Original Article

The relationship between angle kappa and astigmatism after phacoemulsification with implanting of spherical and aspheric intraocular lens

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Purpose: To determine the significance of any association between either change in angle kappa (K°) or the rectilinear displacement (L, mm) of the first Purkinje image relative to the pupil center and unexpected changes in astigmatism after phacoemulsification. **Methods:** Orbscan II (Bausch and Lomb) measurements were taken at 1, 2, and 3 months after unremarkable phacoemulsification in patients implanted with spherical (group 1, SA60AT, Alcon) or aspheric (group 2, SN60WF, Alcon) nontoric IOLs. The outputs were used to calculate L. Astigmatism, measured by autorefractometry and subjective refraction, was subjected to vector analysis (polar and cartesian formats) to determine the actual change induced over the periods 1–2 and 2–3 months postop. **Results:** Chief findings were that the mean (n, ±SD, 95%CI) values for L over each period were as follows: Group 1, 0.407 (38, ±0.340, 0.299–0.521), 0.315 (23, ±0.184, 0.335–0.485); Group 2, 0.442 (45, ±0.423, 0.308–0.577), 0.372 (26, ±0.244, 0.335–0.485). Differences between groups were not significant. There was a significant linear relationship between (A) the change in K (ΔK = value at 1 month-value at 2 months) and K at 1 month (x), where ΔK =0.668-3.794X (r = 0.812, n = 38, P = <0.001) in group 1 and ΔK = 0.263x -1.462 (r = 0.494, n = 45, P = 0.002) in group 2, (B) L and the J_{45} vector describing the actual change in astigmatism between 1 and 2 months in group 2, where J_{45} (by autorefractometry) =0.287L-0.160 (r = 0.487, n = 38, P = 0.001) and J_{45} (by subjective refraction) =0.281L-0.102 (r = 0.490, n = 38, P = 0.002), and (C) J_{45} and ΔK between 2 and 3 months in group 2, where J_{45} (by subjective refraction) =0.086ΔK-0.063 (r = 0.378, n = 26, P = 0.020). **Conclusion:** Changes in the location of the first Purkinje image relative to the pupil center after phacoemulsification contributes to changes in refractive astigmatism. However, the relationship between the induced change in astigmatism resulting from a change in L is not straightforward.

Access this article online
Website:
www.ijo.in
DOI:
10.4103/ijo.IJO_572_21
Quick Response Code:

Key words: Angle kappa, astigmatism, postphacoemulsification, first Purkinje image

Angle kappa (K), the angle between the pupillary and visual axes,[1-3] can affect the optical and visual performance after either corneal refractive surgery[4-12] or implantation of a multifocal IOL[13-19] and compensating for K can enhance these functionalities.[4,6,9-12,14] The mean K value is unaffected by phacoemulsification or FLACS but changes in K could occur in some individuals.[20-22] Previous studies focused on the difference between pre- and postop K values and ignored changes in K occurring from time-to-time after surgery. Could a change in K after phacoemulsification impact on the astigmatism revealed by refraction? The refractive error is moderately stable 1 week after uncomplicated phacoemulsification,[23] but changes in astigmatism are not unusual more than 1 month later. The normal corneal surface is elliptical[24-26] and the off-axis astigmatism can be estimated.[27,28] Aspheric IOLs designed to enhance the performance of the pseudophakic eye are also prone to off-axis astigmatism.[27-32] Variations in astigmatism over the corneal surfaces coupled with the optical effects of any decentration of the IOL are the main sources of unexpected change in refractive astigmatism. Estimating K is dependent upon on the distance separating the points on the corneal surface traversed by the lines joining (a) the fovea and the fixation point [the visual axis] and (b) the entrance pupil with the normal to the anterior corneal surface [pupillary axis].[1] Therefore, the initial question should be changed to: Could any change in this distance from time-to-time after phacoemulsification impact on the astigmatism revealed by refraction? If a change in this distance affects the astigmatism, then the effect may be enhanced, or attenuated, depending upon the characteristics of the IOL.

The eye is not perfectly still, and the ocular surface is continually changing, during refraction, but these phenomena have negligible effects on visual acuity.[33,34] The astigmatism measured during refraction is the average of all the refractions occurring over the ocular surface and remaining optical components of the eye within the limits of the pupil. Such practical limitations may impact on any hypothetical association between K and astigmatism.

The aim of this study was to monitor the parameters used to calculate K and to investigate any clinical correlations with the changes in astigmatism after routine phacoemulsification.

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Received: 13-Mar-2021 Revision: 08-Jun-2021
Accepted: 29-Jun-2021 Published: 26-Nov-2021

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Cite this article as: Tutchenko L, Patel S, Skovron M, Horak O, Voytsekhivskyy O. The relationship between angle kappa and astigmatism after phacoemulsification with implanting of spherical and aspheric intraocular lens. Indian J Ophthalmol 2021;69:3503-10.

Methods

Evaluation of angle kappa, and the distance between the pupil center and first Purkinje image

Corneal topographic systems have been used to evaluate *K*.[2,35-37] Topographers estimate *K* by measuring the distance between the pupil centre and the first Purkinje image of an axial target (the bright corneal reflex) when the eye is in the primary position of gaze. It is assumed that the intercept (a) between the visual axis and the anterior corneal surface coincides with the location of this bright corneal reflex and (b) of the pupillary axis striking the anterior corneal surface coincides with the pupil center. Some topographers display the horizontal and vertical coordinates of the first Purkinje image relative to the pupil center and compute *K* based on constants for the distances between the cornea and nodal points of the eye. Any variation in the location of the first Purkinje image (the bright corneal reflex) relative to the pupil center will affect *K*. The topographer outputs can be used to calculate the rectilinear displacement of this first Purkinje image (call it "*L*") from one time to another by arbitrarily setting the pupil center at the origin (0,0 coordinates) of a cartesian plane. The change in *K* was monitored, and the rectilinear displacement *L* was calculated, over 1–2 and 2–3 months postop.

Treatment of astigmatic data

Vector analysis must be used to describe changes in astigmatism when there are differences in the axis. The procedures developed by Alpins[38] and Thibos *et al*.[39] are widely used for the analysis of astigmatism in ophthalmology. The first procedure expresses the difference in astigmatism between two sets of refractive data in a polar format. The second procedure expresses astigmatism in a cartesian format by reducing pairs of astigmatic power and axis values into single figures (J_0 and J_{45}) that are more amenable to uncomplicated statistical analysis. Astigmatism obtained by autorefractometry and subjective refraction over 1-to-2 and 2-to-3 months postop were subjected to the first procedure to calculate the astigmatism induced during each period. The values of induced astigmatism (IA) were then subjected to the second procedure to calculate the J_0 and J_{45} equivalents.

Clinical assessment of angle kappa and refractive astigmatism

Orbscan II (Bausch and Lomb, Rochester, NY, version 3.2) is a Placido disc, scanning slit, servo-controlled system for the assessment of corneal tomography. In addition, the device captures the locations of the pupil center and the first Purkinje image. From this information, the software provides the distance separating these two landmarks along horizontal (I) and vertical (II) axes, the angular direction of the first Purkinje image from the pupil center (B) and *K*. Starting at the 3 o'clock position (0°) and travelling anticlockwise, B is the meridian connecting the pupil center with the first Purkinje image. A serviced and calibrated single Orbscan II model was used throughout the course of the study as described in the user's handbook. The refractive astigmatism was determined using a single calibrated autorefractometer (Tomey RT-7000, Tomey Corp, Tokyo, Japan) followed by routine subjective refraction. All cases were checked at 1, 2, and 3 months postop.

Study design

This was a prospective, consecutive, partially masked, observational study adhering to the tenets of the Declaration of Helsinki and approved by the local ethics committee. All patients gave signed consent after the purpose and procedures of the study were fully explained. Measurements were made on each patient on a consecutive, case-by-case, basis.

Exclusion criteria

None of the patients enrolled had any history of previous ocular surgery, contact lens wear, corneas thinner than 545 μm, unusual corneal topography (at either surface), corneal opacities, and active or previous conditions linked to either the anterior or posterior segment. All had a need for routine cataract surgery only.

IOL power selection

Biometry was performed by one examiner using IOL Master 700 SWEPT source OCT-biometer, software version 1.70 (Carl Zeiss, Meditec AG, Jena). Eight IOL power formulas were used: Barrett Universal II, Haigis, Hoffer Q, Holladay1, Holladay2, SRK/T, T2, and VRF. All except T2 and VRF were part of the IOL Master 700 software version 1.70. The T2 formula is an upgraded version of the SRK/T formula resulting in 10% improvement in the prediction accuracy of refractive outcomes.[40] This formula has been validated for a wide range of axial lengths and is available as part of the ViOL Commander Software version 2.0.0.0.[41] For short eyes, the Haigis, Hoffer Q, and VRF formulas were used; for eyes with medium axial lengths, Holladay 1 and VRF were used; for eyes with medium to long axial lengths, Holladay1, Holladay2, and T2 were used; for long eyes, Barrett Universal II and SRK/T were used. The final IOL power chosen for each case was at the discretion of the examiner depending on the parameters of the eye and personal experience. The IOL selected for implantation was a hydrophobic acrylic 1-piece monofocal nontoric lens of either a spherical (group 1, SA60AT, Alcon Surgical, Inc) or aspheric (group 2, SN60WF, Alcon Surgical, Inc) or design.

Description of preoperative preparation, surgery, and post-operative treatment

The horizontal axis on the cornea, of the eye scheduled for treatment, was marked by one examiner (LT) using a slit lamp-marking technique under topical anesthesia prior to pupil dilation. The slit-lamp beam width was adjusted to its minimum visible setting, rotated to horizontally align over the pupil center. The slit lamp was moved to the contralateral eye to ensure both eyes were positioned along a common axis. When the first Purkinje images in both eyes were aligned at the same height, the slit lamp was then moved over to the eye scheduled for treatment eye without changing the height of the beam. The horizontal axis was marked on the cornea at 3 and 9 o'clock positions with a 30-gauge sterile needle and stained with 2% collargoli solution (colloidal silver solution). Surgery was performed by one surgeon (LT) under topical anesthesia through a 2.2-mm self-sealing clear corneal incision. In all cases, a corneal tunnel was made at 12 o'clock using a Mendez ring with reference to the preoperative markings. A 1.2-mm paracentesis was made at 3 and 9 o'clock with reference to the preoperative marks. After a 5.0-mm circular capsulorhexis, lens hydrodissection was performed followed by phacoemulsification and bimanual cortex removal using the Infinity Vision System (Alcon Surgical, Inc). A hydrophobic acrylic 1-piece monofocal IOL was positioned in the capsular bag and the wound was closed by stromal hydration. The procedure was completed with injections of dexamethasone (subconjunctival) and betamethasone (parabulbar). Postoperative treatment involved drops of levofloxacin, dexamethasone, and indomethacin with a gradual tapering off, dexpanthenol gel, and a combination of trehalose and hyaluronic acid. IOP was within normal limits at all examinations postoperatively. All treatments were monocular.

Data and statistical analysis

All data were logged onto Excel spread sheets (Microsoft, Redmond, WA) and all refractive data were subjected to vector analysis. Data were then analyzed to determine the significance of any:

i. Intra- and intergroup differences in mean *K* values and associated measurements (I, II, and B, paired and unpaired *t*-test). Intra- and intergroup change in mean *L* values between periods (paired and unpaired *t*-test)
ii. Correlation between the change (Δ) in *K*, I, II, and B, and the values of *K*, I, II, and B at the start of each period within each group (Pearson correlation)
iii. Intra- and intergroup change in the astigmatism determined by refraction during each period (paired and unpaired *t*-test)
iv. Intra- and intergroup differences in the induced astigmatic powers, axes, J_0 and J_{45} vector values between periods (paired and unpaired *t*-test)
v. Correlation between the astigmatic vectors describing the change in astigmatism (induced astigmatic power J_0 and J_{45}) during a period and corresponding Δ*K*, ΔI, ΔII, ΔB and *L* values (Pearson correlation).

Appropriate nonparametric tests were planned for application if any data set was not normally distributed (Kolmogorov–Smirnov test).

Results

Fifty female and 53 male patients of mean (±sd, range) age 69.5 years (±10.4, 40–90) were enrolled in this investigation, 51 were implanted with the spherical (SA60AT, group 1) and 52 with the aspheric (SN60WF, group 2) IOL. Procedures were unremarkable without complications. Ninety-two returned at 1 month, 83 at 2 months, and 49 at 3 months. The main results are shown in Tables 1-3 and Figs. 1-3. All astigmatic values are reported in positive format. The data sets did not significantly differ from the normal distribution ($P > 0.05$). Hence, parametric tests were used throughout.

Change in mean value of angle Kappa (K)

Mean (±sd and 95%CI) values for *K*, supporting data (I, II, and B), and calculated rectilinear displacement of the first Purkinje image (*L*) are shown in Tables 1 and 2. Intra- and intergroup differences in the means from time-to-time were not significant ($P > 0.05$).

Change (Δ) in angle kappa (K), I, II, B and respective values at the start of any period (1 and 2 months, 2 and 3 months)

Some significant associations were found. The least squares numerical expressions describing these associations are shown in Table 3.

Change in mean values of astigmatic power by refraction

Mean (±sd and 95%CI) values for astigmatism are shown in Tables 1 and 2.

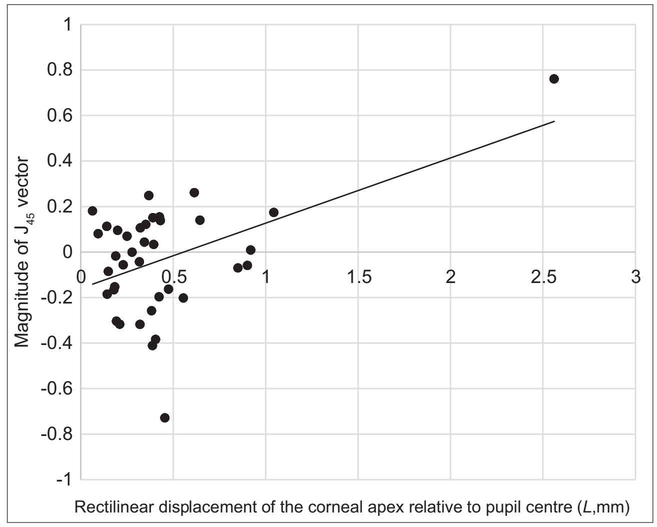

Figure 1: Relationship between the rectilinear displacement (*L*, mm) of the corneal apex relative to the pupil center over the period between 1 and 2 months postop in group 2 (SN60WF aspheric IOL) and J_{45} vector describing the change in astigmatism by autorefractometry. The association between the two parameters is represented by $J_{45} = 0.287L - 0.160$ ($r = 0.487$, $n = 38$, $P = 0.001$)

For the astigmatism revealed by autorefractometry, a significant change was revealed in group 1 between 2 and 3 months postop ($P = 0.045$, $n = 23$), but no significant changes were revealed in group 2. For the astigmatism revealed by subjective refraction, changes in the mean values were not significant ($P > 0.05$).

In the cases that attended at 1 and 2 months postop, significant intergroup differences in mean astigmatism were revealed by autorefractometry ($P = 0.037$) and subjective refraction ($P = 0.024$) at 2 months postop. Apparent intergroup differences in mean astigmatism were not significant at 1 and 3 months postop.

Differences of the induced astigmatism, J_0 and J_{45} vectors

Mean (±sd and 95%CI) values for the induced astigmatism and corresponding J_0 and J_{45} values are shown in Tables 1 and 2. Apparent inter- and intragroup differences for the induced astigmatism and J_0 and J_{45} values were not significant ($P > 0.05$).

Association between induced astigmatic power and induced astigmatic axis with the changes in angle kappa (K), I, II, B, and L

No significant correlations were detected between the induced astigmatism and changes in either *K*, I, II, B, or *L* in either group ($P > 0.05$).

Association between J_0, J_{45}, and changes (Δ) in angle kappa (K), I, II, B, and L

The significant correlations and the least squares numerical expressions describing these associations were:

Changes according to autorefractometry for results between 1 and 2 months in Group 2,

$$J_{45} = 0.287L - 0.160 \ (r = 0.487,\ n = 38,\ P = 0.001) \quad \text{eq. 1}$$

Changes according to subjective refraction for results between 1 and 2 months in Group 2,

$$J_{45} = 0.281L - 0.102 \ (r = 0.490,\ n = 38,\ P = 0.002) \quad \text{eq. 2}$$

Table 1: Characteristics of angle kappa and astigmatism between 1 and 2 months postop

		1 month	2 months
Group 1, Spherical IOL (SA60AT) *n*=38			
Kappa	K	6.40 (±3.25, 5.34-7.44)	5.92 (±1.79, 5.34-6.50)
Angle	B	268.9 (±78.5, 244-294)	250.3 (±106.8, 216-285)
Intercept	I	-0.07 (±0.47, -0.22 to 0.08)	-0.09 (±0.43, -0.23 to 0.05)
	II	-0.10 (±0.36, -0.22 to 0.02)	-0.02 (±0.43, -0.16 to 0.12)
	L	0.407 (±0.340, 0.299-0.521)	
Autorefractometer	Power	1.29 (±0.93, 0.98-1.59)	1.25 (±0.56, 1.06-1.44)
	Axis	65.2 (±64.9, 44.0-86.4)	55.4 (±61.4, 35.4-75.5)
Subjective	Power	0.72 (±0.91, 0.41-1.03)	0.67 (±0.75, 0.42-0.93)
	Axis	52.7 (±70.4, 20.2-85.2)	48.5 (±64.9, 17.7-79.4)
*Induced Astigmatism	0.89 (±0.71, 95% CI 0.66-1.12), 94.1 (±60.1, 95% CI 74.8-113.5)		
*J_o and J_{45}	-0.046 (±0.521, 95% CI-0.214 to 0.122), -0.092 (±0.218, 95% CI -0.164 to -0.021)		
**Induced Astigmatism	0.67 (±0.69, 95%CI 0.45-0.89), 106.0 (±67.26, 95%CI 84.3-127.7)		
**J_o and J_{45}	-0.111 (±0.424, 95%CI-0.249 to 0.028), -0.034 (±0.200, 95%CI -0.099 to -0.032)		
Group 2, Aspheric IOL (SN60WF) *n*=45			
		1 month	2 months
Kappa	K	6.51 (±2.68, 5.66-7.36)	6.26 (±2.33, 5.52-7.00)
Angle	B	260.7 (±69.8, 238-283)	264.8 (±66.9, 243-286)
Intercept	I	-0.07 (±0.64, -0.27 to 0.14)	-0.16 (±0.61, -0.35 to 0.04)
	II	-0.18 (±0.48, -0.33 to -0.03)	-0.10 (±0.31, -0.20 to -0.01)
	L	0.442 (±0.423, 0.308-0.577)	
Autorefractometer	Power	1.00 (±1.08, 0.65-1.35)	0.85 (±0.73, 0.61-1.09)
	Axis	66.1 (±57.3, 47.9-84.4)	70.0 (±58.4, 51.4-88.5)
Subjective	Power	0.51 (±0.71, 0.28-0.74)	0.53 (±0.66, 0.31-0.75)
	Axis	55.5 (±59.2, 25.6-85.5)	48.5 (±56.0, 21.9-75.1)
* Induced Astigmatism	0.75 (±0.63, 95%CI 0.55-0.95), 89.6 (±55.6, 95%CI 71.9-107.2)		
* J_o and J45	0.002 (±0.426, 95%CI-0.134 to 0.137), -0.033 (±0.249, 95%CI -0.112 to 0.047)		
** Induced Astigmatism	0.45 (±0.62, 95%CI 0.25-0.65), 87.4 (±62.1, 95%CI 67.7-107.2)		
** J_o and J_{45}	-0.080 (±0.282, 95%CI -0.171 to 0.011), -0.022 (±0.242, 95%CI -0.056 to 0.100)		

The mean values for angle kappa (K°), the line connecting the pupil center with the first Purkinje image (B°), distance [mm] separating these two landmarks along horizontal (I) and vertical (II) axes, the rectilinear displacement (*L*, mm) of the corneal apex relative to the pupil center over the period, astigmatic powers [DC, diopters] and axes according to autorefractometry and subjective refraction, the induced astigmatism over the period according to data obtained by autorefractometry (*) and subjective refraction (**), and the J_o and J_{45} vectors describing the induced astigmatism (* and **) are shown for the spherical (group 1 SA60AT IOL) and aspheric (group SN60WF) IOLs. Figures in parenthesis are the corresponding standard deviation and 95% confidence intervals. Within each group, changes in mean values between 1 and 2 months postop were not significant. Apparent differences in the mean values between groups were not significant except for mean astigmatism (by autorefractometry *P*=0.037, by subjective refraction *P*=0.024) at 2 months postop

Changes according to autorefractometry results between 2 and 3 months in Group 1,

$$J_{45} = 0.187\text{-}0.396L \; (r = -0.434,\ n = 23,\ P = 0.039) \qquad \text{eq. 3}$$

Changes according to subjective refraction results between 2 and 3 months in Group 2,

$$J_{45} = 0.086\Delta K \text{-}0.063 \; (r = 0.378,\ n = 26,\ P = 0.020) \qquad \text{eq. 4}$$

No other significant comparisons were found.

Discussion

Tables 1 and 2 show the mean values for *K* ranged from 5.62° to 6.51°, and these values were slightly higher when compared with previous reports.[2,3,20,36,42] Differences in the reported values of *K* may result from a variety of factors including age and ethnicity. For example, a Korean study found that *K* was higher in older patients,[40] but Iranian studies reported *K* reduced in older patients.[3,34] There was a slight fall in mean *K* between 1–2 months and 2–3 months. This apparent change supports previous findings where *K* tended to reduce after phacoemulsification,[22] but it was not statistically significant. The mean horizontal (I) and vertical (II) intercept values, respectively, ranged from -0.15 to -0.10 mm and -0.18 to -0.02 mm. According to Zarei-Ghanavati *et al.*[5] and Gharaee *et al.*,[3] the mean horizontal intercept values are -0.56 and -0.42 mm and the corresponding vertical values are 0.16 and 0.04 mm. Again, the differences may be related to ethnic variations. The change in *K* within individual cases over the period 1–2 months correlated with the value measured at 1 month postop. Table 3 shows, in both groups, the expected change in *K*, and most of the supplementary values can be predicted by the values obtained at 1 month postop. The lower incidence of significant comparisons over 2–3 months could be

Table 2: Characteristics of angle kappa and astigmatism between 2 and 3 months postop

		2 months	3 months
Group 1, Spherical IOL (SA60AT) *n*=23			
Kappa	K	5.62 (±1.68, 4.93-6.30)	5.75 (±1.83, 5.00-6.50)
Angle	B	232.6 (±98.3, 192-273)	229.2 (±100.7,188-270)
Intercept	I	-0.10 (±0.51, -0.31 to 0.10)	-0.15 (±0.48, -0.34 to 0.05)
	II	-0.05 (±0.33, -0.19 to 0.09)	-0.05 (±0.28, -0.16 to 0.07)
	L	0.315 (±0.184, 0.335-0.485)	
Autorefractometer	Power	1.38 (±0.63, 1.12-1.64)	1.13 (±0.70, 0.84-1.42)
	Axis	55.3 (±60.1, 29.6-81.0)	75.1 (±69.3, 45.4-104.7)
Subjective	Power	0.82 (±0.82, 0.48-1.14)	0.70 (±0.70, 0.41-0.98)
	Axis	47.3 (±63.1, 13.0-81.6)	69.5 (±77.5, 30.3-108.7)
* Induced Astigmatism	0.72 (±0.74, 95%CI 0.42-1.02), 76.4 (±59.3, 95%CI 52.1-100.6)		
* Jo and J45	-0.089 (±0.480, 95%CI -0.134 to 0.258), 0.062 (±0.167, 95%CI -0.006 to 0.131)		
** Induced Astigmatism	0.39 (±0.62, 95%CI 0.14-0.64), 102.8 (±44.2, 95%CI 84.7-120.9)		
** Jo and J45	-0.063 (±0.337, 95%CI -0.075 to 0.200), -0.065 (±0.125, 95%CI -0.116 to -0.014)		
Group 2, Aspheric IOL (SN60WF) *n*=26			
		2 months	**3 months**
Kappa	K	6.06 (±1.42, 5.53-6.60)	5.84 (±1.43, 5.30-6.37)
Angle	B	276.7 (±66.6, 252-302)	264.1 (±82.1, 233-295)
Intercept	I	-0.07 (±0.47, -0.24 to 0.11)	-0.01 (±0.48, -0.19 to 0.17)
	II	-0.12 (±0.31, -0.24 to 0.00)	-0.09 (±0.35, -0.22 to 0.04)
	L	0.372 (±0.244, 0.335-0.485)	
Autorefractometer	Power	0.74 (±0.80, 0.40-1.08)	0.75 (±0.70, 0.45-1.05)
	Axis	81.6 (±48.6, 61.7-101.5)	83.2 (±58.7, 59.3-107.2)
Subjective	Power	0.50 (±0.68, 0.21-0.79)	0.24 (±0.65, 0.03-0.52)
	Axis	72.6 (±74.9, 30.2-115.0)	83.8 (±65.9, 46.4-121.1)
* Induced Astigmatism	0.57 (±0.34, 95%CI 0.44-0.70), 91.0 (±49.5, 95%CI 72.3-109.7)		
* Jo and J45	0.018 (±0.288, 95%CI -0.090 to 0.126), -0.001 (±0.175, 95%CI -0.065 to 0.067)		
**Induced Astigmatism	0.34 (±0.42, 95%CI 0.18-0.50), 87.1 (±46.5, 95%CI 69.6-104.6		
**Jo and J45	0.051 (±0.213, 95%CI -0.029 to 0.131), -0.037 (±0.155, 95%CI -0.095 to 0.022)		

The mean values for angle kappa (K°), the line connecting the pupil center with the first Purkinje image (B°), distance [mm] separating these two landmarks along horizontal (I) and vertical (II) axes, the rectilinear displacement (*L*, mm) of the corneal apex relative to the pupil center over the period, astigmatic powers [DC, diopters] and axes according to autorefractometry and subjective refraction, the induced astigmatism over the period according to data obtained by autorefractometry (*) and subjective refraction (**), and the J_o and J_{45} vectors describing the induced astigmatism (* and **) are shown for the spherical (group 1 SA60AT IOL) and aspheric (group 2 SN60WF) IOLs. Figures in parenthesis are the corresponding standard deviation and 95% confidence intervals. The change in mean astigmatism in group 1 revealed by autorefractometry was significant (*P*=0.045). All other comparisons were insignificant

Table 3: Change in angle kappa and associated factors

	1-2 months	2-3 months
Group 1, Spherical IOL (SA60AT)		
K	*y*=0.668-3.794*x*, *r*=0.812, *P*=<0.001	ns
B	*y*=0.673*x*-162.4, *r*=0.479, *P*=0.003	*y*=0.470*x*-111.5, *r*=0.484, *P*=0.0194
I	*y*=0.400*x*+0.048, *r*=0.544, *P*=<0.001	*y*=0.408*x*+0.087, *r*=0.479, *P*=0.021
II	*Y*=0.698*x*-0.090, *r*=0.492, *P*=0.002	*y*=0.507*x*+0.035, *r*=0.591, *P*=0.003
Group 2, Aspheric IOL (SN60WF)		
K	*y*=0.263*x*-1.462, *r*=0.494, *P*=0.002	ns
B	ns	ns
I	*y*=0.369+0.114, *r*=0.460, *P*=0.004	*y*=0.194*x*-0.044, *r*=0.294, *P*=0.043
II	*y*=0.778*x*+0.064, *r*=0.790, *P*=<0.001	*y*=0.493*x*+0.029, *r*=0.442, *P*=0.021

Characteristics of the least squares numerical expressions between the change (*y*) in a parameter (*x*) and value of the parameter at the start of the periods 1-2 and 2-3 months postop. The *n* values for the first and second periods were Group 1, 38 and 23; Group 2, 45 and 26. K=angle kappa, B=angle of the line connecting the pupil center with the first Purkinje image, I=distance separating pupil center and the first Purkinje image along horizontal meridian, II=distance separating pupil center and the first Purkinje image along vertical meridian, ns=a significant association between *x* and *y* was not confirmed

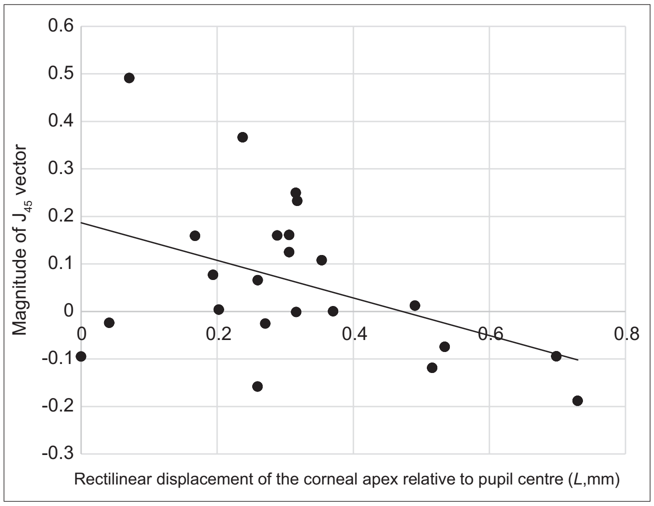

Figure 2: Relationship between the rectilinear displacement (L, mm) of the corneal apex relative to the pupil center over the period between 2 and 3 months postop in group 1 (SA60AT spherical IOL) and J_{45} vector describing the change in astigmatism by autorefractometry. The association between the two parameters is represented by $J_{45} = 0.187 - 0.396L$ ($r = -0.434$, $n = 23$, $P = 0.039$)

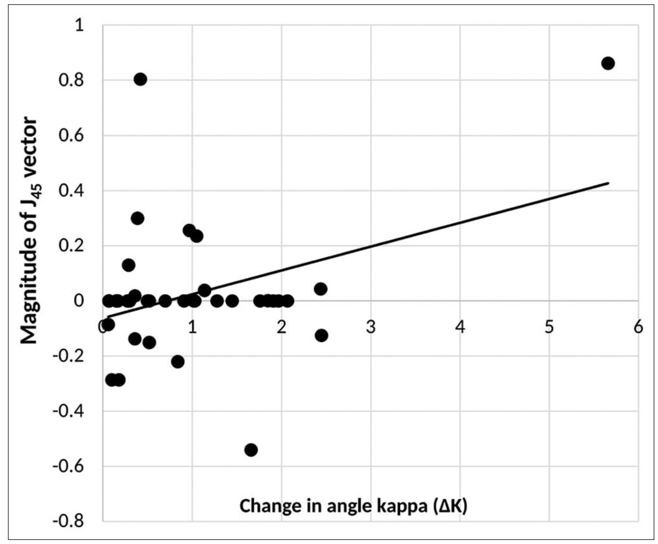

Figure 3: Relationship between the change in angle kappa (ΔK) over the period between 2 and 3 months postop in group 2 (SN60WF aspheric IOL) and J_{45} vector describing the change in astigmatism by subjective refraction. The association between the two parameters is represented by $J_{45} = 0.086\Delta K - 0.063$ ($r = 0.378$, $n = 26$, $P = 0.020$)

due to the lower attendance figures or other factors influencing the value of K.

The mean astigmatism remained stable over both periods, and this supports a more recent conclusion.[23] A change in astigmatism from + 0.25DCX100 to + 0.50DCX30 appears insignificant, but the difference in the axis results in an induced change in astigmatism of + 0.71DCX23. This example illustrates why the induced astigmatic powers, in Tables 1 and 2, exceeded the difference in mean astigmatic powers revealed by refraction. According to the results obtained by autorefractometry, the mean induced astigmatism (IA) was greater than 0.50DC in both groups over both periods. However, the results from subjective refraction show the mean IA exceeded + 0.50DC in group 1 (the spherical IOL) over 1–2 months postop. Objectively, the IA may fluctuate by more than 0.50DC. Subjectively, the patient does not always notice or respond to such changes. The result of a subjective refraction is the sphero-cylindrical average of all the refracted rays passing over the pupil coupled with the subject's perceptual interpretation of events. Autorefractometers measure the refraction by sampling rays passing through discrete regions over the pupil. Thus, the corresponding differences in Tables 1 and 2 are not surprising because the two procedures are not undertaking measurements under identical conditions and criteria.

The prevalence of dry eye (DE) following cataract surgery ranges from 9 to 32%[43,44] and DE is associated with an increase in astigmatism.[45,46] Therefore, after phacoemulsification it is reasonable to connect alterations in the patient's tears to contribute toward any induced astigmatism. The astigmatism induced in DE is, largely confined to the ocular surface, detected by objective techniques, not very stable and its magnitude depends on the duration of the interblink interval.[47,48] The current study was aimed at the astigmatism detected by subjective and objective refraction of the whole eye and not just the astigmatism confined to the ocular surface. Table 1 shows that at 2 months postop the astigmatism was significantly lower in group 2 (aspheric IOL) when compared with group 1 (spherical IOL). This supports previous findings espousing one of the benefits of aspheric IOLs.[30-32] In both groups, the IA expressed in a polar format was neither associated with K nor any of other supplementary values (B, I, II, or L). Nevertheless, some significant associations were found after converting values of IA from the polar to the cartesian format. Eqs. 1–3 describe and Figs. 1 and 2 show significant associations between L and the J_{45} vector. In group 2 (aspheric IOL), L significantly correlated with the corresponding J_{45} values over 1–2 months postop (eqs. 1 and 2). The gradients in eqs 1 and 2 are positive implying that J_{45} increases as L increases. According to these equations, the respective values of L are 0.56 and 0.36 mm when J_{45} is zero. J_{45} is always zero when the axis of the IA is either "with-the-rule" or "against-the-rule" regardless of astigmatic power. J_{45} has a nonzero value when the axis of the IA is predominately oblique. Eqs. 1 and 2 also predict that J_{45}= -0.160 or -0.102 when L is zero. These J_{45} values represent astigmatism of about + 0.75DCX100 and + 0.75DCX95, respectively, implying the IA by other factors are predominantly with-the-rule. Other factors such as tilt and/or decentration of the IOL.[32,43,49,50] In group 1 (spherical IOL), the J_{45} vector describing the IA, revealed by autorefractometry, was significantly correlated with the value of L over 2–3 months postop (eq. 3). The gradient is negative, unlike the gradients in eqs 1 and 2, predicting $J_{45} = 0.187$ when L is zero. This J_{45} value represents astigmatic values such as + 0.75DCX15 or + 1.50DCX7.5. These represent the IA by other factors besides L, but the axes are predominantly against-the-rule. There was no significant association between L and the J_0 vector. The value of J_0 is zero when the axis of IA is either 45° or 135°. When the power of the IA ≥ 0.25DC and the axis is predominantly oblique, then the numerical value of J_{45} will exceed that of J_0. Furthermore, the sd values for J_{45} tended to be lower than the corresponding values for J_0. A combination of the range of IA powers, axes, and lower J_{45} sd values is the likely reason why J_{45}, not J_0, was linked to L on some occasions.

Fig. 3 and eq. 5 show that in group 2 the change in *K* was associated with the J_{45} vector describing the change in subjective astigmatism. This implies that a change in *K* after phacoemulsification is more likely to have an impact on astigmatism when the IOL is aspheric. Yet, the distribution of data points in Fig. 3, coupled with the lack of any significant correlations between *L* and either J_0 or IA, suggests that other factors are primarily responsible for changes in refractive astigmatism. There is insufficient evidence to support the notion that a change in *K* after phacoemulsification affects astigmatism. However, changes in the rectilinear displacement of the first Purkinje image relative to the center of the pupil do appear to affect some aspects of astigmatism.

Conclusion

An unexpected change in astigmatism after phacoemulsification can arise from, for example, changes of IOL position or corneal curvature. When all the likely suspects are eliminated, clinicians should consider changes in the distance between the pupil center and location of the first Purkinje image. Unfortunately, there is no simple way for clinicians to control this distance.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

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