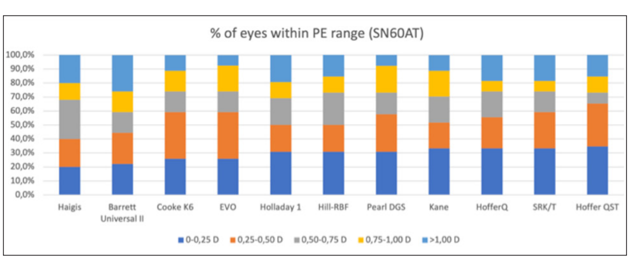

Figure 2. % of eyes within PE range for SN60AT IOL.

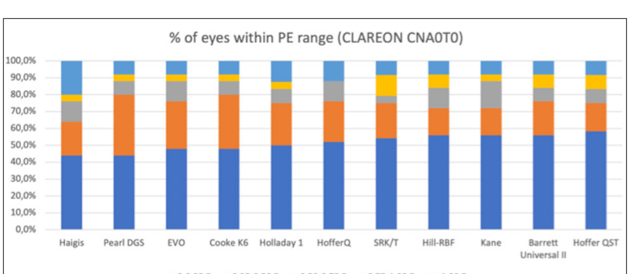

Figure 3. % of eyes within PE range for CLAREON CNA0T0 IOL.

DISCUSSION

Overall, current IOL formulas and technology have shown that refractive accuracy is lower than usual for short eyes. These have idiosyncrasies of its own, namely its low dimensions (which are proportionally more biased by measurement errors than long eyes), high IOL power implantation (more prone to manufacturer inaccuracy), and shorter distance between the secondary principal plane and the internal limiting membrane. Current evidence shows conflicting results for eyes shorter than 22.0 mm, with even fewer work on eyes shorter than 21.0 mm.[7,9,10,20–25] Thus, we wanted to analyze and compare the efficacy of older and modern formulas in this subgroup of particularly short eyes.

Analysis of the total of spherical IOLs revealed modest differences between formulas, except for the Haigis and Barrett Universall II that showed worse performance. There was a tendency for better accuracy with the more recent formulas, such as Pearl DGS, Cooke K6 and Kane.

After correcting for systematic errors by IOL and by formula, the Pearl DGS showed lowest MAE (0.40 D) and STDEV (0.57 D), followed by the Cooke K6 (0.41 and 0.57 D, respectively) and Kane (0.42 and 0.58 D, respectively) formulas. On the other hand, Barrett Universal II (0.51 and 0.71 D, respectively) and Haigis (0.58 and 0.62 D, respectively) formulas showed disappointing results, with the highest MAE.

The Pearl DGS (postoperative spherical equivalent prediction using artificial intelligence and linear algorithms) uses machine learning modelling to predict ELP and adjustment for extreme biometric values, having shown accuracy in small eyes.[13,26–29] In our series, it showed the lowest MAE and standard-deviation when considering the total of monofocal IOLs and in the subgroup with IOL power above 30 D, and one of the highest percentage of eyes within a PE of 0.50 D when considering the group with IOL power below 30 D.

The Kane formula is based on regression and incorporates artificial intelligence based on theoretical optics to enhance its results.[17,30] It has outperformed other formulas regardless of AL and ACD.[5,27,30] It yielded some of the best outcomes, particularly in the group 1, such as the lowest MAE and one of the highest percentage of eyes with a PE within 0.5 D, being a promising modern formula, as previously reported.

Cooke K6 formula has emerged as a thin-lens formula that incorporates a modification of AL determination as a sum-of-segments and a prediction of ELP using thick-formula calculations. It has shown excellent accuracy across all AL spectrum, as was the case in our series.[21,26,29,31]

New formulas are prepared to consider extreme AL and ACD measurements, providing lower errors when comparing with older formulas. Therefore, it was not surprising to confirm its improved accuracy in this subset of eyes, which is in line with available evidence.[4,5,21,23,25,28,31–35] However, the same is not applicable to other formulas, such as the Haigis and Barrett Universal II.

The first estimates ELP using three constants - one of which is highly dependent on AL (a_1) and another highly dependent on ACD (a_2) – thus, its accuracy is expected to be diminished in this particular group of eyes with short AL and variable and extreme ACD.[36,37]

The Barrett Universal II is a thick-lens formula that uses a theoretical model based on Gaussian principles to correlate ACD with AL and K measurements, while taking into account the changes in principal planes that occur with different IOL powers.[38] The location from the iris plane to the principal plane of refraction (lens factor) is different for several IOL manufacturers and is highly dependent on ACD and each IOL A-constant – thus, it is an important component of ELP estimation, which may be more prone to error in very short eyes.

On the other hand, subgroup analysis of MAE showed superiority of Hoffer Q over Haigis (0.47 vs 0.62 D, p=0.002) only in the subgroup with ACD <2.40 mm, which may indicate superiority of the former in eyes with shallow anterior chamber, as previous reported.[25] However, in Hoffer Q, there is a tendency for a myopic PE in eyes with shallow anterior chamber,[4,15,19] which was demonstrated by our study ((PE -0.43 vs -0.21 D, p=0.107) – this happens because preoperative ACD (pACD) is not considered in ELP prediction by this formula. This was addressed in the modern Hoffer QST formula using an artificial intelligence linear model (which includes pACD)[39] and proved by our sample (PE 0.09 vs 0.17 D, p=0.652) – therefore, the new formula avoided the myopic error in short eyes, especially those with shallow anterior chamber.

Regarding all eyes, Hoffer QST showed lower PE over Hoffer Q (0.06 vs -0.32 D, p<0.001), independently of ACD depth. However, after zeroing the PE, MAE analysis revealed no significant differences between both formulas (0.43 D and 0.43 D, p=0.679), which translates the good performance of both formulas in short eyes, in accordance with literature.[10,15,19,23,25,31,34]

However, it should be noted, that classic Hoffer Q showed overall good accuracy in this samples of short eyes, especially when comparing to other third and fourth-generation formulas. This highlights its dominance over more than 30 years and its utility in daily practice (being automatically inserted in most biometers) despite its slight myopic PE, as shown by other studies with short eyes with AL <21.0 mm.[6,32,33]

Despite this, Hoffer Q is inferior to modern formulas, in conflicting evidence with a recent study by Vilaltella *et al* [35] – it should be noted that its efficacy is lower in the very short eyes, especially when considering very shallow (rendering additional myopic error) and deep ACD (rendering additional hyperopic error) – thus, we consider the modern Hoffer QST a more accurate alternative in this subset of eyes, given its AL optimization and ACD/ELP issue enhancement.[15,29,39]

We also found a strong positive correlation between AL and the difference between two formulas, (r^2=0.530, p<0.001) – we believe this may be explained by the known hyperopic error of Hoffer Q in normal and long eyes; and by the heteroscedatic AL optimization method performed in the Hoffer QST formula, which is especially appliable to eyes with long AL, therefore minimizing the previously known hyperopic error.[39]

Subgroup analysis of eyes implanted with the Acrysoft® SN60AT IOL (group 1, IOL power above 30.0 D) revealed lower refractive accuracy when comparing with other IOLs. The Pearl DGS formula obtained the lowest MAE, followed by the Kane formula (0.51 and 0.52 D, respectively). This is in line with other studies regarding extreme axial hyperopia.[4,10,22,40] This represents a subset of challenging eyes, with a mean AL of 20.2 mm and an IOL power range 31.0-37.0 D – which are prone to higher error due to anatomic factors, such as extreme AL and short distance between the principal plane and the retina; and IOL variables, such as the high power (more prone to error) and its anterior asymmetric biconvex design, which may induce a forward ELP with increasing IOL powers.[10] Besides, the available IOL power for this range comes with 1.0 D increments, which limits the surgeon and may contribute to further error. Despite this, at least 50% of eyes ended with a PE within 0.5 D, except for the two worst formulas.

Detailed analysis of both subgroups (Clareon® CNA0T0 and Acrysoft® SN60AT) according to IOL power reveals two sides of the same tale; the former introduces a refined subgroup of small yet larger eyes when comparing with its companion (mean AL 20.8 ± 0.16 vs 20.2 ± 0.50 mm, p<0.001), which contributes to its higher accuracy and highlights the decline in refractive precision with progressively shorter eyes. Besides the overall larger posterior segment, this subgroup also shows significantly deeper ACD (2.62 ± 0.18 vs 2.29 ± 0.23 mm, p<0.001) – we believe these two reasons partly justify its refined accuracy versus group 2, which may render ELP closer to the retina, thereby inducing a hyperopic shift.

Technical similarities between both IOLs should also be noted, such as its anterior aspheric biconvex optic, hydrophobic acrylic, and similar ultraviolet and blue-light filter, thereby mimicking the human crystalline lens in the 400-475 nm wavelength range; this highlights the role of AL and ACD in the observed refractive dissimilarities between both subgroups.

IOL power variation may partly explain some results, such as the ones found in Hill-RBF. It uses adaptative learning to predict refractive outcomes based on artificial intelligence based on a large dataset – hence, due to its low prevalence, the proportion of extreme hyperopic eyes will be low, which may bias accuracy by this formula, as shown in our work, with very accurate results in group 1 but with loss of efficacy towards extremely short eyes (group 2) – thus, while it may not reveal a significant loss of efficacy in the former, it may indicate that vergence-based formulas may be preferred in the latter.

On the other hand, we highlight the excellent results of Pearl DGS formula, especially in group with IOL power above 30D – it is a thick-lens formula that uses machine learning and artificial intelligence to predict ELP and comprises adjustments for extreme biometric values, which may explain it efficacy in the subset of extreme hyperopes.[28]

Our study presents some limitations: it consists of a retrospective analysis, with its inherent limitations. It includes eyes submitted to surgery by several surgeons in different steps of the learning curve, which may bias our results. Ideally, we would have included only eyes operated by the same surgeon – however, due to the rarity of these eyes, it would not be feasible to obtain and adequate sample size in due time. We also included eyes with different implanted IOLs, which may limit its conclusions (however, we zeroed the PE for each IOL and formula to promote its comparison). Besides, IOL comparison is useful, especially to enhance its particular usage (such as Acrysof® SN60AT in extreme axial hyperopes): the problem resides in the eyes and not on the IOL itself.

Despite its limitations, our study provides information regarding the prediction error of one of the largest series of small eyes (AL <21.0 mm) submitted to uneventful cataract surgery. Overall, we describe modest differences between formulas, with a tendency for more accuracy with modern ones, as expected. Currently, Pearl DGS, Cooke K6, EVO 2.0 and Kane seem overall the most accurate for very short eyes. However, it should be noted that older formulas (SRK/T and Hoffer Q) also perform well, except for Haigis and Barrett Universal II. Despite this, care should be taken in eyes requiring IOL power above 30.0 D, in which even modern formulas (particularly Hill-RBF) suffer from loss of refractive accuracy. We believe this adds important information to clinical practice, since older formulas are present in millions of daily printouts of most biometers and are therefore current practice for IOL choice for most surgeons – in fact, these obtain good refractive outcomes even in extreme eyes such as the ones in this sample (over 60% of eyes within ±0.50 D of predicted refraction in the second worst formula).

However, the eternal quest for emmetropia and extreme accuracy demands the application of modern methods and formulas for IOL calculation, which will obtain even more accurate results.

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PM and MCP: Revision of the manuscript

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