Comparing methods to estimate the human lens power

Jos J. Rozema[*†], PhD, David A. Atchison[‡], DSc,
Marie-José Tassignon[*†], MD PhD

[*]Dept of Ophthalmology, Antwerp University Hospital, Edegem, Belgium
[†]Dept of Medicine, Antwerp University, Wilrijk, Belgium
[‡]School of Optometry & Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, Queensland, Australia

Abstract

Purpose: To compare accuracies of different methods for calculating human lens power when lens thickness is not available.

Methods: Lens power was calculated by four methods. Three methods were used with previously published biometry and refraction data of *184* emmetropic and myopic eyes of *184* subjects (age range [*18, 63*] years, spherical equivalent range [*–12.38, +0.75*] *D*). These three methods consist of the Bennett method, which uses lens thickness, our modification of the Stenström method and the Bennett-Rabbetts method, both of which do not require knowledge of lens thickness. These methods include *c* constants, which represent distances from lens surfaces to principal planes. Lens powers calculated with these methods were compared with those calculated using phakometry data available for a subgroup of *66* emmetropic eyes (*66* subjects).

Results: Lens powers obtained from the Bennett method corresponded well with those obtained by phakometry for emmetropic eyes, although individual differences up to *3.5D* occurred. Lens powers obtained from the modified-Stenström and Bennett-Rabbetts methods deviated significantly from those obtained with either the Bennett method or phakometry. Customizing the *c* constants improved this agreement, but applying these constants to the entire group gave mean lens power differences of $0.71 \pm 0.56D$ compared with the Bennett method. By further optimizing the *c* constants, the agreement with the Bennett method was within ± *1D* for *95%* of the eyes.

Conclusion: With appropriate constants, the modified-Stenström and Bennett-Rabbetts methods provide a good approximation of the Bennett lens power in emmetropic and myopic eyes.

Introduction

Ocular refraction is determined by axial length, anterior chamber depth, corneal power and lens power. While axial length and keratometry measurements have become routine clinically, determining lens power is problematic as the lens radii of curvature and refractive index distribution are usually not available. Although techniques have been proposed in the literature to estimate the radii in vivo[1, 2, 3, 4, 5], they are currently too complicated to be used in large scale studies or clinical practice.

Because of this impracticality various methods have been proposed that use ocular biometry, such as keratometry, ocular axial length, anterior chamber depth, lens thickness, and ocular refraction, to estimate the power of an equivalent lens at a location near that of the lens. Since these biometric parameters are easily determined, such methods can provide a quick estimate of the equivalent lens power.

The most well-known of these methods was proposed by Bennett,[6] who used a thick-lens description that makes assumptions about the shape and refractive index distribution of the lens based on the Gullstrand-Emsley schematic eye.[7] From this he could calculate the equivalent lens power in a way which has been shown to be accurate in comparison with phakometry.[8] However his method requires knowledge of the lens thickness, which is sometimes not available.

Other methods do not require this knowledge of the lens thickness, such as the approaches proposed by Stenström[9, 10] and by Bennett and Rabbetts.[11] These approaches might be useful in a clinical practice using biometry devices that do not provide lens thickness (e.g. Zeiss IOL Master), or in analysis of historical biometry data.

The purposes of this study are to i) verify the agreement that Dunne et al.[8] found between the Bennett method and phakometry, to ii) compare lens powers obtained with the Bennett method, our modification of the Stenström method, and the Bennett-Rabbetts method for previously published data of emmetropic and myopic eyes, and to iii) provide customized constants to optimize the performance of these three methods. These results allow improvement of our statistical eye model[12] by including a more reliable method to estimate lens power when lens thickness is not available.

Methods

Subjects

To estimate the accuracy of the lens power calculations with respect to phakometry, we need the biometry and phakometry data of a population of normal subjects. For this purpose we used previously published data by Atchison et al.[13] for a group of *66* eyes of *66* emmetropic subjects (*32* male, *34* female; *62* Caucasian, *4* non-Caucasian). The average spherical equivalent refraction of this group was *+0.01 ± 0.38 D*, range [*–0.88, +0.75*]*D* and the mean age was *42.4 ± 14.4* years, range [*19, 69*] years.

To compare the results of the three power calculation methods for a wider range of refractions, the first dataset was supplemented by a second set from the same research group.[14] This dataset contained *118* eyes of *118* emmetropic and myopic subjects (*43* male, *75* female; *74* Caucasian, *44* non-Caucasian) with a mean spherical equivalent refraction of *–2.69 ± 2.79 D*, range [*–12.38, +0.75*] *D* and an average subject age of *25.4 ± 5.1* years, range [*18, 36*] years. No phakometry data were available for this second dataset.

Inclusion criteria were stringent in order to ensure that only healthy eyes were included. These entailed, among others, a corrected visual acuity better than *6/6* on an ETDRS chart, a Pelli-Robson contrast sensitivity higher than *1.65* for subjects under *40* years and higher than *1.50* for subjects over *40* years, and an intraocular pressure below *21 mmHg*. In the myopic dataset, eyes with astigmatism larger than *0.5 D* were also excluded.

Subjects' eyes were not dilated nor cyclopleged prior to testing. This might have caused some degree of accommodation in some younger subjects, resulting in slightly more hyperopic refraction, increased lens thickness and decreased anterior chamber depth.

The data collection followed the tenets of the Declaration of Helsinki and received ethical committee approval from the QUT University Human Research Ethics Committee and the Prince Charles Hospital Human Research Ethics Committee. All subjects gave written informed consent prior to participation.

Table 1: Overview of the parameters used

Parameter	Unit	Calculation	Description
S	D		Spherical refraction at spectacle back vertex plane
S_{CV}	D	$S/(1 – 0.014\ S)$	Spherical refraction at corneal vertex
S_{PP}	D	$S/(1 – 0.0155\ S)$	Spherical refraction at first principal plane of the eye
K	D		Corneal power
ACD	mm		Anterior chamber depth (corneal epithelium to anterior lens)
T	mm		Lens thickness
L	mm		Axial length
V	mm	$L – ACD – T$	Vitreous depth
P_L	D		Lens power
n	-		Refractive index of aqueous and vitreous humors
n_L	-		Refractive index of crystalline lens
$P_{L,Bennett}$	D	Equation (1)	Lens power using Bennett method
r_{La}	mm		Anterior radius of curvature of lens
r_{Lp}	mm		Posterior radius of curvature of lens
P_{La}	D	$(n_L – n)/r_{La}$	Power of anterior lens surface
P_{Lp}	D	$(n – n_L)/r_{Lp}$	Power of posterior lens surface
c_1T	mm	$1000\ n(n– n_L)T/\ (n_L P_L r_{Lp})$	Distance between anterior lens surface and first principal plane of lens
c_2T	mm	$1000\ n(n– n_L)T\ /(n_L P_L r_{La})$	Distance between posterior lens surface and second principal plane of lens
$P_{L,Sten}$	D	Equation (2)	Lens power using modified-Stenström method
P_{eye}	D	Equation (3)	Equivalent power of combination of eye and a thin correcting lens placed at the cornea
c_{Sten}	mm	Equation (2) + (3) solved for c_{Sten}	Distance between anterior lens surface and first principal plane of lens
$P_{L,BR}$	D	Equation (4)	Lens power using Bennett-Rabbetts method
c_{BR}	mm	Equation (4) solved for c_{BR}	Distance between thin lens position and anterior lens surface

Biometry

Subjects' refractions were determined monocularly using Jackson crossed cylinders in a phoropter. Keratometry was measured with a Medmont E300 device, while axial length, anterior chamber depth, lens thickness and vitreous depth were measured by A-scan ultrasonography (Quantel Medical AXIS-II). For the emmetropic group the radii of curvature of the anterior and posterior lens surfaces, as well as the lens equivalent refractive index, were obtained by analyzing Purkinje images, refraction and biometry using a setup and calculations[13] similar to that described by Rosales and Marcos.[3] Note that phakometry data were not available for the second dataset.

Bennett's method - lens power calculation using known lens thickness

Bennett's method[6] calculates lens power P_L when lens thickness T is available by keeping the distances from the surfaces to the principal planes of the lens in the same proportion as in the lens of the Gullstrand-Emsley eye model.[7] Using the parameters defined in Table 1, the steps in his method can be combined as the single equation:

$$P_{\mathrm{L,\,Bennett}} = \frac{-1000n\,(S_{\mathrm{CV}} + K)}{1000n - (ACD + c_1 T)\,(S_{\mathrm{CV}} + K)} + \frac{1000n}{c_2 T + V} \tag{1}$$

with $n = 4/3$ the aqueous and vitreous index, $c_1 T = 1000n(n - n_{\mathrm{L}})T/(n_{\mathrm{L}} P_{\mathrm{L}} r_{\mathrm{La}})$ the distance between the anterior lens surface and first lenticular principal plane, and $c_2 T = 1000n(n - n_{\mathrm{L}})T/(n_{\mathrm{L}} P_{\mathrm{L}} r_{\mathrm{La}})$ the distance between the posterior lens surface and second lenticular principal plane. The latter is negative because the principal plane is in front of the back surface. Bennett estimated the c_1 and c_2 constants using the Gullstrand-Emsley eye model, for which the lens refractive index $n_L = 1.416$.

Modified-Stenström method - lens power calculation if lens thickness is not known

If lens thickness T is not available, one can estimate the lens power P_L using Stenström's method[9, 10], which provides the lens power referenced to its anterior vertex rather than to the principal planes. We modified the method by including the parameter c_{Sten}, which is the estimated distance between the anterior lens surface and the first lenticular principal plane. The modified-Stenström method is given by:

$$P_{\mathrm{L,\,Sten}} = \frac{1000n\left(P_{\mathrm{eye}} - K\right)}{1000n - K\left(ACD + c_{\mathrm{Sten}}\right)} \tag{2}$$

using the parameters in Table 1 and with $n = 1.336$. This equation contains the equivalent power of the eye P_{eye}. Based on Stenström's derivation, we calculated this as:

$$P_{\text{eye}} = \frac{1}{2(L - ACD - c_{\text{Sten}})}[1000n - (ACD + c_{\text{Sten}})K - S_{\text{PP}}(L - ACD - c_{\text{Sten}}) + \sqrt{(1000n - (ACD + c_{\text{Sten}})K - S_{PP}(L - ACD - c_{Sten}))^2 - 4(ACD + c_{\text{Sten}})K\, S_{\text{PP}}(L - ACD - c_{\text{Sten}})}\,] \tag{3}$$

Here the ocular refraction at the first principal plane of the eye S_{PP} is used. Lens power P_{L} can be found by substituting the value for P_{eye} derived from equation (3) into the right hand side of equation (2).

A simplification of equation (3) was proposed by van Alphen[15] using the approximation $P_{\text{eye}} = 1392/L - S_{\text{PP}}$. However this simplification deviates considerably from values obtained from equation (3) for $c_{\text{Sten}} > 0$ mm, and we did not include it in our analysis.

Bennett-Rabbetts method - lens power calculation if lens thickness is not known

Another approach to calculating P_{L} without knowing T is to modify an equation proposed by Bennett and Rabbetts[11] for the purpose of calculating the spherical refraction of an eye when its biometry is known. They replaced the lens by an equivalent thin lens located at the midpoint between the lenticular principal planes using the Bennett-Rabbetts eye model.[11] If the ocular refraction at the corneal vertex S_{CV} is known, their equation can be rewritten to give P_{L}:

$$P_{\text{L, BR}} = \frac{L\,(S_{\text{CV}} + K) - 1000n}{(L - ACD - c_{\text{BR}})\left(\frac{ACD + c_{\text{BR}}}{1000n}(S_{\text{CV}} + K) - 1\right)} \tag{4}$$

with $n = 1.336$ and c_{BR} the distance between the anterior lens surface and the thin lens position. This parameter can be found by solving equation (4) for c_{BR} when P_{L} is known.

Phakometry

Using the lens surface radii of curvature and lens refractive index determined using phakometry, along with the lens thickness, the lens equivalent power was calculated using the thick lens formula:[16]

$$P_L = P_{La} + P_{Lp} - \frac{T}{1000 n_L} P_{La} P_{Lp} \qquad (5)$$

with P_{La} and P_{Lp} as defined in Table 1.

Comparing lens powers with the different methods

To compare lens powers obtained with the methods detailed above, we determined the c constants c_1, c_2, c_{Sten} and c_{BR} for both Gullstrand-Emsley and Bennett-Rabbetts eye models. As both eye models will differ from actual ocular biometry, we determined the optimal c constants also for each eye individually. For the Bennett method these constants were easily determined by filling in the available phakometry of the emmetropic dataset into the formulas for c_1 and c_2 in Table 1, using $n = 1.336$. The optimal c constants of the modified-Stenström and Bennett-Rabbetts methods were found by using the phakometry lens powers of the emmetropic dataset for P_L and solving equations (2 + 3) and (4) for the c constants, also using $n = 1.336$. The analytical solution for c_{Sten} in the modified-Stenström method was mathematically complicated and could not be used in MS Excel; Mathematica (Wolfram Research, Champaign, IL) was used instead to estimate values numerically. Means and standard deviations of these optimal c constants were called the "customized" c constants and are given in Table 2.

Statistics

Statistical calculations were performed using Excel 2003 (Microsoft Corp, WA, USA) and SPSS 12 (SPSS Inc, Chicago, USA). A significance level of $P < 0.05$ was used.

Results

Agreement between calculated and phakometry derived lens powers for emmetropes

The mean lens power determined with phakometry was $P_L = 22.87 \pm 2.42$ *D*, which may be considered the target value that the calculation methods must approximate

(Table 2). Using both the Gullstrand-Emsley and Bennett-Rabbetts eye models, the lens powers with the Bennett method were not significantly different from phakometry powers. Using the customized *c* constants did not improve the agreement. A Bland-Altman plot shows that the differences between Bennett and phakometry lens power remained between ±*3D* (Figure 1a) and for *45-50%* of the eyes were less than ±*1D* (Table 2). These differences were not correlated with subject age (*Pearson* < *0.01*, $P > 0.05$), which excludes accommodation as a possible source of these differences.

Using the Gullstrand-Emsley and Bennett-Rabbetts eye models, the modified-Stenström and Bennett-Rabbetts methods gave lens powers that were about 1.5 D lower and were significantly different from phakometry lens powers (paired *t* tests, $P < 0.01$). By customizing the *c* constants, the differences with phakometry reduced remarkably to be non-significant (paired *t* tests, $P > 0.05$), and for about *40%* of the eyes the differences were less than ±*1D* (Table 2).

Table 2: Comparison of the measured and calculated lens powers using the biometry and phakometry of the emmetropic data (66 eyes)

Method	Symbol	Eye model	*c* constants	Average	Percentage within ±1D from P_L	Pearson correlation coefficients with phakometry
Phakometry	P_L			*22.87 ± 2.42 D*		
Bennett	$P_{L,Bennett}$	Gullstrand-Emsley	$c_1 = 0.596; c_2 = -0.358$	*22.50 ± 2.02 D*	*45.5%*	*0.778* (*P* <*0.001*)
		Bennett-Rabbetts	$c_1 = 0.599; c_2 = -0.353$	*22.74 ± 2.03 D*	*50.0%*	*0.779* (*P* <*0.001*)
		Customized	$c_1 = 0.571 \pm 0.028$ $c_2 = -0.378 \pm 0.029$	*22.54 ± 2.00 D*	*45.5%*	*0.778* (*P* <*0.001*)
Modified-Stenström	$P_{L,Sten}$	Gullstrand-Emsley	$c_{Sten} = 2.145$ mm	*21.04 ± 1.94 D*	*19.7%*	*0.720* (*P* <*0.001*)
		Bennett-Rabbetts	$c_{Sten} = 2.221$ mm	*21.36 ± 1.97 D*	*27.3%*	*0.720* (*P* <*0.001*)
		Customized	$c_{Sten} = 2.875 \pm 0.763$ mm	*22.78 ± 2.12 D*	*42.4%*	*0.721* (*P* <*0.001*)
Bennett-Rabbetts	$P_{L,BR}$	Gullstrand-Emsley	$c_{BR} = 2.230$ mm	*21.21 ± 1.96 D*	*24.2%*	*0.720* (*P* <*0.001*)
		Bennett-Rabbetts	$c_{BR} = 2.306$ mm	*21.54 ± 1.99 D*	*36.4%*	*0.720* (*P* <*0.001*)
		Customized	$c_{BR} = 2.891 \pm 0.778$ mm	*22.81 ± 2.13 D*	*40.9%*	*0.721* (*P* <*0.001*)

The Pearson correlation coefficients between the calculated and phakometry lens powers were high (Table 2) and independent of the eye model used. The correlation coefficients were higher for the Bennett method than for the modified-Stenström and the Bennett-Rabbetts methods.

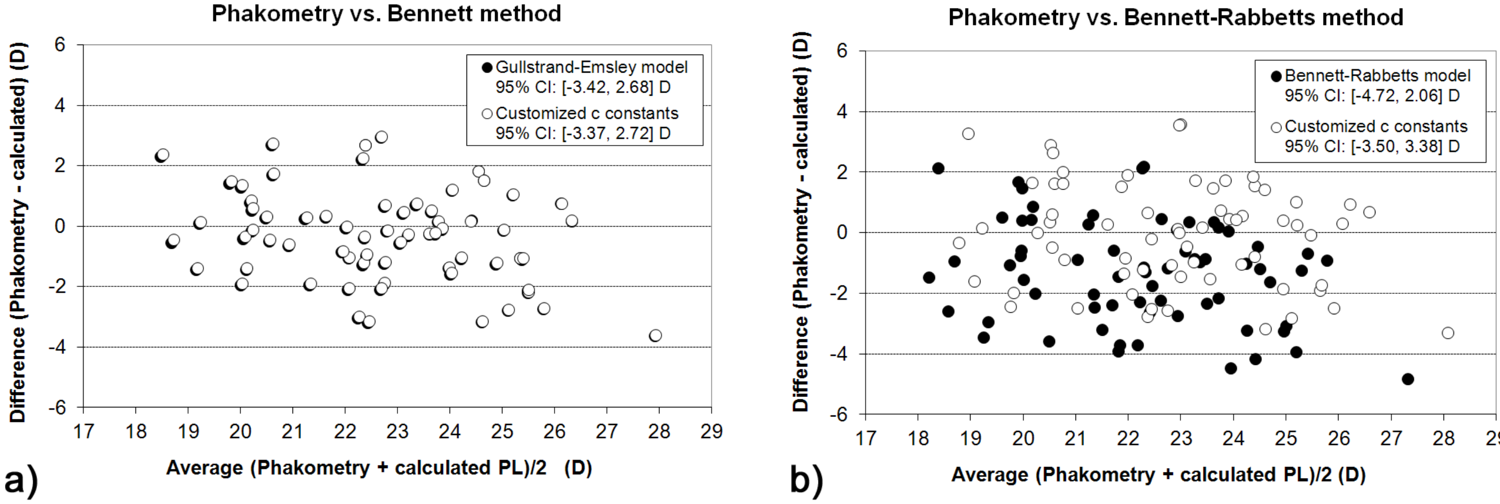

Figure 1: Bland-Altman plots showing the differences between the phakometry lens powers and the lens powers calculated using (a) the Bennett method and (b) the Bennett-Rabbetts method. Powers for the calculation methods are shown for both eye model c constants and customized c constants. As the modified-Stenström and the Bennett-Rabbetts methods gave similar lens powers, results are shown only for the latter. (CI: confidence interval)

Comparison of the three lens power calculation methods for the whole population

Figure 2a shows lens powers calculated using the Bennett method with customized *c* constants calculated for the combination of the two datasets (184 eyes) as a function of axial length *L*. The lens power has a negative correlation with axial length for $L < 24$ *mm* ($r = –0.624; P < 0.001$), with a slope that matches that of the measured lens power data. Above $L = 24$ *mm*, approximately corresponding with the onset of myopia, the lens power plateaus to become constant ($r = –0.036; P > 0.05$). Because phakometry was not available for the second dataset, this plateauing could not be confirmed experimentally. However a similar trend was found in the raw data published by Sorsby et al.[17]. Thus, in absence of phakometry data for the entire dataset, the Bennett power with customized *c* constants was used as a benchmark. This choice is based on Dunne's observation[8] that the Bennett power corresponds well with phakometry in myopic refractions up to *–9.37 D*, including the long eyes for which the plateauing is shown in Figure 2a.

The mean powers with the modified-Stenström and Bennett-Rabbetts methods, using the Gullstrand-Emsley and Bennett-Rabbetts eye models, were *0.5 – 1.0D* less than the mean powers obtained with the Bennett method and its customized *c* constants (Table 2). These differences were statistically significant (paired *t* test, $P < 0.001$). Using customized *c* constants mentioned above, the modified-Stenström and Bennett-Rabbetts methods each yielded lens power values that were *0.71 ± 0.56 D* greater than those with the Bennett method (Table 3), and this was also statistically significant ($P < 0.001$).

To improve the matches of the modified-Stenström and Bennett-Rabbetts methods with the Bennett method, a second *c* constant (named "Customized 2") was determined for the modified-Stenström and Bennett-Rabbetts methods that minimized the mean lens power difference with the Bennett method over the entire population. Using these Customized 2 constants, the lens power differences with the Bennett method were no longer statistically significant ($P > 0.05$), and were within *±1D* for about *95%* of eyes (Table 3). For both methods, the power differences with the Bennett method were correlated significantly with axial length *L* ($r = 0.390$, $P < 0.001$ and $r = 0.329$, $P < 0.001$ for the modified-Stenström and the Bennett-Rabbetts methods, respectively; Figure 2b).

Table 3: Comparison of the measured and calculated lens powers using the biometry of both the emmetropic and myopic datasets (184 eyes)

Method	Symbol	Eye model	*c* constants	Average	Percentage within ±1D from $P_{L,Bennett}$	Pearson correlation coefficient with phakometry
Bennett	$P_{L,Bennett}$	Customized*	$c_1 = 0.571 \pm 0.028$ $c_2 = -0.378 \pm 0.029$	*22.31 ± 1.72 D*		
Modified-Stenström	$P_{L,Sten}$	Gullstrand-Emsley	$c_{Sten} = 2.145$ mm	*21.30 ± 1.61 D*	*61.4%*	*0.942* (*P <0.001*)
		Bennett-Rabbetts	$c_{Sten} = 2.221$ mm	*21.62 ± 1.63 D*	*71.7%*	*0.943* (*P <0.001*)
		Customized*	$c_{Sten} = 2.875 \pm 0.763$ mm	*23.01 ± 1.76 D*	*64.7%*	*0.947*(*P <0.001*)
		Customized 2	$c_{Sten} = 2.550$ mm	*22.30 ± 1.69 D*	*95.1%*	*0.945* (*P <0.001*)
Bennett-Rabbetts	$P_{L,BR}$	Gullstrand-Emsley	$c_{BR} = 2.230$ mm	*21.45 ± 1.62 D*	*67.9%*	*0.946* (*P <0.001*)
		Bennett-Rabbetts	$c_{BR} = 2.306$ mm	*21.77 ± 1.64 D*	*78.8%*	*0.947* (*P <0.001*)
		Customized*	$c_{BR} = 2.891 \pm 0.778$ mm	*23.02 ± 1.76 D*	*66.8%*	*0.950*(*P <0.001*)
		Customized 2	$c_{BR} = 2.564$ mm	*22.31 ± 1.69 D*	*95.1%*	*0.948* (*P <0.001*)

* Customized *c* constants of Table 2

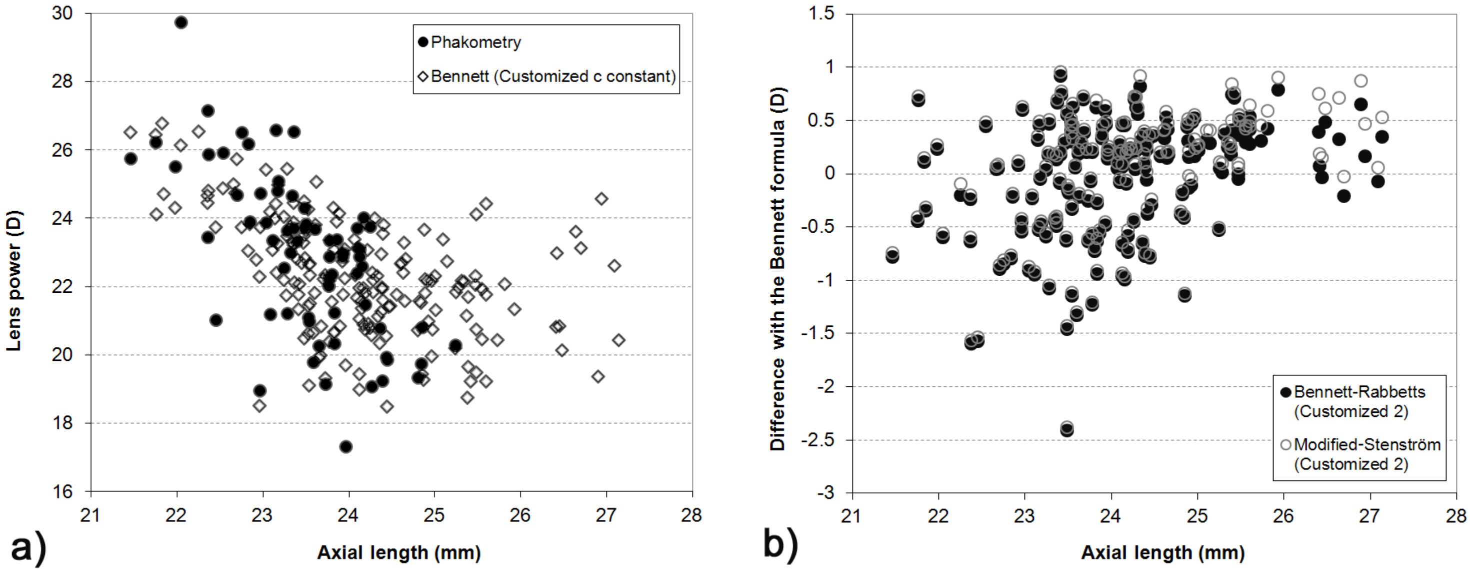

Figure 2: (a) Phakometry lens power and powers calculated using the Bennett method with customized c constants, plotted as a function of axial length L. (b) Difference between the lens power values calculated using the modified-Stenström or Bennett-Rabbetts methods with the "Customized 2" constants and the Bennett method with customized c constants, plotted as a function of axial length L. The calculated powers use data from both datasets (184 eyes), while the phakometry powers contain data only from the first dataset (66 eyes).

Discussion

Using the customized *c* constants all three lens power calculation methods are in reasonable agreement with the phakometry lens power for emmetropic eyes. This answers the first purpose of this paper, which was to confirm the agreement that Dunne et al.[8] found between the Bennett method and phakometry. However for individual eyes differences between calculated and phakometric power of up to *3.5D* occurred (Figure 1, Table 2), which is considerably larger than the differences of up to *0.77D* Dunne reported for the Bennett method. These differences could result from biometric errors and Bennett's assumption that the lens shapes of the eye models are representative for all eyes (the ratio P_{Lp}/P_{La} of posterior to anterior lens powers was *1.52 ± 0.19* for phakometry, but *1.67* and *1.70* for the Gullstrand-Emsley and Bennett-Rabbetts eye models, respectively). Using the argument of Bennett[6] and Dunne[8] that lens power provided by the Bennett method is likely to be more accurate than phakometry due to the inherent difficulties in performing the latter accurately, we considered the Bennett method derived power as a reasonable approximation of the real equivalent lens power and used it as a reference to compare the modified-Stenström and Bennett-Rabbetts methods.

For the Bennett method, the choice of eye model did not influence the calculated lens power significantly, which may be a consequence of the fact that the method is based on ray tracing of a thick lens model rather than a thin lens approximation. It can be used accurately for emmetropic eyes using either the c_1 and c_2 constants of the two eye models or the customized constants derived in this work.

The second purpose of the paper was to compare lens powers obtained with the Bennett method, the modified-Stenström method, and the Bennett-Rabbetts method for emmetropic and myopic eyes. The modified-Stenström and Bennett-Rabbetts methods gave lens powers that were significantly lower than those given by phakometry (mean *1.6D*) and the Bennett method (mean *1.3D*) for emmetropic eyes and for the Bennett method in combined emmetropic and myopic eyes (mean *0.8D*).

The third purpose of the paper was to provide customized constants to optimize the performances of the Bennett, modified-Stenström and Bennett-Rabbetts methods. For the Bennett method using customized *c* constants made little difference to the results, but in emmetropic eyes the customized $c = 2.875$ *mm* and *2.891 mm* for modified-Stenström and Bennett Rabbetts methods, respectively, gave non-significant lens power differences with phakometry and produced more accurate results than the constants of the eye models. When comparing lens powers for combined emmetropic and myopic eyes, the customized *c* constants for emmetropic eyes produced systematic lens power differences between the Bennett method and the modified-Stenström and Bennett-Rabbetts methods. This was improved by new "customized 2" *c* constants for the latter two methods ($c = 2.550$ *mm* and *2.564 mm* for modified-Stenström and Bennett Rabbetts methods, respectively), which brought the lens power differences to within *±1D* for about *95%* of the eyes. If lens thickness is not available, both methods with the "customized 2" constants may be considered as good approximations of the Bennett method.

Although the three calculation methods now match well with each other for a wide range of refractions, there are still theoretical issues to consider. The first issue is that the modified-Stenström and Bennett methods produce the same results when both lenticular principal planes coincide (i.e. $c_1 \cdot T = c_{\mathrm{Sten}}$ and $c_2 \cdot T = T - c_{\mathrm{Sten}}$). This can be confirmed mathematically by comparing equations (1) and (2 + 3) for the special case when $S_{\mathrm{pp}} = S_{\mathrm{CV}} = 0$. The more general case, when S_{pp} and S_{CV} are different from 0, could only be confirmed numerically due to the mathematically complicated equation (3). Although this seems to point at some common origin of both formulas, the meaning of this observation remains unclear.

A second relationship was found between the modified-Stenström and Bennett-Rabbetts methods, which, despite being mathematically very different, produced very similar lens powers. Again a possible relationship between both methods could not be investigated further due to the complexity of equation (3).

As lens power depends on lens refractive index, one could expect a correlation between the c constants and lens refractive index values n_{L} determined from phakometry. For this reason, the results of the lens power calculations were given for each eye model separately. However a significant correlation with n_{L} was seen only for c_1 of the Bennett method; the other c constants were either constant or randomly distributed.

Finally we would like to point out that one could also use IOL calculation formulas, such as the Hoffer Q[18] or the SRK/T formula[19, 20] to calculate the lens power, provided appropriate values for the IOL constants are used. Here one has to deal with the added difficulty of estimating the final postoperative position of the lens,[21, 22] which may explain the large variety in IOL calculation formulas in the literature.

In conclusion, if lens thickness is known the equivalent lens power is best calculated using the Bennett method with either the published or the customized c constants. The modified-Stenström and Bennett-Rabbetts methods, with appropriate c constants, provide reasonable approximations of equivalent lens power when lens thickness is not known. These methods allow applying the concept of our statistical eye model[12] to datasets without lens thickness or can be included into the software of a biometry device alongside IOL calculation formulas, thus providing physicians with access to the important parameter of lens power.

Acknowledgements

The authors thank Kristien Wouters for statistical advice and Rafael Irribaren and Wolfgang Haigis for discussions on the topic of this work.

References

[1] Dunne MCM. Scheme for the calculation of ocular components in a 4-surfaced eye without the need for measurement of the anterior crystalline lens surface Purkinje images. Ophthal. Physiol. Opt. 1992; 12: 370-375.

[2] Garner LF. Calculation of the radii of curvature of the crystalline lens surfaces. Ophthal. Physiol. Opt. 1997;17: 75-80.

[3] Rosales P, Wendt M, Marcos S, Glasser A. Changes in crystalline lens radii of curvature and lens tilt and decentration during dynamic accommodation in rhesus monkeys. J. Vis. 2008; 8: 18, 1–12.

[4] Dubbelman M, Van der Heijde GL. The shape of the aging human lens: curvature, equivalent refractive index and the lens paradox. Vis. Research 2001; 41:1867-1877.

[5] Rosales P, Dubbelman M, Marcos S, van der Heijde R. Crystalline lens radii of curvature from Purkinje and Scheimpflug imaging. J. Vis. 2006; 6:1057–1067.

[6] Bennett AG. A method for determining the equivalent lens powers of the eye and its crystalline lens without resorting to phakometry. Ophthal. Physiol. Opt. 1988;8:53-59.

[7] Emsley HH. Visual Optics (5th edition, Butterworth, London, 1952), Vol. 1: 40-42, 344, 360-361.

[8] Dunne MCM, Barnes DA, Royston JM. An evaluation of Bennett's method for the determining the equivalent lens powers of the eye and its crystalline lens without resorting to phakometry. Ophthal. Physiol. Opt. 1989;9:69-71.

[9] Stenström S. Untersuchungen über die Variation und Kovariation der optischen Elemente des menschlichen Auges. PhD thesis, University of Uppsala 1946.

[10] Stenstrom S. Investigation of the variation and the correlation of the optical elements of human eyes. Part II - Chapter II. Translated by D. Woolf, Am. J. Optom. Arch. Am. Acad. Optom. 1948; **25**: 286-299.

[11] Rabbetts RB. Bennett & Rabbetts' Clinical Visual Optics. 4th ed, 2007. Butterworth-Heinemann, London, pp. 223-227, 412-413, 425-426.

[12] Rozema JJ, Atchison DA, Tassignon MJ. Statistical eye model for normal eyes. Invest. Ophthalmol. Vis. Sci. 2011;52:4525-4533.

[13] Atchison DA, Markwell EL, Kasthurirangan S, Pope JM, Smith G, Swann PG. Age-related changes in optical and biometric characteristics of emmetropic eyes. J. Vis. 2008;8:29.

[14] Atchison DA. Optical models for human myopic eyes. Vis. Research 2006;46:2236–2250.

[15] Van Alphen, GWHM. On emmetropia and ametropia. Ophthalmologica 1961; Suppl: 1-92.

[16] Pedrotti LS, Pedrotti FL. Optics and Vision. 1st ed. Upper Saddle River, NJ: Prentice Hall; 1998:77.

[17] Sorsby A, Benjamin B, Davey JB, Sheridan M, Tanner JM. Emmetropia and its aberrations; a study in the correlation of the optical components of the eye. Spec Rep Ser Med Res Counc (G B). 1957;11(293):1-69.

[18] Hoffer KJ. The Hoffer Q formula: a comparison of theoretic and regression formulas. J. Cataract Refract. Surg. 1993; 19:700-712. Errata: Zuberbuhler B, Morrell AJ. Errata in printed Hoffer Q formula. J. Cataract Refract. Surg. 2007; 33: 2; author reply: 2-3.

[19] Retzlaff JA, Sanders DR, Kraff MC. Development of the SRK/T intraocular lens implant power calculation formula. J. Cataract Refract. Surg. 1990 May;16:333-340.

[20] Sheard RM, Smith GT, Cooke DL. Improving the prediction accuracy of the SRK/T formula: The T2 formula. J. Cataract Refract. Surg. 2010; 36:1829-1834.

[21] Gobin L, Rozema JJ, Tassignon M-J. Review of IOL power calculation: A theoretical analysis of proposed formulas. Chapter 54 in Ashok Garg et al. (Eds.) Mastering the Techniques of IOL Power Calculations. 2nd ed. New Delhi, India Jaypee 2009.

[22] Olsen T. Calculation of intraocular lens power: a review. Acta Ophthalmol. Scand. 2007; 85: 472-485.