

Theoretical Relationship Among Effective Lens Position, Predicted Refraction, and Corneal and Intraocular Lens Power in a Pseudophakic Eye Model

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Received: June 4, 2022

Accepted: July 26, 2022

Published: September 7, 2022

Keywords: IOL power; IOL power formula; lens constant; optimization; refraction

Citation: Gatinel D, Debellemanniè G, Saad A, Rampat R. Theoretical relationship among effective lens position, predicted refraction, and corneal and intraocular lens power in a pseudophakic eye model. *Transl Vis Sci Technol.* 2022;11(9):5. <https://doi.org/10.1167/tvst.11.9.5>

Purpose: To ascertain the theoretical impact of anatomical variations in the effective lens position (ELP) of the intraocular lens (IOL) in a thick lens eye model. The impact of optimization of IOL power formulas based on a single lens constant was also simulated.

Methods: A schematic eye model was designed and manipulated to reflect changes in the ELP while keeping the optical design of the IOL unchanged. Corresponding relationships among variations in ELP, postoperative spherical equivalent refraction, and required IOL power adjustment to attain target refractions were computed for differing corneal powers (38 diopters [D], 43 D, and 48 D) with IOL power ranging from 1 to 35 D.

Results: The change in ELP required to compensate for various systematic biases increased dramatically with low-power IOLs (less than 10 D) and was proportional to the magnitude of the change in refraction. The theoretical impact of the variation in ELP on postoperative refraction was nonlinear and highly dependent on the optical power of the IOL. The concomitant variations in IOL power and refraction at the spectacle plane, induced by varying the ELP, were linearly related. The influence of the corneal power was minimal.

Conclusions: The consequences of variations in the lens constant mainly concern eyes receiving high-power IOLs. The compensation of a systematic bias by a constant increment of the ELP may induce a nonsystematic modification of the predicted IOL power, according to the biometric characteristics of the eyes studied.

Translational Relevance: Optimizing IOL power formulas by altering the ELP may induce nonsystematic modification of the predicted IOL power.

Introduction

The purpose of intraocular lens (IOL) power calculation formulas is to determine the refractive power of an implant that will allow the operated eye to achieve the target refraction.¹ The formula precision and accuracy depend on the reliability of the preoperative biometric measurements, the difference between the achieved versus predicted effective lens position (ELP), and possible postoperative fluctuations in corneal power.^{2–4} The quality of the postoperative ELP prediction is the most critical factor in controlling residual refractive error.⁵ The ELP does not necessarily coincide with the physical position of the IOL front surface, equatorial plane, or back surface. In theoret-

ical thick lens paraxial ocular models, the ELP corresponds to the distance separating the principal image plane of the cornea and the principal object plane of the IOL.⁶ Manufacturers label IOL powers with consistent values, but details of the IOL itself, such as geometrical and optical design, are not as readily available. For the same anatomical position, two implants of the same labeled power that are located at the same physical distance from the corneal endothelium will induce different refractive outcomes if their optical designs are not identical. This variation corresponds to differences in position of the principal object plane of any given IOL depending on its design. The lens constant compensates for these and many other parameters, such as minor systematic differences in power values that arise from the test methods.⁶

In most cases, optimizing an IOL power formula involves canceling a systematic bias—that is, the non-null arithmetic mean of the prediction error (PE), calculated as the difference between the measured and predicted postoperative spherical equivalent (SE). This process, sometimes referred to as zeroization, involves selecting constant values that would adjust for a null mean arithmetic prediction error.⁷ Such customization cannot be generalized and is only valid for a dedicated environment (e.g., for one surgical center with standardized surgical techniques and measurement equipment). Hence, a change of lens constant is generally necessary to optimize a formula to a different type of implant than that for which it has been originally adjusted. When more clinical data are available for various IOLs, their respective lens constants can be refined. The lens constant correlates the postoperative physical location of the lens component of the IOL to its effect on the final refraction.^{8,9} In most formulas based on an optical model, a constant adjustment of the lens equates to modifying the predicted position of the IOL by a specific increment.¹⁰ In this context, the modification of the constant is similar to an incremental change in the predicted position for all implants. In the case of a paraxial optical model in thick lenses, the modification of the lens constant is equivalent to the displacement of the principal object plane of the IOLs.

Several methods exist for this task, depending on the context and structure of the formulas. As part of the comparison of IOL power calculation formulas, through prediction of the postoperative SE, it is possible to communicate the value of the arithmetic mean of the postoperative refractions of the holdout dataset. This dataset contains the preoperative biometric parameters of interest, as well as the type and power of each implanted IOL. The lens constant is then adjusted for each IOL type within each of the compared formulas, until the arithmetic mean of the predicted refractions is equal to the mean value communicated.⁷ This trial-and-error constant optimization can also be performed for the eyes of a smaller external dataset of randomly chosen patients from a non-biased cohort.

When optimizing formulas from a fully populated dataset of operated eyes, formulas with one lens constant can be reorganized and solved for that constant. For each documented clinical case, one can back-calculate which lens constant is required to yield the refraction achieved after cataract surgery. The mean or median of all individual constants is selected as an optimized constant for the dataset.¹¹

Whatever the context and the strategy used, derivation of customized IOL constants for formulas such as

the SRK/T, Hoffer Q, Holladay 1, and single-optimized Haigis formulas results in the determination of one lens constant, which will be added to a function that predicts the ELP. Whether optimizing a formula on a large sample of eyes that have already been operated on or on a hidden dataset, each of the IOL powers used in the baseline computations may influence the constant (value of the theoretical displacement necessary to compensate for the systematic bias in a given eye). If the initially calculated IOL power is retained, moving each IOL by the same increment compared to their baseline predicted ELP would induce a refraction difference. Therefore, when used on a new dataset with the adjusted lens constant, the considered formula will predict a different IOL power to achieve the desired postoperative refraction. Hence, the value of the final increment in ELP allowing the zeroization of the PE (i.e., the lens constant adjustment) will depend on the distribution of the IOL powers within the sample or dataset used for the baseline power calculation.

In this article, we used a thick lens eye model to explore the theoretical relationships between the variations in thick lens effective lens position (ELP_T) and predicted postoperative refraction for various IOL and corneal powers. A variation in ELP_T may be induced by a variation in optical design and/or physical displacement of the implant. When the ELP_T of each IOL is changed by the same increment, without any change in the design of its optics or its haptics, this is equivalent to an anatomical displacement of each IOL. We first investigated the theoretical variation in ELP_T needed to compensate for a given systematic bias (non-null arithmetic mean of PE) as a function of the respective IOL and corneal powers of the considered eye. We then explored the relationships between incremental changes in ELP_T and the SE prediction in spectacle plane corrections for various IOL and corneal powers. Finally, we calculated the difference in power applied to a given IOL to compensate for the change in spectacle refraction induced by a variation of its effective position.

Material and Methods

Thick Lens Schematic Pseudophakic Eye Model

Paraxial optics formulas for calculating the respective optical powers and principal plane positions of the cornea and IOL, modeled as thick lenses, and the resultant power and principal plane positions have been reviewed in a previous publication.¹² Herein, we

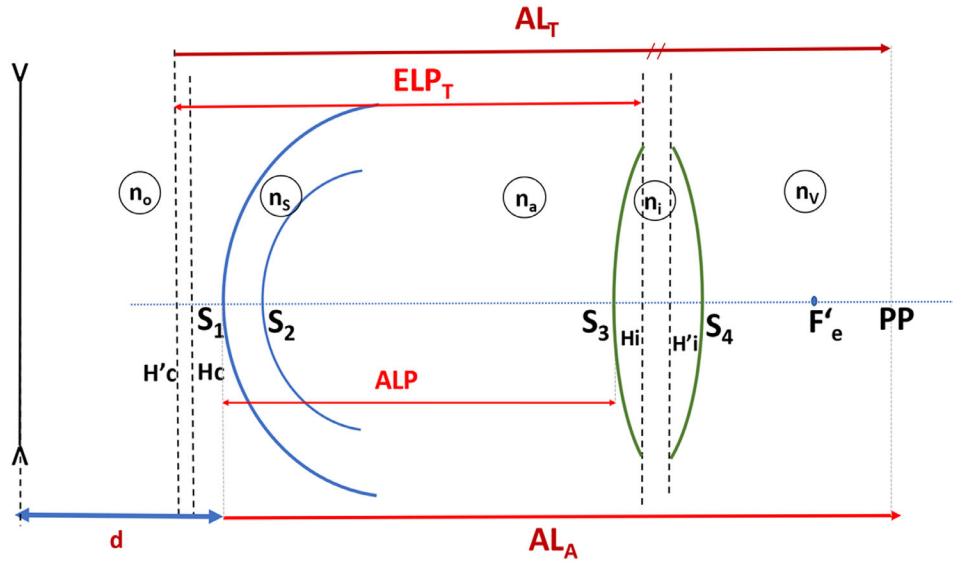


Figure 1. Paraxial, four-surface, thick-lens, pseudophakic eye model. F'_e is the back focal point of the paraxial schematic pseudophakic eye. AL_A is the anatomic axial length from the anterior surface of the cornea to the photoreceptor plane (PP). It is equal to the distance $S_1F'_e$ if the eye is emmetropic. The AL_T is the thick lens axial length, which connects the principal image plane of the cornea H'_c to the PP and is reduced by the distance $H_iH'_i$ separating the two principal planes of the IOL. ALP is the anterior lens position connecting the corneal vertex (S_1) to the IOL vertex (S_3); ELP_T is the effective thick lens position joining the principal image plane of the cornea to the principal object plane of the IOL; and d is the distance to the spectacle plane.

describe an explicit formula allowing back-calculation of the theoretical position of the principal object plane of an IOL. In what follows, the formulas are clearly reported for a pseudophakic eye modeled as thick lenses with four refractive surfaces and distinct refractive indices between the aqueous and vitreous humor (Fig. 1).

The cornea is comparable to a convex–concave lens where the refractive index is attributable to its main layer, the corneal stroma (n_s). The total corneal power is denoted D_c . It can be obtained from the value of the anterior and posterior radii of curvature (R_{ca} and R_{cp}) and the refractive indices of air, stroma, and aqueous humor (n_a).

The optical power of a thick intraocular lens is denoted D_i . It depends on the curvatures of its anterior and posterior surfaces (R_{ia} and R_{ip}), their separating distance (corresponding with the central IOL thickness, d_i), and the index variations between that of the media in contact with these surfaces and that of the lens itself. In this work, the power of the IOL was calculated from identical refractive indices of the aqueous humor and vitreous ($n = 1.336$).

In a thick lens model, depicting the distance between the refractive elements included in the computations involves the position of the principal planes of these elements. The effective thick lens position (ELP_T)

corresponds to the distance between the position of the principal image plane of the cornea and the principal object plane of the IOL. It can be computed from the corneal and IOL design characteristics and the anterior lens position (ALP), which separates the respective anterior surfaces of the cornea and the IOL. The axial length of the thick lens eye model (AL_T) differs from the anatomical axial length (AL_A). It is computed as the difference between the principal corneal image plane and the entire eye focal image point reduced by the distance between the principal planes of the IOL. However, the derived formulas apply to a thin lens eye model, where the axial length and the effective position of the implant have a more direct correlation.

For a given corneal power D_c and IOL power D_i , the distance separating the principal image plane of the cornea (H'_c) from the focal image point of the entire eye (F'_e) is given by¹²

$$H'_cF'_e = ELP_T + \frac{n_v - \frac{n_v}{n_a}D_cELP_T}{D_c + D_i - \frac{D_cD_iELP_T}{n_a}} \quad (1)$$

In an emmetropic eye, $H'_cF'_e = AL_T$, where AL_T is the axial length of the thick lens model eye.

Determination of the Incremental Change in ELP_T Required to Compensate for a Systematic Bias

From the schematic eye, one can calculate the refraction ($SE = R$) at the spectacle plane (d) using the vergence formula:

$$R = - \frac{1}{\frac{1}{\frac{n_a}{(AL_T - ELP_T) + D_i} - ELP_T} + D_c} - d \quad (2)$$

If all the parameters concerning the design of the IOL are considered fixed, a variation of the ELP_T is equivalent to an anatomical displacement of the implant.

Solving Equation 2 for ELP_T allows us to compute the variation in the effective thick lens position (ΔELP_T) that is necessary to compensate for a change in spectacle refraction (ΔR). Within the context of a zeroing procedure, this corresponds to a systematic bias (non-null mean PE) requiring compensation:

$$\Delta ELP_T = \frac{-B + \sqrt{B^2 - 4AC}}{2A} - ELP_T \quad (3)$$

where

$$\begin{aligned} A &= D_i(d(R + \Delta R)D_c + D_c - (R + \Delta R)) \\ B &= -n_a(d(R + \Delta R)(D_c + D_i) - D_c - D_i \\ &\quad - (R + \Delta R)) - (D_i AL_T - n_v) \\ &\quad \times (d(R + \Delta R)D_c - (R + \Delta R) - D_c) \\ C &= n_a((AL_T(R + \Delta R)(d(D_c + D_i) - 1) \\ &\quad - d(R + \Delta R)n_v - AL_T(D_c + D_i) + n_v)) \end{aligned}$$

Theoretical Impact of the Increment in ELP_T on the Refraction of the Pseudophakic Eye

Equation 3 is derived from Equation 2 and makes it possible to directly calculate the theoretical impact of a variation of the ELP_T on the refraction of the pseudophakic eye according to the power of the implant and the corneal diopter. This equation enables computation of the impact on R of a given variation in ELP_T (ΔELP_T), analogous to a change in the lens constant:

$$\Delta R = - \frac{1}{\frac{1}{\frac{n_a}{(AL_T - (ELP_T + \Delta ELP_T)) + D_i} - (ELP_T + \Delta ELP_T)} + D_c} - d - R \quad (4)$$

We limited our simulations to eyes having received positive power implants ($D_i > 0$) between 1 D and 35 D.

Table 1 displays the values used for the numeric simulations. All modeled eyes were emmetropic for their initial ELP_T , corneal and IOL powers, and axial length.

The refractive index values used for numerical simulations were $n_a = 1.336$ (aqueous), $n_v = 1.336$ (vitreous), $n_c = 1.376$ (corneal stroma), and $n_i = 1.45$ (IOL material). All modeled IOL had a symmetrical shape (null Coddington shape factor). The central thickness of the cornea was $t_c = S_1 S_2 = 0.535$ mm. The selected anterior and posterior corneal radii of curvature were $R_{ca} = 8.7$ mm and $R_{cp} = 7.5$ mm ($D_c = 38$ diopters [D]); $R_{ca} = 7.7$ mm and $R_{cp} = 6.8$ mm ($D_c = 43$ D); and $R_{ca} = 6.9$ mm and $R_{cp} = 6$ mm ($D_c = 48$ D). The distance to the spectacle plane was set to $d = 12$ mm.

Relationship Between the Change in Refraction (ΔR) Versus the Change in IOL Power (ΔD_i) Induced by a Specified Change in ELP (ΔELP_T)

Let D_i be the power of an IOL located at the effective lens position (ELP_T). The change in IOL power (ΔD_i) required to keep the target refraction constant when an amount of ΔELP_T shifts the IOL position is given by

$$\Delta D_i = \frac{n_v}{(H'_c F'_e - (ELP_T + \Delta ELP_T))} - \frac{n_v}{(H'_c F''_e - (ELP_T + \Delta ELP_T))} \quad (5)$$

where $H'_c F'_e$ corresponds to the distance separating the principal image plane of the cornea from the focal point of the entire eye when the effective lens position is at $ELP_T + \Delta ELP_T$ (Fig. 2) and can be computed using Equation 1.

Using Equations 3 and 4, one can investigate the relationship between the variation in refraction (ΔR) versus the required variation in IOL power (ΔD_i) induced by ΔELP_T for various combinations of corneal and IOL powers.

We considered 12 theoretical emmetropic pseudophakic eyes with various IOL powers (5 D, 15 D, 25 D, and 35 D) and corneal powers (38 D, 43 D, and 48 D). For each eye, we varied the ELP_T between -0.17 mm and $+0.17$ mm by a ± 0.1 -mm increment and computed (1) the resulting change in refraction in the spectacle plane (ΔR) and (2) the necessary change in IOL power (ΔD_i) to maintain emmetropia. For each

Table 1. Numeric Values Used to Design Baseline Emmetropic Pseudophakic Eyes

IOL Power (D)	IOL Central Thickness (mm)	Anterior Radius (mm)	Posterior Radius (mm)	S_1S_3 (mm)	Axial Length (mm) ($D_c = 38$ D)	Axial Length (mm) ($D_c = 43$ D)	Axial Length (mm) ($D_c = 48$ D)
1	0.4	227.98	-227.98	0.57	34.530	30.541	27.475
2	0.42	113.98	-113.98	0.565	33.928	30.094	27.132
3	0.44	75.98	-75.98	0.56	33.348	29.660	26.797
4	0.46	56.98	-56.98	0.555	32.788	29.239	26.469
5	0.48	45.58	-45.58	0.55	32.248	28.829	26.150
6	0.5	37.98	-37.98	0.545	31.725	28.431	25.838
7	0.52	32.55	-32.55	0.54	31.220	28.044	25.533
8	0.54	28.48	-28.48	0.535	30.731	27.668	25.235
9	0.56	25.31	-25.31	0.53	30.258	27.301	24.943
10	0.58	22.78	-22.78	0.525	29.799	26.943	24.658
11	0.6	20.70	-20.70	0.52	29.354	26.595	24.379
12	0.62	18.98	-18.98	0.515	28.923	26.256	24.105
13	0.64	17.51	-17.51	0.51	28.504	25.925	23.837
14	0.67	16.26	-16.26	0.505	28.100	25.604	23.577
15	0.7	15.17	-15.17	0.5	27.707	25.291	23.323
16	0.74	14.22	-14.22	0.495	27.329	24.989	23.076
17	0.78	13.38	-13.38	0.49	26.961	24.693	22.834
18	0.82	12.63	-12.63	0.485	26.603	24.405	22.597
19	0.86	11.97	-11.97	0.48	26.256	24.124	22.366
20	0.9	11.36	-11.36	0.475	25.917	23.849	22.138
21	0.94	10.82	-10.82	0.47	25.588	23.580	21.916
22	0.98	10.32	-10.32	0.465	25.267	23.318	21.697
23	1.02	9.87	-9.87	0.46	24.954	23.061	21.483
24	1.06	9.46	-9.46	0.455	24.649	22.810	21.273
25	1.1	9.08	-9.08	0.45	24.352	22.564	21.066
26	1.14	8.72	-8.72	0.445	24.062	22.324	20.864
27	1.18	8.40	-8.40	0.44	23.779	22.088	20.665
28	1.22	8.09	-8.09	0.435	23.503	21.858	20.470
29	1.26	7.81	-7.81	0.43	23.233	21.632	20.278
30	1.3	7.55	-7.55	0.425	22.969	21.410	20.090
31	1.34	7.30	-7.30	0.42	22.711	21.193	19.904
32	1.38	7.07	-7.07	0.415	22.459	20.980	19.722
33	1.42	6.85	-6.85	0.41	22.212	20.771	19.543
34	1.46	6.65	-6.65	0.405	21.970	20.566	19.367
35	1.5	6.45	-6.45	0.4	21.734	20.365	19.194

combination of IOL and corneal power, linear regression was performed between the corresponding values of ΔR and ΔD_i to obtain the regression coefficient.

Results

Determination of the Incremental Change in ELP_T Required to Compensate for a Systematic Bias

The required change in ELP_T (ΔELP_T) to compensate for various systematic bias values (analogous to variations in refraction, ΔR) from -0.3 D to $+0.3$ D by 0.1-D steps were computed for different IOL powers

(D_i) ranging from 1 D to 35 D (1-D steps) and three different total corneal powers (D_c): 38 D, 43 D, and 48 D (Figs. 3a, 2b, 3c, respectively).

ΔELP_T increased dramatically with low-power IOLs (less than 10 D), proportional to the magnitude of the change in refraction (ΔR). The flatter the cornea, the higher the difference required for the same planned refractive variation, but the incurred impact was low.

Theoretical Impact of the Increment in ELP_T on the Refraction of the Pseudophakic Eye

There was a linear variation of the change in refraction (ΔR) with IOL power, which increased

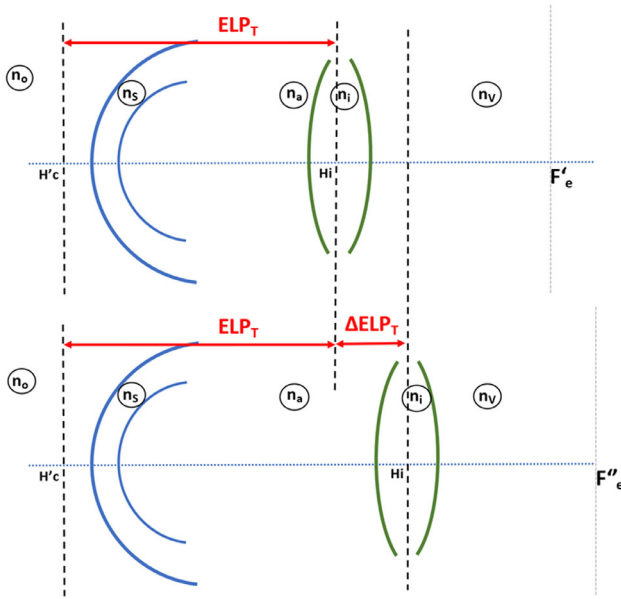


Figure 2. Moving the implant increment equal to ΔELP_T results in a displacement of the focal point of the entire eye. The vergence of the implant must be adjusted by ΔD_i to keep the focal length unchanged.

proportionally with ΔELP_T (Figs. 4a–4c). A positive variation of the ELP_T ($\Delta ELP_T > 0$) resulted in a hyperopic shift in the refraction.

The higher the corneal power, the more significant the change in predicted SE, but the influence of the corneal power was low.

Relationship Between the Change in Refraction (ΔR) Versus the Change in IOL Power (ΔD_i) Induced by ΔELP_T

Figure 5 displays the relationship between the change in spectacle refraction and required change in IOL power to maintain emmetropia incurred by a shift of effective lens position (ELP_T). The regression coefficient expresses the change in spectacle refraction induced by a variation of 1 D in IOL power (Fig. 5). The regression coefficient values were between 0.617 and 0.731. The values of ΔR and ΔD_i obtained for $\Delta ELP_T = +0.1$ mm and $\Delta ELP_T = -0.1$ mm are indicated for each simulation. Table 2 displays the values for the 12 scenarios.

Discussion

Determining the optimum value of a lens constant occurs under various circumstances and can be achieved by various methods. For IOL power calcula-

tion formulas that use a single lens constant, its value correlates to predicting the ELP.

Our results were computed using a thick lens eye model and show that, for the same target refractive change (ΔR), the required theoretical variation in ELP_T is inversely proportional to the power of the implanted IOL. For implants with a power greater than 8 D, the theoretical variation in the effective lens position necessary to induce a refractive correction of ± 0.1 D is less than 250 μ m. For IOL powers less than 8 D, this variation increases exponentially: ± 1 mm of a shift in ELP_T is required to induce a refractive change of ± 0.1 D for an IOL power of +2D. This tendency is relatively insensitive to the value of the corneal power.

Hence, to compensate for the same refractive bias (zeroization), the required theoretical variation in ELP_T tends to be less for short eyes with high-power IOLs and increases dramatically for long eyes with low-power IOLs. This suggests that, for optimization methods that would be based on the determination of an average or median of the optimal constants calculated for each eye of a dataset, the determination of the lens constant will be greatly affected by the distribution of IOL powers within the dataset used. It also suggested that eyes with low-power IOLs will have a stronger influence than eyes with high-power IOLs.

Once determined, the change in the lens constant will result in an identical increment in the predicted effective lens position, which will not affect the predicted refraction of all eyes equally. As shown in Figure 4, the refractive consequences of the same variation in effective IOL position will vary according to the biometry characteristics of the eye concerned. The refraction of eyes with a high-power IOL requirement is much more sensitive to lens constant adjustments than that of eyes with a low-power IOL requirement.

Figure 4 can be interpreted as the theoretical impact that a single change such as an identical offset between the haptics and the optic for all IOL powers would have on the postoperative refraction, before performing the lens constant adjustment of the considered formula. The magnitude of the predicted change in spectacle refraction would increase exponentially for shorter eyes receiving high-power lenses. This nonlinearity means that the change in spectacle refraction will be strongly influenced by the distribution of implant powers within the database used. We presented the theoretical impact of IOL design variations on postoperative refraction, which was greater for high-power implants.¹² This result suggests that the optimization processes induced by a change in implant design (without theoretical variation of their anatomical position) are subject to

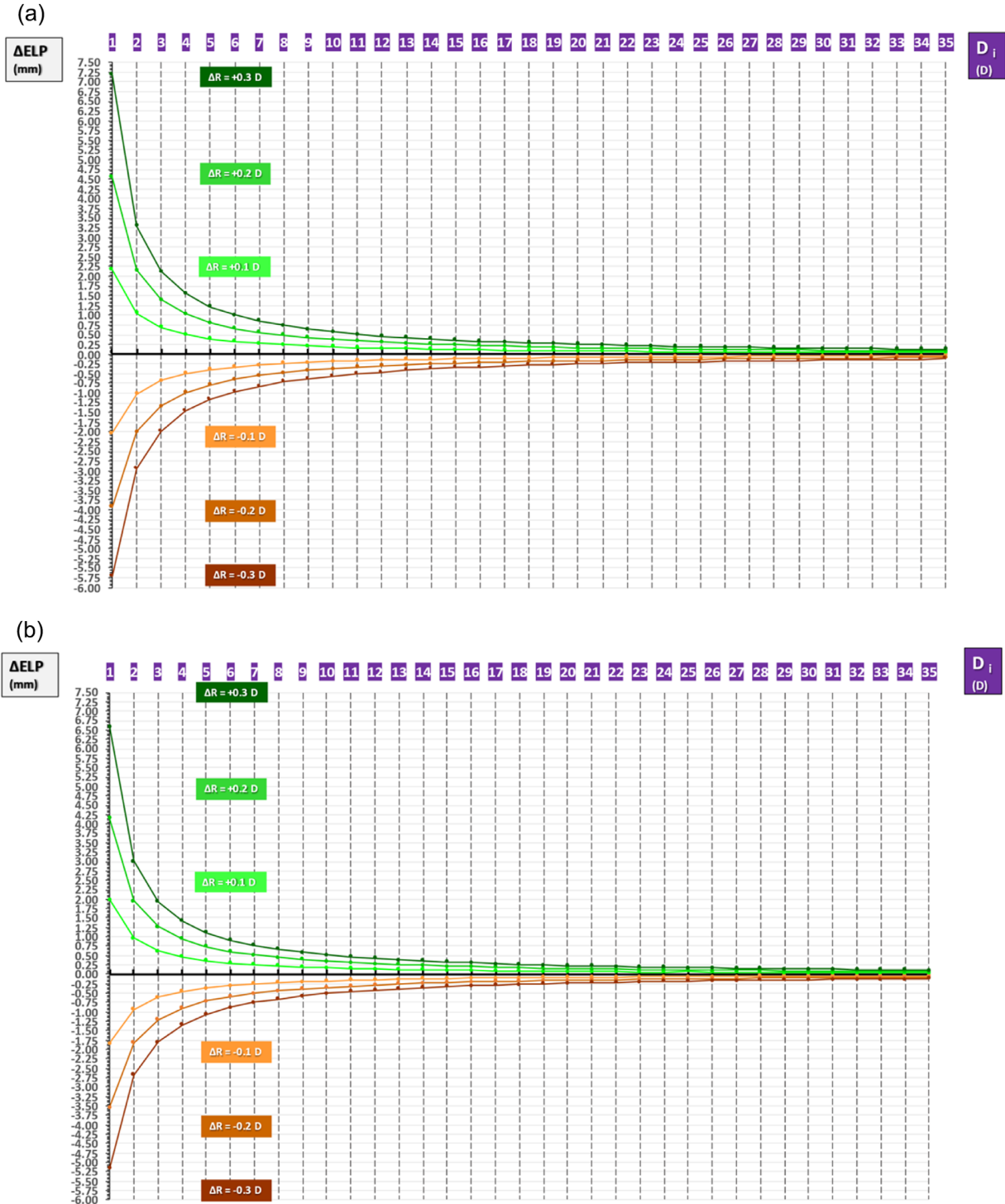


Figure 3. Theoretical change in ELP_T (ΔELP_T) necessary to induce a given variation in the spectacle plane refraction (ΔR) as a function of IOL power (D_i) for total corneal power: (a) $D_c = 38$ D, (b) $D_c = 43$ D, and (c) $D_c = 48$ D. A positive change corresponds to an increase in the ELP_T .

the same effects and the predominance of high-power implants. Due to manufacturing constraints and the variation in optical thickness related to changes in the refractive index and curvature of IOL surfaces, it is

likely that the differences in paraxial refraction induced by different IOLs are related to the conjunction of anatomical displacement of the lens body and a variation in their optical design.

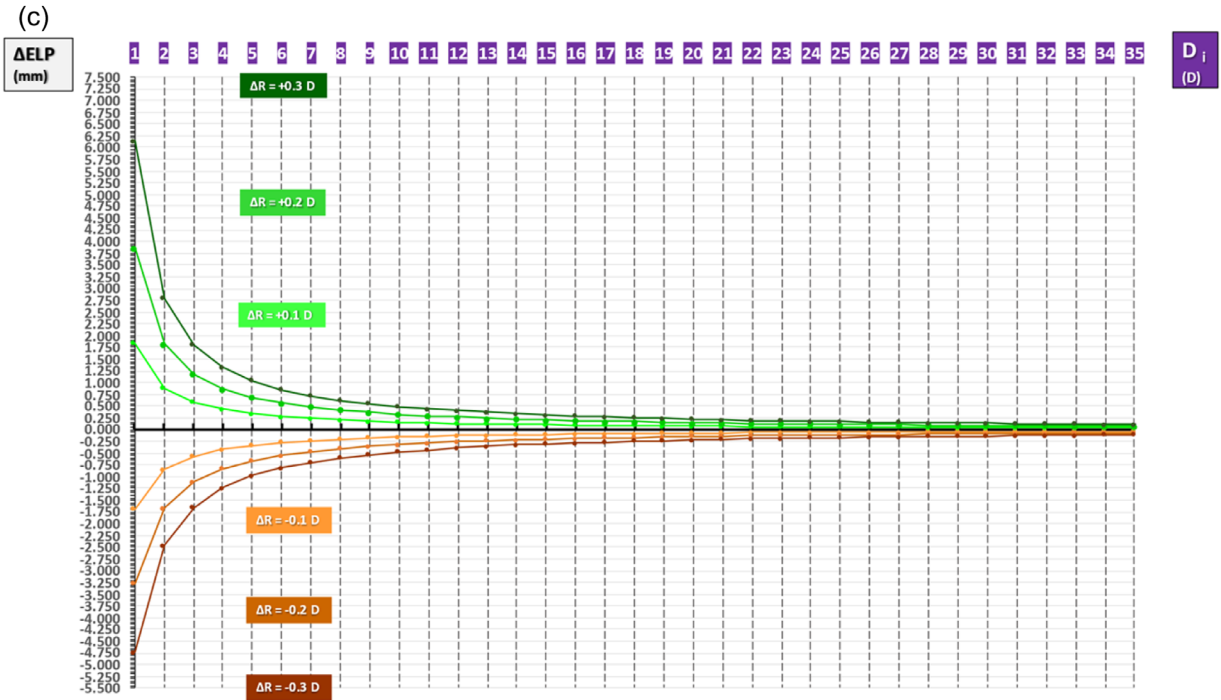


Figure 3. continued.

Holladay et al.¹³ recently put forward convincing arguments in favor of choosing the standard deviation (SD) of the prediction error as the most relevant criterion for comparing the results of formulas with each other after lens constant adjustment is made to nullify the arithmetic mean PE. However, our results suggest that the lens constant value to cancel the systematic bias is likely to unpredictably vary the SD of the recalculated PE. The data presented in Figure 4 show the influence of the implant power on the variation of theoretical refraction for the same variation of the ELP. On the other hand, Table 2 reveals that the ratio between the variation of IOL power and the variation in refraction is relatively constant throughout the IOL power range. An example of an unfavorable scenario for optimization is a formula whose systematic bias would be mainly linked to a larger PE in long eyes (having received a low-power implant, such as <10 D). Our calculations show that the quality of the ELP prediction is not a major determining criterion for long eyes. Yet, as the zeroization process will eventually shift the predicted effective position for all eyes by a constant increment, it may degrade the performance of the formula on short eyes receiving high-power implants. Our results suggest that taking into account the power distribution of implants could be useful in the context of formula optimization.

When analyzing the series retrospectively, some investigators have used the intraocular lens prediction error obtained by subtracting the predicted IOL power targeting the actual refraction following cataract surgery from the power of the IOL implanted.^{14,15} It is often assumed that 1 D of IOL prediction error results in 0.7 D of refractive error at the spectacle plane.^{16–18} However, the theoretical relationships between the refractive and the IOL power errors have not been extensively explored. Our results show that this ratio is valid for most biometric configurations but tends to be slightly different in extreme eyes. A constant increment of the IOL power induces a linear variation of the predicted refraction (Fig. 5), whose coefficient is relatively independent of the power of the considered IOL (Table 2). The compensation of a systematic refractive bias could be achieved by altering the target refraction by an amount equivalent to this bias. This would amount to adding or subtracting some constant value to the nominal power that would have been calculated for the IOLs without this adjustment. Such a zeroization process, based on a systematic variation added to the refractive target, would be less sensitive to the IOL power distribution of the dataset. It remains to be determined if the relative consistency of the ratio between the IOL and refractive prediction error would better preserve the performances obtained by the formula on the considered

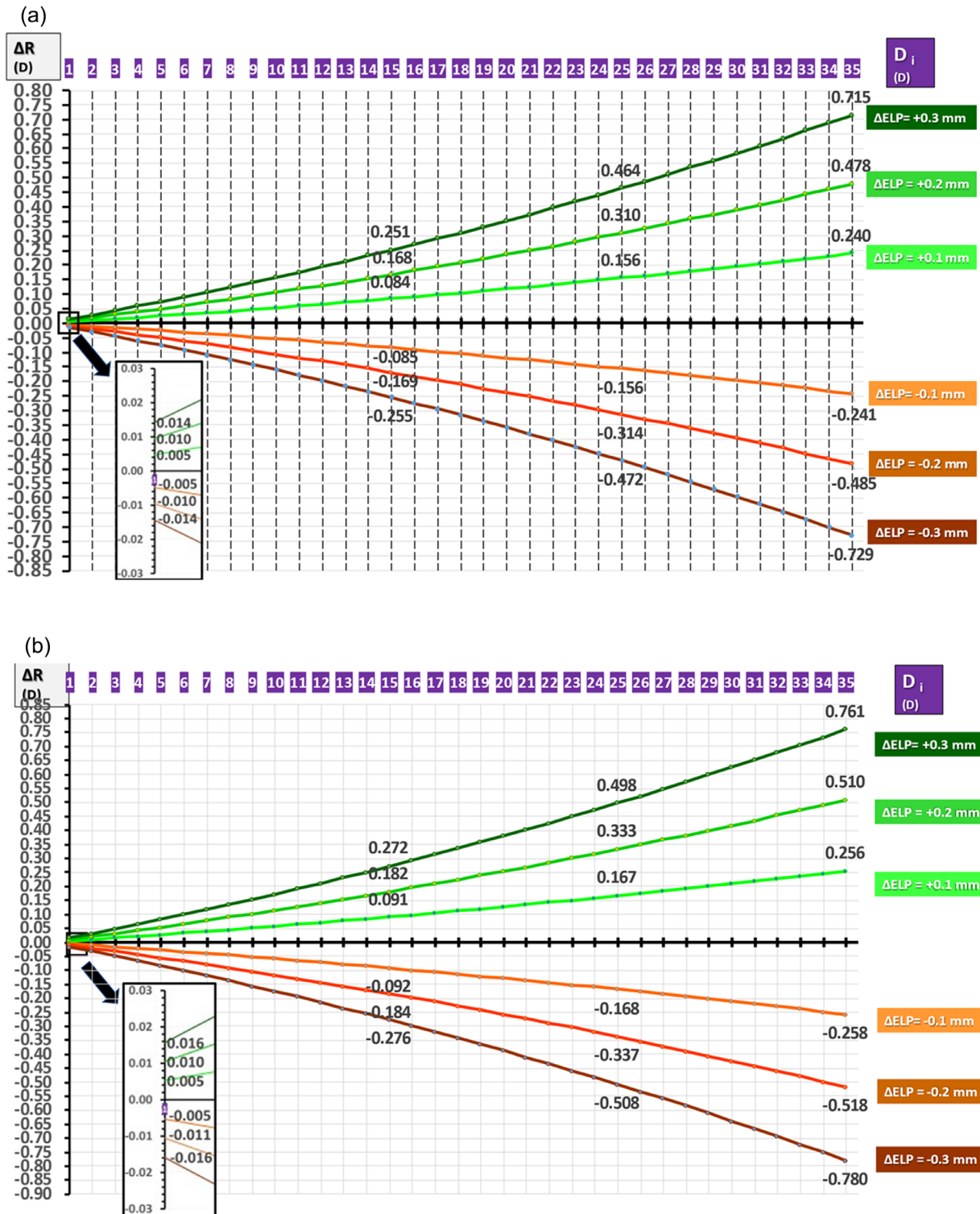


Figure 4. Change in spectacle plane refraction (ΔR) for various increments in ELP_T as a function of IOL power (D_i) for total corneal power: (a) $D_c = 38$ D, (b) $D_c = 43$ D, and (c) $D_c = 48$ D.

group before optimization when eliminating a systematic error. This would be achieved by adjusting for each eye (up or down) by an amount proportional to the arithmetic mean PE. Some of the dispersion and

average error in refractive accuracy are related to variations in IOL design and anatomical position. These variations occur across powers of the same IOL type. Optimizing a formula by adding an offset to the target

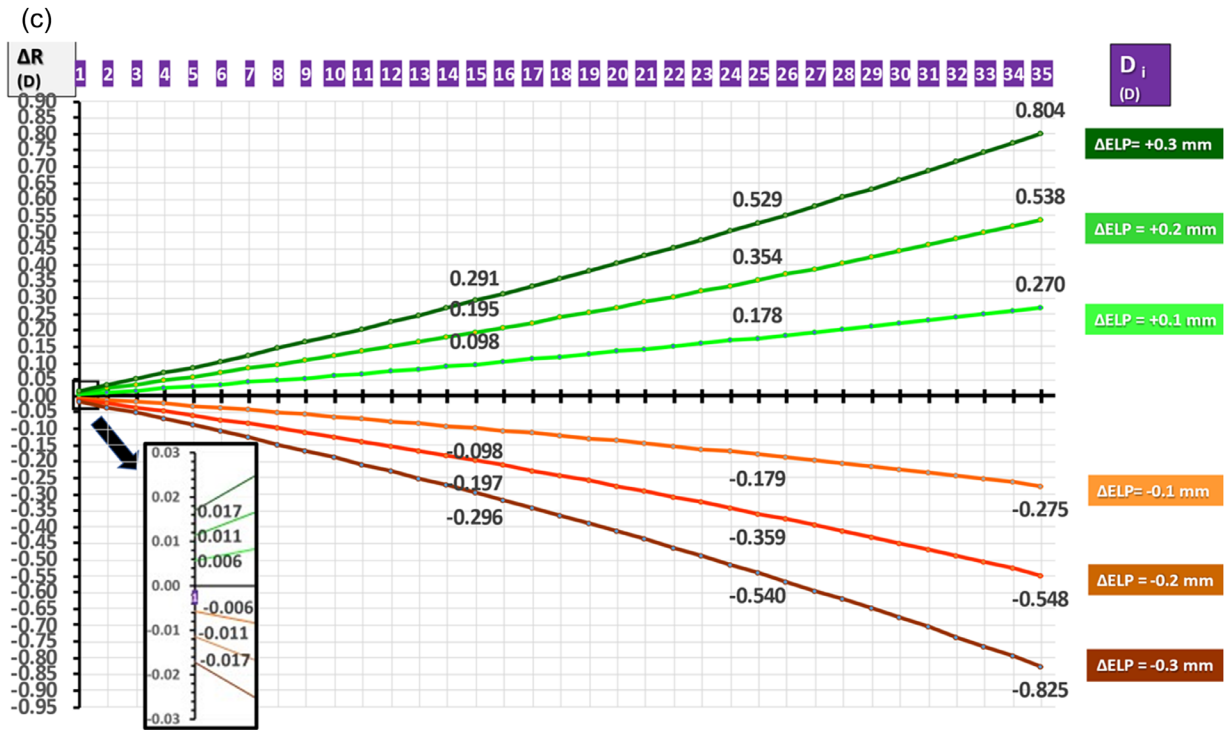


Figure 4. continued.

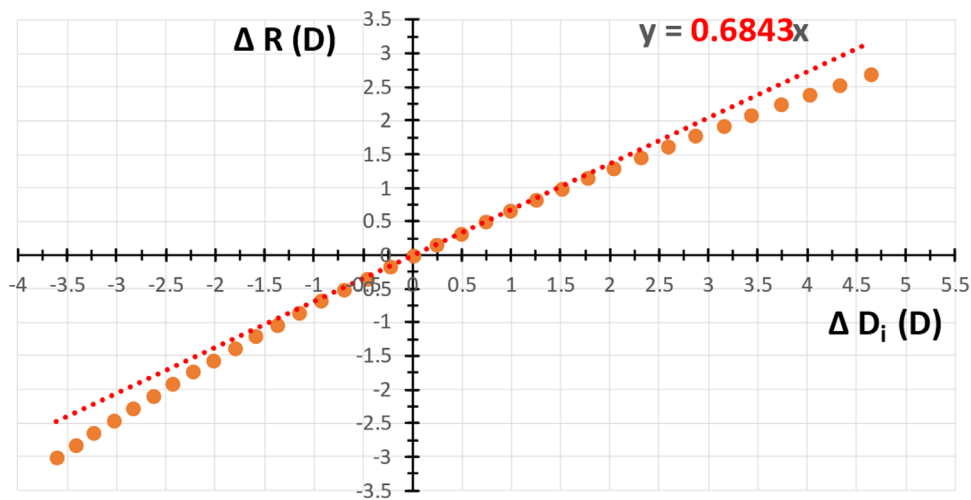


Figure 5. Relationship between the change in spectacle refraction and required change in IOL power to maintain emmetropia incurred by a shift of effective lens position (ELP_r) between -1.7 mm and $+1.7$ mm by 0.1 -mm steps for a pseudophakic eye implanted with an IOL of power $D_i = 25$ D and total corneal power $D_c = 43$ D.

refraction would have a more consistent effect over the entire power range of the IOLs compared with altering the predicted ELP. However, a constant increment of the ELP is justified to address the impact of an average change in the expected position on postoperative refraction caused by a change in IOL style. To overcome these problems, it may be beneficial to know the design characteristics of the implants to improve

the calculation methods using thick lens or ray-tracing-based IOL power formulas.

Our results were limited to formulas using a single lens constant for their optimization and do not perfectly apply to formulas with more than one constant, such as the Haigis and Castrop formulas.^{10,19,20} Instead of the straightforward calculation of the lens constants using formula inversion,

Table 2. Coefficients of Linear Regression (Estimated Ratio \pm 1.96 SD) Between IOL Power and Spectacle Refraction for Various Combinations of Corneal and IOL Powers

Di (D)	Dc (D)	Ratio	$\Delta ELP = +1$ mm		$\Delta ELP = -1$ mm	
			ΔDi (D)	ΔR (D)	ΔDi (D)	ΔR (D)
5	38	0.692 \pm 0.023	-0.34	-0.26	0.38	0.25
15	38	0.707 \pm 0.026	-1.11	-0.86	1.25	0.82
25	38	0.719 \pm 0.030	-2.00	-1.60	2.27	1.52
35	38	0.731 \pm 0.035	-3.00	-2.49	3.46	2.32
5	43	0.654 \pm 0.025	-0.39	-0.28	0.44	0.27
15	43	0.670 \pm 0.290	-1.25	-0.94	1.43	0.89
25	43	0.684 \pm 0.033	-2.23	-1.73	2.58	1.62
35	43	0.698 \pm 0.038	-3.32	-2.67	3.88	2.47
5	48	0.617 \pm 0.027	-0.44	-0.30	0.51	0.29
15	48	0.636 \pm 0.031	-1.40	-1.01	1.62	0.95
25	48	0.651 \pm 0.035	-2.46	-1.85	2.89	1.72
35	48	0.666 \pm 0.040	-3.63	-2.84	4.32	2.59

The variations in IOL power (ΔDi) and refraction at the spectacle plane (ΔR) induced by a variation of +1 mm and -1 mm of ELP_T are displayed. The values of all computed correlation coefficients (not shown) were higher than 0.99.

nonlinear optimization algorithms have been developed with very high performance that could optimize any target parameter with any optimization criterion. It can be a measure that has high relevance for the patient and the patient’s refractive outcome, such as the mean, the mean absolute, the median, or the root mean square error (RMSE) in terms of deviation of the achieved refraction after cataract surgery from the formula predicted refraction.¹⁹ Some prerequisites and methods for successful formula constant optimization have been published recently²⁰ as a nonlinear gradient descent method to search for an optimized constant that yields the lowest mean absolute or RMSE.

Our evaluation was simplified by using theoretical eyes initially focused on an object at infinity, even though in clinical practice an IOL may be chosen so that the best focus of the eye is at a closer distance.

systematic bias. Subsequently, the variation of a lens constant has a greater influence on the power computation in short eyes. This is due to high-power IOLs having a significant impact on the predicted refraction, even for small variations in ELP_T . The optimization of a formula based on multiple constants and nonlinear algorithms is certainly more robust against these biases. Nevertheless, any computational process requiring the adjunct of a constant shift in the predicted ELP value will be theoretically subject to these variations.

Acknowledgments

Disclosure: **D. Gatinel**, None; **G. Debellemanière**, None; **A. Saad**, None; **R. Rampat**, None

Conclusions

Our results highlight the influence of the preoperative biometry characteristics of eyes in the lens constant-based optimization process according to the influence of the IOL power. The corresponding increment in ELP_T is inversely proportional to the IOL power of the considered eye for the compensated

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