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Accuracy of Intraocular Lens Calculation Formulas

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Purpose: To compare the accuracy of intraocular lens (IOL) calculation formulas (Barrett Universal II, Haigis, Hoffer Q, Holladay 1, Holladay 2, Olsen, and SRK/T) in the prediction of postoperative refraction using a single optical biometry device.

Design: Retrospective consecutive case series.

Participants: A total of 13 301 cataract operations with an AcrySof SN60WF implant and 5200 operations with a SA60AT implant (Alcon Laboratories, Inc., Fort Worth, TX).

Methods: All patients undergoing cataract surgery between July 1, 2014, and December 31, 2015, with Lenstar 900 optical biometry were eligible. A single eye per patient was included in the final analysis, resulting in a total of 18 501 cases. We compared the performance of each formula with respect to the error in predicted spherical equivalent and evaluated the effect of applying the Wang–Koch (WK) adjustment for eyes with axial length >25.0 mm on 4 of the formulas.

Results: For the SN60WF, the standard deviation of the prediction error, in order of lowest to highest, was the Barrett Universal II (0.404), Olsen (0.424), Haigis (0.437), Holladay 2 (0.450), Holladay 1 (0.453), SRK/T (0.463), and Hoffer Q (0.473), and the results for the SA60AT were similar. The Barrett formula was significantly better than the other formulas in postoperative refraction prediction ($P < 0.01$) for both IOL types. Application of the WK axial length modification generally resulted in a shift from hyperopic to myopic outcomes in long eyes.

Conclusions: Overall, the Barrett Universal II formula had the lowest prediction error for the 2 IOL models studied. *Ophthalmology 2018;125:169-178 © 2017 by the American Academy of Ophthalmology*

The prediction of refractive outcomes after cataract surgery has steadily improved, with more recent intraocular lens (IOL) power formulas generally outperforming those of prior generations.[1,2] Yet there is still considerable debate about which formula provides the most accurate refractive prediction. Because no single formula has been shown to be highly accurate across a range of eye characteristics, some authors have suggested that cataract surgeons should use different formulas for eyes of varied ocular dimensions.[3,4]

During the study period, by provider or patient preference, 145 surgeons most frequently used an AcrySof SN60WF or SA60AT IOL (Alcon Laboratories, Inc., Fort Worth, TX) for uncomplicated cataract surgery. Although both of these IOL models are made of hydrophobic acrylic and have anterior asymmetric biconvex designs (where the front surface has stronger power), the SN60WF has a yellow chromophore, has an aspheric posterior surface (with nominal negative asphericity of −0.2), and is available in powers of 6.0 to 30.0 diopters (D),[5] whereas the SA60AT has no chromophore, has a spheric posterior surface, and includes IOL powers of 6.0 to 40.0 D.[6]

Our study was designed to address 4 main questions: (1) Of the currently popular IOL calculation formulas (Barrett Universal II, Haigis, Hoffer Q, Holladay 1, Holladay 2, Olsen, and SRK/T), which is the most accurate when evaluating the error in predicted postoperative spherical equivalent including eyes of all ocular dimensions? (2) What is the accuracy of the various formulas when evaluating short, medium, and long eyes? (3) What is the extent of bias within each formula for different biometric dimensions of the eye (anterior chamber depth, axial length, corneal curvature, and lens thickness) that lead to imperfect predictions? (4) Does the use of the Wang–Koch (WK) axial length adjustment for the Haigis, Hoffer Q, Holladay 1, and SRK/T formulas in long eyes lead to improved outcomes?

Methods

Kaiser Permanente Northern California is a large multiprovider medical plan providing comprehensive health care services to a diverse population of approximately 4 million patients.

Consecutive patients who underwent uncomplicated cataract surgery with an implantation of the 2 most commonly used IOLs at our institution (SN60WF or SA60AT) from July 1, 2014, to December 31, 2015, were eligible. A total of 145 surgeons contributed cases, and surgery was performed by clear cornea temporal incision phacoemulsification. All patients were measured preoperatively with the Lenstar 900 (Haag-Streit AG, Koeniz, Switzerland). Manifest refraction was performed at a 1-month postoperative visit with an optometrist. The study was performed under institutional review board approval and conformed to the tenets of the Declaration of Helsinki.

Selection Criteria

Our selection criteria generally followed the recommendations of a recent editorial by Hoffer et al[7] regarding best practices for studies of IOL formulas, namely, the use of optical biometry, the inclusion

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of only 1 eye from each study subject, and the exclusion of patients with less than 20/40 best-corrected vision. In addition, we required a keratometric cylinder less than 4.0 D, lens thickness measurement of at least 2.50 mm, and refraction within the 2-week to 4-month postoperative period. Patients with a history of corneal disease or refractive surgery were excluded. Cases with a postoperative absolute refractive error greater than 2.0 D were reviewed, and 24 cases were excluded because of apparent measurement errors. If both eyes were eligible and the postoperative visual acuity was unequal, the eye with the better visual acuity was selected. If both eyes were eligible and the visual acuity was equal, the first eye was selected if the patients had surgery on separate dates. A random eye was chosen if immediate sequential bilateral surgery was performed. An overview of the selection criteria is shown in Figure 1. Exclusion of patients with corneal or refractive surgery, invalid biometry, missing postoperative refractive information in the 2-week to 4-month postoperative period, or worse than 20/40 vision resulted in a total of 27 191 eligible eyes. Selection of a single eye per patient produced 13 301 study eyes for the SN60WF IOL and 5200 study eyes for the SA60AT.

Formula Calculations

Spherical equivalent formula predictions and lens constant optimizations were performed in collaboration with Haag-Streit, who has licensed versions of the proprietary Barrett Universal II

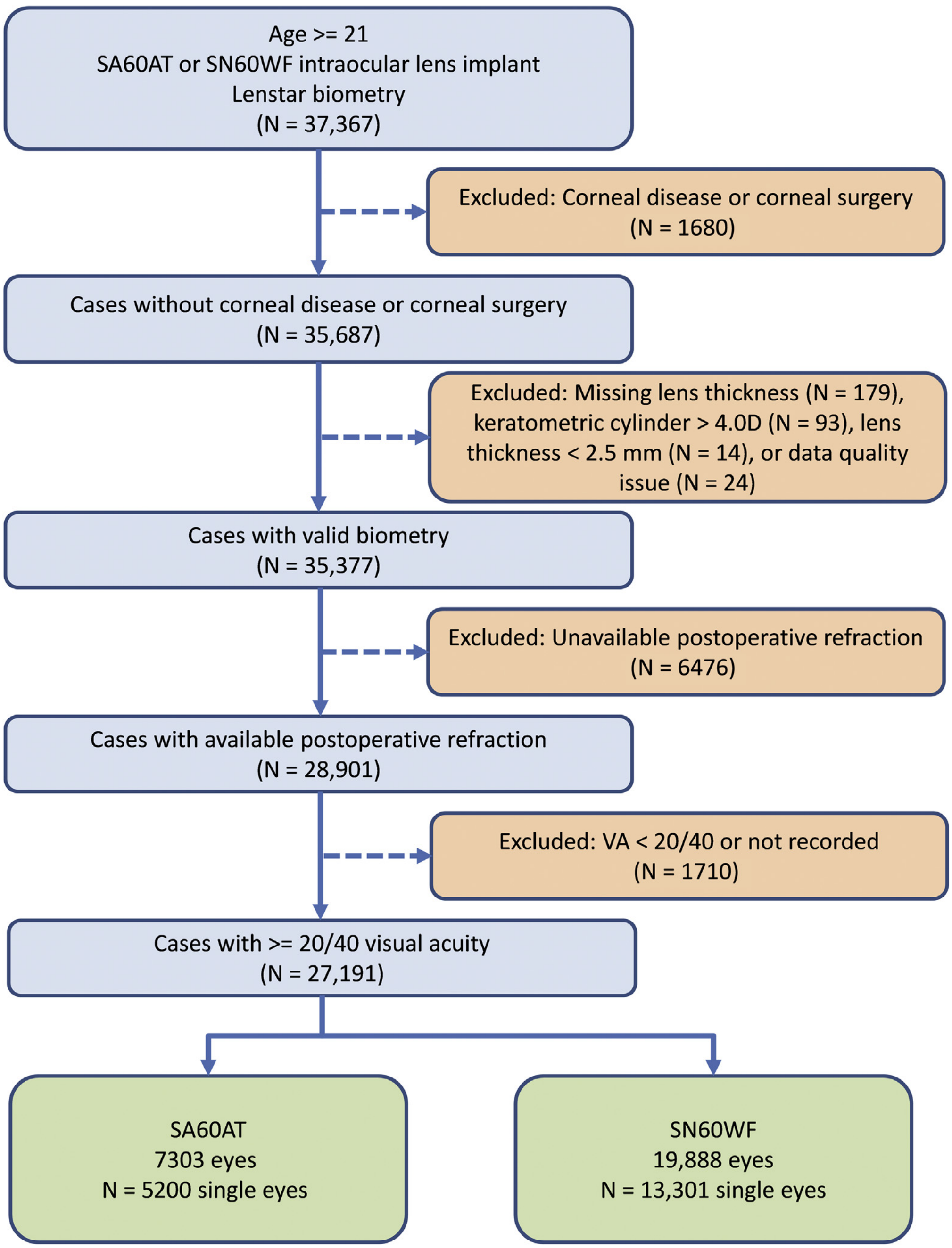

Figure 1. Selection criteria overview. VA = visual acuity.

(hereafter simply referred to as the "Barrett"), Hill Radial Basis Function (RBF), and Olsen formulas, as well as implementations of the open-source Haigis,[8] Hoffer Q,[9] Holladay 1,[10] and SRK/T[11] formulas. The Holladay 2 and WK calculations were performed by the authors. Although we calculated both the single and triple lens constant optimizations for the Haigis formula, we used outcomes for the single optimization in the final analyses to compare the formulas on a more equal basis. However, the a1 and a2 constants we used were the already optimized values for Lenstar 900 biometry for the SN60WF and SA60AT IOLs as listed on the User Group for Laser Interference Biometry (ULIB) website.[12]

The Hill RBF method has an outlier detection feature that excludes certain patients. In our patient population, this function identified 570 of the 13 301 SN60WF cases (4.3%) and 236 of the 5200 SA60AT cases (4.5%) as being out of bounds. Moreover, the current implementation of the Hill RBF is intended for use only in cases where the postoperative target outcome is plano (personal communication, Warren Hill, October 22, 2016). We estimate that 10% of the patients in this study were targeted for intermediate or near vision, so applying these restrictions in addition to the outlier identification would have excluded approximately 15% of patients, making it incomparable to the other formulas. Therefore, the Hill RBF was not included in the final analysis.

The study populations were separated into 3 subgroups by axial length: short (<22.5 mm), medium (22.5–25.5 mm), and long (>25.5 mm). The first group represents the approximate lower 10% of patients, and the last group represents the upper 10% (Table 1). Because many of the theoretical "thin-lens optic" formulas have been associated with hyperopic outcomes in long eyes, Wang et al[13] suggested that the axial length measurement in these eyes be adjusted to offset this potential error. To evaluate the WK axial length modification for eyes longer than 25.0 mm, we used the recommended 1-center regression formulas displayed in Figure 2 of the original article[13] (personal communication, Douglas Koch, February 17, 2017). After applying the respective WK axial length modifications to eyes over 25.0 mm for the Haigis, Hoffer Q, Holladay, and SRK/T formulas, we then optimized the lens constants for the entire data sets to zero the mean error, essentially treating the WK modified versions as distinct formulas.

Statistical comparisons between formula absolute prediction errors were performed using repeated measures analysis of variance (Friedman test with Wilcoxon signed-rank post hoc analyses and Bonferroni correction) (R Studio version 1.0.136, R Foundation; Boston, MA) as suggested by Aristodemou et al[14] and Benavoli et al.[15]

Results

Demographic characteristics of the 2 patient populations are shown in Table 1. More women than men underwent cataract surgery during the study period, and the racial distribution of patients was representative of the diverse population of Northern California.[16] More patients received the SN60WF implant than the SA60AT; otherwise, the 2 groups were similar.

Optimized lens constants are shown in Table 2. Note that the optimized lens constants from this study are slightly higher than the nominal manufacturer-recommended A-constants and slightly lower than the values reported on the ULIB website.[12]

Final outcomes for the SN60WF model IOL are displayed in Table 3 and Figure 2, and results for the SA60AT are shown in Table 4. Figure 3 shows the distribution around the median absolute prediction errors for the SN60WF. The Friedman test confirmed that there were statistical differences between the absolute prediction errors for the various formulas ($P < 0.01$). Post hoc analysis using Wilcoxon signed-rank pairwise comparisons for nonparametric samples with Bonferroni correction showed a significant difference between the Barrett and the other formulas for both IOL types ($P < 0.01$).

Table 1. Demographics of Patients for the Two Intraocular Lens Models Studied

Demographics	IOL Model: *SN60WF**	*SA60AT**
Cases	13 301	5200
Surgeons	127	95
	Count (% of Total)	
Left eye	6200 (47%)	2497 (48%)
Female sex	7854 (59.1%)	3029 (58.3%)
Race		
Asian	2309 (17.4%)	903 (17.4%)
Black	664 (5.0%)	282 (5.4%)
Hispanic	1378 (10.4%)	665 (12.8%)
White	8585 (63.9%)	3168 (60.9%)
Other	445 (3.3%)	182 (3.5%)
	Mean (SD)	
Age	72.8 (9.0)	73.3 (9.2)
Preoperative refraction (days before surgery)	1568.0 (925.5)	1668.4 (854.8)
Postoperative refraction (days after surgery)	47.5 (24.3)	46.0 (24.5)
IOL power	20.21 (3.63)	20.18 (3.49)
Axial length	23.96 (1.30)	23.89 (1.25)
Average keratometry	43.92 (1.52)	43.87 (1.51)
Anterior chamber depth	3.18 (0.41)	3.16 (0.41)
Lens thickness	4.55 (0.47)	4.55 (0.47)
	Count (% of Total)	
Axial length subgroups		
Short (<22.5 mm)	1270 (9.5%)	498 (9.6%)
Medium (22.5–25.5 mm)	10 483 (78.8%)	4190 (80.6%)
Long (>25.5 mm)	1548 (11.6%)	512 (9.8%)
Keratometry subgroups		
Flat (<42.0 D)	1343 (10.1%)	586 (11.3%)
Medium (42.0–46.0 D)	10 803 (81.2%)	4226 (81.3%)
Steep (>46.0 D)	1155 (8.7%)	388 (7.5%)

D = diopters; IOL = intraocular lens; SD = standard deviation.
*Alcon Laboratories, Inc., Fort Worth, TX.

Wang–Koch Adjustment for Long Eyes

Application of the WK adjustment for eyes with axial length over 25.0 mm resulted in variable outcomes, and there were differences between the 2 IOL models studied. For the SN60WF, the adjustment improved outcomes for the Holladay 1 and Hoffer Q formulas, did not significantly change the prediction error for the SRK/T, and led to worse outcomes for the Haigis (Table 3, Fig 4). For the SA60AT, the adjustment resulted in no improvements for the Holladay 1 and Hoffer Q formulas and worse outcomes for the Haigis and SRK/T formulas (Table 4). In general, the WK adjustment caused an overcorrection of hyperopic outcomes in long eyes to result in myopic errors (Fig 4).

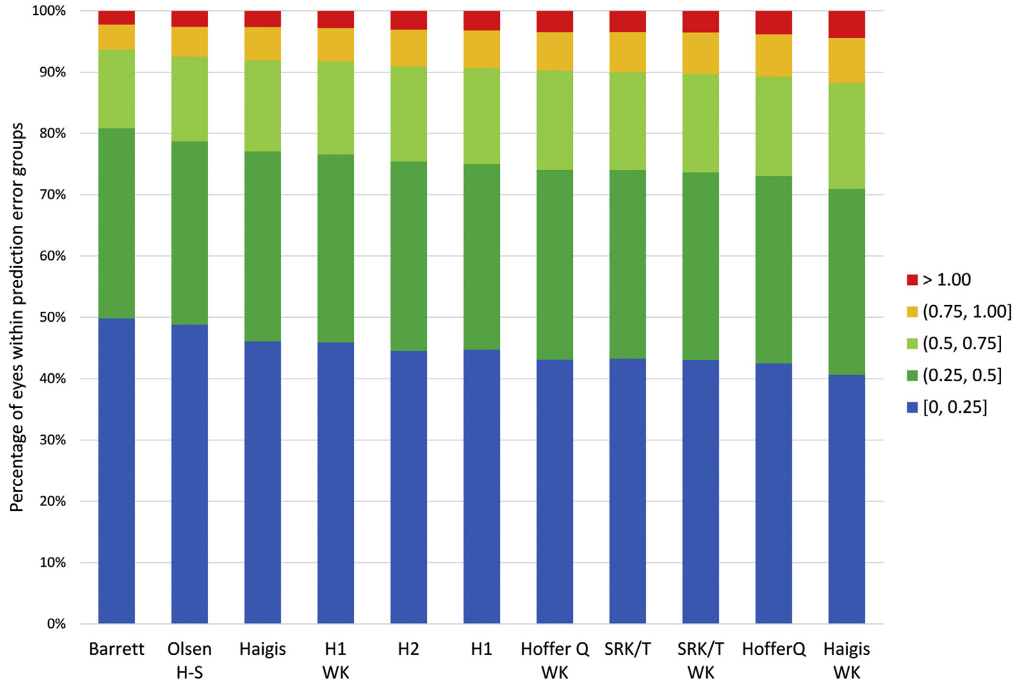

Figure 2. Stacked histogram comparing the percentage of cases within a given diopter range of predicted spherical equivalent refraction outcome for the SN60WF (Alcon Laboratories, Inc., Fort Worth, TX) model intraocular lens. H1 = Holladay 1; H2 = Holladay 2; HS = Haag-Streit; WK = Wang–Koch.

Formula Performance across Ocular Dimensions

As shown in Figure 4, the Barrett had the lowest mean absolute prediction error for short eyes and the Hoffer had the greatest. For long eyes, the Olsen had the lowest mean absolute prediction error and the Holladay 1 and Hoffer had the greatest. Figure 5 illustrates the variation in prediction error with different IOL powers for the SN60WF, as well as the frequency distribution of the IOL implants.

Smoothed line graphs with points representing the bin sample mean of the variation in prediction error for several ocular dimensions are displayed in Figures 6 to 9. The SRK/T in particular is adversely affected by eyes that have flat or steep keratometry (Fig 7). Figure 8 demonstrates that the Hoffer Q and Olsen formulas have significant bias with varying anterior chamber depth (in opposite directions), whereas the Haigis formula shows little deviation in prediction error. On the other hand, the Haigis

Table 2. Optimized Lens Constants

Formula	Lens Constant Name	Optimized Lens Constant	
		SN60WF	*SA60AT*
Barrett	Lens factor	1.90	1.71
Haigis	a0 (a1, a2)	−0.688 (0.331, 0.200)	−0.844 (0.295, 0.203)
$\text{Haigis}_{\text{ULIB}}$	a0, a1, a2	−0.573, 0.331, 0.200	−0.786, 0.295, 0.203
$\text{Haigis}_{\text{WK}}$	a0 (a1, a2)	−0.775 (0.331, 0.200)	−0.916 (0.295, 0.203)
Hoffer Q	ACD	5.64	5.44
Hoffer Q_{ULIB}	ACD	5.73	5.47
Hoffer Q_{WK}	ACD	5.59	5.40
Holladay 1	Surgeon factor	1.83	1.64
Holladay 1_{ULIB}	Surgeon factor	1.94	1.70
Holladay 1_{WK}	Surgeon factor	1.77	1.59
Holladay 2	ACD	5.48	5.29
$\text{Olsen}_{\text{H-S}}$	ACD	4.70	4.67
SRK/T	A constant	118.98	118.69
$\text{SRK/T}_{\text{ULIB}}$	A constant	119.2	118.8
SRK/T_{WK}	A constant	118.95	118.66
Manufacturer	A constant	118.7	118.4

ACD = anterior chamber depth; H-S = Haag-Streit; ULIB = User Group for Laser Interference Biometry; WK = Wang–Koch.
The Haigis a1 and a2 were the optimized values listed on the ULIB website for the Lenstar 900.

Table 3. SN60WF Outcomes, Sorted by Standard Deviation

	Mean	SD	Mean AE	Median AE	Percentage of Eyes within Diopter Range Indicated			
					±0.25 D	*±0.50 D*	*±0.75 D*	*±1.00 D*
Barrett	0.000	0.404	0.311	0.252	49.8%	80.8%	93.7%	97.8%
$Olsen_{H\text{-}S}$	0.000	0.424	0.325	0.258	48.8%	78.7%	92.5%	97.4%
Haigis	0.000	0.437	0.338	0.275	46.1%	77.1%	91.9%	97.3%
Holladay 1_{WK}	0.000	0.439	0.340	0.275	45.9%	76.6%	91.7%	97.2%
Holladay 2	0.000	0.450	0.350	0.285	44.5%	75.4%	91.0%	97.0%
Holladay 1	0.000	0.453	0.351	0.287	44.7%	75.0%	90.7%	96.8%
Hoffer Q_{WK}	0.000	0.461	0.360	0.295	43.1%	74.0%	90.2%	96.5%
SRK/T	0.000	0.463	0.360	0.292	43.3%	74.0%	90.0%	96.5%
SRK/T_{WK}	0.000	0.467	0.363	0.295	43.1%	73.6%	89.7%	96.5%
Hoffer Q	0.000	0.473	0.369	0.303	42.5%	73.0%	89.3%	96.2%
$Haigis_{WK}$	0.000	0.490	0.383	0.318	40.6%	71.0%	88.2%	95.6%

AE = absolute error; D = diopter; H-S = Haag-Streit; SD = standard deviation; WK = Wang-Koch.

is the formula most affected by variation in lens thickness (Fig 9). Overall, the Barrett appears to have the least bias of the formulas as measured by prediction error with variations in axial length, keratometry, anterior chamber depth, and lens thickness.

Discussion

The Barrett and Olsen formulas had the best outcomes in terms of accuracy of postoperative spherical equivalent as measured by difference in mean ranks of Wilcoxon signed-rank comparisons for both of the IOL models in this study and performed well across a range of axial lengths and biometric dimensions. As shown in Figure 6, it is apparent that between axial lengths of 23 and 25 mm, all 7 formulas without the WK adjustment give results that are within 0.1 D of predicted spherical equivalent. The major reason for the difference between the formulas is their performance outside this range. The Haigis and Holladay 1 (with the WK adjustment for the SN60WF and without for the SA60AT) were the best open-source formulas when using a study-specific single optimization of the Haigis a0 constant along with previously optimized a1 and a2 constants for the 2 IOLs from the ULIB website.[12] Contrary to expectation,[3,4] the Hoffer Q had the worst performance in short eyes for both IOL types. These results largely mirror the findings of recent studies by Kane and colleagues[1] and by Cooke and Cooke.[2]

A different version of the Olsen formula is available in a stand-alone software package (PhacoOptics, IOL Innovations ApS, Aarhus, Denmark), which has been reported to have slightly better outcomes than the version currently included with the Lenstar 900 biometer evaluated in this study.[2] Although both versions of the Olsen depend on accurate anterior chamber depth and lens thickness measurement, the stand-alone uses additional variables to predict postoperative anterior chamber depth, namely, the preoperative axial length and preoperative keratometry readings. Thus the stand-alone version is likely more tolerant of errors in anterior chamber depth and lens thickness measurement.

The choice of statistical approach to rank and compare IOL formulas has been controversial.[14,15] Because it has been standard practice to optimize formula-specific lens constants so that the overall mean error is zero, comparison of the means is not possible. Therefore, we used analysis of

Table 4. SA60AT Outcomes, Sorted by Standard Deviation

	Mean	SD	Mean AE	Median AE	Percentage of Eyes within Diopter Range Indicated			
					±0.25	*±0.50*	*±0.75*	*±1.00*
Barrett	0.000	0.424	0.320	0.252	49.8%	80.0%	92.7%	97.3%
$Olsen_{H\text{-}S}$	0.000	0.443	0.337	0.268	47.1%	78.0%	91.5%	96.7%
Haigis	0.000	0.449	0.345	0.278	45.3%	76.3%	90.9%	96.8%
Holladay 1	0.000	0.453	0.348	0.281	45.1%	75.9%	90.1%	96.9%
Holladay 1_{WK}	0.000	0.454	0.350	0.283	44.6%	75.8%	90.1%	96.8%
Holladay 2	0.000	0.456	0.349	0.277	46.1%	75.3%	90.4%	96.6%
SRK/T	0.000	0.471	0.363	0.290	43.7%	74.1%	89.6%	96.0%
Hoffer Q	0.000	0.474	0.365	0.292	43.7%	73.0%	89.4%	96.3%
Hoffer Q_{WK}	0.000	0.476	0.367	0.295	43.4%	72.9%	89.0%	96.0%
SRK/T_{WK}	0.000	0.479	0.370	0.298	42.4%	73.5%	88.8%	95.9%
$Haigis_{WK}$	0.000	0.506	0.395	0.321	40.3%	69.6%	86.8%	95.0%

AE = absolute error; H-S = Haag-Streit; SD = standard deviation; WK = Wang–Koch.

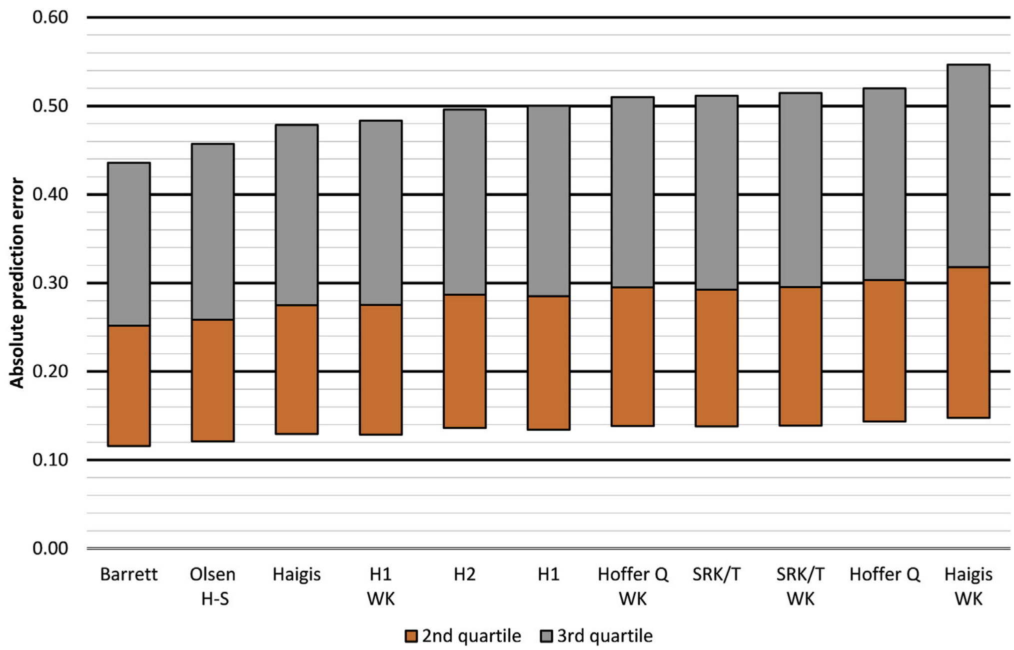

Figure 3. Box plot graph of the mean absolute error (in diopters) for the SN60WF model intraocular lens. *Orange boxes* represent the second quartile, and *gray boxes* represent the third quartile. H1 = Holladay 1; H2 = Holladay 2; H-S = Haag-Streit; WK = Wang–Koch.

variance, which measures the precision or consistency in the formula predictions, as to how close the data cluster around the zero mean. For the current study, we ranked the formulas by standard deviation (Tables 3 and 4), but a ranking by mean absolute error would not have changed the outcomes. We also display the median absolute error, which in nearly every case was consistent with the variance rank by standard deviation or mean absolute

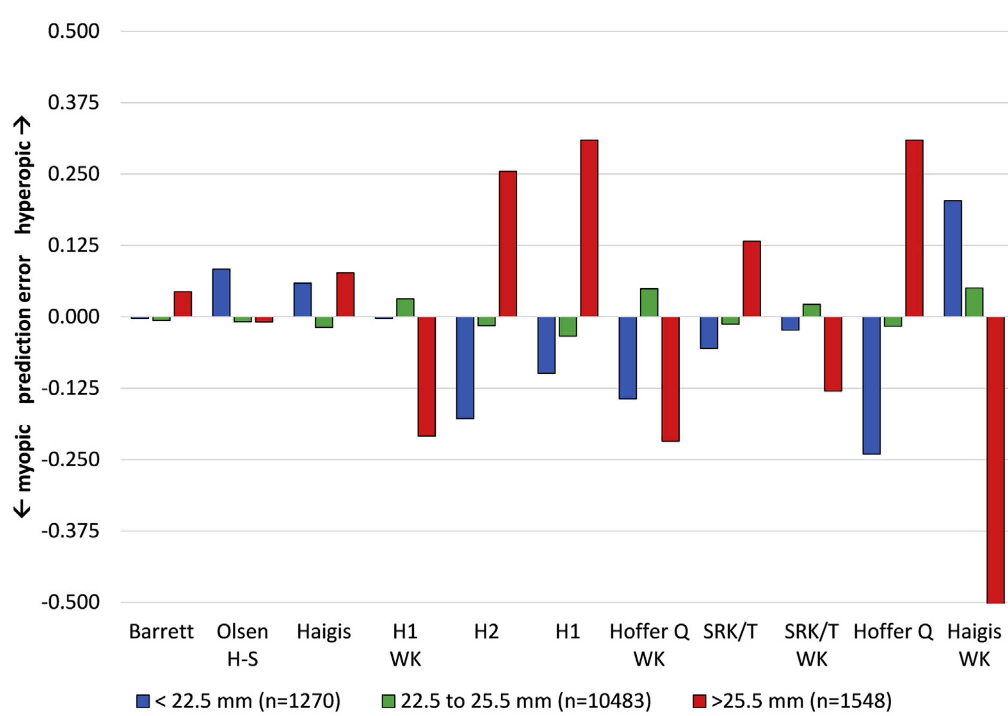

Figure 4. Comparison of prediction errors (in diopters) for 7 formulas plus 4 Wang–Koch (WK) modified formulas in short (<22.5 mm), medium (22.5–25.5 mm), and long (>25.5 mm) eyes for the SN60WF. H1 = Holladay 1; H2 = Holladay 2; H-S = Haag-Streit. Note that myopic prediction errors are indicated by negative values.

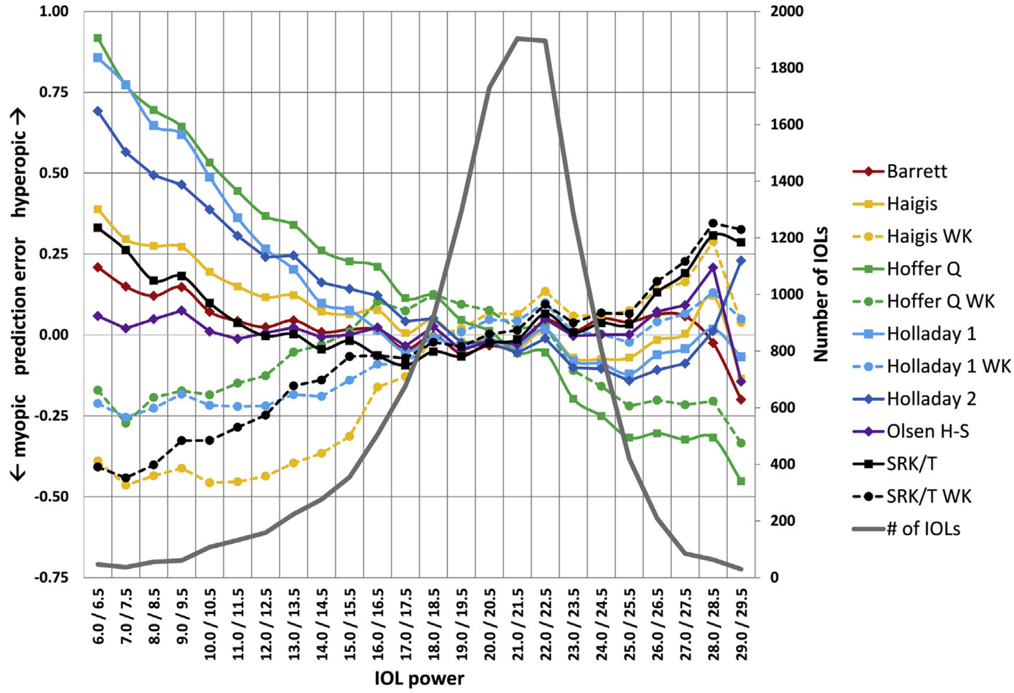

Figure 5. Smoothed line graph of prediction error (in diopters) versus intraocular lens (IOL) power (SN60WF) and frequency distribution of implants used in the study (*gray line*). H-S = Haag-Streit; WK = Wang–Koch.

error. Use of the median absolute error negates the effects of outliers, but clearly one characteristic of a "better" formula is that it reduces the chance of having large outlier outcomes.

Are the statistical differences we demonstrated between the various formulas clinically significant? We believe the difference between the best and the worst formulas do represent a modest but relevant difference. It is encouraging

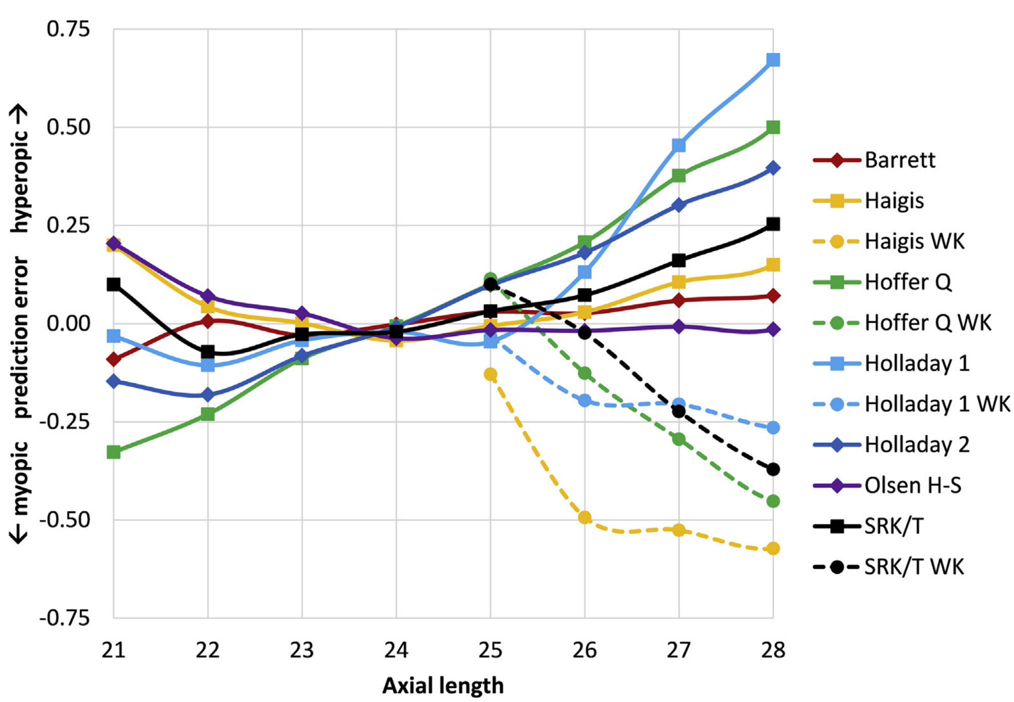

Figure 6. Smoothed line graph of prediction error (in diopters) versus axial length (in millimeters) (SN60WF). The Wang–Koch (WK) modified formulas are shown as *dashed lines* in the same color as the unmodified formula. H-S = Haag-Streit.

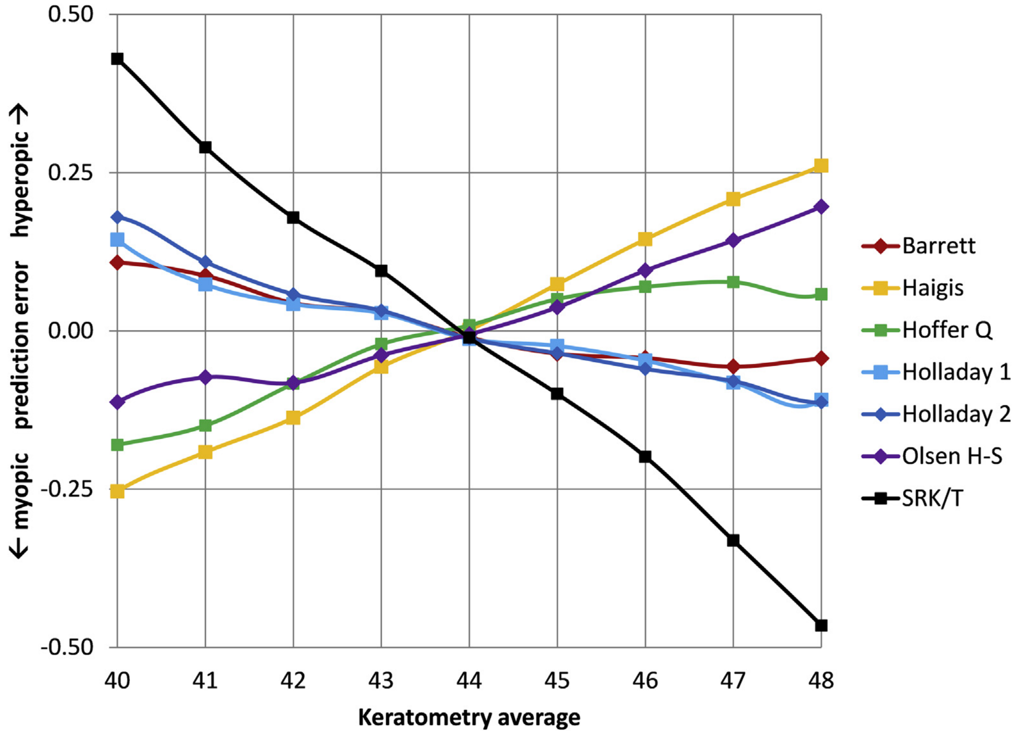

Figure 7. Smoothed line graph of prediction error (in diopters) versus average keratometry (in diopters) (SN60WF). H-S = Haag-Streit.

that more than 95% of patients had a spherical equivalent result within ±1.00 D of the predicted outcome with any of the formulas studied. It is important to note that the 7 formulas did vary in having from 72% to 80% of eyes within ±0.50 D, which is often accepted as the value for which the blur allows independence from spectacles[17,18] (Fig 2).

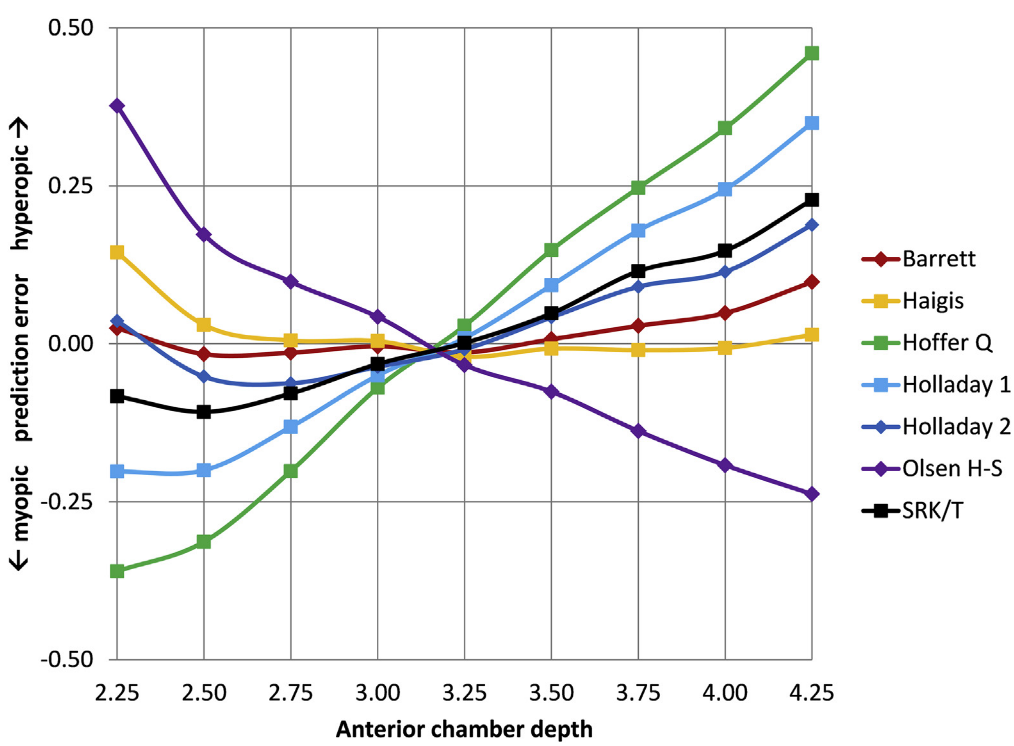

Figure 8. Smoothed line graph of prediction error (in diopters) versus anterior chamber depth (in millimeters) (SN60WF). H-S = Haag-Streit.

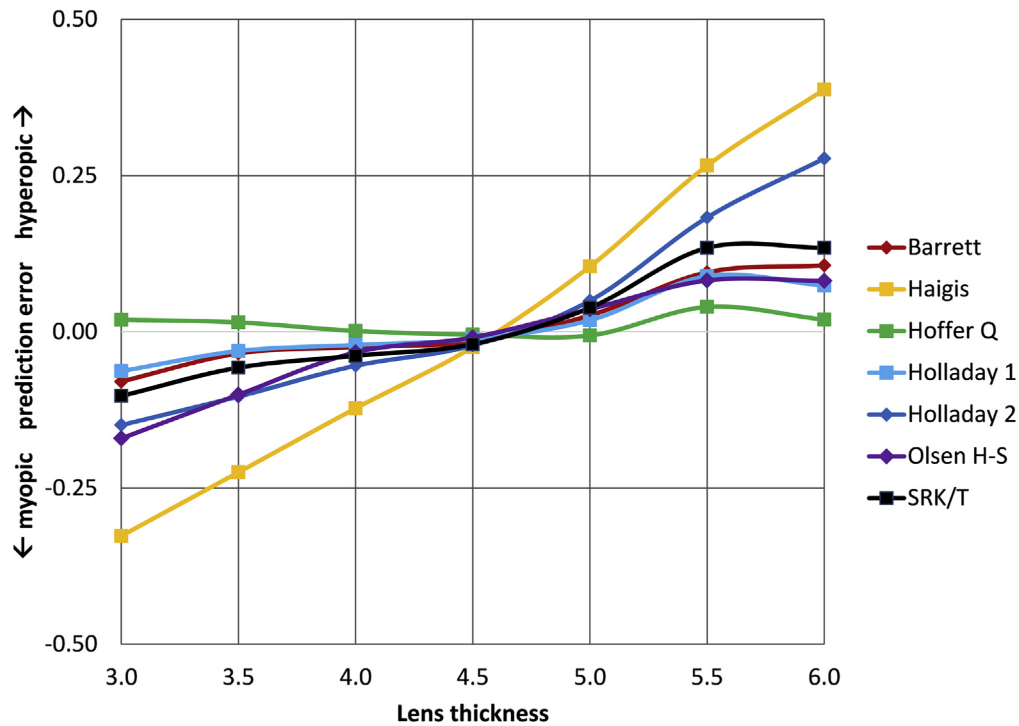

Figure 9. Smoothed line graph of prediction error (in diopters) versus lens thickness (in millimeters) (SN60WF). H-S = Haag-Streit.

Study Limitations

Although the rankings of the formulas were similar between the 2 popular IOL models that we evaluated, we caution that these results may not be generalizable to IOL models of different design. Both of the IOLs evaluated in our study were of anterior asymmetric biconvex (stronger front surface) design from a single manufacturer. Many other IOL designs, such as equi-biconvex (with the same radii on both the front and back surfaces for any given lens power), also are common. The difference in IOL shape could affect prediction errors and change the relative performance of the formulas tested. A notable limitation of the study was that a significant number of patients did not have a refraction captured in the electronic medical record during the designated postoperative period. Some of these patients saw an optometrist outside of our health plan for their final refraction, but we also suspect that some did not return for their normally scheduled 1-month postoperative examination because they were highly satisfied with their refractive outcome without spectacles. If that supposition is true, our study may be biased in terms of slightly worse outcomes for the various formulas than if all patients were included. However, we do not believe that this excluded subgroup would affect the comparison of outcomes between formulas.

The WK modification of axial length for long eyes appears to overcorrect the hyperopic outcomes observed in several of the theoretical "thin-lens" formulas and result in myopic errors. We used the 1-center study regression as recommended by Koch (personal communication, Douglas Koch, February 17, 2017), which is stated to be more aggressive.[13] If we had used the 2-center study, the overcorrection might have been slightly less. A further exploration of this effect will be the focus of a follow-up report.

As shown in Figures 6 to 9, we found notable biases in the prediction errors of most of the formulas when plotted versus axial length, keratometry, anterior chamber depth, and lens thickness. We hope that the illustration of these errors will help the authors of IOL power calculation formulas refine their models and lead to even more accurate prediction of postoperative refraction after cataract surgery.

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Data collection: Melles, Holladay

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Abbreviations and Acronyms:
D = diopter; **IOL** = intraocular lens; **WK** = Wang−Koch.

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