Five-Year Changes in Corneal Astigmatism After Combined Femtosecond-Assisted Phacoemulsification and Arcuate Keratotomy

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• PURPOSE: To investigate the long-term stability of corneal astigmatism after combined femtosecond (fs)-assisted phacoemulsification and arcuate keratotomy.

• DESIGN: Retrospective, interventional case series.

• METHODS: Surgery was performed using a Victus (Bausch & Lomb) platform. A single, 450-μm-deep arcuate keratotomy was paired at the 8-mm zone with the main phacoemulsification incision in the opposite meridian. The keratotomy incisions were not opened. Corneal astigmatism measurements obtained preoperatively and at 2 and 5 years postoperatively were analyzed using vector analysis.

• RESULTS: A total of 44 eyes of 44 patients (mean age 66.0 ± 10.1 years) were included. The mean preoperative corneal astigmatism was 1.40 ± 0.66 diopters (D). This was reduced to 0.74 ± 0.54 D at 2 years and 0.70 ± 0.50 at 5 years postoperatively ($P < .001$). There were no statistically significant differences between postoperative corneal astigmatism at 2 years and at 5 years ($P = .609$). Both magnitude of error and absolute angle of error were comparable between the 2 postoperative time points ($P > .805$). At the end of 5 years, 65% of the eyes were within 15 degrees of the preoperative astigmatic meridian. Comparative analysis showed significantly higher surgically induced astigmatism, lower differences in vector and absolute angles of error for the eyes with preoperative with-the-rule (WTR) astigmatism than eyes with against-the-rule (ATR) astigmatism at 5 years ($P < .004$).

• CONCLUSIONS: Our study showed the stability of femtosecond (fs)-assisted arcuate keratotomy was well-maintained over 5 years. There was a tendency of increasing overcorrection of preoperative WTR astigmatism and undercorrection of ATR astigmatism over time. **(Am J Ophthalmol 2020;217:232–239.**

APPROXIMATELY ONE-THIRD OF THE EYES RECEIVING cataract surgery have a corneal astigmatism greater than 1.0 diopter (D), and 8% have more than 2.0 D.[1] Residual astigmatism induces symptomatic blurred vision, reduces uncorrected visual acuity, and causes spectacle dependence.[2] The 2 major techniques for the correction of corneal astigmatism during cataract surgery are corneal incision and toric intraocular lens implantation. Arcuate keratotomy uses partial thickness incisions at the steep corneal meridian to induce flattening of the steep axis while steepening the flat axis.[3] It has been manually performed over decades to reduce corneal astigmatism. However, arcuate keratotomy has often been associated with low predictability due to the lack of reproducibility in incision length and axis alignment.[4] The femtosecond (fs) laser technology allows creation of arcuate keratotomy incisions with favorable accuracy, safety, and reproducibility, reducing astigmatism associated with keratoplasty[5–8] and residual astigmatism after cataract and refractive surgery.[9,10] Several studies investigated the efficacy of fs-assisted arcuate keratotomy at the time of cataract surgery with study durations ranging from 1 to 6 months.[11–15] By using different incision architecture, this technique has been shown to reduce astigmatism by 36%-50%.[16]

The present authors reported 2-year outcomes of fs-assisted arcuate keratotomy during cataract surgery, demonstrating the stability of corneal astigmatism over time.[17] The current study was a follow-up study of corneal astigmatism after combined fs-assisted phacoemulsification and arcuate keratotomy, increasing the observation period from 2 to 5 years. A single penetrating arcuate keratotomy was paired with an opposite phacoemulsification incision along the steep axis in eyes with low-to-moderate corneal astigmatism.

SUBJECTS AND METHODS

THIS WAS A RETROSPECTIVE STUDY PERFORMED AT THE Hong Kong Laser Surgery Centre. Consecutive patients

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Accepted for publication May 1, 2020.

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  0002-9394/$36.00
https://doi.org/10.1016/j.ajo.2020.05.004

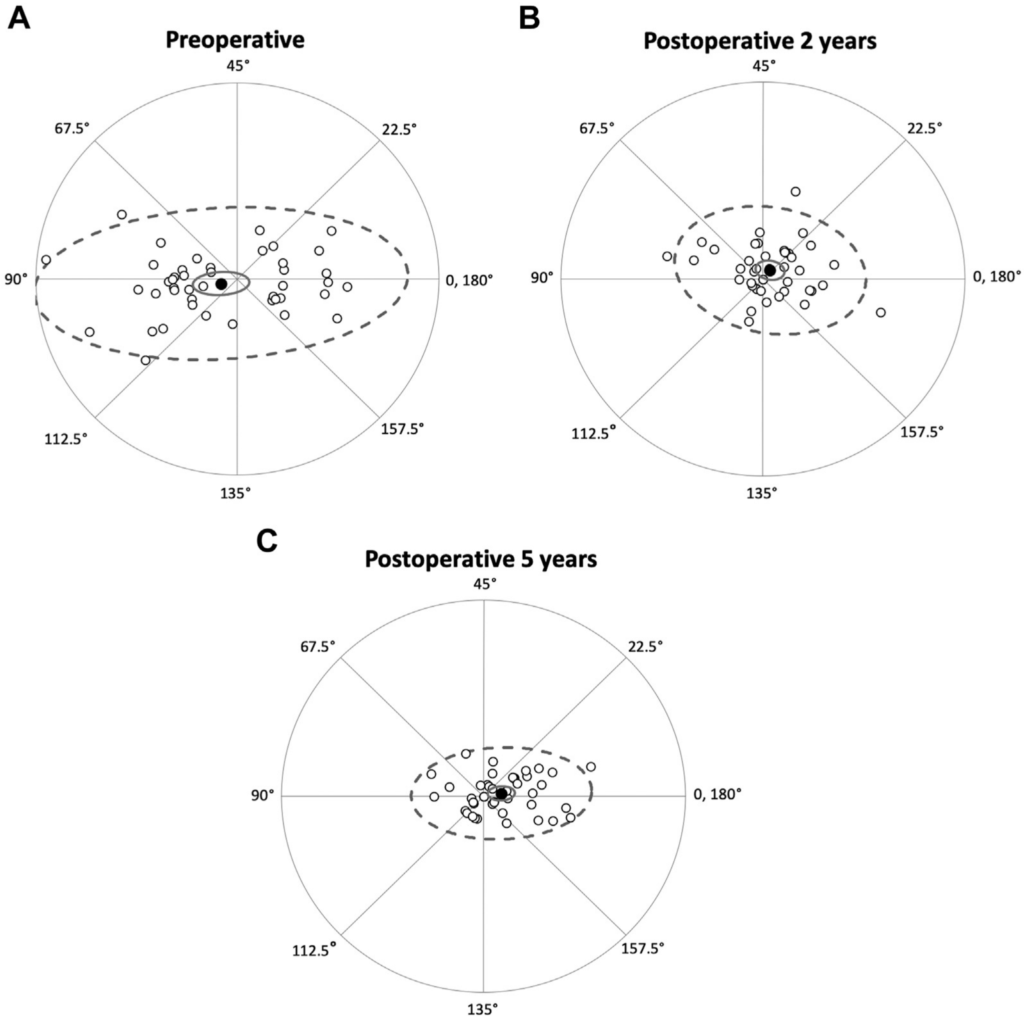

FIGURE 1. Double-angle plot of preoperative (A) and postoperative corneal astigmatism at 2 years (B) and at 5 years (C). The solid circle represents the centroid, and the open circles represent all patients. The curves marked by solid and dashed lines represent the 95% confidence ellipses of the centroid and all patients, respectively.

who underwent combined fs-assisted phacoemulsification and arcuate keratotomy between September 2013 and February 2014 and completed the 5-year postoperative follow-up assessment were included. These patients had cataract and corneal astigmatism of 0.5-2.5 D. The Joint Chinese University of Hong Kong-New Territories East Cluster Clinical Research Ethics Committee approved the study protocol. The study was conducted in accordance with the tenets of the Declaration of Helsinki.

All patients underwent a detailed preoperative ophthalmological evaluation including slit-lamp and fundus examinations. Intraocular lens power calculation was performed using partial coherence interferometry (IOLMaster 500; Carl Zeiss Meditec, Dublin, California). Planning of the arcuate keratotomy was performed using a corneal topographer (Nidek OPD-Scan III; Nidek Technologies, Aichi, Japan). A single reference point at the temporal limbus was marked while the patient sat upright. Treatment alignment was performed using the corneal topographer immediately before the surgery. The marking and alignment technique has been published previously.[18]

Phacoemulsification and arcuate keratotomy were performed using the Victus fs laser platform (Bausch & Lomb, Dornach, Germany). A single arcuate keratotomy incision was paired in the opposite meridian with the main corneal incision for phacoemulsification along the steep axis. The phacoemulsification incision was created between the superior and temporal peripheral cornea. The depth of the astigmatic keratotomy was set at 450 μm with a 90-degree side-cut angle. The optical zone diameter was set at 8 mm. The range of the angular arc length of the keratotomy incision was between 30 and 80° according to the surgeon's nomogram.[17] The main corneal incision had a triplanar configuration with a width of 3.0 mm and length ranging from approximately 1.8 to 2.0 mm. Two 1.5-mm-wide peripheral incisions with a

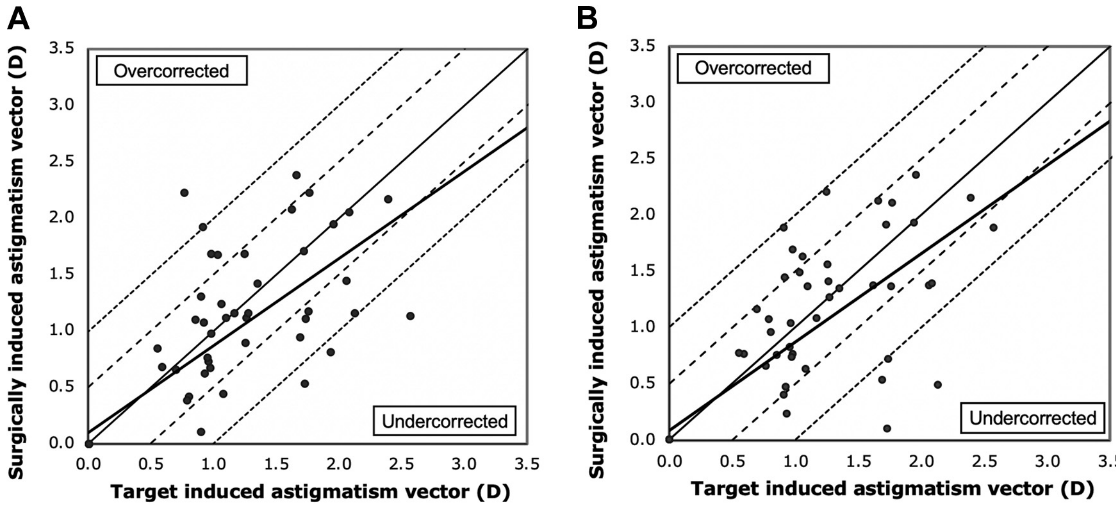

FIGURE 2. Scatterplot of surgically induced astigmatism (SIA) versus target-induced astigmatism (TIA) after combined fs-assisted phacoemulsification and arcuate keratotomy at 2 years (A) and at 5 years (B).

triplanar configuration were made 60° to each side of the main corneal incision.

A fs laser was used to create the anterior capsulotomy, lens fragmentation, corneal incisions, and arcuate keratotomy in this sequence. Phacoemulsification was performed using the Infiniti system (Alcon Laboratories, Fort Worth, Texas) with implantation of a monofocal nontoric single-piece hydrophilic acrylic intraocular lens (Akreos Adapt AO, Bausch & Lomb, Rochester, New York). The arcuate keratotomy incisions were not opened after the procedure. Postoperatively, a combination of topical dexamethasone 0.1% and tobramycin 0.3% (both Alcon Laboratories) eye drops were used 4 times a day for 1 month.

Preoperative and postoperative corneal astigmatism was measured in the 6-mm zone by corneal topography (Nidek OPD-Scan III; Nidek Technologies). Astigmatic magnitude and meridian of simulated keratometry was evaluated by using the refractive index of the cornea set as 1.3375. Preoperative and postoperative measurements at 2 years and 5 years were compared. Vector analysis was performed to evaluate the effective correction of astigmatism using the Alpins method.[19] The target-induced astigmatism (TIA) vector is the intended astigmatic change after surgery. The TIA is equivalent to the preoperative corneal astigmatism. The surgically induced astigmatism (SIA) vector is the actual astigmatic change induced by the operation. The difference vector (DV) is the astigmatic change that would enable the initial surgery to achieve its intended goals. The DV is equivalent to the postoperative corneal astigmatism. The magnitude of error is the arithmetic difference between the SIA and TIA. The angle of error (AE) is the angle described by vectors of SIA versus TIA. The correction index (CI) is calculated as the SIA-to-TIA ratio. The CI indicates an overcorrection if it is higher than 1 or an undercorrection if it is lower than 1. The index of success (IOS) is the DV-to-TIA ratio and measures the success with an ideal value of 0.

With-the-rule (WTR) astigmatism and against-the-rule (ATR) astigmatism were defined as having steep corneal meridians at 67.5 to 112.5° and either 0 to 22.5° or 157.5 to 180°, respectively. Oblique astigmatism was defined as all values in between.[20] Double-angle plots were used to display the preoperative and postoperative corneal astigmatism measurements.

Statistical analyses were performed using the SPSS version 21 software (IBM, Chicago, Illinois). The one-way analysis of variance with repeated measures was used to analyze changes over time. Comparisons between eyes with WTR and ATR astigmatism were performed using the parametric *t*-test. The relationship between TIA and SIA was assessed using the Pearson correlation. Statistical significance was defined as *P* value <.05.

RESULTS

IN THE ORIGINAL STUDY, 50 EYES OF 50 PATIENTS WERE included.[17] Of those, 44 patients (27 females, 17 males) were available for examination 5 years after surgery. The mean age at the time of surgery was 66.0 ± 10.1 years. The mean preoperative corneal astigmatism or TIA was 1.40 ± 0.66 D. This was significantly reduced to 0.74 ± 0.54 D at 2 years and to 0.70 ± 0.50 D at 5 years postoperatively ($P < .001$). The corresponding refractive cylinder values were −0.78 ± 0.56 D and −0.73 ± 0.52 D, respectively. No differences were found between postoperative corneal astigmatism and DV measurements at 2 and 5 years ($P = .609$). Double-angle plots of preoperative and postoperative corneal astigmatism are shown in Figure 1. A high

TABLE 1. Vector Analysis of Keratometric Astigmatic Correction after fs-Assisted Combined Phacoemulsification and Arcuate Keratotomy Using the Alpins Method

Vector Analysis Parameters	2 Years	5 Years	*P* Value
TIA			
Arithmetic mean ± SD, D	1.40 ± 0.66		/
Range, D[a]	1.37 to 1.43		
SIA			
Arithmetic mean ± SD, D	1.26 ± 0.61	1.28 ± 0.62	.850
Range, D[a]	1.23 to 1.29	1.25 to 1.30	
DV			
Arithmetic mean ± SD, D	0.74 ± 0.54	0.70 ± 0.50	.609
Range, D[a]	0.72 to 0.77	0.68 to 0.72	
ME			
Arithmetic mean ± SD, D	−0.14 ± 0.62	−0.12 ± 0.61	.850
Range, D[a]	−0.17 to −0.11	−0.15 to −0.10	
AE			
Arithmetic mean ± SD, degrees	3.1 ± 17.6	1.7 ± 22.0	.594
Range, degrees[a]	2.3 to 3.9	0.7 to 2.7	
Absolute AE			
Arithmetic mean ± SD, degrees	12.8 to 12.4	13.4 ± 17.4	.805
Range, degrees[a]	12.2 to 13.3	12.6 to 14.2	
CI			
Geometric mean	0.86	0.85	/
Range[a]	0.84 to 0.88	0.83 to 0.87	
IOS			
Geometric mean	0.50	0.47	/
Range[a]	0.48 to 0.53	0.45 to 0.49	

AE = angle of error; CI = correction index; D = diopter; DV = difference vector; IOS = index of success; ME = magnitude of error; SIA = surgically induced astigmatism; SD = standard deviation; TIA = target-induced astigmatism

[a]95% confidence interval.

correlation was noted between preoperative TIA and postoperative SIA at 2 years (r = 0.533; $P < .001$) and 5 years (r = 0.474; $P = .001$) (Figure 2). AE and absolute AE were similar at the examined postoperative time points ($P > .594$) (Table 1). Histograms showing the distribution of AE are shown in Figure 3. At the end of the 5-year postoperative period, 66% of the eyes had less than 0.75 D residual astigmatism, whereas 65% were within 15 degrees of the preoperative astigmatic meridian. The geometric means of the CI were 0.86 and 0.85 at 2 years and 5 years, respectively, demonstrating undercorrection. The corresponding IOS values were 0.50 and 0.47 indicating success in 50% and 53% of the cases, respectively (Table 1).

There were 24 WTR astigmatism eyes, 16 ATR astigmatism eyes, and 4 eyes with oblique preoperative corneal astigmatism. No significant differences in TIA were detected between WTR astigmatism eyes and ATR astigmatism eyes ($P = .414$). The comparative analysis at 5 years revealed significantly higher SIA, lower DV, and absolute AE values for eyes with preoperative WTR astigmatism ($P < .004$). Measuring from postoperative 2 to 5 years, a significant increase and decrease in SIA were noted in eyes with preoperative WTR and ATR astigmatism, respectively ($P < .020$). The geometric mean of CI changed from 0.98 to 1.14 for eyes with WTR astigmatism and from 0.71 to 0.63 for eyes with ATR astigmatism. At 5 years postoperatively, the IOS values were 0.33 and 0.67 for eyes with WTR and ATR astigmatism, indicating a success of 67% and 33%, respectively (Table 2).

No intra- or postoperative corneal complications including corneal perforation, wound dehiscence, inflammation, and infection were observed in any of the eyes.

DISCUSSION

THE USE OF FS LASERS REPRESENTS AN IMPORTANT advancement in the field of cataract surgery. With an fs laser, wound creation, anterior capsulotomy, and corneal incisions can be performed accurately.[21] Differences in keratotomy architecture and nomograms were used in studies of fs-assisted arcuate keratotomy at the time of cataract surgery. Two commonly used techniques are penetrating and intrastromal keratotomies.[16] In the current study, a single penetrating keratotomy was paired with

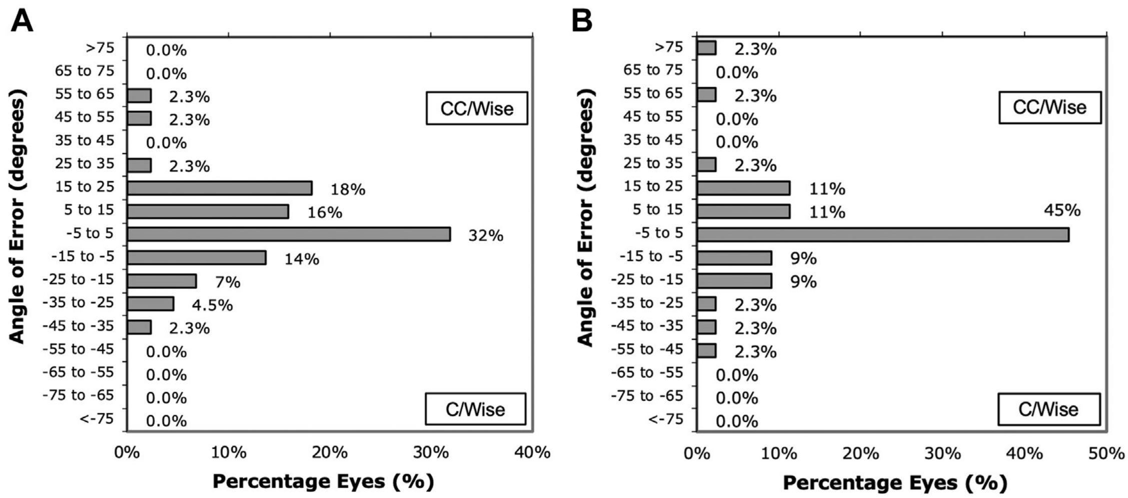

FIGURE 3. Distribution of the angle of error after combined fs-assisted phacoemulsification and arcuate keratotomy at 2 years (A) and at 5 years (B).

the main phacoemulsification incision. This resulted in undercorrection of the astigmatism at 2 years (CI = 0.86) and 5 years (CI = 0.85). A recently published study reported a higher CI (0.94) at 3 months after paired penetrating fs-assisted arcuate keratotomy combined with cataract surgery in 189 eyes.[22] Day and associates,[13] using paired fs-assisted intrastromal keratotomies during cataract surgery, also reported undercorrection of astigmatism at 1 month postoperatively in 196 eyes. The lower CI of 0.63 in the study by Day and associates could be attributed to an intact Bowman's layer for the intrastromal technique.[13] Using the same surgical nomogram and fs laser settings described by Day and associates,[13] Roberts and associates[11] demonstrated a higher CI (0.73) with the main phacoemulsification incisions created on the steep axis rather than on the temporal side.

In the current study, a simple nomogram was used without considering the astigmatism meridian. The present results showed a significantly higher SIA in eyes with preoperative WTR astigmatism than that in eyes with ATR astigmatism. Wang and associates[14] also reported overcorrection of astigmatism 1 month after penetrating fs-assisted arcuate keratotomy in most eyes with preoperative WTR corneal astigmatism. Using regression analysis, Day and associates[13] found that WTR astigmatism was associated with a 0.13-D higher SIA than ATR astigmatism for intrastromal astigmatic keratotomy.[23] This could be attributed to the additional refractive effect of the posterior cornea, which was also seen following toric intraocular lens implantation and refractive surgery.[24] In an evaluation of 715 corneas, ATR astigmatism was reported in 87% of the posterior corneas.[25] Löffler and associates[26] analyzed the effects of anterior, posterior, and total corneal astigmatism in eyes that underwent fs-assisted arcuate keratotomy and found a significant reduction in anterior and total but not in posterior corneal astigmatism. Astigmatic corrections that are solely based on anterior keratometry are likely to cause overcorrection in eyes with WTR astigmatism and undercorrection in eyes that have ATR astigmatism. Therefore, when performing an arcuate keratotomy, the surgeon must account for posterior corneal astigmatism either by adjusting the nomogram or by using the total corneal astigmatism for surgical planning. Using computer modelling strategy to optimize surgical parameters for arcuate keratotomy can possibly lead to more reliable postoperative outcomes.[27]

The present study reported the long-term corneal astigmatic changes following combined fs-assisted arcuate keratotomy and phacoemulsification. Use of vector analysis demonstrated that the overall astigmatic effect was maintained from 2 to 5 years postoperatively. No significant differences were observed in the parameters SIA, DV, magnitude of error, AE, and absolute AE over time. The values for CI and IOS at 2 years were also similar to those at 5 years. No other study has investigated the long-term efficacy of fs-assisted arcuate keratotomy in eyes with simultaneous cataract surgery. In a previous publication, evaluation of the same patient cohort showed a stable astigmatic correction at 2 weeks and 2 years after surgery.[17] Evidence describing the long-term outcomes of manual arcuate keratotomy at the time of cataract surgery is also limited.[28] A retrospective case series evaluating paired limbal relaxing incisions during cataract surgery reported a regression of keratometric values from 2 to 10 weeks after surgery, but these values remained stable afterward from 10 weeks to 3 years.[29]

In the subgroup analysis performed by the present authors over 5 years after surgery, a discrepancy of treatment efficacy was noted between eyes with preoperative WTR and ATR astigmatism. Eyes with preoperative WTR

TABLE 2. Vector Analysis of Keratometric Astigmatic Correction after fs-Assisted Combined Phacoemulsification and Arcuate Keratotomy Using the Alpin Method

	WTR			ATR			WTR versus ATR	
Vector Analysis Parameters	2 Years	5 Years	*P* Value[b]	2 Years	5 Years	*P* Value[b]	*P* Value at 2 Years	*P* Value at 5 Years
TIA								
Arithmetic mean ± SD, D	1.52 ± 0.77		/	1.34 ± 0.51		/	.414	
Range, D [a]	1.46-1.58			1.28-1.40				
SIA								
Arithmetic mean ± SD, D	1.43 ± 0.55	1.63 ± 0.50	.020	1.05 ± 0.60	1.01 ± 0.60	.136	.019	<.001
Range, D [a]	1.39-1.48	1.59-1.67		0.98-1.13	0.93-1.08			
DV								
Arithmetic mean ± SD, D	0.70 ± 0.55	0.53 ±0.36	.128	0.78 ± 0.54	0.94 ± 0.62	.011	.950	.004
Range, D [a]	0.65-0.74	0.50-0.56		0.72-0.85	0.86-1.01			
ME								
Arithmetic mean ± SD, D	−0.09 ± 0.60	0.11 ± 0.52	.020	−0.28 ± 0.41	−0.33 ± 0.60	.136	.148	.001
Range, D [a]	−0.14 to −0.04	0.07-0.15		−0.33 to −0.23	−0.41 to −0.26			
AE								
Arithmetic mean ± SD, degrees	5.0 ± 12.8	1.4 ± 8.2	.089	−0.7 ± 25.3	−2.4 ± 36.8	.415	.252	.773
Range, D [a]	3.9-6.0	0.7-2.1		−3.8 to 2.4	−6.9 to 2.2			
Absolute AE								
Arithmetic mean ± SD, degrees	10.4 ± 8.7	5.5 ± 6.2	.013	17.4 ± 17.7	25.7 ± 25.6	.044	.320	<.001
Range, degrees [a]	9.7-11.1	4.9-6.0		15.3-19.6	22.5-28.8			
CI								
Geometric mean	0.98	1.14	/	0.71	0.63	/	/	/
Range [a]	0.95-1.01	1.11-1.17		0.68-0.75	0.58-0.68			
IOS								
Geometric mean	0.41	0.33	/	0.56	0.67	/	/	/
Range [a]	0.38-0.43	0.30-0.36		0.51-0.60	0.61-0.73			

AE = angle of error; ATR = against-the-rule; CI = correction index; D = diopter; DV = difference vector; IOS = index of success; ME = magnitude of error; SIA = surgically induced astigmatism; SD = standard deviation; TIA = target-induced astigmatism; WTR = with-the-rule.

[a]95% confidence interval.

[b]Comparison between 2 and 5 years.

astigmatism presented a significant increase in SIA and decrease in absolute AE. By contrast, eyes with ATR astigmatism showed a decrease in SIA and increase in absolute AE. Over time, there was a trend toward increasing overcorrection of WTR astigmatism (CI from 0.98 to 1.14) and undercorrection of ATR astigmatism (CI from 0.71 to 0.63). This observation could be explained by the shift of the anterior corneal surface from WTR to ATR astigmatism and the persistence of posterior corneal ATR astigmatism with aging.[30] A corneal ATR change of 0.2 to 0.4 D occurred within 10 years of phacoemulsification, and this change was comparable to that in nonoperated eyes.[31,32] We noted an ATR shift of the double-angle plot centroid from 2 to 5 years with a vector mean of 0.24 D at 165° (Figure 1). The magnitude observed in the present study (0.08 D per year) was greater than those reported for natural aging (0.02 to 0.04 D per year). The ATR shift of corneal astigmatism along with aging might have augmented the effect of the arcuate keratotomy that was originally aimed at correcting the preoperative WTR astigmatism, thus leading to overcorrection. For eyes with preoperative ATR astigmatism, such an ATR shift would increase the amount of residual astigmatism that the original arcuate keratotomy was planned to correct, leading to undercorrection. However, the exact mechanism for the change in the efficacy of fs-assisted arcuate keratotomy over time and its discrepancy in keratometric drift compared to natural aging remains to be elucidated. Based on these results, the surgeon should consider the age of each patient to determine the amount of WTR astigmatism that should remain or be induced at the time of surgery. Mild residual WTR astigmatism is often preferred over ATR, as it allows better distant and near vision.[33] In our cohort of patients, eyes with preoperative WTR astigmatism showed further reduction in residual astigmatism over time (DV from 0.70 D to 0.53 D), whereas eyes with ATR astigmatism demonstrated further increase in residual astigmatism (DV from 0.78 D to 0.94 D).

The current study was limited by its retrospective design and the small sample size. Corneal measurements were performed using the OPD-III topographer. It did not measure pachymetry and posterior corneal topography. There were few drawbacks of the design of the arcuate keratotomy in this study. A standard depth of 450 μm could give varied efficacy compared to an incision made at a given percentage of corneal thickness. Asymmetry between the width of the phacoemulsification main incision and the arcuate keratotomy may induce corneal aberrations. In a previous study by the present authors, higher order aberrations of the cornea increased after fs-assisted arcuate keratotomy and remained stable over 2 years.[17] In the present study, there were no significant changes in corneal higher order aberrations from 2 to 5 years, and none of the present patients experienced glare or halo (data not shown). Lee and associates[34] also found that the corneal total higher order aberration was higher in eyes that had undergone fs arcuate keratotomy than in eyes that had not received arcuate keratotomy during cataract surgery.[34]

The present study showed that combined on-axis phacoemulsification paired with an opposite single arcuate keratotomy by using a fs laser was effective for the treatment of low to moderate corneal astigmatism. The overall treatment effect was well maintained over 5 years with the tendencies of increasing overcorrection of preoperative WTR astigmatism and undercorrection of ATR astigmatism over time. This could be attributed to the ATR shift of corneal astigmatism along with aging. Further long-term evaluation of the astigmatic outcomes following fs-assisted arcuate keratotomy with consideration of the posterior cornea and the effect of aging is warranted to support the present findings.

ALL AUTHORS HAVE COMPLETED AND SUBMITTED THE ICMJE FORM FOR DISCLOSURE OF POTENTIAL CONFLICTS OF INTEREST and none were reported.
Funding/Support: None.
Financial disclosures: No financial disclosures.

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