Original Article

Preliminary validation of an optimized algorithm for intraocular lens power calculation in keratoconus

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Purpose: This study aimed to evaluate the theoretical influence on intraocular lens power (P_{IOL}) calculation of the use of keratometric approach for corneal power (P_c) calculation in keratoconus and to develop and validate an algorithm preliminarily to minimize this influence. **Methods:** P_c was calculated theoretically with the classical keratometric approach, the Gaussian equation, and the keratometric approach using a variable keratometric index (n_{kadj}) dependent on r_{1c} (P_{kadj}). Differences in P_{IOL} calculations (ΔP_{IOL}) using keratometric and Gaussian P_c values were evaluated. Preliminary clinical validation of a P_{IOL} algorithm using P_{kadj} was performed in 13 keratoconus eyes. **Results:** P_{IOL} underestimation was present if P_c was overestimated, and vice versa. Theoretical P_{IOL} overestimation up to −5.6 D and −6.2 D using Le Grand and Gullstrand eye models was found for a keratometric index of 1.3375. If n_{kadj} was used, maximal ΔP_{IOL} was ±1.1 D, with most of the values ≤±0.6 D. Clinically, P_{IOL} under- and over-estimations ranged from −1.1 to − 0.4 D. No statistically significant differences were found between P_{IOL} obtained with P_{kadj} and Gaussian equation ($P > 0.05$). **Conclusion:** The use of the keratometric P_c for P_{IOL} calculations in keratoconus can lead to significant errors that may be minimized using a P_{kadj} approach.

Key words: Cataract surgery, intraocular lens power, keratoconus, keratometric index, keratometry

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It has been demonstrated theoretically and clinically that differences (ΔP_c) between the central corneal power (P_c) calculated with the classical keratometric approach (assumption of only one corneal surface and a fictitious index of refraction, keratometric index, (n_k) (P_k) and that considering the curvature of both corneal surfaces and the Gaussian equation (P_c^{Gauss}) can be significant and lead to errors in clinical practice.[1-5] Specifically, the keratometric approach for estimating the P_c has been shown to be able to induce over- and under-estimations of intraocular lens power (P_{IOL}) in a range between +0.14 D and −3.01 D.[6]

In simulations in normal and nonpathological corneas, P_k (n_k = 1.3375) has been found to be able to overestimate P_c^{Gauss} up to 2.50 D. Similarly, in eyes with previous myopic laser refractive surgery, P_k can theoretically overestimate P_c^{Gauss} up to 3.50 D if n_k = 1.3375 is used.[4] These theoretical outcomes were confirmed clinically using a commercially available Scheimpflug imaging-based topography system.[5] According to this, our research group proposed a variable termed keratometric index (adjusted keratometric index, n_{kadj}) dependent on r_{1c} as a simple option to calculate the P_c and to minimize the significant errors associated with the keratometric approach (named P_{kadj}).

In keratoconus, the use of the classical keratometric index of 1.3375 has shown to produce an overestimation of P_c in theoretical simulations and clinical measurements, with a range of overestimation among 0.5 and 2.5 D found in a sample of 44 keratoconic corneas evaluated with a Scheimpflug imaging-based system.[1] As the use of a single value of n_k for the calculation of P_c has been demonstrated to be also imprecise in keratoconus, our research group developed eight different algorithms according to the severity of keratoconus to also obtain a variable called keratometric index (n_{kadj}) and a calculation of P_{kadj}. This adjusted P_c minimized the error associated to the use of the keratometric approach for P_c calculation to a range of ±0.7 D.[1] However, the impact of the use of the classical and adjusted keratometric approach for P_c estimation has not been evaluated in keratoconus. The aim of the current study was to evaluate the theoretical influence on P_{IOL} calculation of the error in the calculation of P_c (ΔP_c) due to the use of the keratometric index (n_k) in a preliminary sample of keratoconus eyes (no previous ocular surgeries) as well as the potential benefit of using our adjusted keratometric algorithms.

Methods

P_c was calculated for a range of anterior and posterior curvatures that can be found in keratoconus according to the peer-reviewed literature using n_k and also using the Gaussian equation that considers the contribution of two corneal surfaces.[7,8] The n_k values corresponding to the Gullstrand and Le Grand eye models (1.3315 and

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1.3304, respectively) as well as the classical value of 1.3375 were used. Differences in P_{IOL} calculation obtained with a simplified formula using the keratometric and Gaussian approaches to determine P_c were determined and modeled by regression analysis. All calculations and simulations were performed by means of Matlab software (MathWorks Inc., Natick, MA, USA).

Calculation of the Gaussian and keratometric intraocular lens power

The starting point of almost all theoretical formulas for P_{IOL} calculation is the use of a simplified eye model, with thin cornea and lens models.[9] According to such scheme, the power of the IOL (P_{IOL}) that replaces the lens can be easily calculated using the Gauss equations in paraxial optics:

$$P_{IOL} = \frac{n_{hv}}{AL - ELP} - \frac{n_{ha}}{\left(\dfrac{n_{ha}}{R_{des} + P_c} - ELP\right)} \tag{1}$$

In this equation, P_c represents the total P_c, effective lens position (ELP), the effective lens plane, axial length (AL), the AL, n_{ha}, the aqueous humor refractive index, n_{hv}, the vitreous humor refractive index, and R_{des} represents the postoperative desired refraction calculated at corneal vertex.

When a keratometric P_c (P_k) was used, the P_{IOL} was defined as $P_{IOL}{}^{K}$, and when Gaussian P_c ($P_c{}^{Gauss}$) was used, it was defined as $P_{IOL}{}^{Gauss}$. The calculation of P_k and $P_c{}^{Gauss}$ has been described in detail in a previous article.[6] The corresponding equations were performed as follows:

$$P_{IOL}^{k} = \frac{n_{hv}}{AL - ELP} - \frac{n_{ha}}{\left(\dfrac{n_{ha}}{R_{des} + \dfrac{n_k - 1}{r_{1c}}} - ELP\right)} \tag{2}$$

$$P_{IOL}^{Gauss} = \frac{n_{hv}}{AL - ELP} - \frac{n_{ha}}{\left(\dfrac{n_{ha}}{R_{des} + \left(\dfrac{n_c - n_a}{r_{1c}} + \dfrac{n_{ha} - n_c}{r_{2c}} - \dfrac{e_c}{n_c} \times \dfrac{n_c - n_a}{r_{1c}} \times \dfrac{n_{ha} - n_c}{r_{2c}}\right)} - ELP\right)} \tag{3}$$

It is important to note that, in equations 2 and 3, the P_c is referenced from different planes due to the one-surface and two-surface corneal models that were considered. However, the secondary principle plane for corneas in the normal range is only around a fraction of millimeter from the corneal vertex. Therefore, it is unable to introduce any significant bias in the calculations proposed.

We defined the *k* ratio as the relation between the anterior corneal radius and the posterior corneal radius ($k = r_{1c}/r_{2c}$). When this parameter was used in equation 3, we obtained the following expression:

$$P_{IOL}^{Gauss} = \frac{n_{hv}}{AL - ELP} - \frac{n_{ha}}{\left(\dfrac{n_{ha}}{R_{des} + \left(\dfrac{n_c - n_a}{r_{1c}} + \dfrac{n_{ha} - n_c}{\frac{r_{1c}}{k}} - \dfrac{e_c}{n_c} \times \dfrac{n_c - n_a}{r_{1c}} \times \dfrac{n_{ha} - n_c}{\frac{r_{1c}}{k}}\right)} - ELP\right)} \tag{4}$$

In all these expressions, n_k is the keratometric index, r_{1c} is the anterior corneal surface radius, r_{2c} is the posterior corneal radius, n_a is the refractive index of air, n_c is the refractive index of the cornea, n_{ha} is the refractive index of the aqueous humor, and e_c is the central corneal thickness.

Difference between the Gaussian and keratometric intraocular lens power

The difference between the keratometric and Gaussian P_{IOL} calculation (ΔP_{IOL}) was calculated using equations 2 and 4 as follows:

$$\Delta P_{IOL} = P_{IOL}^{k} - P_{IOL}^{Gauss} = \frac{n_{ha}}{\left(\dfrac{n_{ha}}{R_{des} + \dfrac{n_k - 1}{r_{1c}}} - ELP\right)} - \frac{n_{ha}}{\left(\dfrac{n_{ha}}{R_{des} + \left(\dfrac{n_c - n_a}{r_{1c}} + \dfrac{n_{ha} - n_c}{r_{2c}} - \dfrac{e_c}{n_c} \times \dfrac{n_c - n_a}{r_{1c}} \times \dfrac{n_{ha} - n_c}{r_{2c}}\right)} - ELP\right)} \tag{5}$$

If the k ratio was used in equation 5, we obtained the following expression:

$$\Delta P_{IOL} = \frac{n_{ha}}{\left(\dfrac{n_{ha}}{R_{des} + \dfrac{n_k - 1}{r_{1c}}} - ELP\right)} - \frac{n_{ha}}{\left(\dfrac{n_{ha}}{R_{des} + \left(\dfrac{n_c - n_a}{r_{1c}} + \dfrac{n_{ha} - n_c}{\frac{r_{1c}}{k}} - \dfrac{e_c}{n_c} \times \dfrac{n_c - n_a}{r_{1c}} \times \dfrac{n_{ha} - n_c}{\frac{r_{1c}}{k}}\right)} - ELP\right)} \tag{6}$$

As can be seen in equations 5 and 6, ΔP_{IOL} was not dependent on AL.

ΔP_{IOL} was calculated for the range of corneal curvature defined for the keratoconus population. According to the peer-reviewed literature, we considered that the anterior corneal radius in the keratoconus population ranged between 4.2 and 8.5 mm, whereas the posterior corneal radius ranged between 3.1 and 8.2 mm.[1,2] Therefore, we assumed *k* ratio values ranging from 0.96 to 1.56 in our theoretical calculations.[2] It should be considered that differences among keratometric and Gaussian P_c are commonly zeroed by constant optimization in the range of corneal curvature of the normal healthy eyes, but not for eyes with significantly higher corneal curvature, as in keratoconus. In addition, we considered that ELP could vary between 2 and 6 mm in the calculations performed in the current study according to previous authors dealing with this issue.[6,10] The desired postoperative refraction was also modified in the calculations, performing an analysis of ΔP_{IOL} for values of R_{des} of 0, +1, and −1 D.

Difference between Gaussian and keratometric intraocular lens power calculation using the adjusted keratometric index

Using our eight algorithms[1] [Table 1] for adjusting the keratometric estimation of P_c, a new value named adjusted keratometric P_c (P_{kadj}) can be calculated using the classical keratometric P_c formula. Therefore, P_{IOL}^{ADJ} was defined as the P_{IOL} calculated from equation 2 using the n_{kadj} value for the estimation of P_c (P_{kadj}). After that, ΔP_{IOL} was also calculated considering the adjusted P_{IOL} (P_{IOL}^{ADJ}) and the Gaussian P_{IOL} (P_c^{Gauss}).

Preliminary clinical validation

A preliminary validation of the P_{IOL} calculation with the algorithm proposed in this study was performed in a sample of keratoconus eyes with AL between 21 and 27 mm. Specifically, 13 eyes of eight candidates for cataract surgery who were screened at the Department of Ophthalmology (Oftalmar) of the Vithas Medimar International Hospital (Alicante, Spain) were included. Eyes with other active ocular pathologies or previous ocular surgeries were excluded from the study. All patients were informed about the study and signed an informed consent document in accordance with the Declaration of Helsinki.

A comprehensive ophthalmologic examination was performed in all cases, which included optical biometry (IOLMaster, Carl Zeiss Meditec) and analysis of the corneal structure by means of a Scheimpflug photography-based tomographer, the Pentacam system (software version 1.14r01, Oculus Optikgeräte GmbH, Germany). P_{IOL} calculation was performed with the IOL-Master software and also with our paraxial approximation using the n_{kadj} (P_{IOL}^{ADJ}) and the True Net Power ($P_{IOL}^{True\ Net}$). The True Net Power is the Pentacam system P_c calculated using the Gaussian equation P_c^{Gauss} with the Gullstrand eye model neglecting the corneal thickness (e_c).

$$\text{True net power} = \frac{1.376-1}{r_{1c}} \times 1000 + \frac{1.336-1.376}{r_{2c}} \times 1000 \qquad (7)$$

A comparative analysis of our estimations with those obtained with the other established formulas was performed using the statistical software SPSS version 19.0 for Windows (IBM, Armonk, NY, USA). Normality of data distributions was first evaluated by means of the Shapiro–Wilk test. The Mann–Whitney U-test was used for analyzing the statistical significance of differences between P_{IOL} calculations, whereas the Bland–Altman method was used for evaluating the interchangeability of such calculations. In addition, Pearson's correlation coefficients were used to assess the correlation between differences among calculations and different clinical parameters.

Table 1: Algorithms for n_{kadj} to obtain the adjusted keratometric power (P_{kadj}) using the Le Grand and Gullstrand eye models

r_{1c} (mm)	k	Le Grand (n_{kadj})	Gullstrand (n_{kadj})
4.2, 4.7	1.20, 1.52	$-0.01207r_{1c} + 1.3789$	$-0.01217r_{1c} + 1.3777$
4.8, 5.6	1.17, 1.56	$-0.01036r_{1c} + 1.3787$	$-0.01043r_{1c} + 1.3774$
5.7, 6.2	1.21, 1.55	$-0.00919r_{1c} + 1.3785$	$-0.00926r_{1c} + 1.3773$
6.3, 6.4	1.05, 1.31	$-0.00736r_{1c} + 1.3782$	$-0.00741r_{1c} + 1.3770$
6.5, 6.8	1.14, 1.45	$-0.00771r_{1c} + 1.3783$	$-0.00776r_{1c} + 1.3771$
6.9, 7.5	1.03, 1.39	$-0.00664r_{1c} + 1.3780$	$-0.00669r_{1c} + 1.3768$
7.6, 7.8	1.09, 1.39	$-0.00638r_{1c} + 1.3781$	$-0.00643r_{1c} + 1.3767$
7.9, 8.5	0.96, 1.35	$-0.00557r_{1c} + 1.3779$	$-0.00561r_{1c} + 1.3768$

Additionally, r_{1c} and k ratio ranges corresponding to the anterior and posterior corneal surfaces of the keratoconus population simulated are shown

Results

Relationship between ΔP_{IOL} and ΔP_c

For all possible combinations of r_{1c} and r_{2c}, $P_{k\,(1.3375)}$ ranged from 80.4 D to 39.7 D. If Le Grand or Gullstrand eye models were used, $P_{k\,(1.3304)}$ ranged from 78.7 D to 38.9 D and $P_{k\,(1.3315)}$ from 78.9 D to 39 D, respectively. P_c^{Gauss} ranged from 78.9 D to 38.2 D and from 78.5 D to 37.9 D for Le Grand and Gullstrand eye models, respectively. If n_{kadj} was used, P_{kadj} ranged from 38.9 D to 78.1 D for the Le Grand eye model and between 38.7 D and 77.8 D if the Gullstrand eye model was used. Considering the keratometric P_c, the P_{IOL} (P_{IOL}^{k}) was calculated (equation 2) for each r_{1c}/r_{2c} potential combination in keratoconus. If the Le Grand eye model was used (n_k = 1.3304), P_{IOL}^{k} ranged between − 32.7 D and 20.5 D and between −35.2 D and 19.5 D if n_k = 1.3375 was used. For the Gullstrand eye model (n_k = 1.3315), P_{IOL}^{k} ranged between −33.86 D and 19.9 D, and if n_k = 1.3375 was used, P_{IOL}^{k} ranged between −36 D and 19 D. When the Gaussian P_c was used, we obtained P_{IOL}^{Gauss} values ranging from −32.96 D to 21.36 D and from −33.17 D to 21.1 D for Le Grand and Gullstrand eye models, respectively [Table 2]. When P_{kadj} was used, P_{IOL}^{ADJ} ranged between −31.9 D and 20.5 D and between −32.1 D and 20.2 D for the Le Grand and Gullstrand eye models, respectively. Differences between P_{IOL}^{ADJ} and P_{IOL}^{Gauss} were calculated and are summarized in Table 3.

Table 4 summarizes the ΔP_{IOL} data obtained for the range of anterior corneal curvature in keratoconus (r_{1c}, from 4.2 to 8.5 mm) using the Le Grand and Gullstrand eye models and different values of n_k. The edges of the interval shown for each value of ΔP_{IOL} and ΔP_c corresponded to the values associated to the extreme values of the keratoconus range defined for r_{2c}, from 3.1 mm to 8.2 mm. As shown in Table 4, there were many over- and under-estimations of P_c when P_{IOL}^{k} was compared to P_{IOL}^{Gauss}, although more underestimations were present with the Gullstrand eye model. The largest overestimation was found for the combination of r_{1c} = 7.9 mm with r_{2c} = 8.2 mm (unlikely corneal curvature combination), with values of + 1.0 D and + 1.4 D for the Le Grand and Gullstrand eye models (n_k = 1.3304 and n_k = 1.3315), respectively. The lowest underestimation was found for r_{1c} = 4.7 mm combined with r_{2c} = 3.1 mm, with values of − 3.5 D and − 4.3 D for the Le Grand and Gullstrand eye models, respectively.

When n_k = 1.3375 was used in both eye models, an underestimation of P_{IOL}^{k} over P_{IOL}^{Gauss} was observed in almost

Table 2: Maximum and minimum ranges of keratometric corneal power and keratometric intraocular lens power when Le Grand and Gullstrand eye models were used, considering the range of anterior and posterior corneal curvatures reported in the peer-reviewed literature for keratoconus

Parameter	Range
r_{1c} (mm)	4.2-8.5
r_{2c} (mm)	3.1-8.2
$P_{k(1.3375)}$ (D)	39.7-80.4
LeGrand	
P_c^{Gauss} (D)	38.2-78.9
$P_{k(1.3304)}$ (D)	38.9-78.7
P_{kadj} (D)	38.9-78.1
$P_{IOL\ 1.3304}{}^{k}$ (D)	−32.7-20.5
$P_{IOL\ 1.3375}{}^{k}$	−35.2-19.5
P_{IOL}^{Gauss} (D)	−32.96-21.36
Gullstrand	
P_c^{Gauss} (D)	37.9-78.5
$P_{k(1.3315)}$ (D)	39.0-78.9
P_{kadj} (D)	38.7-77.8
$P_{IOL\ 1.3315}{}^{k}$ (D)	−33.86-19.9
$P_{IOL\ 1.3375}{}^{k}$ (D)	−36.0-19.0
P_{IOL}^{Gauss} (D)	−33.17-21.1

P_{IOL}: Intraocular lens power

all cases. The magnitude of this underestimation was higher than 0.5 D in almost all possible combinations of r_{1c} and r_{2c}. The maximum underestimation was found again for the combination of r_{1c} = 4.7 mm with r_{2c} = 3.1 mm, with values of −5.6 D and −6.2 D for the Le Grand and Gullstrand eye models, respectively.

All these trends for ΔP_{IOL} were modeled by means of linear regression analysis. Specifically, a predictive linear equation (R^2: 0.99) relating ΔP_{IOL} and k ratio as a function of r_{1c} in 0.1-mm steps was found for the two eye models used in this study [Tables 4 and 5]. Likewise, ΔP_{IOL} data could also be adjusted by a quadratic expression (R^2: 0.99) dependent on r_{2c} [Fig. 1]. As an example, ΔP_{IOL} data corresponding to r_{1c} = 4.2 mm using the Gullstrand eye model and n_k = 1.3375 could be adjusted to the quadratic expression $\Delta P_{IOL} = -1.5562\, r^2_{2c} + 15.578\, r_{2c} - 38.3007$, where r_{2c} is expressed in millimeters [Fig. 1]. The equivalent equation depending on k was $\Delta P_{IOL} = -13.7170\, k + 13.6189$ [Table 5].

Relationship between ΔP_{IOL} and effective lens position

The dependency of ΔP_{IOL} variation with ELP was analyzed. In our calculations, the value of ELP was considered to be equal to the anatomical anterior chamber depth$_a$ of the two eye models used (3.05 and 3.10 mm for Le Grand and Gullstrand eye models, respectively). Additional calculations were performed considering a range of variation of ELP between 2 and 6 mm, with no variation in the rest of parameters. When ELP = 2 mm was used in our model instead of the anatomical value, differences in ΔP_{IOL} calculation did not become clinically significant in both Le Grand and Gullstrand eye models, with the largest variation of ΔP_{IOL} reaching 0.15 D. When ELP = 6 mm was used, a maximum variation of ΔP_{IOL} of 0.6 D

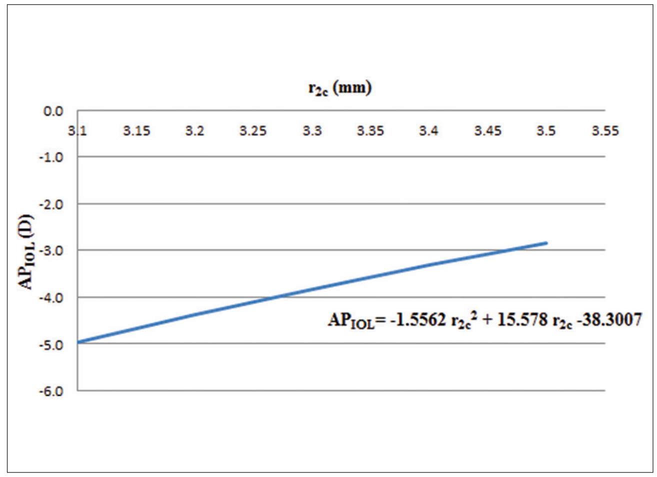

Figure 1: Relationship between ΔP_{IOL} using the Gullstrand eye model and n_k = 1.3375 and the curvature of the posterior corneal surface (r_{2c}). This relation could be adjusted to a quadratic expression dependent on r_{2c} (R^2: 0.99)

was found in both Le Grand and Gullstrand eye models when r_{1c} = 4.7 mm and r_{2c} = 3.1 mm or 3.5 mm, with most of the rest of combinations providing variations of <0.5 D.

Relationship between ΔP_{IOL} and R_{des}

For a range of R_{des} between − 1 D and +1 D and keeping constant the other parameters, the variation of ΔP_{IOL} was of 0.02 D or less in comparison with the values obtained for R_{des} = 0 D.

ΔP_{IOL} using n_{kadj} for minimizing ΔP_c

If n_{kadj} derived from our eight algorithms [Table 1] was used for the calculation of keratometric P_c and then for the calculation of $P_{IOL}{}^{k}$, a maximal error of ± 1.1 D in ΔP_{IOL} was observed independently from the eye model used, r_{1c} and R_{des}. Considering that 1 D of variation of P_{IOL} induces approximately 0.9 D of change in patients' refraction at the corneal vertex, ΔP_{IOL} obtained was clinically acceptable, with most of the simulations not exceeding ± 0.60 D for most r_{1c}-r_{2c} combinations. Only ΔP_{IOL} was maximal for the extreme values [Table 3].

Preliminary clinical validation

This study comprised 13 eyes of eight patients with keratoconus (four eyes of women [30.8%] and nine eyes of men [69.2%] with a mean age of 41.1 years ± 19.1, range from 20 to 69 years). The sample comprised seven left eyes (53.8%) and six right eyes (46.2%). Mean anterior and posterior corneal radius of curvature were 7.28 mm (standard deviation [SD]: 0.64; median: 7.27; range: 6.30–8.26 mm) and 6.67 mm (SD: 0.99; median: 6.37; range: 5.58–8.45 mm), respectively. Mean central and minimum corneal thicknesses were 497.5 µm (SD: 44.7; median: 510.0; range: 419.0–510.0 µm) and 476.0 µm (SD: 51.7; median: 480.0; range: 385.0–539.0 µm), respectively. The location of the cone was inferior in all cases. According to the Amsler-Krumeich classification system, a total of eight eyes (61.5%) had keratoconus Grade I, four eyes (30.8%) had Grade II, and one eye (7.7%) had keratoconus Grade III.

An underestimation was always present when $P_{IOL1.3375}{}^{k}$ was compared with P_{IOL}^{Gauss}, ranging from −0.9 D to −2.9 D. Differences between $P_{IOL1.3375}{}^{k}$ and P_{IOL}^{Gauss} were statistically significant (P < 0.05, unpaired Student's t-test). A very

Table 3: Comparative analysis of differences between the intraocular lens power estimated using the adjusted keratometric power (P_{IOL}^{Adj}) and that obtained using the Gaussian corneal power (P_{IOL}^{Gauss}) with the Gullstrand and Le Grand eye models

r_{1c} (mm)	k	Comparative P_{LIO}^{Adj} (D) and P_{LIO}^{Gauss} (D)					
		Le Grand			Gullstrand		
		P_{LIO}^{Adj}	P_{LIO}^{Gauss}	$\Delta P_{LIO}^{Adj-Gauss}$	P_{LIO}^{Adj}	P_{LIO}^{Gauss}	$\Delta P_{LIO}^{Adj-Gauss}$
4.2	1.20, 1.35	−31.91	−32.96, −30.87	1.0, −1.0	−32.11	−33.17, −31.04	1.1, −1.1
4.3	1.23, 1.39	−28.83	−29.86, −27.79	1.0, −1.0	−29.01	−30.06, −27.96	−1.0, −1.1
4.4	1.26, 1.42	−25.91	−26.93, −24.89	1.0, −1.0	−26.09	−27.13, −25.05	1.0, −1.0
4.5	1.29, 1.45	−23.15	−24.17, −22.14	1.0, −1.0	−23.33	−24.36, −22.30	1.0, −1.0
4.6	1.31, 1.48	−20.55	−21.55, −19.54	1.0, −1.0	−20.72	−21.74, −19.70	1.0, −1.0
4.7	1.34, 1.52	−18.07	−19.07, −17.08	1.0, −1.0	−18.24	−19.25, −17.23	1.0, −1.0
4.8	1.17, 1.33	−18.06	−18.97, −17.14	0.9, −0.9	−18.25	−19.18, −17.32	0.9, −0.9
4.9	1.19, 1.36	−15.80	−16.71, −14.89	0.9, −0.9	−15.99	−16.92, −15.08	0.9, −0.9
5.0	1.22, 1.39	−13.66	−14.56, −12.76	0.9, −0.9	−13.85	−14.76, −12.94	0.9, −0.9
5.1	1.24, 1.42	−11.62	−12.51, −10.72	0.9, −0.9	−11.80	−12.71, −10.90	0.9, −0.9
5.2	1.27, 1.44	−9.67	−10.55, −8.78	0.9, −0.9	−9.85	−10.76, −8.95	0.9, −0.9
5.3	1.29, 1.47	−7.81	−8.69, −6.92	0.9, −0.9	−7.99	−8.89, −7.10	0.9, −0.9
5.4	1.32, 1.50	−6.03	−6.90, −5.15	0.9, −0.9	−6.21	−7.10, −5.32	0.9, −0.9
5.5	1.34, 1.52	−4.32	−5.19, −3.45	0.9, −0.9	−4.50	−5.39, −3.62	0.9, −0.9
5.6	1.37, 1.56	−2.69	−3.55, −1.82	0.9, −0.9	−2.87	−3.75, −2.00	0.9, −0.9
5.7	1.21, 1.43	−2.62	−3.58, −1.67	1.0, −0.9	−2.83	−3.80, −1.87	1.0, −1.0
5.8	1.23, 1.45	−1.11	−2.06, −0.17	0.9, −0.9	−1.32	−2.28, −0.36	1.0, −1.0
5.9	1.26, 1.48	0.34	−0.61, 1.28	0.9, −0.9	0.13	−0.82, 1.08	1.0, −1.0
6.0	1.28, 1.50	1.73	0.79, 2.66	0.9, −0.9	1.52	0.57, 2.47	1.0, −1.0
6.1	1.30, 1.53	3.07	2.14, 4.00	0.9, −0.9	2.86	1.92, 3.81	0.9, −0.9
6.2	1.32, 1.55	4.36	3.43, 5.29	0.9, −0.9	4.16	3.22, 5.09	0.9, −0.9
6.3	1.05, 1.29	3.31	2.37, 4.25	0.9, −0.9	3.07	2.13, 4.02	1.0, −1.0
6.4	1.07, 1.31	4.52	3.59, 5.45	0.9, −0.9	4.28	3.34, 5.23	1.0, −1.0
6.5	1.14, 1.38	6.12	5.19, 7.04	0.9, −0.9	5.88	4.95, 6.83	0.9, −1.0
6.6	1.16, 1.40	7.24	6.32, 8.16	0.9, −0.9	7.00	6.08, 7.95	0.9, −0.9
6.7	1.18, 1.43	8.33	7.41, 9.24	0.9, −0.9	8.09	7.17, 9.03	0.9, −0.9
6.8	1.19, 1.45	9.37	8.46, 10.29	0.9, −0.9	9.14	8.22, 10.07	0.9, −0.9
6.9	1.03, 1.28	9.10	8.19, 9.96	0.9, −0.9	8.85	7.94, 9.72	0.9, −0.9
7.0	1.04, 1.30	10.08	9.18, 10.94	0.9, −0.9	9.84	8.93, 10.70	0.9, −0.9
7.1	1.06, 1.31	11.04	10.14, 11.89	0.9, −0.8	10.79	9.88, 11.66	0.9, −0.9
7.2	1.07, 1.33	11.96	11.07, 12.81	0.9, −0.8	11.72	10.81, 12.58	0.9, −0.9
7.3	1.09, 1.35	12.86	11.97, 13.70	0.9, −0.8	12.61	11.71, 13.47	0.9, −0.9
7.4	1.10, 1.37	13.72	12.84, 14.57	0.9, −0.8	13.48	12.58, 14.33	0.9, −0.9
7.5	1.12, 1.39	14.57	13.68, 15.41	0.9, −0.8	14.32	13.43, 15.17	0.9, −0.9
7.6	1.09, 1.36	15.05	14.20, 15.91	0.8, −0.9	14.83	13.94, 15.67	0.8, −0.9
7.7	1.10, 1.38	15.84	14.99, 16.70	0.8, −0.9	15.63	14.73, 16.46	0.8, −0.9
7.8	1.11, 1.39	16.61	15.77, 17.47	0.8, −0.9	16.40	15.51, 17.23	0.8, −0.9
7.9	0.96, 1.25	16.40	15.52, 17.27	0.9, −0.9	16.13	15.25, 17.02	0.9, −0.9
8.0	0.98, 1.27	17.13	16.25, 18.00	0.9, −0.9	16.86	15.98, 17.75	0.9, −0.9
8.1	0.99, 1.29	17.85	16.97, 18.71	0.9, −0.9	17.57	16.69, 18.46	0.9, −0.9
8.2	1.00, 1.30	18.54	17.66, 19.40	0.9, −0.9	18.26	17.39, 19.15	0.9, −0.9
8.3	1.01, 1.32	19.21	18.34, 20.07	0.9, −0.9	18.93	18.06, 19.82	0.9, −0.9
8.4	1.02, 1.33	19.87	18.99, 20.73	0.9, −0.9	19.59	18.72, 20.47	0.9, −0.9
8.5	1.04, 1.35	20.50	19.63, 21.36	0.9, −0.9	20.23	19.36, 21.11	0.9, −0.9

Maximum and minimum values are remarked

strong and statistically significant correlation was found between $P_{IOL1.3375}^{k}$ and the P_{IOL}^{Gauss} ($r = 0.99$, $P < 0.01$). Likewise, strong and statistically significant correlations of ΔP_{IOL} with r_{2c} (r = 0.96, $P < 0.01$), r_{1c} ($r = 0.84$, $P < 0.01$), and central corneal

Table 4: Summary of the differences between the keratometric and Gaussian intraocular lens power (ΔP_{IOL}) obtained within the keratoconus range of anterior corneal curvature (r_{1c}: from 4.2 to 8.5 mm) for Le Grand and Gullstrand eye models as well as for the different keratometric index values used (n_k: 1.3304, 1.3315, and 1.3375)

r_{1c} (mm)	Comparative ΔP_{IOL} and ΔP_c							
	Le Grand				Gullstrand			
	n_k: 1.3304		n_k: 1.3375		n_k: 1.3315		n_k: 1.3375	
	ΔP_c (D)	ΔP_{IOL} (D)	ΔP_c (D)	ΔP_{IOL} (D)	ΔP_c (D)	ΔP_{IOL} (D)	ΔP_c (D)	ΔP_{IOL} (D)
4.2	−0.2, −1.2	0.3, −1.8	1.5, 2.9	−2.3, −4.3	0.5, 1.9	−0.7, −2.8	1.9, 3.3	−2.8, −5.0
4.3	0.1, 1.5	−0.1, −2.2	1.7, 3.1	−2.6, −4.6	0.7, 2.1	−1.1, −3.2	2.1, 3.5	−3.1, −5.2
4.4	0.3, 1.8	−0.5, −2.5	2.0, 3.4	−2.9, −4.9	1.0, 2.4	−1.4, −3.5	2.3, 3.8	−3.4, −5.5
4.5	0.6, 2.0	−0.8, −2.9	2.2, 3.6	−3.1, −5.2	1.2, 2.6	−1.7, −3.8	2.5, 4.0	−3.7, −5.7
4.6	0.8, 2.2	−1.2, −3.2	2.4, 3.8	−3.4, −5.4	1.4, 2.8	−2.0, −4.1	2.7, 4.2	−3.9, −6.0
4.7	1.0, 2.5	−1.5, −3.5	2.6, 4.0	−3.6, −5.6	1.6, 3.1	−2.3, −4.3	2.9, 4.3	−4.2, −6.2
4.8	−0.4, 1.0	0.5, −1.3	1.1, 2.4	−1.6, −3.4	0.2, 1.5	−0.3, −2.2	1.5, 2.8	−2.1, −3.9
4.9	1.2, −0.1	0.2, −1.6	1.3, 2.6	−1.8, −3.6	0.4, 1.7	−0.6, −2.4	1.6, 2.9	−2.3, −4.1
5.0	0.1, 1.4	−0.1, −1.9	1.5, 2.8	−2.0, −3.8	0.6, 1.9	−0.8, −2.7	1.8, 3.1	−2.5, −4.3
5.1	0.2, 1.5	−0.3, −2.1	1.6, 2.9	−2.3, −4.0	0.8, 2.1	−1.1, −2.9	1.9, 3.3	−2.7, −4.5
5.2	0.4, 1.7	−0.6, −2.4	1.8, 3.1	−2.5, −4.2	0.9, 2.3	−1.3, −3.1	2.1, 3.4	−2.9, −4.7
5.3	0.6, 1.9	−0.8, −2.6	1.9, 3.2	−2.6, −4.4	1.1, 2.4	−1.5, −3.3	2.2, 3.6	−3.1, −4.9
5.4	0.8, 2.1	−1.0, −2.8	2.1, 3.4	−2.8, −4.6	1.3, 2.6	−1.7, −3.5	2.4, 3.7	−3.2, −5.0
5.5	0.9, 2.2	−1.2, −2.9	2.2, 3.5	−3.0, −4.7	1.4, 2.7	−1.9, −3.7	2.5, 3.8	−3.4, −5.2
5.6	1.1, 2.4	−1.4, −3.2	2.4, 3.7	−3.1, −4.9	1.6, 2.9	−2.1, −3.9	2.6, 4.0	−3.6, −5.3
5.7	0.0, 1.5	−0.0, −1.9	1.3, 2.7	−1.7, −3.6	0.5, 2.0	−0.7, −2.6	1.6, 3.0	−2.1, −4.0
5.8	0.2, 1.6	−0.2, −2.1	1.4, 2.8	−1.9, −3.8	0.6, 2.1	−0.9, −2.8	1.7, 3.1	−2.2, −4.1
5.9	0.3, 1.8	−0.4, −2.3	1.5, 3.0	−2.0, −3.9	0.8, 2.2	−1.0, −2.9	1.8, 3.2	−2.4, −4.3
6.0	0.5, 1.9	−0.6, −2.5	1.6, 3.1	−2.1, −4.0	0.9, 2.4	−1.2, −3.1	1.9, 3.4	−2.5, −4.4
6.1	0.6, 2.0	−0.8, −2.6	1.7, 3.2	−2.3, −4.1	1.0, 2.5	−1.3, −3.2	2.0, 3.5	−2.6, −4.5
6.2	0.7, 2.2	−0.9, −2.8	1.9, 3.3	−2.4, −4.3	1.1, 2.6	−1.5, −3.4	2.1, 3.6	−2.8, −4.6
6.3	−1.0, 0.5	1.2, −0.6	0.2, 1.6	−0.2, −2.1	−0.5, 0.9	0.7, −1.2	0.4, 1.9	−0.5, −2.4
6.4	−0.8, 0.6	1.1, −0.8	0.3, 1.7	−0.4, −2.2	−0.4, 1.0	0.6, −1.3	0.5, 2.0	−0.7, −2.6
6.5	−0.4, 1.1	0.5, −1.4	0.7, 2.2	−0.9, −2.8	0.0, 1.5	−0.0, −1.9	0.9, 2.4	−1.2, −3.1
6.6	−0.3, 1.2	0.3, −1.5	0.8, 2.3	−1.0, −2.9	0.1, 1.6	−0.2, −2.0	1.0, 2.5	−1.3, −3.2
6.7	−0.2, 1.3	0.2, −1.6	0.9, 2.3	−1.1, −3.0	0.2, 1.7	−0.3, −2.2	1.1, 2.6	−1.4, −3.3
6.8	−0.1, 1.4	0.1, −1.8	1.0, 2.4	−1.3, −3.1	0.3, 1.8	−0.4, −2.3	1.2, 2.7	−1.6, −3.4
6.9	−1.0, 0.4	1.2, −0.5	0.1, 1.5	−0.1, −1.8	−0.6, 0.8	0.8, −1.0	0.3, 1.7	−0.4, −2.1
7.0	−0.9, 0.5	1.1, −0.7	0.1, 1.5	−0.2, −1.9	−0.5, 0.9	0.6, −1.1	0.4, 1.8	−0.5, −2.2
7.1	−0.8, 0.6	0.9, −0.8	0.2, 1.6	−0.3, −2.0	−0.4, 1.0	0.5, −1.3	0.4, 1.8	−0.6, −2.3
7.2	−0.7, 0.7	0.9, −0.9	0.3, 1.7	−0.4, −2.1	−0.3, 1.1	0.4, −1.4	0.5, 1.9	−0.6, −2.4
7.3	−0.6, 0.8	0.7, −1.0	0.4, 1.8	−0.5, −2.2	−0.2, 1.2	0.3, −1.5	0.6, 2.0	−0.7, −2.5
7.4	−0.5, 0.9	0.6, −1.1	0.5, 1.9	−0.6, −2.3	−0.2, 1.3	0.2, −1.6	0.7, 2.1	−0.8, −2.6
7.5	−0.4, 1.0	0.5, −1.2	0.5, 1.9	−0.7, −2.4	−0.1, 1.3	0.1, −1.7	0.7, 2.1	−0.9, −2.7
7.6	−0.6, 0.8	0.7, −1.0	0.3, 1.7	−0.4, −2.1	−0.2, 1.2	0.3, −1.4	0.5, 1.9	−0.7, −2.4
7.7	−0.5, 0.9	0.6, −1.1	0.4, 1.8	−0.5, −2.2	−0.2, 1.2	0.2, −1.5	0.6, 2.0	−0.8, −2.5
7.8	−0.4, 1.0	0.5, −1.2	0.5, 1.9	−0.6, −2.3	−0.1, 1.3	0.1, −1.6	0.7, 2.1	−0.8, −2.6
7.9	−1.2, 0.3	1.4, −0.3	−0.3, 1.2	0.3, −1.4	−0.8, 0.6	1.0, −0.7	−0.1, 1.4	0.1, −1.7
8.0	−1.1, 0.3	1.3, −0.4	−0.2, 1.2	0.2, −1.5	−0.8, 0.7	0.9, −0.8	0.0, 1.4	0.0, −1.8
8.1	−1.0, 0.4	1.2, −0.5	−0.1, 1.3	0.2, −1.6	−0.7, 0.7	0.9, −0.9	0.0, 1.5	−0.1, −1.8
8.2	−0.9, 0.5	1.2, −0.6	−0.1, 1.4	0.1, −1.6	−0.6, 0.8	0.8, −1.0	0.1, 1.5	−0.1, −1.9
8.3	−0.9, 0.6	1.1, −0.7	0.0, 1.4	0.0, −1.7	−0.6, 0.9	0.7, −1.1	0.2, 1.6	−0.2, −2.0
8.4	−0.8, 0.6	1.0, −0.8	0.0, 1.5	0.0, −1.8	−0.5, 0.9	0.6, −1.2	0.2, 1.7	−0.3, −2.0
8.5	−0.7, 0.7	0.9, −0.8	0.1, 1.5	−0.1, −1.8	−0.4, 1.0	0.5, −1.2	0.3, 1.7	−0.3, −2.1

The interval shown for each value of r_{1c} is the maximum and minimum values of ΔP_c (differences between the keratometric and Gaussian corneal power) and ΔP_{IOL} corresponding to the values associated to the extreme values of the keratoconus range defined for r_{2c} (from 3.1 mm to 8.2 mm). P_{IOL}: Intraocular lens power

Table 5: Linear equations (all R^2: 0.99) relating ΔP_{IOL} and *k* ratio as a function of r_{1c} in 0.1 mm steps using the Gullstrand and Le Grand eye models

r_{1c} (mm)	Gullstrand		Le Grand	
	n_k=1.3315	n_k=1.3375	n_k=1.3304	n_k=1.3375
	ΔP_{IOL} (D)=ak + b	ΔP_{IOL} (D)=ak + b	ΔP_{IOL} (D)=ak + b	ΔP_{IOL} (D)=ak + b
4.2	−13.7170k+15.7686	−13.7170k+13.6189	−13.4946k+16.4643	−13.4946k+13.9420
4.3	−13.2511k+15.2182	−13.2511k+13.1405	−13.0399k+15.8943	−13.0399k+13.4559
4.4	−12.8152k+14.7034	−12.8152k+12.6931	−12.6142k+15.3609	−12.6142k+13.0011
4.5	−12.4066k+14.2209	−12.4066k+12.2738	−12.2150k+14.8608	−12.2150k+12.5747
4.6	−12.0227k+13.7676	−12.0227k+11.8800	−11.8399k+14.3909	−11.8399k+12.1741
4.7	−11.6614k+13.3412	−11.6614k+11.5097	−11.4867k+13.9486	−11.4867k+11.7972
4.8	−11.4263k+13.0821	−11.4263k+11.3033	−11.2544k+13.6680	−11.2544k+11.5783
4.9	−11.1014k+12.7010	−11.1014k+10.9722	−11.9366k+13.2727	−10.9366k+11.2413
5.0	−10.7941k+12.3407	−10.7941k+10.6591	−10.6360k+12.8999	−10.6360k+10.9227
5.1	−10.5032k+11.9995	−10.5032k+10.3628	−10.3512k+12.5447	−10.3512k+10.6209
5.2	−10.2272k+11.6760	−10.2272k+10.0818	−10.0811k+12.2089	−10.0811k+10.3347
5.3	−9.9652k+11.3689	−9.9652k+9.8151	−9.8245k+11.8900	−9.8245k+10.0630
5.4	−9.7161k+11.0770	−9.7161k+9.5616	−9.5805k+11.5867	−9.5805k+9.8047
5.5	−9.4790k+10.7991	−9.4790k+9.3203	−9.3482k+11.2980	−9.3482k+9.5588
5.6	−9.2531k+10.5344	−9.2531k+9.0904	−9.1267k+11.0229	−9.1267k+9.3245
5.7	−9.0933k+10.3603	−9.0933k+8.9496	−8.9689k+10.8357	−8.9689k+9.1761
5.8	−8.8860k+10.1185	−8.8860k+8.7396	−8.7657k+10.5842	−8.7657k+8.9620
5.9	−8.6878k+9.8873	−8.6878k+8.5390	−8.5713k+10.3439	−8.5713k+8.7574
6.0	−8.4982k+9.6662	−8.4982k+8.3470	−8.3854k+10.1140	−8.3854k+8.5616
6.1	−8.3166k+9.4545	−8.3166k+8.1631	−8.2072k+9.8938	−8.2072k+8.3740
6.2	−8.1425k+9.2515	−8.1425k+7.9869	−8.0363k+9.6826	−8.0363k+8.1943
6.3	−8.0517k+9.1568	−8.0517k+7.9179	−7.9455k+9.5759	−7.9455k+8.1177
6.4	−7.8897k+8.9691	−7.8897k+7.7550	−7.7865k+9.3808	−7.7865k+7.9515
6.5	−7.7200k+8.7717	−7.7200k+7.5813	−7.6202k+9.1768	−7.6202k+7.7753
6.6	−7.5705k+8.5985	−7.5705k+7.4309	−7.4735k+8.9965	−7.4735k+7.6218
6.7	−7.4266k+8.4318	−7.4266k+7.2862	−7.3322k+8.8231	−7.3322k+7.4741
6.8	−7.2881k+8.2712	−7.2881k+7.1469	−7.1961k+8.6560	−7.1961k+7.3319
6.9	−7.1941k+8.1657	−7.1941k+7.0617	−7.1029k+8.5421	−7.1029k+7.2419
7.0	−7.0645k+8.0163	−7.0645k+6.9320	−6.9757k+8.3866	−6.9757k+7.1095
7.1	−6.9395k+7.8721	−6.9395k+6.8068	−6.8529k+8.2364	−6.8529k+6.9817
7.2	−6.8288k+7.7379	−6.8188k+6.6860	−6.7343k+8.0915	−6.7343k+6.8583
7.3	−6.7022k+7.5984	−6.7022k+6.5693	−6.6197k+7.9515	−6.6197k+6.7391
7.4	−6.5895k+7.4678	−6.5895k+6.4565	−6.5089k+7.8161	−6.5089k+6.6239
7.5	−6.4805k+7.3427	−6.4805k+6.3474	−6.4017k+7.6852	−6.4017k+6.5124
7.6	−6.3835k+7.2316	−6.3835k+6.2523	−6.6031k+7.5686	−6.3061k+6.4147
7.7	−6.2812k+7.1138	−6.2812k+6.1501	−6.2055k+7.4458	−6.2055k+6.3102
7.8	−6.1821k+6.9997	−6.1821k+6.0510	−6.1081k+7.3269	−6.1081k+6.2090
7.9	−6.1113k+6.9191	−6.1113k+5.9850	−6.0379k+7.2405	−6.0379k+6.1398
8.0	−6.0178k+6.8117	−6.0178k+5.8919	−5.9459k+7.1287	−5.9459k+6.0446
8.1	−5.9271k+6.7076	−5.9271k+5.8015	−5.8567k+7.0202	−5.8567k+5.9522
8.2	−5.8390k+6.6066	−5.8390k+5.7139	−5.7701k+6.9149	−5.7701k+5.8626
8.3	−5.7535k+6.5085	−5.7535k+5.6287	−5.6860k+6.8126	−5.6860k+5.7756
8.4	−5.6705k+6.4132	−5.6705k+5.5461	−5.6043k+6.7133	−5.6043k+5.6911
8.5	−5.5898k+6.3206	−5.5898k+5.4657	−5.5248k+6.6168	−5.5248k+5.6090

The linear adjustment for the keratometric indexes of 1.3315, 1.3304, and 1.3375 and for the range defined for r_{1c} is shown. P_{IOL}: Intraocular lens power

thickness (r = 0.73, P < 0.01) were found. Furthermore, a good correlation of ΔP_{IOL} with anterior corneal astigmatism (r = 0.64, P < 0.05), AL (r = 0.64, P < 0.05), and minimum corneal thickness (r = 0.57, P < 0.05) was found. The Bland–Altman method revealed the presence of a mean difference between $P_{IOL1.3375}{}^{k}$ and $P_{IOL}{}^{Gauss}$ of −1.79 D, with limits of agreement of −0.59 and −3.00 D. Fig. 2a shows the Bland–Altman plot corresponding to this agreement analysis.

P_{IOL}^{Adj} under- and over-estimated P_{IOL}^{Gauss} in a magnitude ranging from −1.1 to −0.4 D (within the limits established theoretically). No statistically significant differences between P_{IOL}^{Adj} and P_{IOL}^{Gauss} were found ($P > 0.05$, unpaired Student's *t*-test). Likewise, a very strong and statistically significant correlation was found between P_{IOL}^{Adj} and P_{IOL}^{Gauss} ($r = 0.99$, $P < 0.01$). Only ΔP_{IOL} was found to correlate significantly with r_{2c}, being this correlation of moderate strength ($r = 0.51$, $P > 0.05$). The Bland–Altman method revealed the presence of a mean difference between P_{IOL}^{Adj} and P_{IOL}^{Gauss} of −0.31 D, with limits of agreement of −1.34 and 0.72 D [Fig. 2b].

When P_{IOL}^{Adj} was compared with $P_{IOL}^{True\ Net}$, under- and over-estimations ranging between − 1.3 and 0.2 D were found. Differences between these two P_{IOL} values were statistically significant ($P < 0.01$, unpaired Student's *t*-test), with a very strong and statistically significant correlation between them ($r = 0.99$, $P < 0.01$). These differences correlated moderately with r_{2c} ($r = 0.55$, $P > 0.05$). The Bland–Altman method showed a mean difference between P_{IOL}^{Adj} and $P_{IOL}^{True\ Net}$ of −0.48 D, with limits of agreement of −1.53 and 0.57 D [Fig. 2c].

An overestimation was always present when $P_{IOL}^{True\ Net}$ was compared with P_{IOL}^{Gauss}, ranging from 0.1 D to 0.2 D. Differences between these two P_{IOL} values were statistically significant ($P < 0.01$, unpaired Student's *t*-test). A very strong and statistically significant correlation was found between $P_{IOL}^{True\ Net}$ and P_{IOL}^{Gauss} ($r = 1$, $P < 0.01$). Furthermore, significant correlations of ΔP_{IOL} with r_{2c} ($r = 0.92$, $P < 0.01$), r_{1c} ($r = 0.93$, $P < 0.01$), and central corneal thickness (r = 0.65, $P < 0.05$) were found. The Bland–Altman method revealed the presence of a mean difference between $P_{IOL}^{True\ Net}$ and P_{IOL}^{Gauss} of 0.17 D, with limits of agreement of 0.12 D and 0.22 D. Fig. 2d shows the Bland–Altman plot corresponding to this agreement analysis.

Discussion

In the present study, we have demonstrated that the use of keratometric P_c in P_{IOL} calculations can lead to significant errors in such population with a theoretical simulation using the range of corneal curvature in keratoconus. Specifically, an underestimation of P_{IOL}^{k} with respect to P_{IOL}^{Gauss} was present due to an overestimation of the P_c and vice versa. This difference in the calculation of P_{IOL} (ΔP_{IOL}) has been demonstrated to be dependent on the n_k value, k ratio (consequently on r_{1c} and r_{2c}) as well as on the theoretical eye model used for calculations. The n_k values derived from the Le Grand and Gullstrand eye models (1.3304 and 1.3315, respectively) were shown to generate over- and under-estimations of P_{IOL} (P_{IOL}^{k} with respect to P_{IOL}^{Gauss}), with more trend to underestimations. The maximum over- and under-estimations were + 1.4 D and + 1.0 D and − 3.5 D and − 4.3 D for Le Grand and Gullstrand eye models, respectively. Furthermore, underestimations were always present when $n_k = 1.3375$ was used, with a maximum value of −6.2 D for the Gullstrand eye model and −5.6 D for the Le Grand eye model. All these outcomes are similar to those found in normal healthy eyes,[6] although underestimations are higher

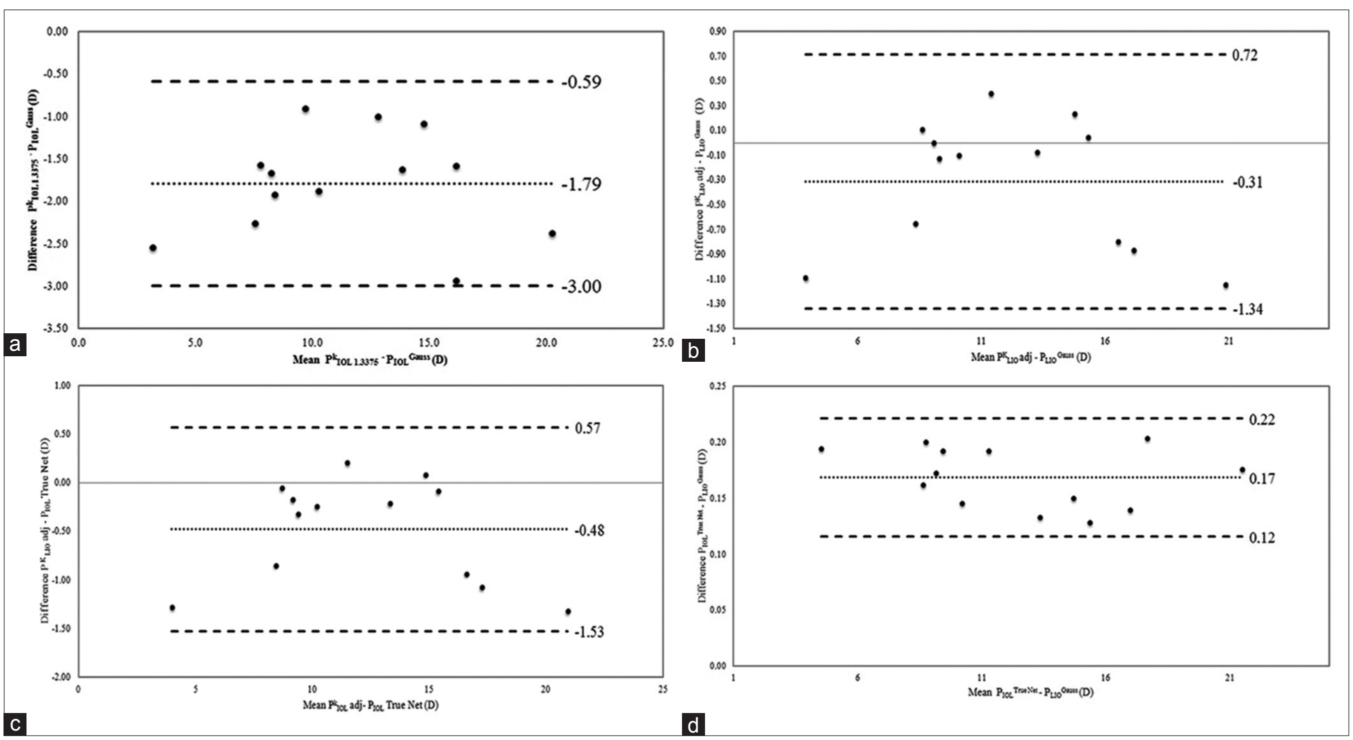

Figure 2: Bland–Altman plots of the comparative analyses performed in the current study. (a) Comparison between the P_{IOL} obtained using the classical keratometric approach ($P_{IOL1.3375}^{k}$) and that obtained using the Gaussian equation ($P_{IOL}^{Gaussian}$). (b) Comparison between the P_{IOL} obtained using the adjusted keratometric approach (P_{IOLadj}^{k}) and that obtained using the Gaussian equation ($P_{IOL}^{Gaussian}$). (c) Comparison between the P_{IOL} obtained using the adjusted keratometric approach (P_{IOLadj}^{k}) and that obtained using the True Net estimation ($P_{IOL}^{True\ Net}$). (d) Comparison between the P_{IOL} obtained using the True Net approach ($P_{IOLadj}^{True\ Net}$) and that obtained using the Gaussian equation ($P_{IOL}^{Gaussian}$). Upper and lower lines represent the limits of agreement calculated as mean of differences ± 1.96 standard deviation

in the keratoconus population. For example, when $n_k = 1.3375$ is used in a normal eye, the maximum underestimation of P_{IOL} is −3.01 D and −2.77 D for Gullstrand and Le Grand eye models,[6] respectively, instead of the values of −6.2 and −5.6 D found in keratoconus.

As in normal healthy eyes, for each value of r_{1c} in 0.1-mm steps within the range of curvature for the keratoconus population,[7,11,12] a linear equation dependent on k ratio as well as a quadratic equation dependent on r_{2c} allows to obtain a highly accurate prediction of ΔP_{IOL} [Table 5]. These equations may be useful to calculate the magnitude of the error associated to the use of a specific keratometric P_c in P_{IOL} calculation (P_{IOL}^{k}). The consistency of our simulation model was studied by analyzing the dependency of ΔP_{IOL} on ELP or R_{des}. This analysis revealed that the variation in ΔP_{IOL} was not clinically significant for a range of ELP between 2 and 6 mm or for an interval of R_{des} ranging from + 1 to −1 D.

With the aim of minimizing the error associated to the use of the classical keratometric approach of P_c estimation, the variations of ΔP_{IOL} were also analyzed when using the correction of the keratometric power with the algorithm developed by our research group consisting on the use of a variable keratometric index (n_{kadj}) depending on r_{1c} [Table 1].[1] Using this algorithm, the theoretical differences between P_{IOL}^{Adj} and P_{IOL}^{Gauss} never exceeded ± 1.1 D, independently of the r_{1c} value or theoretical eye model used. This error range was not clinically significant for most of the r_{1c}/r_{2c} combinations at the corneal vertex plane. Therefore, P_{IOL}^{Adj} can be considered a useful algorithm to be used in keratoconus for P_{IOL} calculation when posterior corneal curvature data are not available.

Besides this theoretical analysis, a preliminary clinical validation with a reduced number of keratoconus eyes was performed in which P_c^{Gauss} ranged between 40 and 52 D. Using P_{IOL}^{k} with $n_k = 1.3375$, P_{LIO}^{k} was found to underestimate significantly P_{IOL}^{Gauss} in a range between −0.9 and −2.9 D ($P < 0.05$, unpaired Student's *t*-test). The Bland–Altman method confirmed the clinical relevance of this underestimation, with a mean difference of − 1.79 D, and limits of agreement of −0.59 and −3.00 D. Differences between $P_{IOL1.3375}^{k}$ and P_{IOL}^{Gauss} were found to be in relation with r_{2c} ($r = 0.96$, $P < 0.01$), r_{1c} ($r = 0.84$, $P < 0.01$), and central corneal thickness ($r = 0.73$, $P < 0.01$). Therefore, in keratoconus, the contribution of the combined effect of posterior corneal curvature and corneal thickness to the total P_c seems to be clinically relevant and should be considered when the value of P_c is used in P_{IOL} calculations. This is in agreement with previous studies clinically evaluating the impact of using the keratometric P_c for P_{IOL} calculation in keratoconus.[13-15] Park *et al*.[13] found that, in patients with posterior keratoconus, P_{IOL} calculation from conventional keratometry may be inaccurate, and secondary piggyback IOL procedure may be needed after cataract surgery. Thebpatiphat *et al*.[14] in a retrospective cases series evaluating 12 keratoconus eyes undergoing cataract surgery concluded that IOL calculation was more predictable in mild keratoconus than in moderate and severe diseases. It should be considered that an increase in posterior corneal curvature and a decrease in central corneal thickness are present in more severe keratoconus cases.[7]

When an adjusted keratometric index (n_{kadj}) was used to obtain P_{kadj} in the calculation of P_{IOL}^{Adj}, differences with P_{IOL}^{Gauss} did not exceed ± 1.1 D (range from 0.4 to −1.1 D) as the theoretical analysis predicted, obtaining an ΔP_{IOL} between −0.1 and 0.4 D in 61.5% of cases. These differences between P_{IOL}^{Adj} and P_{IOL}^{Gauss} did not reach statistical significance ($P > 0.05$), but the Bland–Altman analysis revealed a mean difference of −0.31 D, with clinically relevant limits of agreement (−1.34 and 0.72 D). The correlation between P_{IOL}^{Adj} and P_{IOL}^{Gauss} was strong ($r = 0.99$, $P < 0.01$), being only the posterior corneal radius the main factor interfering in this relationship ($r = 0.51$, $P > 0.05$). This result supposes an improvement compared to those obtained when P_c is calculated with the classical $n_k = 1.3375$, and differences among P_{IOL}^{Adj} and P_{IOL}^{Gauss} can be considered acceptable in most of the cases. When P_{IOL}^{Adj} and $P_{IOL}^{True\ Net}$ were compared, differences among them were found to be statistically significant ($P < 0.01$, unpaired Student's *t*-test), with clinically relevant differences in the Bland–Altman analysis (mean difference: −0.48 D, limits of agreement: −1.53 and 0.57 D). Likewise, differences between $P_{IOL}^{True\ Net}$ and P_{IOL}^{Gauss} were also statistically significant ($P < 0.01$, unpaired Student's *t*-test), but not clinically relevant. This suggests that corneal thickness has a limited effect on the calculation of P_c in keratoconus and therefore the use of the true net power in keratoconus can be considered as acceptable for clinical purposes. Specifically, the influence of central corneal thickness was studied considering a range of this parameter in keratoconus between 200 μm and 600 μm. The maximum errors considering corneal thickness in the calculation of P_{IOL} were 0.4 and −0.1 D for Le Grand and Gullstrand eye models, respectively. Consequently, the clinical relevance of corneal thickness variations in our model seemed to be limited for the range of thickness of the keratoconus population. On the other hand, the study is based on two theoretical eye models, providing very similar results of ΔP_{IOL}. The choice of one model or another is therefore not decisive and has minimal clinical relevance in keratoconus eyes.

It should be acknowledged that there are some potential weaknesses in this study: the use of paraxial optics, not considering the effect of asphericity, the effect of variations in corneal thickness, and the use of a limited number of theoretical eye models for the simulations. Future studies evaluating the validity of our model for nonparaxial optics as well as evaluating whether there is an improvement with clinical relevance when using a more complex optical estimation are required. In addition, we have not evaluated the impact of the adjustment developed for P_{IOL} calculation in a prospective study and consequently the prediction error was not evaluated. Once the potential benefit of using our adjustment is demonstrated, a future study will be conducted to compare the prediction error with our formula and other commonly used formulas. Before beginning a prospective study involving a modification of the P_{IOL} calculation, we prefer to confirm the potential improvement theoretically and if confirmed to conduct the corresponding prospective study. For this reason, the sample size was limited and therefore this study can be only considered as a preliminary experience to evaluate the potential applicability of the algorithms developed. Furthermore, it should be mentioned that only one case of severe keratoconus was included in the clinical validation and therefore the conclusions of the study cannot be extrapolated to this type of cases. Severe keratoconus cases should be included in the future prospective studies, clinically validating the algorithms for P_{IOL} calculation.

Conclusion

We have shown that the use of a single value of n_k in keratoconus for the calculation of P_{IOL} can lead to inaccuracies that could explain the refractive surprises in keratoconus population and after cataract surgery. These inaccuracies in P_{IOL} calculations can be minimized theoretically using a variable n_k depending on the radius of curvature of the anterior corneal surface with a maximum error in most of the cases of approximately 0.6 D and over 1 D in very few cases. A preliminary clinical validation of this model has been performed, with results very close to those predicted theoretically. Our n_{kadj} algorithm for P_c estimation in keratoconus may be especially useful in those clinical settings in which topographic devices providing posterior corneal surface data are not available, although a clinical validation with a larger sample size including severe keratoconus cases should be performed to obtain consistent conclusions. Our theoretical models of correction of the error introduced by n_k and their clinical implications in P_{IOL} calculations should be evaluated with clinical data in the future to validate their significance and applicability to other ectatic diseases or previous ocular surgeries as cross-linking or intracorneal ring segment implantation in keratoconus.

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Conflicts of interest

There are no conflicts of interest.

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