ARTICLE

Femtosecond laser–assisted arcuate keratotomy at the time of cataract surgery for the management of preexisting astigmatism

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Purpose: To evaluate the outcomes of femtosecond laser–assisted arcuate keratotomy combined with cataract surgery in eyes with low-to-moderate corneal astigmatism.

Setting: Eyes of York Private Practice Ophthalmology Clinic, York, Pennsylvania, USA.

Design: Retrospective case series.

Methods: This retrospective analysis included case records of patients with preexisting corneal astigmatism ranging from 0.5 to 2.0 diopter (D). Study parameters included corneal astigmatism, refractive astigmatism, and uncorrected (UDVA) and corrected (CDVA) distance visual acuities. The results, which were analyzed at 3 months postoperatively, included frequency distribution histograms, vector analysis, and single-angle polar plots.

Results: The study comprised case records of 189 eyes of 143 patients (56 men and 87 women). The postoperative refractive astigmatism was reduced significantly compared with preoperative corneal astigmatism to 0.14 D $\pm$ 0.23 (SD) from 0.92 $\pm$ 0.34 D ($P < .001$). One hundred eighty-one eyes (95.8%) demonstrated postoperative refractive astigmatism of 0.5 D or less. The mean surgically induced change along the preoperative steep axis was -0.59 ± 0.56 D, and the change along the orthogonal axis was 0.01 $\pm$ 0.35 D. Postoperatively, 171 eyes (90.5%) had astigmatism angle of error of 15 degrees or less. The postoperative mean UDVA and CDVA were 0.09 $\pm$ 0.16 logarithm of the minimum angle of resolution (logMAR) and 0.02 $\pm$ 0.05 logMAR, respectively. One hundred seventy eyes (90%) had a postoperative UDVA of 20/30 or better. The results demonstrated stability at 12 months postoperatively. No intraoperative or postoperative arcuate keratotomy-related events were observed.

Conclusion: The results suggest that femtosecond laser–assisted arcuate keratotomy represents a safe and effective method for astigmatism correction at the time of cataract surgery with demonstrated stability of correction for at least 1 year postoperatively.

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Among patients undergoing cataract surgery, corneal astigmatism is a sizable component of ametropia, with an estimated 50% of cataract patients exhibiting more than 1.0 diopter (D) of astigmatism.[1] Although it is possible for some patients to achieve acceptable unaided visual acuity with up to 1.0 D of residual refractive astigmatism after cataract surgery with a monofocal intraocular lens (IOL) implant, most patients would require spectacle correction to address residual astigmatism postoperatively. At the same time, technological advancements in cataract surgery and IOL optics have raised patients' expectations for good uncorrected postoperative vision, whether at distance, intermediate, or near.

Residual corneal astigmatism of 0.75 D or more might induce symptomatic blur, reducing uncorrected visual acuity and causing halos and ghosting of images.[2] Multifocal or extended depth-of-focus IOL technologies with diffractive optics are even less forgiving, and patients receiving such IOLs could be affected by as little as 0.5 D of residual refractive astigmatism.[3] Therefore, managing preexisting corneal astigmatism at the time of cataract surgery is critical to achieving excellent visual outcomes and meeting patients' expectations for complete, spectacle-free visual rehabilitation.[4] Conventionally, recommended postoperative astigmatism has been targeted at 0.25 to 0.5 D with-the-rule (WTR) to accommodate the gradual against-the-rule

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(ATR) drift expected with aging. Because this drift can happen over decades, the author's preference is to target near zero residual astigmatism at the time of cataract surgery.

Arcuate keratotomy is an effective and low-cost method of reducing astigmatism. However, because of a lack of reproducibility in incision depth, length, and alignment,[5–7] the manual arcuate keratotomy procedure has frequently been associated with unpredictable results and complications.[8–10] As a result, the predictability of arcuate keratotomy is believed to be lower than that of toric IOLs. The introduction of image-guided femtosecond laser technology to arcuate keratotomy procedures has substantially improved the precision of incision parameters (arc length, diameter, and depth of the incision) with the reported mean difference between intended and achieved laser incision sizes of 0.1 mm.[11] In addition, iris registration technology with the femtosecond laser has made highly accurate automated cyclotorsion compensation possible. The iris registration maneuver allows for precise alignment of arcuate keratotomy incisions on the intended meridian, thereby significantly improving the predictability of the procedure.[12]

It is highly desirable that astigmatism be managed at the time of cataract surgery to provide patients with the best possible uncorrected visual acuity with a single procedure. Some previous studies have documented good outcomes when performing arcuate keratotomies postoperatively in pseudophakic eyes to correct residual astigmatism.[4,7,13–15] Arcuate keratotomy nomograms in pseudophakic eyes are usually based on postoperative manifest refraction and already include the combined effects from the clear corneal incision (CCI), posterior corneal astigmatism, and lens centration. However, when arcuate keratotomies are performed at the time of cataract surgery, the nomogram is primarily based on anterior corneal astigmatism and must be modified by directly measuring or estimating the astigmatic effect of the CCI and posterior corneal astigmatism. The current study was designed to evaluate safety and efficacy of femtosecond laser–assisted arcuate keratotomy for astigmatism correction during laser cataract surgery in eyes with preexisting mild-to-moderate corneal astigmatism with the use of a nomogram that includes adjustments for surgically induced astigmatism (SIA) and posterior corneal astigmatism.

PATIENTS AND METHODS

This retrospective analysis reviewed case records of consecutive patients who underwent femtosecond laser–assisted cataract surgery combined with arcuate keratotomy for preexisting corneal astigmatism between January 2015 and November 2016. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by Salus Institutional Review Board with a waiver of consent because the data were collected as a part of normal practice care provision.

The primary inclusion criteria for the study were visually significant cataract, regular corneal astigmatism from 0.5 to 2.0 D, expected potential visual acuity of at least 20/25 as determined by preoperative clinical evaluation and history, and complete data at a 3-month follow-up visit.

Patients with abnormal corneal topography and/or irregular astigmatism, previous intraocular or corneal surgery, and patients with coexisting ocular pathology or systemic conditions likely to result in a poor or unpredictable response to surgery (eg, collagen vascular disease, diabetic retinopathy) were excluded.

Arcuate Keratotomy Nomogram and Surgical Technique

The astigmatic magnitude and axis values used for calculations were determined by the surgeon based on preoperative corneal data from an LED corneal analyzer (Cassini color LED, Cassini Technologies, B.V.) and a 3-dimensional wavefront topography system (OPD-Scan III, NIDEK Co., Ltd.). The refractive target was determined by the surgeon after reviewing available preoperative diagnostic data. The arcuate keratotomy parameters, including meridian, arc, and depth, were calculated using keratometric power analysis of the values entered for total corneal astigmatism and estimated SIA.

Combined femtosecond laser–assisted cataract surgery and arcuate keratotomy were performed using a femtosecond laser system (LENSAR Laser System, LENSAR, Inc.) by the same experienced surgeon (D.M.V.) under topical anesthesia. The femtosecond laser was used to construct the anterior capsulotomy, perform lens fragmentation, construct the CCI, and perform arcuate keratotomy in this sequence. Paired arcuate keratotomies based on a personalized modification of the Nichamin-Woodcock nomogram[13,16] were constructed perpendicular to the coronal plane at a depth of 90% of corneal thickness, with diameter of 8.6 mm, pulse energy of 4.3 μJ, line spacing of 4 μm and shot spacing of 6 μm. All treatments regardless of orientation, WTR, ATR, or oblique, were paired (Table 1). In ATR cases, the CCI was moved approximately 0.5 mm clockwise or counterclockwise of the arcuate keratotomy and the SIA was adjusted appropriately. SRK/T[17] and ORA guidance[18] were used intraoperatively for IOL power calculations. Cyclotorsion was compensated by iris registration based on preoperative images acquired with corneal topography measurements. All incisions were opened at the end of the surgery. All eyes underwent phacoemulsification followed by implantation of nontoric monofocal or multifocal IOLs (AcrySof SN60WF [Alcon Laboratories, Inc.], enVista MX60 [Bausch & Lomb, Inc.], and Tecnis ZKBOO and ZLBOO [both Johnson & Johnson Vision Care, Inc.]).

Postoperatively, all patients received a combination of antibiotic, nonsteroidal, and steroid eyedrops for at least 1 month and continued thereafter, if necessary. Patients were followed up at 1 day, 2 weeks, and 3 months after the surgery.

Outcome Measures

The change in preoperative corneal to postoperative refractive astigmatism was analyzed by comparison of means ± SD, frequency distribution histograms, and single-angle vector plots. The change in keratometric astigmatism along the original steep and orthogonal meridians was also determined. The difference between the change in keratometric astigmatism along the original steep meridian and that orthogonal to it demonstrated the total net astigmatic effect induced by arcuate keratotomy. Any complications related to corneal relaxing incisions were recorded. Additional study parameters analyzed included postoperative uncorrected (UDVA) and corrected (CDVA) distance visual acuities.

Analyses of astigmatic outcomes were performed using the Alpins method,[19–21] with calculation of the following 3 vector parameters: target-induced astigmatism (TIA), SIA, and difference vector. The TIA is defined as the intended astigmatic correction. The SIA represents astigmatic change achieved by surgery. The difference vector is defined as the additional astigmatic change that would enable the initial surgery to achieve its intended target.

Table 1. Femtosecond laser–assisted arcuate keratotomy nomogram.

Paired Arcs*	Degrees			
	Age Range (Y)			
	21–45	46–60	61–75	≥76
ATR astigmatism				
Range, ΔK (D)				
0.20–0.60	29	26	24	22
0.61–1.24	37	33	30	28
1.25–1.87	49	44	40	37
1.88–2.63	64	58	52	49
2.64–3.00	78	70	64	59
WTR astigmatism				
Range, ΔK (D)				
0.20–0.60	29	26	24	22
0.61–1.24	37	33	30	28
1.25–2.00	52	47	43	40
2.01–2.74	68	61	56	52
2.75–3.00	79	71	65	60

ΔK = corneal astigmatism; ATR = against-the-rule; WTR = with-the-rule
*Radius = 4.3 mm, 90% depth

The correction index is the ratio of SIA to TIA with a value greater than 1.0 indicating overcorrection and less than 1.0 indicating undercorrection. The angle of error is the arithmetic difference between the angles of SIA and TIA, with values less than 0 degrees and greater than 0 degrees indicating that the achieved correction was clockwise or counterclockwise, respectively, to the intended axis.

Statistical Analysis

Data analysis was performed using SPSS Statistics for Windows software (version 17.0, SPSS, Inc.). Data distribution for normality was checked using Kolmogorov-Smirnov test and quantile–quantile plots. A paired *t* test was used to compare the differences before and after the surgery. A *P* value less than 0.05 was considered statistically significant.

Results are presented as standard graphs for reporting the outcomes of refractive surgery and IOL-based refractive surgery.[22] Additional parameters included the correction index and angle of error.

RESULTS

This study comprised the case records of 189 eyes of 143 consecutive patients. The mean age of the 56 men and 87 women was 68.3 ± 8.1 years (range 44 to 91 years).

Compared with the preoperative corneal astigmatism (0.92 ± 0.34 D), the postoperative refractive astigmatism was reduced significantly to 0.14 ± 0.23 D ($P < .001$) (Figure 1). Figure 2 shows the noncumulative frequency distribution of preoperative corneal and postoperative refractive astigmatism. Whereas 161 (85.2%) of the 189 eyes had more than 0.5 D of corneal astigmatism preoperatively, 181 (95.8%) of the 189 eyes had postoperative refractive astigmatism of 0.5 D or less (Figure 2, *A*). Among the 3 subgroups based on preoperative corneal astigmatism (≥0.5 to <1.0, ≥1.0 to ≤1.5, and >1.5 D), residual refractive astigmatism of 0.5 D or less was observed in 108 (96.4%) of 112 eyes, 66 (94.3%) of 70 eyes, and 7 (100%) of 7 eyes, respectively (Figure 2, *B* to *D*). Figure 3, *A* to *D*, show the single-angle polar plots for TIA, SIA, difference vector, and correction index. Postoperatively, 171 (90.5%) of the 189 eyes had an astigmatism angle of error of 15 degrees or lower (Figure 4). Figure 5 shows a scatter plot of TIA versus SIA. The postoperative spherical equivalent within ±0.5 D was achieved in 175 (92.6%) of the 189 eyes (Figure 6).

Table 2 presents the vector analysis of change in keratometric astigmatism. The mean change along the original keratometric astigmatism meridian was −0.59 ± 0.56 D, and the change along the orthogonal meridian was 0.01 ± 0.35 D. The first component represents the intended effect along the steep corneal meridian.

At 3 months postoperatively, the mean UDVA and CDVA were 0.09 ± 0.16 logarithm of the minimum angle of resolution (logMAR) (Snellen equivalent 20/24.60) and 0.02 ± 0.05 logMAR (Snellen equivalent 20/20.94), respectively. Figure 7 shows the cumulative frequency distribution of the postoperative UDVA. One hundred seventy (90%) of the 189 eyes had a postoperative UDVA of 20/30 or better.

In a subcohort of 77 eyes with data available at a 12-month follow-up, the mean refractive astigmatism at 3 months (0.17 ± 0.24 D) was found to be maintained 12 months after surgery (0.18 ± 0.26 D) ($P = 1.000$). Correspondingly, 74 (96%) of the 77 eyes at 3 months and 71 (92%) of the 77 eyes at 12 months had postop refractive astigmatism of 0.50 D or more. As a result, the mean UDVA at 3 months postoperatively (0.13 ± 0.21 logMAR, Snellen equivalent 20/26.97) was found to be stable at 12 months (0.14 ± 0.20 logMAR, Snellen equivalent 20/27.60). In addition, 66 (86%) of the 77 eyes achieved a postoperative UDVA of 20/30 or better at 3 months postoperatively, which remained unchanged at 12 months postoperatively.

Complications

No intraoperative or postoperative arcuate keratotomy-related events, including perforation, wound gape, or infection were observed.

DISCUSSION

Femtosecond laser–assisted arcuate keratotomy has been successfully used for reducing naturally occurring astigmatism, high astigmatism associated with post-keratoplasty, and residual astigmatism post refractive or cataract surgery.[23] However, there is limited experience with arcuate keratotomy for the correction of low-to-moderate corneal astigmatism during cataract surgery with the use of monofocol IOLs. In the present study, we evaluated the safety and efficacy of femtosecond laser–assisted arcuate keratotomy during cataract surgery and found promising results.

To obtain predictable outcomes with arcuate keratotomies, it is important to perform a comprehensive preoperative workup. Errors in the anterior corneal measurements might result in refractive surprises postoperatively; therefore, ensuring reproducibility of quality corneal measurements on a healthy surface is necessary to generate reliable data for planning treatment and achieving good

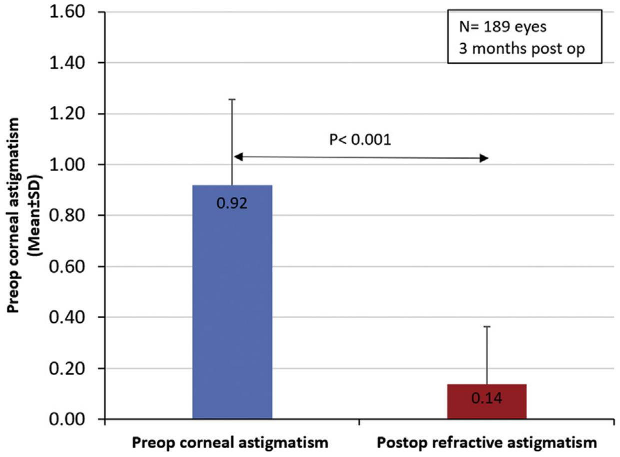

Figure 1. Histogram showing preoperative corneal and postoperative refractive astigmatism. The postoperative refractive astigmatism was reduced significantly to 0.14 D compared with the preoperative corneal astigmatism (0.92 D) ($P < .001$).

postoperative results. Anterior keratometric measurements can be influenced by an unstable tear film, which could compromise the accuracy of measurements. High tear osmolarity (>316 mOsm/L in at least one eye), an important hallmark of dry-eye disease, has been associated with statistically significantly poor repeatability of average keratometry and anterior corneal astigmatism readings, compared with normal eyes (<308 mOsm/L in both eyes).[24] In dry-eye patients, it is important to appropriately treat dry eye before obtaining corneal measurements for planning an arcuate keratotomy.

The posterior corneal surface can be a significant contributor to total corneal astigmatism. Traditional keratometry measures only the anterior corneal surface and assumes a fixed correlation with the posterior corneal surface. Thus, calculations for corneal astigmatism that are based only on anterior keratometry are likely to cause error in predicting residual refractive astigmatism; most commonly overcorrection in eyes that have WTR astigmatism and undercorrection in eyes that have ATR astigmatism.[25] Therefore, adjustments for posterior corneal astigmatism in the surgeon's arcuate keratotomy nomogram are imperative, either by direct measurement or nomogram adjustment, which indirectly estimates the effect of posterior corneal astigmatism on total corneal cylinder. Löffler et al.[26] reported that posterior corneal astigmatism is not significantly influenced by penetrating femtosecond laser–assisted arcuate keratotomy. However, the authors concluded that these findings were based on low sample sizes and do not allow for a definitive statement about the effect of penetrating femtosecond laser–assisted arcuate keratotomy on posterior corneal curvature, and that the effect of both anterior and posterior corneal astigmatism should be accounted for when planning simultaneous cataract refractive surgery and femtosecond laser–assisted arcuate keratotomy. The influence of arcuate incisions on posterior corneal astigmatism was also not evaluated in this study; however, it is a subject for future research.

Although technologies such as LED reflection, Scheimpflug, and swept-source optical coherence tomography are able to measure the posterior corneal curvature fairly accurately, they are not precise and repeatable enough to be relied upon exclusively.[27] Alternatively, the Baylor regression nomogram[25] or the Barrett theoretical modeling[28] use anterior keratometry, anterior chamber depth, or axial

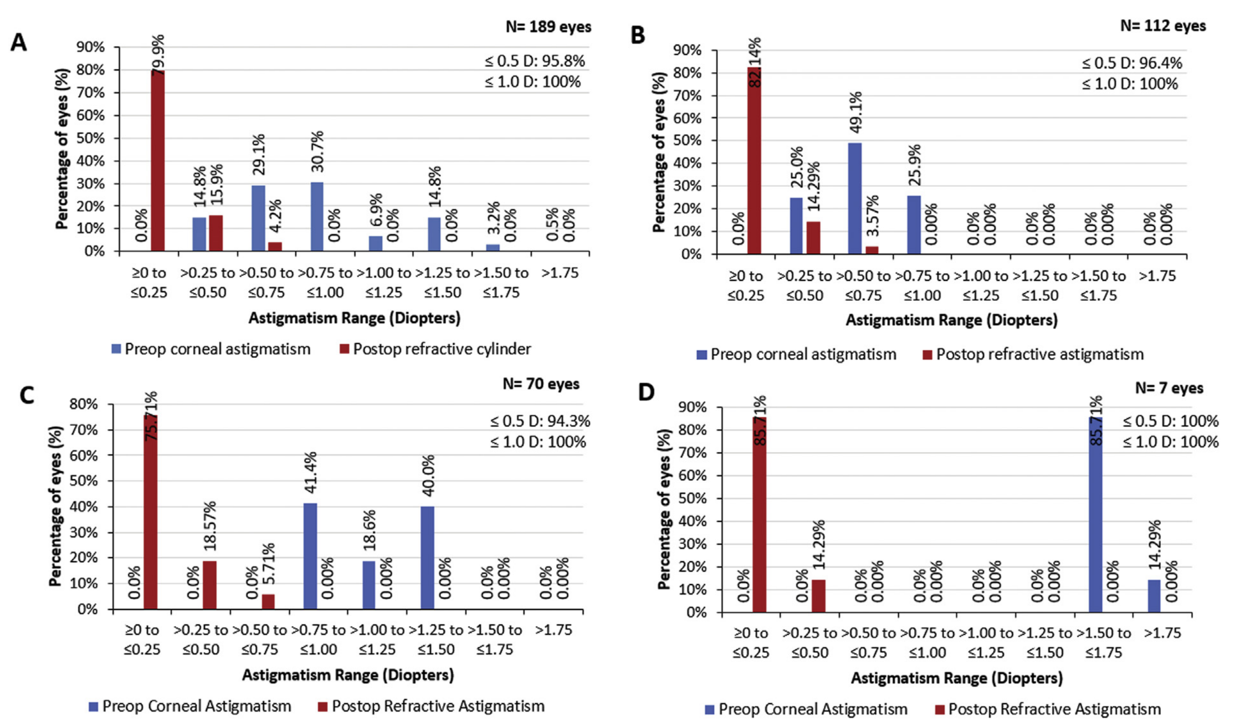

Figure 2. Noncumulative frequency distribution of preoperative corneal and postoperative refractive astigmatism in the overall dataset (*A*), subgroup with preoperative corneal astigmatism of ≥0.5 to <1.0 (*B*), subgroup with preoperative corneal astigmatism of ≥1.0 to ≤1.5 (*C*), and subgroup with preoperative corneal astigmatism of >1.5 D (*D*).

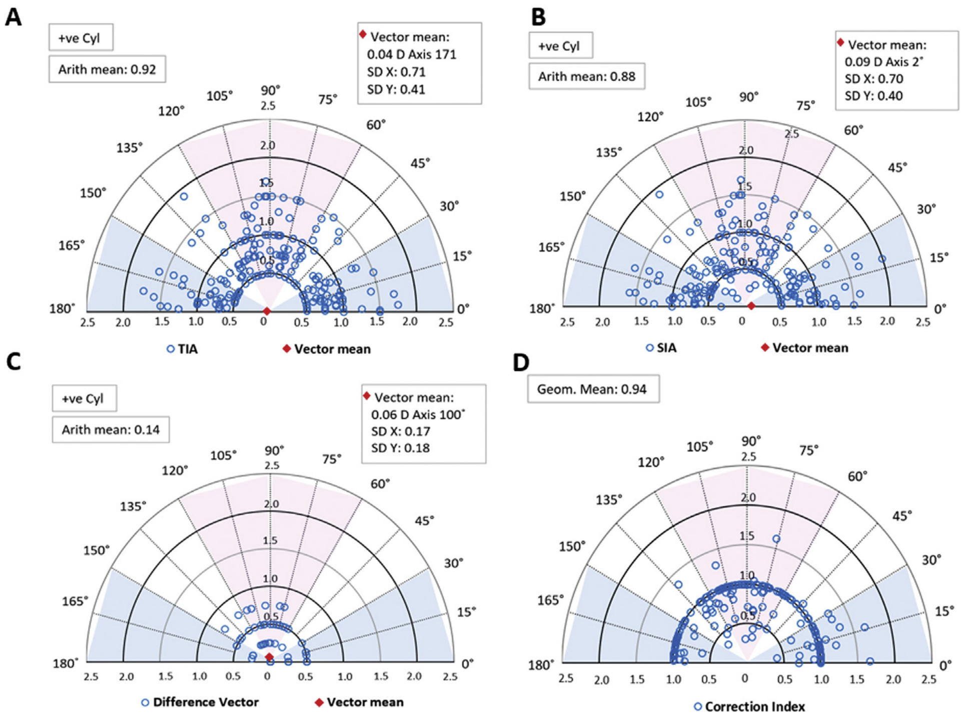

Figure 3. Single-angle polar plots for TIA (*A*), SIA (*B*), difference vector (*C*), and correction index (*D*) after femtosecond laser–assisted arcuate keratotomy (+ve cyl = positive cylinder; Arith. = arithmetic; Geom. = geometric; SIA = surgically induced astigmatism; TIA = target-induced astigmatism).

length data to account for posterior corneal astigmatism and provide adjusted corneal measurements; nevertheless, such adjustments might also overcompensate because of the associated methodologic error. In the authors' experience, using a process of comparing direct measurements with the Barrett formula yields a reliable overall assessment of total corneal cylinder ranges for magnitude and axis on a healthy corneal surface with reproducible, consistent topographies.

Another source of variability arises from the change in corneal shape because of the creation of the primary CCI in cataract surgery. These incisions might produce significant alterations to the magnitude and orientation of the steep meridian postoperatively.[19,29,30] In fact, the influence of a CCI's SIA gains greater importance when dealing with lower levels of astigmatism. Several factors such as accurate keratometry measurements, corneal biomechanics and healing responses, and age might affect SIA.[31–35] The methods of calculation also affect the magnitude of average SIA. Conventionally, the mean SIA for a surgeon has been calculated using the magnitude of SIA and ignoring its vector, yielding values close to 0.5 D. An aggregate method recommended by Holladay et al.[29] uses centroid means, and it yields values close to 0.1 D.

During femtosecond laser–assisted cataract surgery, clinically significant cyclotorsion error can occur. A recent

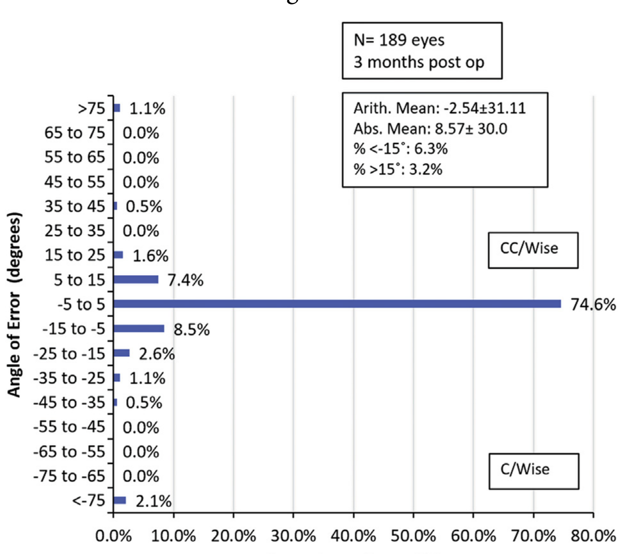

Figure 4. Histogram showing refractive astigmatism angle of error for patients treated with femtosecond laser–assisted arcuate keratotomy (Abs. = absolute; Arith. = arithmetic; C/Wise = clockwise; CC/Wise = counterclockwise).

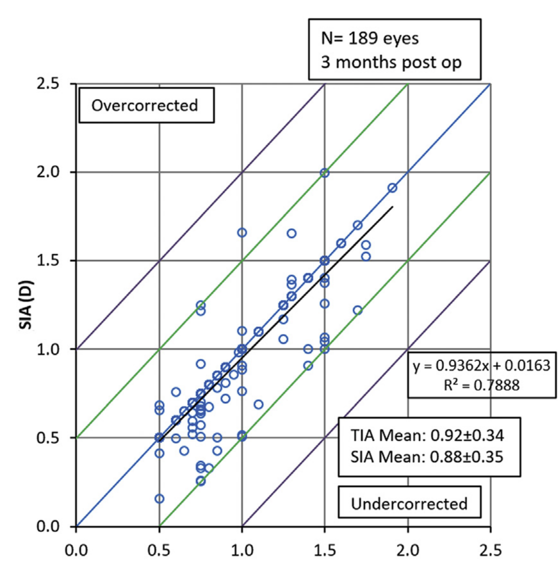

Figure 5. Scatter plot of TIA versus SIA after femtosecond laser–assisted arcuate keratotomy (SIA = surgically induced astigmatism; TIA = target-induced astigmatism).

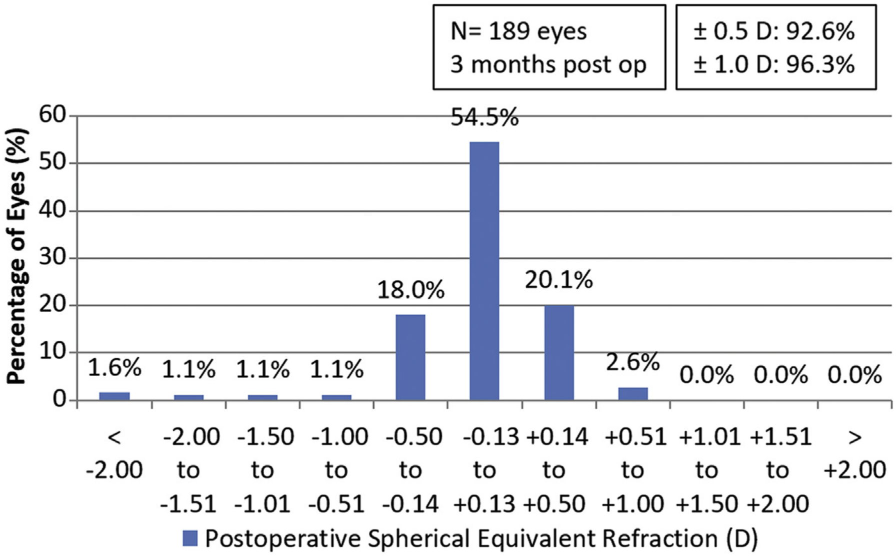

Figure 6. Histogram showing noncumulative distribution of postoperative spherical equivalent refraction. One hundred seventy-five (92.6%) of the 189 eyes had a postoperative spherical equivalent within ± 0.5 D.

study by Hummel et al.[12] found cyclorotation as high as 17 degrees in patients undergoing cataract surgery. If not accounted for intraoperatively, cyclotorsion can cause rotational errors in the axis alignment when creating arcuate keratotomies.[36] Every degree of rotational error negatively affects the astigmatism treatment by approximately 3.5%.[37] The incorporation of iris registration technology into the femtosecond laser system allows automatic cyclotorsion compensation and accurate creation of arcuate keratotomies on the intended meridian. Excellent refractive outcomes achieved in this study might in part be attributed to the use of iris registration-guided laser–assisted arcuate keratotomy placement.

Of note, laser arcuate keratotomies do not exhibit their full refractive effect until they are opened because the integrity of femtosecond laser incisions can have variability. Some surgeons advocate leaving incisions partially or completely unopened after cataract surgery with the option of opening them fully postoperatively to titrate the astigmatic outcome. Alternatively, we feel that variability in femtosecond incisions can sabotage the creation of an accurate nomogram and thus needs to be eliminated. After opening, all incisions become the same, and arcuate keratotomy nomograms can be titrated with confidence after evaluating outcomes. The data in this study were produced after all nomogram adjustments were finalized, and they were obtained from incisions that were all opened thoroughly and completely.

Femtosecond laser–assisted arcuate keratotomies are usually made perpendicular to the corneal surface (at the site of incision). Although these incisions have been reported to produce stable outcomes, previous studies showed regression of astigmatic treatment effect before 2 months postoperatively.[6,38] This is probably because the epithelial plug that deeply fills the gap is partially replaced by a loosely arranged fibrotic scar, inducing wound contraction over time and reducing the surgical effect of the relaxing incision.[39] In contrast, beveled arcuate keratotomies allow the anterior cornea to slide forward in relation to the posterior cornea and the realigned stroma heals without wound gaping or formation of an epithelial plug.[40] Freilinger[A] hypothesized that in the absence of an epithelial plug, femtosecond laser–assisted arcuate keratotomies oriented perpendicular to the coronal plane would likely be associated with a reduced risk for astigmatism

Table 2. Vector analysis of keratometric changes (166 eyes).

	Change in Corneal (Keratometric) Astigmatism (D)	
Properties	Mean ± SD	Range
Total change	0.72 ± 0.51	0.00, 2.77
Change along original steep K meridian	−0.59 ± 0.56	−2.74, 0.96
Change along orthogonal to steep K meridian	0.01 ± 0.35	−1.20, 1.39
Difference in keratometric astigmatism along original steep K and orthogonal K meridians	−0.60 ± 0.63	−3.11, 0.55

K = keratometry

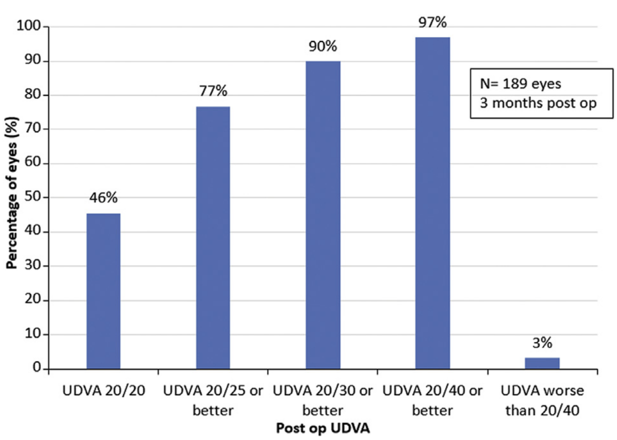

Figure 7. Histogram showing cumulative distribution of postoperative UDVA. One hundred seventy (90%) of the 189 eyes had a postoperative UDVA of 20/30 or better (UDVA = uncorrected distance visual acuity).

regression. The current study's stable astigmatic effect observed between 3 months and 12 months postoperatively indicates the absence of regression.

The corneal biomechanical properties, measured as corneal hysteresis and corneal resistance factor, vary across the population. Preoperative hysteresis and astigmatism correction obtainable with arcuate keratotomies seem to correlate negatively, that is, high corneal hysteresis is associated with lower astigmatic correction. Multivariable regression analysis has shown corneal hysteresis and corneal resistance factor to be independent predictors of astigmatic change.[41] As such, future nomograms might potentially improve accuracy by accounting for corneal biomechanical parameters.[42]

Although it was not the objective of this study to determine the astigmatism correction outcomes of arcuate keratotomy relative to toric IOLs, a review of literature documenting correction of lower amounts of astigmatism with toric IOLs (up to 2.25 D) revealed that residual refractive astigmatism ranged from 0.19 to 1.02 D,[9,43–45] with residual refractive astigmatism of 0.50 D or less between 81% and 94.7%.[43,45] These findings indicate that femtosecond laser–assisted arcuate keratotomy might be equally or more effective than toric IOLs for correcting lower amounts of astigmatism during cataract surgery.

In conclusion, this study demonstrates that femtosecond laser–assisted arcuate keratotomies performed during cataract surgery were effective in reducing astigmatism. This procedure appeared to be safe with no intraoperative or postoperative complications during the follow-up. The 12-month outcomes found in this study support long-term refractive stability of femtosecond laser–assisted arcuate keratotomies performed during cataract surgery.

WHAT WAS KNOWN

- Femtosecond laser–assisted arcuate keratotomy has been successful in the management of naturally occurring astigmatism, high astigmatism post keratoplasty, and residual astigmatism after refractive or cataract surgery.
- There is limited published data regarding arcuate keratotomy for the correction of low-to-moderate corneal astigmatism at the time of cataract surgery.
- To achieve predictable outcomes when performing arcuate keratotomy at the time of cataract surgery, it is important to accurately measure keratometry and account for posterior corneal astigmatism and surgically induced astigmatism.

WHAT THIS PAPER ADDS

- Femtosecond laser–assisted arcuate keratotomy during cataract surgery demonstrated residual refractive astigmatism of 0.5 D or less in nearly 96% of eyes.
- The refractive outcomes were stable 12 months postoperatively.
- With careful preoperative surgical planning and nomogram adjustment, femtosecond laser–assisted arcuate keratotomy combined with cataract surgery can effectively manage low-to-moderate astigmatism.

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