An Analysis of the Factors Influencing the Residual Refractive Astigmatism After Cataract Surgery With Toric Intraocular Lenses

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Purpose. To investigate the influence of posterior corneal astigmatism, surgically-induced corneal astigmatism (SICA), intraocular lens (IOL) orientation, and effective lens position on the refractive outcome of toric IOLs.

Methods. Five models were prospectively investigated. Keratometric astigmatism and an intended SICA of 0.2 diopters (D) were entered into model 1. Total corneal astigmatism, measured by a rotating Scheimpflug camera, was used instead of keratometric astigmatism in model 2. The mean postoperative SICA, the actual postoperative IOL orientation, and the influence of the effective lens position were added, respectively, into models 3, 4, and 5. Astigmatic data were vectorially described by meridional and torsional powers. A set of equations was developed to describe the error in refractive astigmatism (ERA) as the difference between the postoperative refractive astigmatism and the target refractive astigmatism.

Results. We enrolled 40 consecutive eyes. In model 1, ERA calculations revealed significant cylinder overcorrection in with-the-rule (WTR) eyes (meridional power = -0.59 ± 0.34 D, $P < 0.0001$) and undercorrection in against-the-rule (ATR) eyes (0.32 ± 0.42 D, $P = 0.01$). When total corneal astigmatism was used instead of keratometric astigmatism (model 2), the ERA meridional power decreased in WTR (-0.13 ± 0.42 D) and ATR (0.07 ± 0.59 D) eyes, both values being not statistically significant. Models 3 to 5 did not lead to significant improvement.

Conclusions. Posterior corneal astigmatism exerts the highest influence on the ERA after toric IOL implantation. Basing calculations on total corneal astigmatism rather than keratometric astigmatism improves the prediction of the residual refractive astigmatism.

Keywords: astigmatism, toric IOL, mathematics, polar values

Toric intraocular lenses (IOLs) are a common choice to correct corneal astigmatism at the time of cataract surgery. Several articles have shown good results, but the refractive outcome is not yet perfect.[1–3] Over- or undercorrection of the cylinder may be related to the influence of several factors, including posterior corneal astigmatism.[3–6]

To evaluate the optical results of surgery and the influence of each factor, we developed a set of equations describing the astigmatism along the steeper corneal meridian of each eye. For this purpose, we first performed a standard analysis based on keratometric astigmatism and a mean estimated surgically-induced corneal astigmatism (SICA). The influence of the remaining factors was assessed by progressively adding information related to posterior corneal astigmatism, actual SICA, IOL orientation, and the effective lens position (ELP) of the individual case.

Methods

A sample of consecutive patients undergoing phacoemulsification and toric IOL implantation was prospectively enrolled. Exclusion criteria were the following: corneal cylinder less than 1 diopter (D), previous corneal or intraocular surgery, any corneal pathology, amblyopia, and any macular disease precluding full visual recovery.

The study was conducted in accordance with the ethical standards stated in the Declaration of Helsinki and approved by the local clinical research ethics committee with informed consent obtained after explanation of the nature and possible consequences of the study.

Preoperative Corneal Astigmatism Measurements

Preoperatively, patients were examined by means of a Placido-disk corneal topographer (Keratron, Optikon, Italy) and a rotating Scheimpflug camera (Pentacam, Oculus, Germany). The following astigmatism values were considered:

1. Keratometric astigmatism (KA): This is the difference between the power of the steepest and flattest corneal meridians at the 3.0-mm diameter as measured by simulated keratometry (SimK) with the corneal topographer.[7] The corneal radii are converted into dioptric power (P) by means of the keratometric index of refraction (1.3375); and

2. Total corneal astigmatism (TCA): This is measured through ray tracing with the Pentacam, as previously described.[8] An area of 3.0 mm centered on the pupil center was used for measurements.

According to keratometric data, astigmatism was classified as with-the-rule (WTR; 60–120°), against-the-rule (ATR; 0–30° or 150–180°) and oblique (30–60° or 120–150°).[4,6]

The selection of the IOL cylinder was based on the astigmatism measured by the corneal topographer. The spherical power of the IOL was calculated after entering the axial length, as measured by immersion ultrasound biometry (Ocuscan; Alcon Laboratories, Fort Worth, TX, USA), and SimK into the Hoffer Q, Holladay 1, or SRK/T formulas, using optimized constants.[9–11]

Surgical Technique

Preoperatively, initial markings were made with the patient sitting up to avoid cyclorotation. The eye was marked at 0 degrees and 180 degrees using a Nuijts/Lane Toric Reference Marker (ASICO, Westmont, IL, USA). During surgery, these reference marks were used to determine the desired axis of IOL orientation, which was then marked using a Mendez ring with a Nuijts toric axis (ASICO).

Phacoemulsification was performed in a routine fashion through a 2.75-mm temporal near-clear stab incision. The IOL was inserted into the capsular bag with a Monarch II injector and D cartridge (Alcon Laboratories) and finally rotated until it was aligned with the preoperative markings.

Postoperative Measurements

At 1 month postoperatively, subjective refraction was measured by an experienced ophthalmologist, after accounting for the results of automated refraction (only patients with postoperative best-corrected visual acuity ≥20/25 were included). The mean subjective cylinder at the spectacle plane was then converted to the corneal plane using a vertex distance of 12 mm. Intraocular lens rotation was evaluated at the slit lamp by checking the position of the indentations locating the flat meridian of the optic and using slit orientation referenced to the degree scale on the slit lamp.

Measurement Models

To systematically delineate the causes of error in the calculations, all eyes were examined with the following five models:

Model 1. Preoperative KA, intended IOL implantation axis and an intended SICA of –0.2 D;

Model 2. Preoperative Scheimplug TCA, intended IOL implantation axis, and a –0.2 D SICA. This methodology excludes errors derived from the posterior corneal astigmatism;

Model 3. Preoperative Scheimpflug TCA, intended IOL implantation axis, and the observed (not estimated) average SICA. This methodology excludes errors derived from the posterior corneal astigmatism and the SICA;

Model 4. Preoperative Scheimpflug TCA, observed SICA, and the postoperatively recorded toric IOL axis. This methodology excludes errors derived from the posterior corneal astigmatism, SICA, and IOL axis alignment; and

Model 5. Preoperative Pentacam TCA, observed SICA, postoperatively recorded IOL axis, and calculation of cylinder IOL correction at the corneal plane accounting for the influence of the ELP.[12,13] This methodology excludes errors derived from the posterior corneal astigmatism, SICA, IOL axis alignment, and ELP-dependent variations in IOL astigmatic correction.

Astigmatism Transformation Into Polar Values

The net astigmatism (M @ α), where M is the astigmatic magnitude in diopters and α is the astigmatic direction in degrees, was transformed into two polar values[14]:

$$\textit{Polar value along the meridian } \Phi = KP(\Phi) = M^* \cos\left(2^*(\alpha - \Phi)\right). \quad (1)$$

This polar value indicated the net meridional power along the reference meridian Φ:

$$\textit{Polar value along the meridian } (\Phi + 45) = KP(\Phi + 45) = M^* \sin\left(2^*(\alpha - \Phi)\right). \quad (2)$$

This polar value indicated the net torsion over the meridian Φ, giving rise to a change in cylinder axis.

In the specific case of analysis along fixed meridians at zero degrees, $\Phi =$ zero, and Equations 1 and 2 are reduced to

$$\textit{Polar value along the zero degree meridian} = KP(0) = M^* \cos(2^*\alpha), \quad (3)$$

$$\textit{Polar value along the 45 degree meridian} = KP(45) = M^* \sin(2^*\alpha). \quad (4)$$

All polar values are expressed in diopters. In this study, the net corneal astigmatisms were derived using SimK and Scheimpflug ray tracing and directly converted to polar values with Equations 1 and 2. Refractive data were transformed from the vertex to the corneal plane and then further to polar values, as described by Næser.[15]

Any set of polar values may be reconverted to the usual net cylinder notation by means of the following general equations:

$$M = \sqrt{KP(\Phi)^2 + KP(\Phi + 45)^2} \quad (5)$$

$$\alpha = \arctan\left(\frac{M - KP(\Phi)}{KP(\Phi + 45)}\right) + \Phi. \quad (6)$$

Concepts and Definitions

Astigmatisms are conceived as two-dimensional vectors, characterized by the two polar values given in Equations 1 to 4. Vectors are written in bold. All astigmatism data are converted to the corneal plane. In each group, the purpose of the calculations is to determine the error in refractive astigmatism (**ERA**).

Model 1. The *intended* **SICA** is a 0.2-D flattening of the temporal corneal incision; this is equivalent to the net cylinder (0.2 D @ 90°). The **target corneal astigmatism** is the sum of **KA** and **SICA**, with the reference meridian $\Phi =$ zero.

$$\textbf{\textit{Target corneal astigmatism}} = \textbf{\textit{Keratometric astigmatism}} + \textbf{\textit{SICA}} \quad (7)$$

The steeper meridian of the **target corneal astigmatism** is used as the reference plane Φ in all subsequent assessments.

Table 1. Surgically-Induced Corneal Astigmatism

	Type of Astigmatism	All Eyes	WTR	ATR
Preoperative KA	KP(0)	−0.58 ± 1.53 (−4.71 to 2.37)	−1.59 ± 0.90 (−4.71 to −0.12)	1.10 ± 0.52 (0.36 to 2.37)
	KP(45)	0.02 ± 0.77 (−2.69 to 1.14)	−0.04 ± 0.89 (−2.69 to 1.14)	0.13 ± 0.53 (−0.81 to 1.10)
	Net astigmatism	0.58 D @ 89°	1.60 D @ 90°	1.11 D @ 3°
Postoperative KA	KP(0)	−0.73 ± 1.44 (−4.35 to 1.90)	−1.65 ± 0.91 (−4.35 to 0.53)	0.80 ± 0.61 (−0.12 to 1.90)
	KP(45)	0.02 ± 0.80 (−2.96 to 1.09)	0.01 ± 0.86 (−2.96 to 1.09)	0.03 ± 0.72 (−1.51 to 1.06)
	Net astigmatism	0.73 D @ 89°	1.65 D @ 90°	0.80 D @ 1°
SICA	KP(0)	−0.15 ± 0.40 (−0.81 to 0.79) $P = 0.0171$	−0.06 ± 0.35 (−0.56 to 0.79) P = n.s. (0.4390)	−0.30 ± 0.37 (−0.81 to 0.51) $P = 0.0073$
	KP(45)	−0.01 ± 0.48 (−1.25 to 1.27) P = n.s. (0.9441)	0.05 ± 0.52 (−1.25 to 1.27) P = n.s. (0.6177)	−0.10 ± 0.40 (−0.73 to 0.54) P = n.s. (0.3369)
	Net astigmatism	0.15 D @ 91°	0.07 D @ 69°	0.32 D @ 99°

Polar values and net astigmatisms for pre- and postoperative KA. Data are reported in diopters as mean ± SD (range). The polar value KP(0) refers to the net meridional power along the surgical meridian in 0/180 degrees; KP(45) indicates the torsion over the surgical meridian; SICA is the paired difference between the pre- and postoperative polar values; and the *P* values of the paired *t*-test indicate the statistical significance of this difference. n.s., not statistically significant.

Intraocular lens astigmatism is the corneal plane toric power calculated with the Alcon Web calculator and lens optic markings aligned with the most powerful corneal meridian Φ.

The **target refractive astigmatism** is the sum of the **target corneal astigmatism** and the IOL toricity at the corneal plane:

$$\textbf{\textit{Target refractive astigmatism}} = \textbf{\textit{Target corneal astigmatism}} + \textbf{\textit{IOL astigmatism}}. \qquad (8)$$

Refractive astigmatism is the postoperatively measured manifest refractive astigmatism at the corneal plane.[15] The **ERA** is the difference between the measured and the target refractive astigmatisms:

$$\textbf{\textit{ERA}} = \textbf{\textit{Refractive astigmatism}} - \textbf{\textit{Target refractive astigmatism}}. \qquad (9)$$

The **ERA** polar value along the meridian Φ is negative for astigmatic overcorrections and positive for undercorrections. The polar value along the meridian ($\Phi + 45$) is negative for clockwise and positive for counterclockwise errors in rotations of astigmatic refractive cylinder: such errors are caused by misalignments between corneal toricity, IOL meridians, and refractive astigmatism. A torsional value of zero indicates an unchanged astigmatic meridian.

Model 2. Scheimpflug TCA and the assumed −0.2-D SICA are used to obtain a corneal target astigmatism with a new reference meridian Φ:

$$\textbf{\textit{Target corneal astigmatism}} = \textbf{\textit{TCA}} + \textbf{\textit{SICA}}. \qquad (10)$$

The remaining calculations are performed with Equations 8 and 9.

Model 3. The *observed* **SICA** from Table 1 is used to calculate a new **target corneal astigmatism**. Observed SICA KP(0) values of −0.15, −0.3, and 0 D are entered for the total group, the ATR, and the WTR eyes, respectively, in this model, as well as in models 4 and 5. No torsional change is assumed. The remaining calculations are the same as for model 2.

Model 4. The postoperatively-observed IOL axis is entered into calculations. Additional calculations are the same as for model 3.

Model 5. Intraocular lens toricity is calculated at the corneal plane considering the influence of ELP according to meridional analysis.[12,13] Remaining calculations are the same as for model 4.

Surgically-Induced Corneal Astigmatism. The observed **SICA** is the difference between the post- and preoperative **KAs**, as measured by the Placido disc corneal topographer and expressed in polar values. It is calculated with Equations 3 and 4 using a fixed reference meridian $\Phi = 0°$, because all incisions were placed along 0/180 degrees:

$$\textbf{\textit{SICA}} = \textit{Postop}\ \textbf{\textit{keratometric astigmatism}} - \textit{Preop}\ \textbf{\textit{keratometric astigmatism}}. \qquad (11)$$

A full calculated example is given in the Appendix in the Supplementary Material.

Statistics

Statistical tests were performed using MedCalc, version 12.3 (MedCalc Software, Ostend, Belgium) and InStat, version 3a (GraphPad Software, San Diego, CA, USA). Paired and unpaired *t*-tests, ANOVA with Tukey-Kramer multiple comparison test, and correlation (Pearson correlation coefficient) were performed once a Gaussian distribution had been determined with the Kolmogorov-Smirnov test. Confidence ellipses were obtained by means of the XLstat (Addinsoft, Inc., Paris, France) statistical software program. A *P* value less than 0.05 was considered statistically significant.

The sample size was estimated after considering that the precision of autokeratometry, expressed as the SD of the difference in polar values between two successive measurements, is approximately 0.3 D.[16] Assuming type 1 and 2 errors of 0.05 and 0.80, a minimum number of 24 eyes was required to detect a clinically significant difference of 0.25 D.

Results

Forty-one eyes of 31 patients (20 females; mean age: 67.4 ± 9.2 years) were enrolled. Astigmatism was classified as WTR in 25 eyes, ATR in 15 eyes, and oblique in 1 eye, which was subsequently excluded from all analyses.

Surgically-Induced Corneal Astigmatism

Table 1 shows the mean preoperative and postoperative KA and SICA.

In the whole sample, the SICA KP(0) averaged −0.15 ± 0.40 D along the reference meridian at zero degrees, and the average torsion was practically zero. This means that the actually achieved flattening of the surgical meridian averaged 0.15 D rather than the targeted 0.2 D. In the ATR eyes, the SICA

KP(0) averaged –0.30 ± 0.37 D ($P = 0.01$; paired *t*-test), indicating a clinically and statistically significant flattening of the horizontal meridian. None of the other SICA components differed significantly from zero. In the WTR eyes, average meridional and torsional values were close to zero, indicating an astigmatically neutral incision. For practical purposes *observed* SICA flattenings of 0.15, 0.3, and 0 D were assumed respectively for the total group, the ATR eyes, and the WTR eyes in models 3 to 5.

Intraocular Lens Orientation

The difference between the postoperatively observed and target meridian of the IOL averaged –0.73° ± 6.69° (mean absolute difference = 5.28° ± 4.09°). The difference between the target meridian and postoperatively observed meridian of the IOL was ≤15° in 100% of eyes, ≤10° in 82.5% of eyes, and ≤5° in 65% of eyes.

Error in Refractive Astigmatism

Tables 2 through 4 show the astigmatism analysis of the five models.

Whole Sample (Table 2)

For measurements based on preoperative KA and expected SICA (model 1), a mean cylinder overcorrection was observed (KP(Φ) = –0.25 ± 0.58 D, $P = 0.01$). Such an overcorrection was not detected once posterior corneal astigmatism was included in the analysis (model 2), as well as for models 3 to 5. However, these results disguise the fact that WTR and ATR eyes have quite different biometry and no further statistical analyses were performed.

Eyes With WTR Astigmatism (Table 3)

The mean 2.01 ± 0.86 D KA was significantly higher than the mean 1.53 ± 0.64 D Pentacam TCA ($P = 0.0004$). Error in refractive astigmatism calculations based on KA (model 1) revealed a mean overcorrection with a statistically significant –0.59 ± 0.34 D ERA meridional power, whereas ERA calculations based on TCA (model 2) demonstrated a lower and statistically nonsignificant trend toward overcorrection (–0.13 ± 0.42 D). A further improvement in ERA was achieved by including the SICA (model 3), which allowed us to reduce the mean ERA meridional power to 0.04 ± 0.42 D. Models 4 and 5 provided similar excellent values for mean ERA curvital power. In all models, the ERA torsional values did not significantly differ from zero.

Analysis of variance disclosed a statistically significant difference ($P < 0.0001$) among the ERA meridional power of the five models. Posttest analysis showed a statistically significant difference ($P < 0.001$) between model 1 and the other models, whereas no differences were detected among models 2 to 5.

The mean ERA torsional power of the five models did not show any statistically significant difference according to ANOVA.

No statistically significant correlation was found between the preoperative Target KA and the ERA meridional power (model 1).

Eyes With ATR Astigmatism (Table 4)

In the ATR group, the mean KA (1.04 ± 0.54 D) was lower than TCA (1.11 ± 0.44 D), although this difference was not statistically significant. Error in refractive astigmatism calculations based on the KA (model 1) revealed a statistically significant undercorrection (KP[Φ] = 0.32 ± 0.42 D, $P = 0.01$). Such an ERA undercorrection was lower (KP[Φ] = 0.07 ± 0.56 D) and not statistically significant from zero when calculations were based on TCA measurements (model 2). No improvements for ERA net meridional power were provided by models 3, 4, and 5. In all models, the ERA torsional values did not significantly differ from zero, although a slight increase was observed when TCA measurements were used.

Analysis of variance disclosed a statistically significant difference ($P = 0.0471$) among the ERA meridional power of the five models. Posttest analysis showed a statistically significant difference ($P < 0.05$) only between model 1 and model 2.

The mean ERA torsional power of the five models did not show any statistically significant difference according to ANOVA.

No statistically significant correlation was found between the preoperative Target KA and the ERA meridional power (model 1).

Bivariate tolerance ellipses for the five models are displayed in Figures A through E.

Discussion

This study was designed to analyze errors in toric IOL refractive outcome from relevant procedural steps.[17] The spherical power of the IOL was calculated using optimized constants. The intended and postoperatively observed IOL axis orientations were recorded, separately evaluated, and found to differ only slightly. Corneal power was measured and calculated by means of two validated devices, whose precision has been shown to be high with a coefficient of variation for the central 3-mm corneal curvature ranging between 0.3% and 0.4%.[18] Postoperatively, one experienced operator (GS) performed autorefraction and subsequent subjective refraction. Only patients with high best-corrected visual acuity were enrolled, which makes refraction assessment repeatable.[19]

To evaluate the outcome in astigmatism, we developed a number of optical equations based on the Næser polar value concept.[14] Each eye was subjected to vector analysis with both fixed and individualized reference meridians. All incisions were performed along 0/180°. Polar value analysis of SICA was performed with zero as the fixed reference meridian, giving a minimal flattening of 0.15 ± 0.40 D for the whole group, practically zero induced astigmatism for the WTR eyes, and a stronger and statistically significant 0.30 ± 0.37 D flattening in the ATR group. We do not have a clear explanation for such a difference, and further studies specifically designed to address this issue are warranted.

Surgically-induced corneal astigmatism was added vectorially to the preoperatively measured astigmatisms to give target KA and target TCA of specific magnitudes and meridians. These meridians, variable and different for each eye, were used as reference planes in the subsequent vector analyses. The ultimate outcome was the ERA expressed as the flattening and torsion along the variable reference meridian. Model 1, based on keratometry, produced a mean 0.59-D cylinder overcorrection for WTR eyes and a mean 0.32-D undercorrection for ATR eyes. When information about the posterior corneal curvature was added and calculations were based on the Pentacam TCA in models 2 to 5, these errors became statistically nonsignificant. Such results are in good agreement with previous studies showing that posterior corneal astigmatism tends to compensate for

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Table 2. Vectorial Analysis of Astigmatism in the Whole Sample

	All Eyes (n = 40)				
	Model 1 KA (Placido-Disc Corneal Topography)	**Model 2 TCA (Rotating Scheimpflug Camera)**	**Model 3 TCA (Rotating Scheimpflug Camera)**	**Model 4 TCA (Rotating Scheimpflug Camera)**	**Model 5 TCA (Rotating Scheimpflug Camera)**
Types of astigmatism	SICA = −0.2 D	SICA = −0.2 D	SICA = −0.15 D	SICA = −0.1 D Postoperative IOL orientation considered	SICA = −0.1 D Postoperative IOL orientation considered ELP influence on corneal cylinder effect considered
Target corneal astigmatism					
KP(Φ)	1.64 ± 0.90 (0.20 to 4.91)	1.38 ± 0.59 (0.50 to 3.10)	1.36 ± 0.58 (0.55 to 3.05)	1.35 ± 0.58 (0.60 to 3.00)	1.37 ± 0.64 (0.50 to 2.90)
KP(Φ + 45)	0	0	0	0	0
Net astigmatism	1.64 D @ Φ°	1.38 D @ Φ°	1.36 D @ Φ°	1.35 D @ Φ°	1.37 D @ Φ°
IOL astigmatism					
KP(Φ)	−1.53 ± 0.73 (−4.11 to −0.67)	−1.42 ± 0.78 (−4.08 to −0.21)	−1.42 ± 0.77 (−4.08 to −0.36)	−1.39 ± 0.74 (−3.92 to −0.29)	−1.36 ± 0.73 (−4.06 to −0.31)
KP(Φ + 45)	0	−0.03 ± 0.52 (−1.04 to 1.29)	−0.03 ± 0.52 (−1.04 to 1.34)	−0.07 ± 0.63 (−1.23 to 1.71)	−0.06 ± 0.64 (−1.28 to 1.81)
Net astigmatism	1.53 @ (Φ + 90)°	1.42 D @ (Φ + 91)°	1.42 D @ (Φ + 90)°	1.39 D @ (Φ + 91)°	1.36 D @ (Φ + 91)°
Target refractive astigmatism					
KP(Φ)	0.12 ± 0.43 (−0.76 to 1.09)	−0.04 ± 0.43 (−0.98 to 0.85)	−0.06 ± 0.42 (−1.03 to 0.80)	−0.03 ± 0.43 (−0.87 to 0.84)	−0.01 ± 0.43 (−1.06 to 0.87)
KP(Φ + 45)	0	−0.03 ± 0.52 (−1.04 to 1.29)	−0.03 ± 0.52 (−1.04 to 1.34)	−0.07 ± 0.63 (−1.23 to 1.71)	−0.06 ± 0.64 (−1.28 to 1.81)
Net astigmatism	0.12 @ Φ°	0.05 @ (Φ + 115)°	0.07 D @ (Φ + 105)°	0.08 D @ (Φ + 120)°	0.06 D @ (Φ + 130)°
Refractive astigmatism					
KP(Φ)	−0.13 ± 0.39 (−1.00 to 0.51)	−0.09 ± 0.37 (−0.89 to 0.63)	−0.09 ± 0.37 (−0.89 to 0.64)	−0.09 ± 0.37 (−0.89 to 0.64)	−0.09 ± 0.37 (−0.89 to 0.64)
KP(Φ + 45)	0.05 ± 0.49 (−1.25 to 1.73)	0.04 ± 0.52 (−1.08 to 1.99)	0.04 ± 0.52 (−1.08 to 1.99)	0.04 ± 0.52 (−1.08 to 2.00)	0.04 ± 0.52 (−1.08 to 2.00)
Net astigmatism	0.14 D @ (Φ + 80)°	0.10 D @ (Φ + 79)°	0.10 D @ (Φ + 79)°	0.10 D @ (Φ + 79)°	0.09 D @ (Φ + 78)°
ERA					
KP(Φ)	−0.25 ± 0.58 (−1.22 to 0.92) P = 0.0094	−0.05 ± 0.49 (−1.12 to 0.98) P = n.s. (0.49)	−0.03 ± 0.48 (−1.16 to 1.03) P = n.s. (0.67)	−0.06 ± 0.48 (−1.19 to 0.87) P = n.s. (0.41)	−0.07 ± 0.48 (−1.28 to 1.06) P = n.s. (0.33)
KP(Φ + 45)	0.05 ± 0.49 (−1.25 to 1.73) P = n.s. (0.56)	0.07 ± 0.58 (−1.10 to 1.38) P = n.s. (0.43)	0.07 ± 0.57 (−1.10 to 1.33) P = n.s. (0.43)	0.10 ± 0.58 (−0.79 to 1.45) P = n.s. (0.27)	0.10 ± 0.57 (−0.71 to 1.45) P = n.s. (0.27)
Net astigmatism	0.25 D @ (Φ + 85)°	0.09 D @ (Φ + 63)°	0.08 D @ (Φ + 57)°	0.12 D @ (Φ + 61)°	0.13 D @ (Φ + 63)°

The ERA is expressed as polar values and net astigmatisms in the five different measurement models. The polar value KP(Φ) is the net meridional power along the steeper corneal meridian Φ of the target corneal astigmatism. KP(45) indicates the torsion over the meridian Φ, hereby giving rise to a rotation of the cylinder. The ERA is the difference between the observed and the target refractive astigmatisms, and the P values refer to a paired t-test comparing these magnitudes. All polar values are expressed in diopters as mean ± SD (range). The net astigmatisms are calculated with Equations 5 and 6. All astigmatic directions are inclinations relative to the reference meridian Φ. The IOL astigmatism demonstrates the dynamics resulting from the reference meridian Φ: In model 1 the intended IOL implantation axis is identical to the reference meridian. The torsion is zero and meridional power equates nominal IOL power. Small deviations between reference meridians and intended (models 2 and 3) or observed (models 4 and 5) IOL implantation axes result in reduced meridional power and emergence of torsion.

Table 3. Vectorial Analysis of Astigmatism in the Eyes With WTR Astigmatism

	WTR Astigmatism (n = 25)				
	Model 1 KA (Placido-Disc Corneal Topography)	**Model 2 TCA (Rotating Scheimpflug Camera)**	**Model 3 TCA (Rotating Scheimpflug Camera)**	**Model 4 TCA (Rotating Scheimpflug Camera)**	**Model 5 TCA (Rotating Scheimpflug Camera)**
Types of astigmatism	SICA = −0.2 D	SICA = −0.2 D	SICA = 0 D	SICA = 0 D postoperative IOL orientation considered	SICA = 0 D Postoperative IOL orientation considered ELP influence on corneal cylinder effect considered
Target corneal astigmatism					
KP(Φ)	2.01 ± 0.87 (1.19 to 4.91)	1.53 ± 0.64 (0.69 to 3.10)	1.37 ± 0.64 (0.50 to 2.90)	1.37 ± 0.64 (0.50 to 2.90)	1.37 ± 0.65 (0.50 to 2.90)
KP(Φ + 45)	0	0	0	0	0
Net astigmatism	2.01 D @ Φ°	1.53 D @ Φ°	1.37 D @ Φ°	1.37 D @ Φ°	1.37 D @ Φ°
IOL astigmatism					
KP(Φ)	−1.65 ± 0.82 (−4.11 to −0.67)	−1.60 ± 0.80 (−4.08 to −0.62)	−1.58 ± 0.80 (−4.07 to −0.59)	−1.50 ± 0.80 (−3.91 to −0.59)	−1.47 ± 0.78 (−4.26 to −0.65)
KP(Φ + 45)	0	0.05 ± 0.46 (−0.79 to 1.29)	0.06 ± 0.53 (−0.88 to 1.49)	0.01 ± 0.74 (−1.26 to 1.85)	0.01 ± 0.73 (−1.30 to 1.91)
Net astigmatism	1.65 D @ (Φ + 90)°	1.60 D @ (Φ + 89)°	1.58 D @ (Φ + 89)°	1.50 D @ (Φ + 90)°	1.47 D @ (Φ + 90)°
Target refractive astigmatism					
KP(Φ)	0.35 ± 0.30 (−0.25 to 1.09)	−0.07 ± 0.42 (−0.98 to 0.85)	−0.21 ± 0.44 (−1.17 to 0.66)	−0.13 ± 0.48 (−1.01 to 0.75)	−0.10 ± 0.48 (−1.15 to 0.78)
KP(Φ + 45)	0	0.05 ± 0.46 (−0.79 to 1.29)	0.06 ± 0.53 (−0.88 to 1.49)	0.01 ± 0.74 (−1.26 to 1.85)	0.01 ± 0.73 (−1.30 to 1.91)
Net astigmatism	0.35 D @ Φ°	0.08 D @ (Φ + 70)°	0.22 D @ (Φ + 82)°	0.14 D @ (Φ + 82)°	0.10 D @ (Φ + 86)°
Refractive astigmatism					
KP(Φ)	−0.24 ± 0.40 (−1.00 to 0.49)	−0.19 ± 0.36 (−0.89 to 0.48)	−0.17 ± 0.36 (−0.88 to 0.48)	−0.17 ± 0.36 (−0.88 to 0.48)	−0.17 ± 0.36 (−0.88 to 0.48)
KP(Φ + 45)	0.08 ± 0.53 (−0.86 to 1.73)	0.06 ± 0.58 (−0.73 to 1.99)	0.06 ± 0.59 (−0.75 to 2.00)	0.06 ± 0.59 (−0.75 to 2.00)	0.06 ± 0.59 (−0.75 to 2.00)
Net astigmatism	0.25 D @ (Φ + 81)°	0.20 D @ (Φ + 81)°	0.18 D @ (Φ + 81)°	0.18 D @ (Φ + 81)°	0.18 D @ (Φ + 81)°
ERA					
KP(Φ)	−0.59 ± 0.34 (−1.22 to 0.02) P < 0.0001	−0.13 ± 0.42 (−1.10 to 0.98) P = n.s. (0.14)	0.04 ± 0.42 (−0.91 to 1.17) P = n.s. (0.64)	−0.04 ± 0.43 (−1.08 to 1.01) P = n.s. (0.65)	−0.07 ± 0.43 (−1.20 to 1.15) P = n.s. (0.42)
KP(Φ + 45)	0.08 ± 0.53 (−0.86 to 1.73) P = n.s. (0.49)	0.01 ± 0.56 (−1.10 to 1.38) P = n.s. (0.93)	0.00 ± 0.55 (−1.07 to 1.17) P = n.s. (0.9908)	0.04 ± 0.59 (−0.71 to 1.26) P = n.s. (0.7225)	0.04 ± 0.58 (−0.70 to 1.30) P = n.s. (0.72)
Net astigmatism	0.60 D @ (Φ + 86)°	0.13 D @ (Φ + 88)°	0.04 D @ Φ°	0.06 D @ (Φ + 67)°	0.08 D @ (Φ + 75)°

A mean (statistically significant) overcorrection of 0.59 D was observed for measurements based on KA (model 1). The Pentacam TCAs of models 2 to 5 resulted in nonsignificant errors in refractive astigmatism.

Table 4. Vectorial Analysis of Astigmatism in the Eyes With ATR Astigmatism

	ATR Astigmatism (n = 15)				
	Model 1 KA (Placido-Disc Corneal Topography)	**Model 2 TCA (Rotating Scheimpflug Camera)**	**Model 3 TCA (Rotating Scheimpflug Camera)**	**Model 4 TCA (Rotating Scheimpflug Camera)**	**Model 5 TCA (Rotating Scheimpflug Camera)**
Types of astigmatism	SICA = −0.2 D	SICA = −0.2 D	SICA = −0.3 D	SICA = −0.3 D Postoperative IOL orientation considered	SICA = −0.3 D Postoperative IOL orientation considered ELP influence on corneal cylinder effect considered
Target corneal astigmatism					
KP(Φ)	1.04 ± 0.54 (0.20 to 2.19)	1.11 ± 0.41 (0.50 to 1.80)	1.04 ± 0.41 (0.40 to 1.71)	1.04 ± 0.41 (0.40 to 1.71)	1.04 ± 0.43 (0.40 to 1.71)
KP(Φ + 45)	0	0	0	0	0
Net astigmatism	1.04 @ Φ°	1.11 @ Φ°	1.04 @ Φ°	1.04 @ Φ°	1.04 @ Φ°
IOL astigmatism					
KP(Φ)	−1.32 ± 0.53 (−2.57 to −0.67)	−1.11 ± 0.66 (−2.57 to −0.21)	−1.07 ± 0.70 (−2.56 to 0.07)	−1.11 ± 0.67 (−2.52 to 0.00)	−1.09 ± 0.68 (−2.57 to 0.00)
KP(Φ + 45)	0	−0.18 ± 0.59 (−1.04 to 0.84)	−0.18 ± 0.62 (−1.03 to 0.94)	−0.19 ± 0.58 (−1.03 to 0.79)	−0.19 ± 0.57 (−1.05 to 0.77)
Net astigmatism	1.32 D @ (Φ + 90)°	1.13 D @ (Φ + 95)°	1.08 @ (Φ + 95)°	1.13 D @ (Φ + 95)°	1.11 D @ (Φ + 95)°
Target refractive astigmatism					
KP(Φ)	−0.28 ± 0.30 (−0.76 to 0.36)	0.00 ± 0.44 (−0.76 to 0.61)	−0.03 ± 0.51 (−0.86 to 0.87)	−0.07 ± 0.48 (−0.81 to 0.80)	−0.05 ± 0.48 (−0.86 to 0.80)
KP(Φ + 45)	0	−0.18 ± 0.59 (−1.04 to 0.84)	−0.18 ± 0.62 (−1.03 to 0.94)	−0.19 ± 0.58 (−1.03 to 0.79)	−0.19 ± 0.57 (−1.05 to 0.77)
Net astigmatism	0.28 D @ (Φ + 90)°	0.18 D @ (Φ + 135)°	0.18 D (Φ + 130)°	0.2 D @ (Φ + 125)°	0.2 D @ (Φ + 128)°
Refractive astigmatism					
KP(Φ)	0.04 ± 0.30 (−0.72 to 0.51)	0.07 ± 0.32 (−0.70 to 0.63)	0.07 ± 0.32 (−0.68 to 0.62)	0.07 ± 0.32 (−0.68 to 0.62)	0.07 ± 0.32 (−0.68 to 0.62)
KP(Φ + 45)	0.00 ± 0.43 (−1.25 to 0.98)	0.00 ± 0.41 (−1.08 to 0.97)	0.00 ± 0.41 (−1.09 to 0.97)	0.00 ± 0.41 (−1.09 to 0.97)	0.00 ± 0.41 (−1.09 to 0.97)
Net astigmatism	0.04 D @ (Φ + 179)°	0.07 D @ Φ°	0.07 D @ (Φ + 1)°	0.07 D @ (Φ + 1)°	0.07 D @ (Φ + 1)°
ERA					
KP(Φ)	0.32 ± 0.42 (−0.87 to 0.92) P = 0.01	0.07 ± 0.59 (−1.12 to 0.71) P = n.s. (0.64)	0.10 ± 0.64 (−1.03 to 0.81) P = n.s. (0.56)	0.14 ± 0.61 (−1.03 to 0.81) P = n.s. (039)	0.12 ± 0.61 (−1.04 to 0.87) P = n.s. (0.46)
KP(Φ + 45)	0.00 ± 0.43 (−1.25 to 0.98) P = n.s. (0.99)	0.18 ± 0.63 (−0.88 to 1.11) P = n.s. (0.29)	0.18 ± 0.67 (−1.02 to 1.14) P = n.s. (0.32)	0.19 ± 0.68 (−0.99 to 1.49) P = n.s. (0.29)	0.19 ± 0.67 (−0.96 to 1.50) P = n.s. (0.29)
Net astigmatism	0.32 D @ Φ°	0.19 D @ (Φ + 34)°	0.20 D @ (Φ + 31)°	0.24 D @ (Φ + 27)°	0.23 D @ (Φ + 29)°

A statistically significant 0.32 D undercorrection was observed for measurements based on KA (model 1). Measurements based on Pentacam TCA revealed a nonsignificant mean undercorrection ranging between 0.07 and 0.14 D (models 2 to 5).

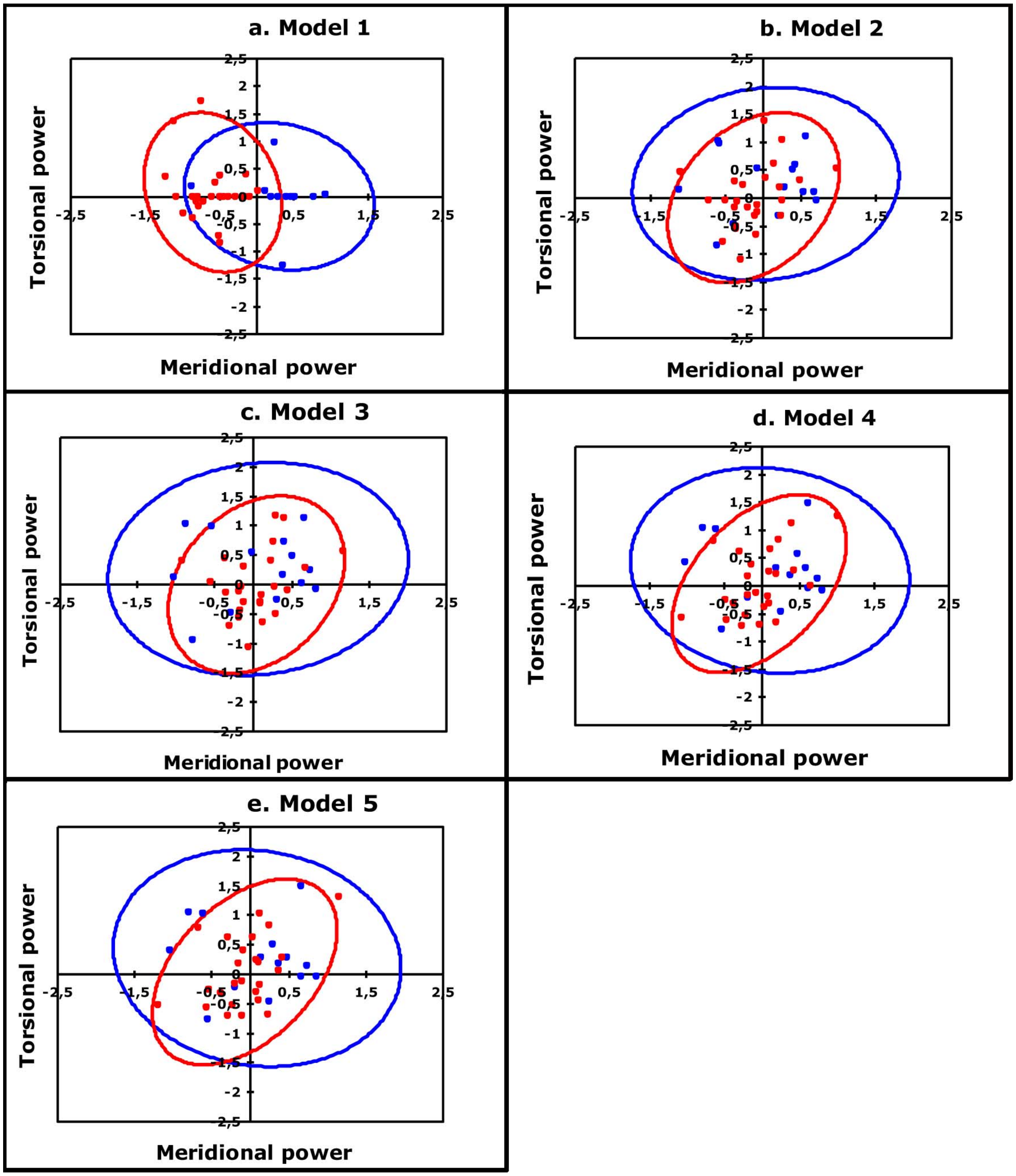

Figure. (A–E) The ERA displayed as 95% tolerance ellipses for observations.[22] The length and orientation of the ellipse axes depend on the SDs of and correlations between the involved meridional and torsional powers. Generally, the ellipses in models 2 through 5 are positioned closer to the origin and have longer axes (larger variance and therefore less precision) than model 1 and therefore graphically illustrate the SDs listed in Tables 3 and 4. WTR eyes: *red*; ATR eyes: *blue*.

WTR KA and add to ATR KA.[4–6] Therefore, evaluation of keratometry-based toric IOL refractive results should be performed separately for WTR and ATR eyes. Results of unselected groups will only reflect the relative distribution of WTR/ATR astigmatism. Our results strongly suggest that Scheimpflug imaging should be relied on to better assess corneal astigmatism.

In all models, a similar range of error was observed for both meridional and torsional power. The quite unpredictable SICA, which on average is low but has large interpatient variability, is one of the main reasons for such range of error. The progressive sophistication of models 2 through 5 did not further diminish the average and spread of the meridional error in astigmatism. These results would be quite different in case of relevant IOL misalignment and in a sample including a higher rate of myopic and hyperopic eyes, where individual ELP values may affect the mean refractive outcome.

The ERA SD was actually lower for the keratometry-based model 1 than the Pentacam-derived estimates, which probably may be attributed to differences in measurement accuracy. Keratometry may be validated by measurements on surfaces of known dimensions,[16] but to our knowledge such validation has not been reported for posterior corneal Scheimpflug imaging. Moreover, the repeatability of posterior corneal curvature by Scheimpflug cameras has been shown to be lower than that for anterior corneal curvature.[20]

Our data show a partial discrepancy with those of a similar study comparing toric IOL outcomes as predicted by KA and TCA.[21] The authors, in fact, found that TCA improved astigmatism prediction only in ATR eyes. The difference between the two studies is likely to depend on the different devices used to measure TCA and the different methods used to analyze the ERA. In the Koch[21] study, the error in astigmatism was calculated along fixed meridians, while the present study employed variable reference meridians based on the steeper meridian in each eye.

This study highlights the importance of specific vector analysis to fully characterize the refractive outcome of toric IOLs. Our method offers several advantages, as it enables us to investigate the effect of cylinder correction on the steeper preoperative corneal meridian for each eye (thus revealing whether over- or undercorrection of astigmatism occurred); separately assess the influence of any torsional effect; and simultaneously include the effects of TCA, SICA, IOL orientation, ELP influence, and subjective postoperative refraction in a single value (ERA), which gives us the final result of our surgery.

The present study also has some limitations that need to be considered. First, a larger sample size study is required to confirm our data. Second, we did not have postoperative Scheimpflug measurements for all eyes, so we did not include these data in our analysis. They might have been useful to further characterize our findings. Third, the repeatability of posterior corneal astigmatism measurements is not as high as that of anterior astigmatism measurements,[20] so future technological improvements are likely to provide better refractive outcomes. Finally, we did not evaluate long-term results, where IOL rotation may play a role.

In conclusion, based on our data, we suggest that directly measured TCA values and mean SICA values (according to the incision location) should be entered into toric calculators to achieve the highest accuracy when selecting the cylinder power of the IOL to be implanted in eyes undergoing astigmatism correction at the time of lens extraction. Specific vector analysis that separately considers the effect of astigmatism magnitude along a reference meridian and the effect of torsion is required to appropriately analyze the refractive outcomes.

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