Agreement Between Refractive and Corneal Astigmatism in Pseudophakic Eyes

Jaime Tejedor, MD, PhD† and Antonio Guirao, PhD‡*

Purpose: To examine the agreement and relationship between refractive and corneal astigmatism in a population of pseudophakic eyes.

Methods: Patients of age at least 40 years, visual acuity 20/40 or better, and no ocular disease were included (n = 111). Refractive astigmatism was obtained by subjective refraction. Corneal astigmatism was measured by automated keratometry and Scheimpflug scanning analysis. All refractive values were converted to power vector components J_0 and J_{45} for comparison and regression analysis of refractive versus corneal astigmatism. Main outcome measures were refractive and corneal astigmatism components.

Results: Median single Jackson cylinder (J) was similar in refractive [0.37 diopter (D)], keratometric (0.46 D), and Pentacam astigmatism (0.49 D) ($P = 0.157$). Median J_0 astigmatic component was slightly negative, indicating against-the-rule (ATR) astigmatism, in refractive and Scheimpflug, but not in keratometric astigmatism (refractive J_0: −0.10 D; keratometric J_0: 0.05 D; Pentacam J_0: −0.08 D) ($P = 0.049$). J_{45} astigmatic component was nearly zero and similar with the 3 methods ($P = 0.416$). Refractive and keratometric J_0 were significantly correlated ($r = 0.7$, $P < 0.01$), as well as the corresponding J_{45} values ($r = 0.65$, $P < 0.01$). Refractive and Pentacam astigmatic components were worse correlated (J_0: $r = 0.36$, $P = 0.01$; J_{45}: $r = 0.45$, $P < 0.01$). Keratometric and Pentacam astigmatic components were also significantly correlated (J_0: $r = 0.58$, $P < 0.01$; J_{45}: $r = 0.51$, $P < 0.01$).

Conclusions: Mean internal ATR astigmatism, which comes mainly from the posterior corneal surface, adds to anterior corneal astigmatism, resulting in ATR refractive astigmatism. Correlation between refractive and corneal astigmatism components is better when keratometric data are used.

Key Words: pseudophakia, refractive astigmatism, corneal astigma tism

(*Cornea* 2013;32:783–790)

Received for publication April 27, 2012; revision received August 3, 2012; accepted August 4, 2012.

From the *Department of Ophthalmology, Hospital Ramón y Cajal, Madrid, Spain; †Faculty of Medicine, Universidad Autónoma de Madrid, Madrid, Spain; and ‡Department of Physics, Universidad de Murcia, Murcia, Spain.

Supported by a grant from Fundación Séneca, Agencia de Ciencia y Tecnología de la Región de Murcia, Spain (08,805/PI/08).

Presented in part at ARVO Annual Meeting, May, 2011, Fort Lauderdale, FL.

The authors declare no conflicts of interest.

Reprints: Jaime Tejedor, Department of Ophthalmology, Hospital Ramón y Cajal, C Colmenar km 9100, Madrid 28034, Spain (e-mail: jaime.tejedor@telefonica.net).

Most human eyes show at least a slight degree of astigmatism. The 2 main contributory factors in refractive (ocular) astigmatism are the cornea and the crystalline lens. The curvature of the front surface of the cornea is the principal factor causing refractive astigmatism and can readily be measured by classical keratometry. The remaining factors are considered responsible for internal astigmatism, including the posterior corneal surface, the crystalline lens, and some unknown "retinal" components. In clinical practice, it is commonly accepted that the lens tends to compensate for moderate corneal astigmatism. However, the degree of balance between cornea and lens depends on each individual and changes with age.[1,2]

Keratometric corneal measurements are taken from points in the central anterior cornea and estimate the total corneal power by a reduced refractive index, that is, an averaged corneal refractive index that takes into account the anterior surface, different layers of the cornea, and negative power of the corneal back surface, not actually measured.

Javal[3] found that refractive astigmatism could be calculated from keratometric corneal astigmatism when the principal meridians of the eye were 0 degree and 90 degrees (Javal's rule), as follows:

$$\text{Correcting cylinder} = 1.25 \times \text{Keratometric astigmatism} + (-0.50 \times 90^\circ)$$

although the relationship between refractive and keratometric astigmatism could be regarded as nonlinear.[4] Javal assumed a constant value of −0.5 diopter (D) associated with the internal astigmatism of the eye, but it is an average estimate of the population because there is a lenticular component that varies individually.

Although a lenticular component may be a significant source of refractive astigmatism in phakic normal subjects, in pseudophakic patients, corneal astigmatism is considered, virtually, the only important factor, as toric intraocular lens (IOL) calculation methods assume, particularly when incisional astigmatic corneal change is induced.[5,6] However, we have found discrepancies between the axis of refractive and corneal astigmatism, and between refractive and corneal astigmatic power, in pseudophakic patients. Influence of the posterior cornea and, to a lesser extent, of the IOL, and other factors is presumed. Understanding and describing this discrepancy is of interest because astigmatic error has a much greater effect on the likelihood of spectacle use than overall error after routine cataract surgery.[7] This information may be valuable to correct astigmatism during cataract surgery, using toric IOL implantation or corneal limbal relaxing incisions.

Descriptions of the correlation between pseudophakic corneal and refractive astigmatism are few and use keratometric values.[8] Directly obtained measurements based on corneal elevation or height data and posterior corneal measurements are not included. In the present study, we investigate the agreement between power and axis of refractive and corneal astigmatism, and the ability to predict refractive astigmatism, using keratometry and elevation-based anterior and posterior corneal power measurements in pseudophakic eyes.

METHODS

Subjects

Consecutive eligible patients who had undergone cataract surgery were considered for this study. Research followed the tenets of the Declaration of Helsinki and was approved by the Ethics Committee (grant 08,805/PI/08). Informed consent was obtained from the subjects after explanation of the nature and possible consequences of the study. Inclusion criteria comprised visually significant cataract causing difficulty in daily tasks, developed as an adult of at least 40 years. Subjects with postoperative visual acuity worse than 0.3 logarithm of the minimum angle of resolution (Snellen equivalent 20/40), amblyopia, or ocular disease other than cataract were excluded.

Cataract Surgery Procedure

Preoperative evaluation included uncorrected and corrected visual acuity at distance (ETDRS chart), refraction, keratometry (IOLMaster V. 4.07; Carl Zeiss, Göttingen, Germany), eye scanner analysis (Pentacam; Oculus, Wetzlar, Germany), intraocular pressure, biomicroscopy, biometry and IOL calculation using SRK/T formula (IOLMaster), and funduscopy. In axial length measurements below 22.0 mm or above 26.0 mm, Hoffer Q and Holladay formulae were used, respectively, to check SRK/T calculation values. An index of refraction of 1.3375 was set in IOLMaster for corneal measurements. Default index of refraction was used in Pentacam measurements ($n_{cornea} = 1.376$, $n_{aqueous} = 1.336$, $n_{total\ cornea} = 1.3375$). Surgery was performed under topical anesthesia or retrobulbar block. We made a 3-step clear corneal incision (2.75-mm blade) in all cases, following previously published guidelines. Temporal incisions were used for astigmatism lower than 0.5 D, and nasal and superior incisions were used when the steepest axis was located at approximately 180 degrees and 90 degrees, respectively.[9,10] After introduction of viscoelastic material into the anterior chamber, a 5-mm capsulorrhexis was followed by hydrodissection, stop and chop phacoemulsification technique, aspiration of cortical masses, and introduction of Acrysof SA60AT single-piece foldable IOL (Alcon Laboratories, Fort Worth, TX) through an IOL insertion cartridge (Monarch II "C" cartridge; Alcon Laboratories).

In postoperative examinations, we repeated testing of visual acuity, keratometry, intraocular pressure, and biomicroscopy at 2 weeks and at 1, 3, and 6 months. Eye scanner (Scheimpflug) analysis was repeated only at 6 months.

Astigmatism Measurements and Analysis

Refractive astigmatism was obtained by subjective refraction. Corneal astigmatism was measured by 2 different methods: keratometry ($corneal_k$) and Scheimpflug camera scanning analysis ($corneal_s$). All measurements were systematically taken by the same person (J.T.). In keratometry, the mean of 3 measurements was used for the analysis. Scheimpflug technology measurements were acceptable when automatic image acquisition (automatic release) well-centered images, considered as valid by the device (Quality Specification OK), were obtained. Scheimpflug measurements were determined on the 3-mm ring of the cornea because, in these meridians, orthogonality is easily established [Pentacam (Oculus) instruction manual, page 44] and resemble keratometric measurements. To obtain $corneal_s$, anterior cornea and posterior cornea (negative) data provided by the Scheimpflug method were added by the authors, not directly obtained from Pentacam readings, for an estimation of the total contribution of the cornea to astigmatism (using the formula $corneal_s = Kant + Kpost - (t/1.376)Kant \times Kpost$, where Kant = anterior corneal power, Kpost = posterior corneal power, and t = corneal thickness). Thus, $corneal_s$ includes posterior measured corneal astigmatism, whereas $corneal_k$ includes an average constant posterior astigmatism. From both kinds of measurements, internal astigmatism (with possible contribution of IOL, retinal or unknown factors, and a possible residual for the posterior cornea in $corneal_k$) was derived as the difference between refractive and $corneal_k$ or $corneal_s$ vector components.

All refractive values were converted from diopters to power vector components,[11] as previously described,[9] to examine the effect of 2.8-mm corneal incisions: spherical lens of power M, Jackson cross cylinder at axis 180 degrees of power J_0, and Jackson cross cylinder at axis 45 degrees of power J_{45}. Power J_{45} represents oblique astigmatism. The projection of the power vector P (interpreted as a measure of the overall blurring effect) onto the astigmatic plane, called vector J (which represents the cylinder as a single Jackson cylinder lens), was also derived. Negative cylinder notation was always used throughout. In this representation, positive values of J_0 indicate with-the-rule (WTR) astigmatism and negative values indicate against-the-rule (ATR) astigmatism.[11]

The main outcome measure was refractive and corneal astigmatism components at 6 months postoperatively. Comparisons were made using the Friedman test because 3 variables were compared in the same subject, with distributions that were not always normal (refractive, keratometric, and Scheimpflug astigmatic components). We used Spearman rank correlation coefficients to study correlations between variables, and comparisons of correlation coefficients were made by the Hotelling test. Bland–Altman plots were created to estimate the agreement between measurements, and 95% limits of agreement were also yielded as the mean $\pm$ 1.96 SD of the difference. A significance level of $P < 0.05$ was chosen for all tests. Statistical analysis was run using SPSS (SPSS Inc, Chicago, IL).

RESULTS

Of 128 potential eligible subjects, 111 patients were included in the study (one eye per patient). Six patients declined participation and 11 were excluded because of poor visual acuity (with the diagnosis of age-related macular degeneration changes in 6, optic neuropathy in 3, and presumable amblyopia in 2). Preoperative characteristics of the patients included are summarized in Table 1. Six-month postoperative median refractive cylinder power was −0.75 D (range: −2.50 to 0 D), keratometric median corneal cylinder power was −0.93 D (range: −2.26 to −0.10 D), and Scheimpflug scan median corneal cylinder power was −0.98 D (range: −3.33 to −0.10 D), as depicted in Figure 1 (P = 0.157). Median cylinder axis at 6 months postoperatively was not significantly different between refractive (95 degrees; range: 0.17 degree–180 degrees), keratometric (102.6 degrees, range: 0.57 degree–180 degrees), and Scheimpflug scan (103.7 degrees, range: 20.6 degrees–174.8 degrees) measures (P = 0.323). For a more appropriate description and statistical analysis of the magnitude and axis of astigmatism, vector decomposition is recommended.

Variable distribution departed from normality in all refractive components but was compatible with normality in corneal_k and corneal_s astigmatic components. After power vector decomposition, median J (which represents the cylinder as a single Jackson cylinder) was similar in refractive (0.37 D; range: 0–1.25 D), corneal_k (0.46 D; range: 0.05–1.13 D), and corneal_s obtained using Scheimpflug scanning technology (0.49 D; range: 0.05–1.67 D) (P = 0.157). J_{45} astigmatic component was nearly zero, and not significantly different, in refractive, corneal_k, and corneal_s astigmatism (median refractive J_{45}: −0.000 D, range: −0.99 to 0.62 D; median corneal_k J_{45}: −0.002 D, range: −0.77 to 0.64 D; median corneal_s J_{45}: −0.11 D, range: −1.46 to 1.06 D) (P = 0.416). Median J_0 astigmatic component was slightly negative, indicating ATR astigmatism, in refractive and Scheimpflug but not in keratometric astigmatism (refractive J_0: −0.10 D, range: −1.25 to 0.86 D; corneal_k J_0: 0.05 D, range: −1.03 to 1.02 D; corneal_s J_0: −0.08 D, range: −0.85 to 0.79 D) (P = 0.049, with significant refractive–keratometric pairwise comparison, $P < 0.01$). Refractive J_0 was the only clearly left-skewed (negative) component. Interestingly, median anterior corneal_s J_0 was negative (−0.026 D, range: −1.20 to 0.82 D), whereas posterior corneal_s J_0 was positive (0.07 D, range: −0.50 to 0.34 D). However, because the transition of the posterior corneal surface to the aqueous humor causes subtraction of refractive power, the more curvature (ie, power) at or near the vertical meridian in the back corneal surface contributes to the induction of ATR. Thus, both anterior and posterior corneal surfaces contribute, on average, to the described refractive ATR astigmatism in pseudophakic eyes, although some unknown internal factors could participate.

Correspondence Between Keratometric and Refractive Astigmatism

Linear regression and correlation between refractive and corneal_k astigmatism components were obtained. Refractive and corneal_k J_0 were significantly correlated (r = 0.7, $P <$ 0.01; Fig. 2A), and also the corresponding J_{45} values (r = 0.65, $P < 0.01$; Fig. 2B).

The linear regression equations obtained were as follows:

$$\text{RefJ}_0 = 0.61 \times \text{Cor}_k\text{J}_0 + (-0.13)$$

$$\text{RefJ}_{45} = 0.64 \times \text{Cor}_k\text{J}_{45} + (0.01)$$

Using the above equations, refractive astigmatism may be inferred from keratometric astigmatism in pseudophakic patients, as previously described in phakic patients at different ages. Bland-Altman plots show good agreement between refractive and keratometric J_0 (difference: −0.147 D ± 0.682) and J_{45} astigmatic components (difference: 0.032 ± 0.432) (Figs. 3A, B, respectively).

Median internal astigmatism J_0 was −0.19 D (range: −1.21 to 1.08 D), which indicates ATR astigmatism, and median internal J_{45} obtained was 0.01 D (range: −0.68 to

TABLE 1. Preoperative Characteristics of Patients Included

	N	Mean	95% Confidence Interval	Median	Range
Age, yr	111	73.1	71.2 to 75.0	76	50 to 81
Cylinder, D					
Corneal_k	111	−0.98	−1.10 to −0.86	−0.84	−3.05 to 0
Corneal_s	111	−1.01	−1.23 to −0.85	−0.90	−3.11 to −0.03
J_0					
Corneal_k	111	0.04	−0.05 to 0.13	0.04	−1.41 to 1.13
Corneal_s	111	−0.08	−0.18 to 0.08	−0.06	−1.28 to 1.37
Negative	62				
Positive	47				
Null	2				
J_{45}					
Corneal_k	111	−0.02	−0.08 to 0.03	−0.002	−1.20 to 0.74
Corneal_s	111	0.03	−0.06 to 0.09	0.02	−0.83 to 1.27
Incision					
Temporal	55				
Nasal	51				
Superior	5				

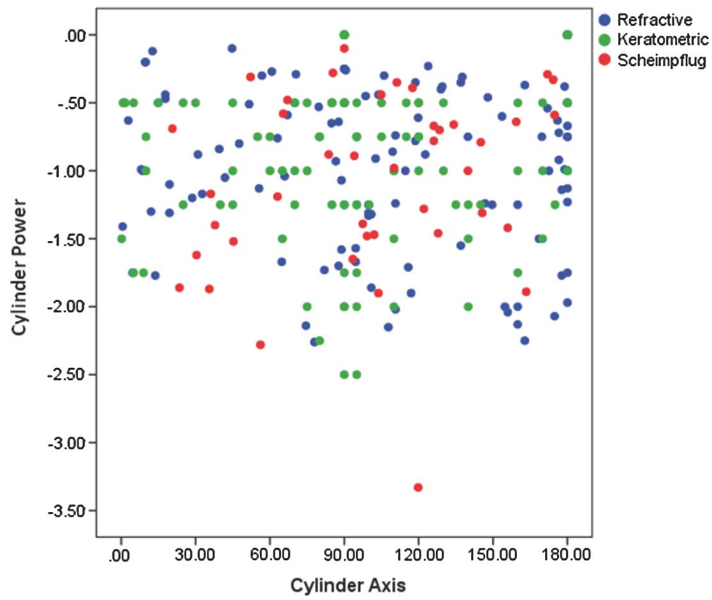

FIGURE 1. Axis distribution (degrees) of refractive (blue circles) and corneal keratometric (green circles) and Scheimpflug (red circles) astigmatic cylinder (diopters) in pseudophakic patients of the study group.

0.67 D). The resulting median refractive, corneal$_k$, and internal astigmatism components and spherocylinder expressions are listed in Table 2. An internal ATR astigmatism counterbalances a small WTR corneal$_k$ astigmatism, resulting in slightly ATR refractive astigmatism.

Correspondence Between Scheimpflug Corneal and Refractive Astigmatism

Refractive and corneal$_s$ astigmatic components were significantly correlated (refractive and corneal$_s$ J_0: $r = 0.36$, $P = 0.01$; refractive and corneal$_s$ J_{45}: $r = 0.45$, $P < 0.01$) (Figs. 2C, D).

The linear regression equations obtained were as follows:

$$\text{RefJ}_0 = 0.40 \times \text{Cor}_s \ J_0 + (-0.15)$$

$$\text{RefJ}_{45} = 0.25 \times \text{Cor}_s \ J_{45} + (-0.028)$$

These equations, like those presented above for keratometric values, are useful to infer refractive astigmatism from corneal astigmatism in pseudophakic patients. Agreement between refractive and corneal$_s$ J_0 (difference: -0.113 ± 0.844) and J_{45} (difference: 0.005 ± 0.892) astigmatic components was good (Figs. 3C, D, respectively).

Internal astigmatism components were attributable to factors different from the cornea [median values of −0.16 D (range: −0.95 to 1.07 D) for J_0, thus ATR astigmatism; 0.03 D (range: −0.93 to 1.47 D) for J_{45}].

Correspondence Between Keratometric and Scheimpflug Corneal Astigmatism

Corneal$_k$ and corneal$_s$ astigmatic components were significantly correlated (corneal$_k$ and corneal$_s$ J_0: $r = 0.58$, $P < 0.01$; corneal$_k$ and corneal$_s$ J_{45}: $r = 0.51$, $P < 0.01$) (Figs. 2E, F).

The linear regression equations obtained were as follows:

$$\text{Cor}_k \ J_0 = 0.67 \times \text{Cor}_s \ J_0 + (-0.03)$$

$$\text{Cor}_k \ J_{45} = 0.266 \times \text{Cor}_s \ J_{45} + (-0.057)$$

Figures 3E, F display agreement between corneal$_k$ and corneal$_s$ J_0 (difference: -0.006 ± 0.741) and J_{45} (difference: -0.022 ± 0.929) astigmatic components.

Comparison of Correlations

Correlation between refractive and corneal$_k$ J_0 components was significantly better than correlation between refractive and corneal$_s$ J_0 components ($P = 0.01$). Correlation between refractive and corneal$_k$ J_{45} components was also significantly better than that between refractive and corneal$_s$ J_{45} ($P < 0.01$).

DISCUSSION

In pseudophakic patients, we have examined the relation between corneal astigmatism, as evaluated by keratometric and Scheimpflug scan technology, and refractive astigmatism, after 2.8-mm corneal incisions for phacoemulsification. Scheimpflug anterior segment scanner has the advantage of measuring the posterior cornea and obtains directly corneal elevation or height data. We have also studied the influence of internal astigmatism on refractive astigmatism of pseudophakic eyes. Using power vector decomposition, we can analyze astigmatism with the steepest corneal axis in the vertical or horizontal meridian, and oblique astigmatism. Because the corneal incision was placed based on preexisting astigmatism to decrease it or shift the steep axis to the vertical meridian,[9,10] mean resultant corneal astigmatism is relatively small, showing a wide axis distribution

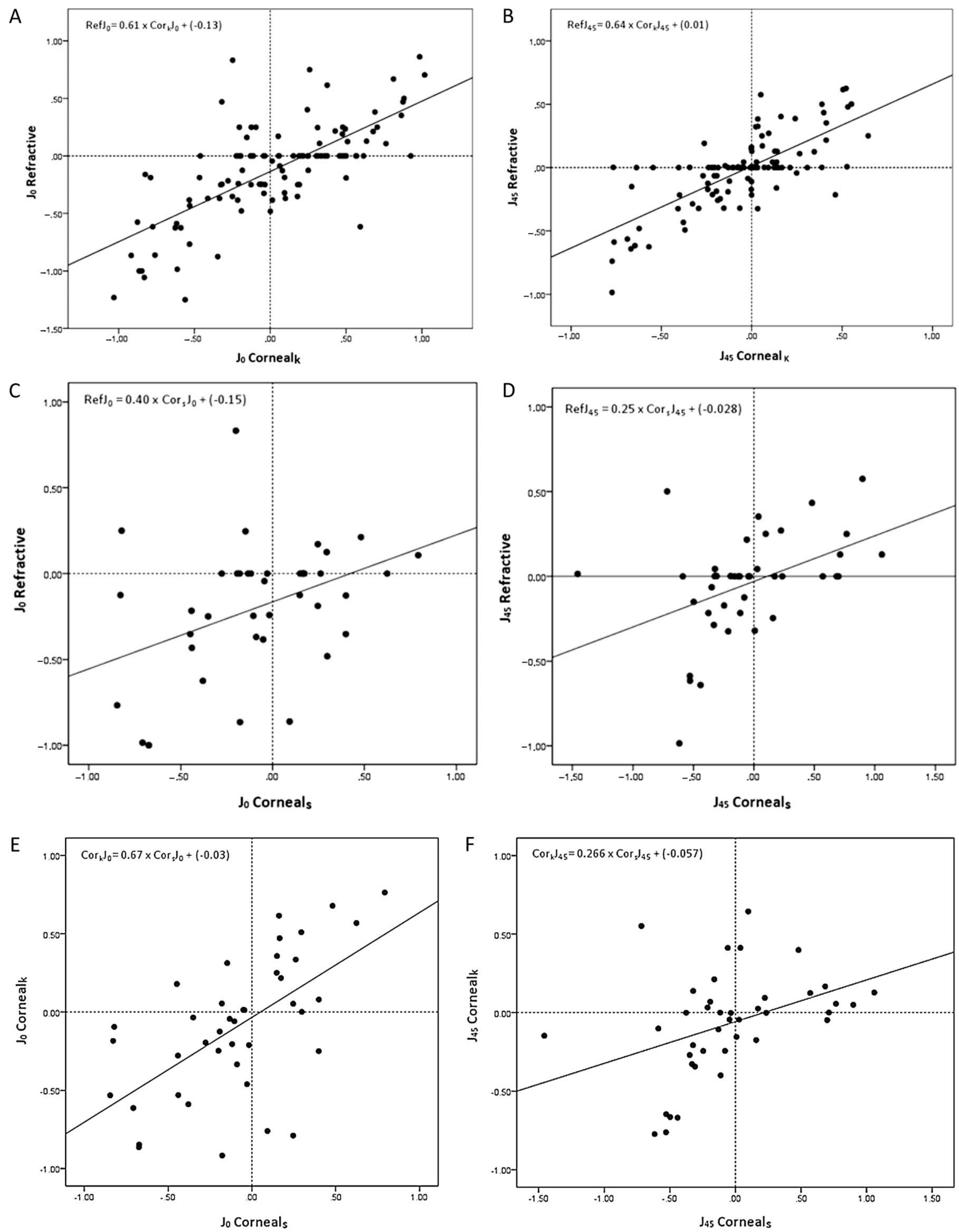

FIGURE 2. Regression lines between refractive and corneal$_k$ J_0 (A) and J_{45} (B), refractive and corneal$_s$ J_0 (C) and J_{45} (D), and corneal$_k$ and corneal$_s$ J_0 (E) and J_{45} (F) astigmatic components (diopters).

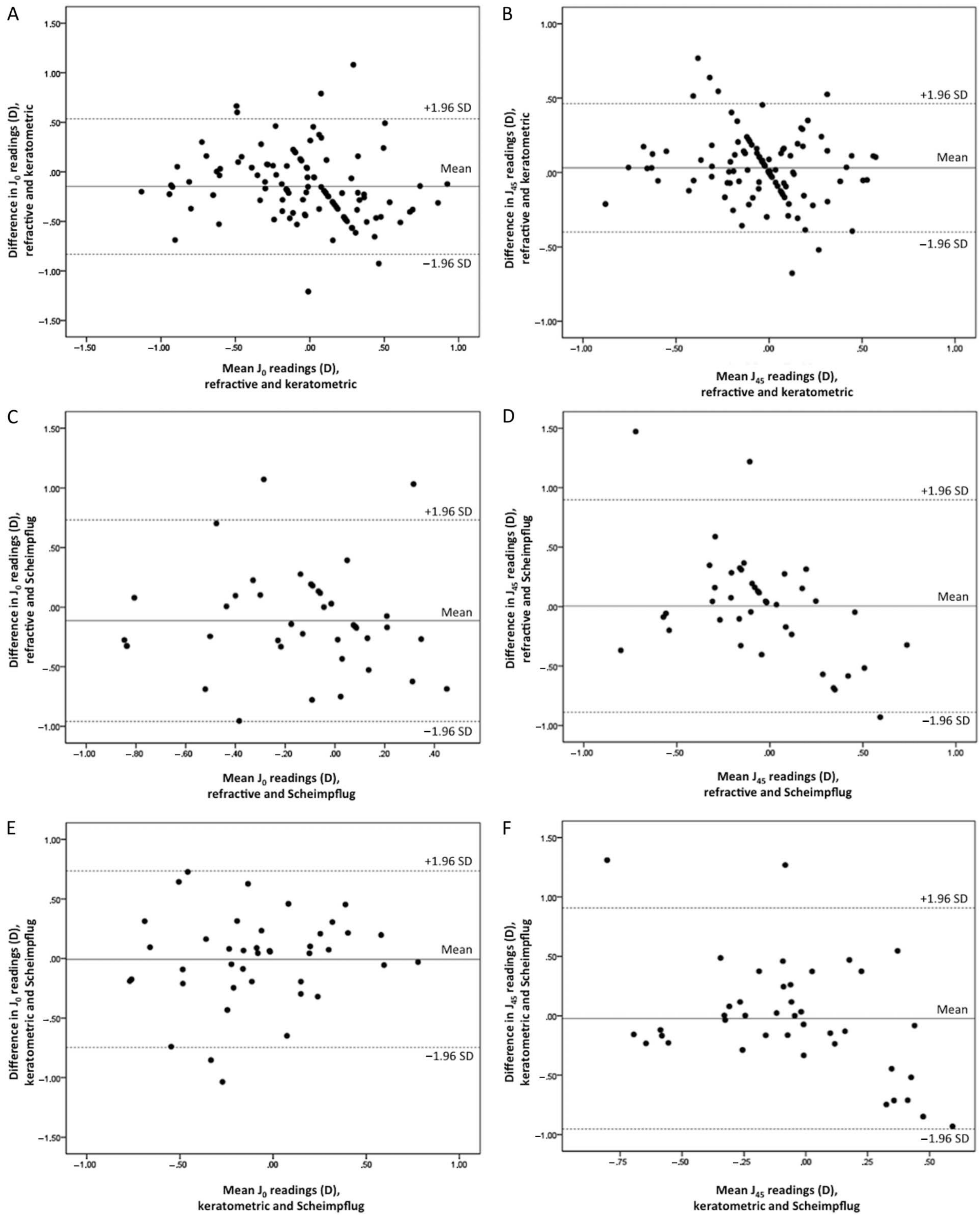

FIGURE 3. Bland–Altman plots of the difference between refractive and corneal$_k$ J_0 (solid line: mean, dotted lines: mean ± 1.96 SD) against their mean (A), between refractive and corneal$_k$ J_{45} against their mean (B), between refractive and corneal$_s$ J_0 (C) and J_{45} (D), and between corneal$_k$ and corneal$_s$ J_0 (E) and J_{45} (F) astigmatic components (diopters), respectively.

TABLE 2. Median Corneal, Refractive, and Internal* Astigmatism Components and Spherocylinder in Pseudophakic Eyes of the Study Group (Diopters)

	J_0	J_{45}	Spherocylinder
Refractive	−0.10	−0.000	−0.15, −0.20 × 90 degrees
Corneal_k	0.05	−0.002	44.51, −0.10 × 178 degrees
Internal_k	−0.19	0.01	−44.46, −0.38 × 88 degrees
Corneal_s	−0.09	−0.11	38.14, −0.28 × 115 degrees
Internal_s	−0.16	0.03	−38.09, −0.33 × 84 degrees

*Internal astigmatism was derived as the difference between refractive and corneal_k or corneal_s vector components, respectively.

(ATR and WTR). However, refractive astigmatism is slightly ATR, as shown by a small negative and left skewed J_0 value. Corneal_s J_0 values are more similar than corneal_k J_0 component to the corresponding refractive value but with differences in the limit of significance. In corneal_s, the posterior corneal surface is actually measured and added (as negative power) to anterior corneal measurements, whereas corneal_k is inferred assuming a constant back corneal surface. Corneal and refractive astigmatisms are approximately ATR in 51 patients and WTR in the remaining 60 patients. Astigmatic components determined using Scheimpflug technology lead to the conclusion that both anterior and posterior corneal surfaces contribute, on average, to the described mean refractive ATR astigmatism in pseudophakic eyes.

It is in principle unexpected that the correlation between corneal_k and refractive astigmatic components is better than that between corneal_s and refractive parameters. Pentacam corneal curvature measurements could have relatively poorer repeatability than automated keratometry.[12,13] A significant difference between K readings obtained with Pentacam and automated keratometry has been reported.[13] Pentacam "True net power" values, obtained by addition of anterior and posterior corneal data (not used in the present study), are not recommended for use in IOL calculation formulae (Pentacam Instruction Manual, page 53). Correlation between corneal_k and refractive astigmatic components could be less strong in a different sample of pseudophakic eyes, as previously reported.[8] The correlation between refractive and corneal astigmatism in pseudophakic eyes is lower than that found in adult phakic eyes.[14] Another source of disagreement with refractive astigmatism for both keratometric and Scheimpflug measures is the assumptions made during calculations. If "total corneal refractive power," provided by the Pentacam, and based on ray-tracing calculations, had been used, agreement with refractive astigmatism could have been better.

Most existing studies of pseudophakic astigmatism concentrate on changes induced by cataract surgery,[15–17] or describe the correlation between refractive and keratometric astigmatism,[8] but do not take into account posterior corneal measurements, do not use corneal elevation data, nor analyze internal astigmatic influence on refractive outcome. We have developed regression equations that simulate a vector-based Javal's rule for pseudophakic eyes. In these eyes, the internal ATR astigmatism is of less magnitude on average (−0.38 × 88 degrees using corneal_k, −0.33 × 84 degrees using corneal_s) than that previously described in phakic nonoperated eyes (−0.5 × 87 − 90 degrees).[14]

IOL tilt and decentration have been reported to cause myopic shift and oblique astigmatism,[18] but only when they are of a certain magnitude may induce a significant amount of astigmatism.[19–21] Today, with the extended use of phacoemulsification, capsulorrhexis, and in-the-bag implantation of one-piece foldable IOLs, as in the currently described cohort, the average reported IOL tilt is 1.3 to 2.3 degrees,[22,23] and consequently minimal astigmatic errors are induced.

Clinically observed discrepancies between corneal and refractive astigmatic amount and axis are considered important when microcoaxial phacoemulsification is planned. The introduction of toric IOLs in the last few years could have a potential role to counterbalance internal astigmatism, therefore reducing total refractive astigmatic error, but could also induce optical distortion in combination with a toric cornea. Using the correlation formulae obtained in this study, refractive astigmatism may be calculated from estimated postoperative corneal astigmatism (the latter value based on surgically induced astigmatism). Toric IOL power could subsequently be derived by transformation from the refractive to the IOL plane. At best, 50% to 52% of the variation in refractive astigmatic components can be accounted for by variation in corneal astigmatic components (coefficient of determination, r^2). Understanding the influence of different variables in pseudophakic refractive astigmatism is of interest because, after routine cataract surgery, astigmatic error has a much greater effect on the likelihood of spectacle use than overall error.

REFERENCES

1. Artal P, Berrio E, Guirao A. Contribution of the cornea and internal surfaces to the change of ocular aberrations with age. *J Opt Soc Am A Opt Image Sci Vis*. 2002;19:137–143.
2. Artal P, Guirao A, Berrio E, et al. Compensation of corneal aberrations by the internal optics in the human eye. *J Vis*. 2001;1:1–8.
3. Javal E. Memoires d'ophthalmometrie. Paris: G. Masson, *Libraire de l'Academie de Medicine*. 1890;130–131.
4. Grosvenor T, Ratnakaram R. Is the relation between keratometric astigmatism and refractive astigmatism linear? *Optom Vis Sci*. 1990;67:606–609.
5. Rabbetts RB. *Bennett & Rabbetts Clinical Visual Optics*. 3rd ed. Oxford, England: Butterworth-Heinemann; 1998:79–80.
6. Horn JD. Status of toric intraocular lenses. *Curr Opin Ophthalmol*. 2007; 18:58–61.
7. Wilkins MR, Allan B, Rubin G; Moorfields IOL Study Group. Spectacle use after routine cataract surgery. *Br J Ophthalmol*. 2009;93:1307–1312.
8. Teus MA, Arruabarrena C, Hernández-Verdejo JL, et al, Correlation between keratometric and refractive astigmatism in pseudophakic eyes. *J Cataract Refract Surg*. 2010;36:1671–1675.
9. Tejedor J, Pérez-Rodríguez JA. Astigmatic change induced by 2.8-mm corneal incisions for cataract surgery. *Invest Ophthalmol Vis Sci*. 2009; 50:989–994.
10. Tejedor J, Murube J. Choosing the location of corneal incision based on preexisting astigmatism in phacoemulsification. *Am J Ophthalmol*. 2005; 139:767–776.
11. Thibos LN, Wheeler W, Horner D. Power vectors: an application of Fourier analysis to the description and statistical analysis of refractive error. *Optom Vis Sci*. 1997;74:367–375.
12. Goggin M, Patel I, Billing K, et al. Variation in surgically induced astigmatism estimation due to test-to-test variations in keratometry. *J Cataract Refract Surg*. 2010;36:1792–1793.

13. Módis L Jr, Szalai E, Kolozsvári B, et al. Keratometry evaluations with the Pentacam high resolution in comparison with the automated keratometry and conventional corneal topography. *Cornea*. 2012;31:36–41.
14. Remón L, Benlloch J, Furlan WD. Corneal and refractive astigmatism in adults: a power vectors analysis. *Optom Vis Sci*. 2009;86:1182–1186.
15. Axt JC, McCaffery JM. Reduction of postoperative against-the-rule astigmatism by lateral incision technique. *J Cataract Refract Surg*. 1993;19:380–386.
16. Kohnen S, Neuber R, Kohnen T. Effect of temporal and nasal unsutured limbal tunnel incisions on induced astigmatism after phacoemulsification. *J Cataract Refract Surg*. 2002;28:821–825.
17. Masket S, Wang L, Belani S. Induced astigmatism with 2.2- and 3.0-mm coaxial phacoemulsification incisions. *J Refract Surg*. 2009;25:21–24.
18. Korynta J, Bok J, Cendelin J, et al. Computer modeling of visual impairment caused by intraocular lens misalignment. *J Cataract Refract Surg*. 1999;25:100–105.
19. Oshika T, Kawana K, Hiraoka T, et al. Ocular higher-order wavefront aberration caused by major tilting of intraocular lens. *Am J Ophthalmol*. 2005;140:744–746.
20. Kozaki J, Tanihara H, Yasuda A, et al. Tilt and decentration of the implanted posterior chamber intraocular lens. *J Cataract Refract Surg*. 1991;17:592–595.
21. Korynta J, Bok J, Cendelin J. Changes in refraction induced by change in intraocular lens position. *J Refract Corneal Surg*. 1994;10:556–564.
22. Hayashi K, Harada M, Hayashi H, et al. Decentration and tilt of polymethyl methacrylate, silicone, and acrylic soft intraocular lenses. *Ophthalmology*. 1997;104:793–798.
23. Baumeister M, Neidhardt B, Strobel J, et al. Tilt and decentration of three-piece foldable high-refractive silicone and hydrophobic acrylic intraocular lenses with 6-mm optics in an intraindividual comparison. *Am J Ophthalmol*. 2005;140:1051–1058.