**NEW APPROACH FOR THE CALCULATION OF TOTAL CORNEAL
ASTIGMATISM CONSIDERING THE MAGNITUDE AND ORIENTATION OF
POSTERIOR CORNEAL ASTIGMATISM AND THICKNESS**

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Abstract

Purpose: To evaluate a new method of calculation of total corneal astigmatism based on Gaussian optics and the power design of a spherocylindrical lens (C) in the healthy eye and to compare it with keratometric (K) and power vector (PV) methods.

Methods: A total of 92 healthy eyes of 92 patients (age, 17 to 65 years) were enrolled. Corneal astigmatism was calculated in all cases using K, PV and our new approach C that considers the contribution of corneal thickness. An evaluation of the interchangeability of our new approach with the other two methods was performed using the Bland-Altman analysis.

Results: Statistically significant differences between methods were found in the magnitude of astigmatism ($p < 0.001$), with the highest values provided by K. These differences in the magnitude of astigmatism were clinically relevant when K and C were compared (Limits of agreement, LoA -0.40 to 0.62 D), but not for the comparison between PV and C (LoA, -0.03 to 0.01 D). Differences in axis of astigmatism between methods did not reach statistical significance ($p = 0.408$). However, they were clinically relevant when comparing K and C (LoA, -5.48 to 15.68°), but not for the comparison between PV and C (LoA, -1.68 to 1.42°).

Conclusion: The use of our new approach for the calculation of total corneal astigmatism provides comparable astigmatic results to the power vector method, suggesting that the effect of pachymetry on total corneal astigmatism is minimal in healthy eyes.

Keywords: total corneal astigmatism, Gaussian optics, keratometry, power vectors, keratometric astigmatism

Introduction

The calculation of total corneal astigmatism has become a hot topic since the introduction of toric intraocular lenses (IOLs) for the correction of pre-existing corneal astigmatism after cataract surgery.¹ Until recently, the classical keratometric approximation was used for the estimation of total corneal astigmatism, assuming that the cornea was a single dioptric surface separating two media, air and one fictitious media represented by the keratometric refractive index.² However, several studies have demonstrated that this approach can lead to significant errors in clinical practice,³ especially in eyes with abnormal corneal shape, such as keratoconus corneas⁴ or corneas after refractive surgery.⁵ Koch and colleagues⁶ concluded from a prospective study evaluating the anterior corneal astigmatism (ACA) and posterior corneal astigmatism (PCA) in healthy eyes that the effect of PCA on total astigmatism was not negligible. Specifically, these authors confirmed that the magnitude of PCA was correlated with ACA for patients with with-the-rule (WTR) astigmatism, while there was a weak and no correlation for oblique and against-the-rule (ATR) eyes, respectively.⁶ Miyake et al⁷ found that the magnitude and axis of PCA was not constant in the healthy cornea, especially when ATR ACA was present. Savini and colleagues⁸ found in a prospective case series evaluating corneal astigmatism in 157 healthy eyes with moderate to high corneal astigmatism that a difference in astigmatism magnitude of 0.50 D or more between keratometric and total corneal astigmatism was present in 16.6% of cases and a difference in the location of the steep meridian of more than 10° was present in 3.8% of cases.

The contribution of PCA to total astigmatism can lead to significant errors in toric IOL power calculations when classical approaches are used to estimate corneal

astigmatism. Several methods have been described in the last years for the estimation of total corneal astigmatism considering the effect of PCA, most of them aimed at optimizing the outcomes of toric IOLs.⁹⁻¹⁴ Goggin et al¹³ defined a coefficient of adjustment of 0.75 for WTR eyes and 1.41 for ATR eyes to be applied to the anterior corneal astigmatism power value in the calculation of toric IOL power. These adjustment coefficients applied only to those eyes that would have received IOLs with 2 diopters of cylinder or less and calculated with unadjusted measurements.¹³ Another method widely used is the Baylor toric IOL nomogram.¹⁴ Basically, the recommendation of this nomogram is to increase the recommended corneal astigmatism ranges for implantation in eyes with WTR ACA and to decrease them for eyes with ATR ACA.¹⁴ This approach allows for incorporating PCA in toric IOL power determination based on preoperative anterior corneal astigmatism. The aim of the current study was to define a new method of calculation of total corneal astigmatism using Gaussian optics and to study with it the real contribution of anterior and posterior corneal astigmatism to total corneal astigmatism in the healthy eye.

Methods

Calculation of total corneal astigmatism

We proposed a new method of calculation of total corneal astigmatism considering the geometric parameters of both corneal surfaces and pachymetry, and analyzing the corneal power in each meridian. For such purpose, the cornea was considered as an astigmatic surface with a behavior comparable to that of an ophthalmic lens. Therefore, the optical power in each meridian could be calculated independently.

A similar expression to that used by Dubbleman et al¹⁵ in 2006 was used. This expression considered the radius of curvature in each corneal meridian as a function of the orientation:

$$R(\theta) = R_1 - \Delta R \cos^2(\theta - axis) \quad (1)$$

,where R_1 was the radius in the reference meridian, ΔR the difference between curvature radii in the principal meridians, θ the orientation of the radius selected and *axis* the reference meridian axis.

In our study, this expression was used for the calculation of the optical power in both corneal surfaces (anterior P_1 and posterior P_2) as a function of the orientation (θ) in steps of 2.5° . Specifically, the expressions used for our calculations were the following:

$$P_1(\theta) = P_{1H} + (P_{1V} - P_{1H}) \sin^2(\theta - \alpha_1) \quad (2)$$

$$P_2(\theta) = P_{2H} + (P_{2V} - P_{2H}) \sin^2(\theta - \alpha_2) \quad (3)$$

,where $P_1(\theta)$ and $P_2(\theta)$ were the optical powers of the anterior and posterior surfaces of the cornea in the meridian θ , P_{1H} and P_{2H} the optical powers of the anterior and posterior surfaces of the cornea in the axes α_1 and α_2 , respectively, and P_{1V} and P_{2V} the optical powers of the anterior and posterior surfaces of the cornea in the perpendicular axes to α_1 and α_2 , respectively.

The total corneal power in each meridian was calculated afterwards in paraxial optics using the Gaussian equation for the calculation of the power of two-surface optical system:

$$P_C(\theta) = P_1(\theta) + P_2(\theta) - \frac{CCT}{n} P_1(\theta) P_2(\theta) \quad (4)$$

,where $P_C(\theta)$ was the total corneal power in the meridian evaluated, CCT the central corneal thickness, and n the refractive index of the cornea.

Once calculated the total corneal power values in each meridian, the principal meridians of the cornea were identified as those with the maximum and minimum power. With such information, the spherocylindrical expression could be obtained, considering the corneal astigmatism as the difference among the optical power of the two principal meridians, P_{Cmax} y P_{Cmin} . The corneal astigmatism was then calculated with the following expression:

$$CA_{calculated} = P_{Cmax} - P_{Cmin} \quad (5)$$

Clinical study

A total of 92 healthy eyes of 92 patients ranging in age from 17 to 65 years were enrolled in this prospective consecutive study. All patients were selected randomly from patients attending to the refractive surgery unit of the Department of Ophthalmology (Oftalmar) of the Vithas Medimar International Hospital (Alicante, Spain). Exclusion criteria were active ocular or systemic pathologies, previous ocular surgeries, corneal opacities or scars and any suspect of subclinical keratoconus. All patients were informed about their inclusion in the study and signed an informed consent in accordance with the tenets of the Declaration of Helsinki. The study was approved by the University ethics committee.

In all cases, a comprehensive ophthalmologic examination was performed including manifest refraction, corrected distance visual acuity, slit lamp biomicroscopy, Goldmann applanation tonometry and detailed examination of the corneal structure by

means of the Scheimpflug imaging-based topography system Pentacam (software version 1.14r01, Oculus Optikgeräte GmbH, Germany). With this topography system, the following parameters were recorded: radii of curvature in the principal meridians of the anterior corneal surface (r_{1H} y r_{1V}), radii of curvature in the principal meridians of the posterior corneal surface (r_{2H} y r_{2V}), magnitude and axis of anterior, posterior and total corneal astigmatism, and central corneal thickness (CCT). Likewise, total corneal astigmatism was also calculated with the method previously described considering then the magnitude and orientation of anterior and posterior corneal astigmatism and also using power vectors. For such calculations, the following refractive index values were considered: air ($n_a=1$), cornea ($n: 1.376$), and aqueous humour ($n_{ha}= 1.336$). The vector components J_0 and J_{45} as well as the overall strength blur (B) were calculated for anterior and posterior corneal power measurements using the standard procedure defined for such purpose.^{16,17} Total corneal power components were estimated as the sum of the power vector of both corneal surfaces. The magnitude and axis of total corneal astigmatism was obtained then considering the following expressions:^{16,17}

$$J_0 = (-C/2) \cos (2 \varphi) \text{ and } J_{45} = (-C/2) \sin (2 \varphi) \quad (6)$$

$$C=-2\text{sqrt}(J_0^2+J_{45}^2) \text{ and } \varphi =1/2 \arctan (J_{45}/J_0) \quad (7)$$

Data analysis

Data analysis was performed using the statistical software SPSS version 19.0 for Windows (IBM, Armonk, NY, USA). Normality of data distributions was first confirmed by means of the Kolmogorov-Smirnov test. The one-way repeated measures analysis of variance (ANOVA) was used for comparisons between methods of estimation of corneal astigmatism, with the use of the Bonferroni method as a test for post-hoc analysis. Besides

the analysis of differences between methods of calculation of total astigmatism, an evaluation of the interchangeability of our new approach with the keratometric and power vector methods was performed using the Bland-Altman method. The limits of agreement (LoA) were defined as the mean ± 1.96 standard deviation (SD) of the differences. In addition, Pearson correlation coefficients were used to assess the correlation between different parameters. For all statistical tests, a p-value of less than 0.05 was considered as statistically significant.

Results

A total of 92 healthy right eyes of 92 patients ranging in age from 21 to 52 years old were evaluated. Table 1 summarizes the main characteristics of the sample evaluated. An anterior with-the-rule corneal astigmatism was present in 71 eyes (77.2%), whereas against-the-rule and oblique astigmatisms were present in 12 (13.0%) and 9 eyes (9.8%), respectively. Table 2 displays a comparative analysis of the astigmatism calculations obtained with each method. As shown, statistically significant differences between methods in mean keratometry and magnitude of astigmatism were found ($p < 0.001$), with the highest values provided by the keratometric approach. In contrast, differences in axis of astigmatism between methods did not reach statistical significance ($p = 0.390$).

The difference in magnitude of astigmatism between the keratometric method and our approach ranged from -1.68 to 0.42 D, with a mean value of 0.11 D. Significant differences were found in this difference between eyes with WTR, ATR and oblique astigmatisms, as shown in Figure 1 ($p = 0.013$). Specifically, a significantly higher difference between methods in the magnitude of astigmatism was found in eyes with WTR astigmatism compared to those with oblique component ($p = 0.003$). The Bland and

Altman analysis revealed the presence of clinically relevant differences between the magnitudes of astigmatism calculated with keratometric method and our approach (Figure 2A), with LoA of -0.40 and 0.62 D. In contrast, no clinically relevant differences were found between our new approach and power vector method in terms of magnitude of astigmatism (Figure 2B), with LoA of -0.03 and 0.01 D.

Concerning astigmatism axis, the difference between the keratometric method and our approach ranged from 0° to 28.40°, with a mean value of 5.09°. There were also significant differences in the axis discrepancy among eyes with WTR, ATR and oblique astigmatism ($p<0.001$) (Figure 3). Specifically, the astigmatism axis difference among our approach and the keratometric method was significantly lower in those eyes with WTR astigmatism compared to those with ATR ($p=0.019$) or oblique astigmatism ($p<0.001$) (Figure 3). The Bland and Altman analysis revealed the presence of clinically relevant differences between the axes of astigmatism calculated with keratometric method and our approach (Figure 4A), with LoA of -5.48 and 15.68°. In contrast, no clinically relevant differences were found between our new approach and power vector method in terms of magnitude of astigmatism (Figure 4B), with LoA of -1.68 and 1.42°.

The analysis of the relationship between the difference in the magnitude of astigmatism obtained with the keratometric method and our approach, and the magnitude of the astigmatism revealed the presence of a poor but statistically significant correlation was found ($r=0.321$, $p=0.002$) (Supplemental digital content Figure 1). Concerning astigmatism axis, no significant correlation was found between the differences in astigmatism axis between methods and the axis of astigmatism calculated with the keratometric approach ($r=-0.194$, $p=0.064$) (Supplemental digital content Figure 2).

Discussion

A precise calculation of total corneal astigmatism is necessary in clinical practice to avoid unexpected residual refractive errors in eyes implanted with phakic and pseudophakic toric IOLs.¹⁸⁻²⁰ For such purpose, the contribution of the posterior corneal surface to total corneal astigmatism must be considered as its effect is not negligible as it is assumed by the keratometric approach.⁶⁻⁸ This is especially relevant in eyes with keratoconus in which the contribution of an altered posterior corneal surface shape is clinically relevant.²¹ This has led in the last years to the definition of different approaches to consider the contribution of posterior corneal astigmatism to total corneal astigmatism.⁹⁻¹⁴ Abulafia and colleagues²² developed a new regression formula (Abulafia-Koch) to calculate the total corneal astigmatism using as a basis the standard keratometry measurements. They concluded in a retrospective case series study the adjustment of commercial toric IOL calculators by the Abulafia-Koch formula significantly improved the prediction of postoperative astigmatic outcome.²² Likewise, some Scheimpflug imaging-based topography systems have included estimations of total corneal astigmatism based on different approaches that are not completely interchangeable.^{23,24} In the current study, we proposed a new methodology of calculation of total corneal astigmatism, considering not also the contribution of posterior corneal curvature, but also the contribution of corneal thickness. We have compared the outcomes obtained with this methodology with the power vector methodology that considers the astigmatism of both corneal surfaces and also with the classical keratometric astigmatism.

In our sample of healthy eyes, significant differences were obtained among magnitude of total corneal astigmatism calculated using our new approach and using the

classical keratometric method. The Bland and Altman analysis confirmed that these differences were not only statistically significant, but also clinically relevant, with large values of LoA. This confirms the results of previous studies demonstrating that neglecting the contribution of the posterior corneal surface to total astigmatism can lead to significant errors.⁶⁻⁸ These inaccuracies in the estimation of the total corneal astigmatism using the keratometric approximation are one of the main sources of predictability errors in cataract surgery with implantation of toric IOLs, as the IOL power calculation is biased due to the use of an imprecise value of corneal astigmatism.^{18-20,25} Specifically, we have found a trend of the keratometric astigmatism to overestimate WTR astigmatisms and to underestimate ATR astigmatisms compared to our method. Other authors have found the same trend comparing with the classical Gaussian method or other approaches of calculating total corneal astigmatism.^{6,21,26,27} Therefore, our approach reproduces the same trends found with other methods of analysis. Zhang et al²⁶ compared the automated keratometer method with the total corneal astigmatism provided by the Galilei dual rotating camera Scheimpflug-Placido tomographer and also found that keratometry tended to overestimate WTR astigmatism and underestimate ATR astigmatism. Savini and colleagues²¹ found a mean value of keratometric overestimation in WTR astigmatisms of 0.22 ± 0.32 D, mean keratometric underestimation of ATR astigmatisms of -0.21 ± 0.26 D, and mean overestimation of oblique astigmatisms of 0.13 ± 0.37 D. These outcomes are very similar to those found in our sample when the keratometric approach is compared to our method, with mean values of 0.19, -0.29 and 0.06 D, respectively. Eom et al²⁸ concluded in a prospective study including healthy eyes that posterior corneal astigmatism should be considered for more accurate corneal astigmatism predictions, especially in eyes with anterior corneal astigmatism greater than 2.0 D of WTR astigmatism or greater than 1.8 D of ATR astigmatism.

Concerning the axis of astigmatism, no significant differences were found between methods in our study. However, there were clinically relevant differences among the axes obtained with the keratometric method and that obtained with our new approach according to the Bland and Altman analysis, with differences between methods up to 15°. These differences were especially large in eyes with oblique astigmatism which is consistent with the findings of previous studies demonstrating the poor correlation among the astigmatisms of the anterior and posterior corneal surfaces.^{7,14} In contrast, no statistically significant and clinically relevant differences were found between the axis of the astigmatism calculated with the power vector and our method which suggests that the contribution of thickness to the difference in axis between power vector and our method is negligible.

Several factors contribute to the error of the keratometric approach in providing a precise estimation of total corneal astigmatism, including the contribution of the magnitude of posterior corneal astigmatism, the difference between the axes of anterior and posterior corneal astigmatisms,^{7,8} and the potential effect of corneal thickness. With our approach, we consider all these factors, including the potential pachymetric influence. When comparing our outcomes with those obtained with the power vector method, no statistically significant and clinically relevant differences were found, which suggests that the potential contribution in healthy eyes of errors in the estimation of total corneal astigmatism is minimal.

In conclusion, the use of a vector analysis is recommended to estimate the total corneal astigmatism as the keratometric approach can lead to clinically relevant errors. Therefore, the contribution of posterior corneal astigmatism to total corneal astigmatism should be considered in clinical decisions, especially in toric IOL power calculations. The use of a new approach for the calculation of total corneal astigmatism based on Gaussian

optics and the power design of a spherocylindrical lens is a useful method that provides comparable astigmatic results to the power vector method. This method considers the contribution of pachymetry to total corneal astigmatism that has been shown to be minimal in our population of healthy eyes. Future studies including eyes with abnormal corneal thickness, such as keratoconus or corneal edema, should be conducted to confirm if our approach of total corneal astigmatism calculation is more accurate than the power vector method.

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Figure legends

Figure 1.- Mean difference in the magnitude of astigmatism between the keratometric method and our approach in eyes with WTR, ATR and oblique astigmatism.

Figure 2.- Bland-Altman plot for the comparison between the magnitudes of astigmatism obtained with the keratometric method (K) and our new calculated approach (C) (A), and between the power vector method (PV) and our new calculated approach (C) (B). The dashed lines show the limits of agreement ($\pm 1.96SD$) and the dotted line the mean difference between the methods compared.

Figure 3.- Mean difference in the axis of astigmatism between the keratometric method and our approach in eyes with WTR, ATR and oblique astigmatism.

Figure 4.- Bland-Altman plot for the comparison between the axes of astigmatism obtained with the keratometric method (K) and our new calculated approach (C) (A), and between the power vector method (PV) and our new calculated approach (C) (B). The dashed lines show the limits of agreement ($\pm 1.96SD$) and the dotted line the mean difference between the methods compared.

Supplemental digital content figure legends

Supplemental digital content figure 1:

- Title: relationship between the magnitude of astigmatism and the difference between methods of estimation
- Brief summary: scattergram showing the relationship between the difference in the magnitude of astigmatism obtained with the keratometric method and our new approach, and the magnitude of keratometric astigmatism.

Supplemental digital content figure 2:

- Title: relationship between the axis of astigmatism and the difference between methods of estimation
- Brief summary: scattergram showing the relationship between the difference in the axis of astigmatism obtained with the keratometric method and our new approach, and the axis of keratometric astigmatism.

Tables

Table 1.- Main features of the sample evaluated.

Parameter	Mean (SD)
	Median (Range)
K1a (D)	7.76 (0.25)
	7.78 (7.27 to 8.59)
K2a (D)	7.58 (0.25)
	7.63 (6.96 to 8.28)
K1p (D)	6.48 (0.24)
	6.48 (5.95 to 7.09)
K2p (D)	6.13 (0.25)
	6.14 (5.38 to 6.67)
CCT (μm)	559.23 (34.04)
	560.00 (485 to 665)

*Abbreviations: SD, standard deviation; D, diopters; K1a, corneal radius of the flattest meridian of the anterior corneal surface in the central 3-mm zone; K2a, corneal radius of the steepest meridian of the anterior corneal surface in the central 3-mm zone; K1p, corneal radius of the flattest meridian of the posterior corneal surface in the central 3-mm zone; K2p, corneal radius of the steepest meridian of the anterior corneal surface in the central 3-mm zone; CCT, central corneal thickness.

Table 2.- Differences among keratometric (K), power vector (PV) and our approach in terms of total corneal astigmatism (C) in the sample evaluated.

Mean (SD) Median (Range)	Keratometric (K)	Power vectors (PV)	New method (C)	P-value
<i>Mean corneal power (D)</i>	44.04 (1.34)	43.22 (1.45)	43.34 (1.46)	<0.001
	43.96 (40.03 to 46.95)	43.05 (39.11 to 46.82)	43.17 (39.22 to 46.96)	K-C <0.001 K-PV <0.001 PV-C <0.001
<i>AST (D)</i>	1.16 (0.97)	1.04 (0.91)	1.05 (0.92)	<0.001
	0.88 (0.06 to 5.77)	0.76 (0.05 to 5.37)	0.77 (0.05 to 5.41)	K-C <0.001 K-PV <0.001 PV-C <0.001
<i>Axis (D)</i>	92.10 (73.06)	99.86 (70.16)	100.00 (70.20)	0.390
	94.55 (0.60 to 180)	109.32 (0.18 to 179.71)	109.50 (0.00 to 180)	

*Abbreviations: SD, standard deviation; D, diopters; AST, magnitude of corneal astigmatism.

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