One-Year Results of Arcuate Keratotomy in Patients With Low to Moderate Corneal Astigmatism Using a Low-Pulse-Energy Femtosecond Laser

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• PURPOSE: To investigate corneal astigmatism (CA) reduction and corneal optical quality after surface-penetrating femtosecond laser arcuate keratotomies (Femto AK) considering anterior (CA_{ant}) and posterior corneal curvature (CA_{post}), total corneal refractive power astigmatism (CA_{tot}), and corneal higher-order aberrations (HOAs) through 1 year.

• DESIGN: Prospective interventional case series.

• METHODS: Setting: Department of Ophthalmology, Medical University of Vienna. Patient Population: Forty-three eyes of 43 patients with age-related cataract and CA_{tot} between 1 and 3 diopters (D). Intervention: Paired keratotomies were created with a low-energy femtosecond laser (LDV Z8; Ziemer Ophthalmic Systems, Port, Switzerland) and combined with an astigmatic neutral manual posterior-limbal cataract incision. CA and HOAs measurements were obtained preoperatively and after 1 month, 3 months, and 1 year. Main Outcome Measure: Change of CA and HOAs after low-energy Femto AK through 1 year.

• RESULTS: Mean preoperative CA_{ant} and CA_{tot} (1.62 ± 0.49 D and 1.58 ± 0.44 D) were significantly reduced, to 0.66 ± 0.38 and 0.50 ± 0.30 D ($P < .001$) 1 year after surgery, respectively. CA_{post} showed no significant change, from 0.31 ± 0.19 D preoperatively to 0.31 ± 0.13 D ($P = .732$) at the 1-year follow-up period. Astigmatism as calculated by vector astigmatism analysis stayed stable at 1 month, 3 months, and 1 year. Corneal wavefront HOAs significantly improved at 1 month, 3 months, and 1 year.

• CONCLUSIONS: Paired surface-penetrating keratotomies created by a low-energy femtosecond laser showed efficient and stable CA reduction within 1 year after surgery. The optical quality of the cornea was preserved with lower HOAs than preoperatively. (Am J Ophthalmol 2021;224:53–65.

Arcuate keratotomy (AK) reduces corneal astigmatism (CA) by performing corneal incisions at the corneal steep meridian to induce flattening of the steep axis while steepening the flat axis.[1] Conventional options for reducing CA at the time of cataract surgery include on-axis positioning of the cataract incision, AK and implantation of a toric intraocular lens (tIOL), or a combination of the latter with corneal incisions.[2–5] Performing manual AK is more advantageous than tIOL implantation when treating CA below 1 diopter (D) but lacks precision in incision length and depth, as well as axis alignment, potentially resulting in reduced reproducibility and regression.[6]

The use of femtosecond laser (FSL) to perform arcuate keratotomy has the advantages over manual AK of better precision, safety, and reproducibility of the procedure when combined with cataract surgery and after keratoplasty.[7–10] Mathematical models that determine the factors predictive of the change in CA have been developed and integrated in nomograms to optimize the outcome of corneal incisional correction using FSL arcuate incisions (AIs).[11]

More than one-third of cataract patients present a CA between 1 and 3 D, and even more than two-thirds (71%) above 0.5 D, and are thus potential candidates for FSL-assisted arcuate keratotomy (Femto AK) at the time of cataract surgery.[12] Studies have shown successful and long-lasting reductions of low-to-moderate astigmatism up to 2.5 D of the anterior corneal curvature and total corneal refractive power after Femto AK when using a high-energy FSL device.[13,14]

To the best of our knowledge, our study is the first prospective evaluation of Femto AK to treat low-to-moderate astigmatism up to 3 D during cataract surgery with a low-energy FSL device that includes the assessment of total corneal refractive power astigmatism.

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METHODS

THIS WAS A PROSPECTIVE INTERVENTIONAL CASE SERIES performed between July 2017 and April 2020 at the Department of Ophthalmology, Medical University of Vienna, Austria. The protocol was approved by the local ethics committee and the tenets of the Declaration of Helsinki were followed throughout the study. The study was registered at ClinicalTrials.gov (registration number: NCT04321226).

Patients were consecutively enrolled for FSL-assisted cataract surgery together with surface-penetrating arcuate keratotomy (Femto AK) and provided written informed consent to participate in the study.

Inclusion criteria were age-related cataract necessitating surgery with an intraocular lens implantation and a cornea with a symmetric and regular low-to-moderate total corneal refractive power astigmatism between 1.0 D and 3.0 D. Eyes with irregular corneal refractive power astigmatism, corneal opacities, previous corneal surgery, acute or chronic ophthalmic diseases of the anterior segment, or intraoperative complications were not included in this study. A total of 43 eyes of 43 patients met the inclusion criteria.

• **MEASUREMENTS:** Patients underwent a standard ophthalmologic examination 1 week before surgery including optical biometry (IOLMaster 700; Carl Zeiss Meditec, Jena, Germany) and applanation tonometry. Corneal topography was measured with a Placido-based topographer (ATLAS; Carl Zeiss Meditec, Jena, Germany) that analyzed the anterior corneal curvature (CA_{ant}). After 8 eyes, a novel swept-source Fourier-domain anterior segment optical coherence tomographer (SS-OCT) (CASIA2; Tomey, Nagoya, Japan) was added to the investigation protocol. This device measures the total corneal curvature including the posterior corneal plane. On the basis of these data, the total corneal refractive power astigmatism (CA_{tot}) as well as the astigmatism of the CA_{ant} and the posterior corneal curvature (CA_{post}) are measured and presented in millimeters (mm) and D. For further calculations, the CA_{ant} and axis of astigmatism measured at the 3.0-mm zone as displayed by the default on the ATLAS interface were considered for the CA_{ant} evaluation. CASIA2 measurements in the 3.0-mm zone were used to calculate CA_{post} and CA_{tot}. Measurements were included for data analysis only if the internal CASIA2 software labeled the quality "OK." Otherwise, the measurement was repeated. Femto AK was planned before the surgery based on the CA_{ant}, which was the only measurement in the first 8 eyes, and also on the additional CA_{tot} measurement in the following 35 eyes. Figure 1 shows the preoperative distribution of CA_{ant} and CA_{tot}. The Castrop Femto AK nomogram was used, which is based on the nomogram for arcuate keratotomy by Oshika and associates as adjusted for Femto AK by Hoffmann and associates.[15] In this nomogram, the arc length only is varied while using a fixed 8.5-mm optical zone (OZ) diameter and 80% of local corneal thickness cut depth. The actual postoperative corneal cut depth, including the total corneal depth and remaining depth, were measured with the corneal 2D analysis tool of the CASIA2 anterior segment OCT (Figure 2). High-order aberrations (HOAs) were measured with Placido-based corneal aberrometry (ATLAS; Carl Zeiss Meditec) and described with Zernike coefficients up to the fourth order using the Optical Society of America notation for a 6-mm analysis diameter.[16] Analysis included spherical aberration and vertical and horizontal coma. The root mean square value for total HOAs was calculated as the square root of the sum of the squares of the third- and fourth-order Zernike coefficients. Follow-up visits were conducted 1 month, 3 months, and 1 year after surgery and included slit-lamp examination, funduscopy, applanation tonometry, and assessment of best sphere-corrected visual acuity.

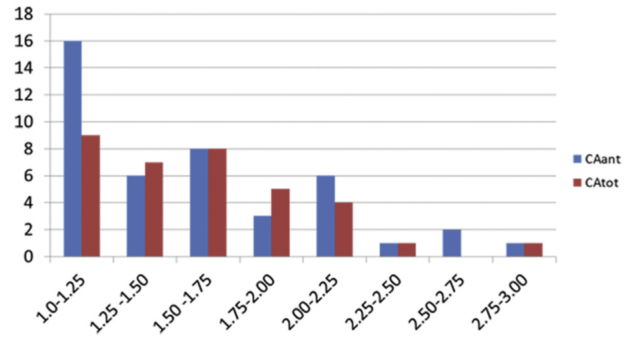

FIGURE 1. Distribution of anterior (CA_{ant}) and total corneal astigmatism (CA_{tot}) preoperatively, in diopters.

• **SETTING:** Pupils were dilated with 5% phenylephrine (Neosynephrin-POS; Ursapharm, Saarbrücken, Germany), 0.5% tropicamide (Mydriaticum; Agepha Pharma, Senec, Slovakia), and 1% cyclopentolate (Cyclopentolate hydrochloride; Alcon Pharma, Freiburg im Breisgau, Germany). One experienced surgeon (R.M.) performed surgery on all eyes using a FEMTO LDV Z8 FSL (Ziemer Ophthalmic Systems, Port, Switzerland). The laser optics of this FSL device are housed in the application handpiece, which allows a reduction in the focal length and thus an increase of the numerical aperture of the laser focusing optics compared with other machines on the market. As a consequence, the laser focus diameter is strongly reduced, and the laser pulse energy can also be reduced from the microjoules to the nanojoules range. By accordingly increasing the pulse frequency from kilohertz to megahertz, this laser creates unsurpassed smooth cuts without tissue bridges, as compared to high-energy laser systems.[17,18]

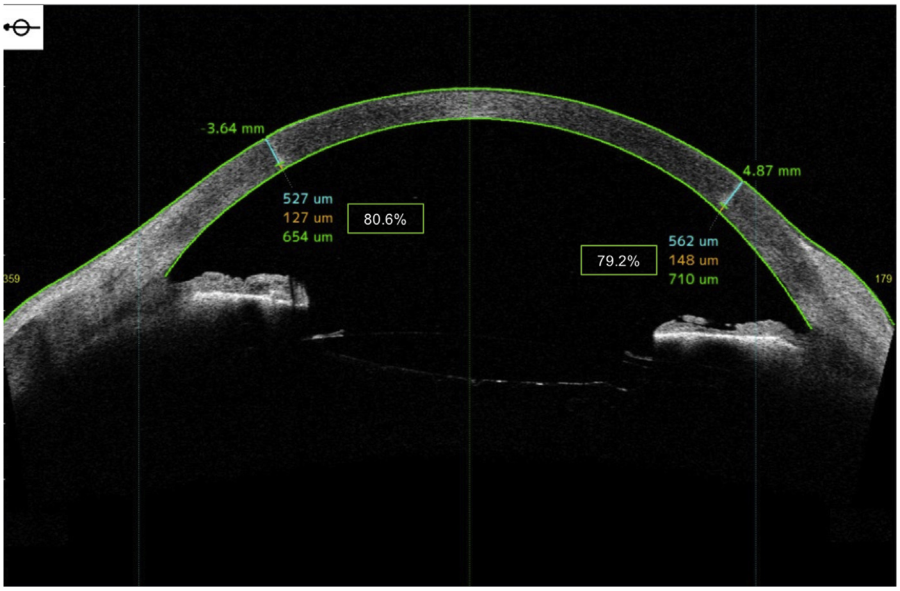

FIGURE 2. Anterior segment optical coherence tomography showing corneal cut depth, remaining depth, and total corneal depth.

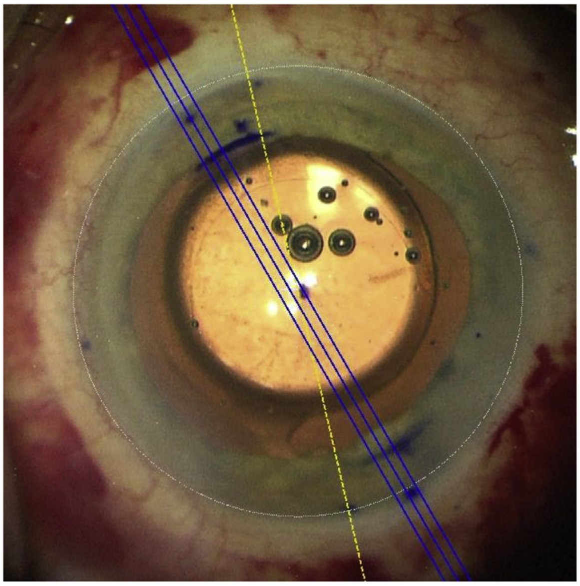

FIGURE 3. Top view with Callisto (Carl Zeiss Meditec) overlay at the end of surgery: the main axes are marked blue; the yellow dashed line shows the horizontal reference axis; the parallel blue lines show the targeted axis; arcuate incisions have been stained, showing no tissue bridges.

• **SURGERY:** In the early series (ID 1-9), the 2 main axes were marked on the limbus at the slit lamp before surgery. Later on, a computer-guided marking system (ID 10-43) (Callisto; Carl Zeiss Meditec) was used on the operating table before docking the FSL handpiece (Figure 3).

The FSL was used for all AIs. The handpiece with the laser optics was centered on the limbus. To keep the time lag between planning and performing the AIs as short as possible, AIs are on the LDV Z8 routinely planned as the last step during the docking procedure and AI cuts are performed first, before capsulotomy and lens fragmentation. AIs were placed at an OZ diameter of 8.5 mm and 80% of corneal thickness as measured by the integrated optical coherence tomographer at multiple locations along the planned AI cuts (Figure 4). Subsequently, manual cataract surgery was performed as follows: A temporal 2.2-mm posterior limbal incision and 2 paracenteses were created manually after the LDV Z8 procedure was completed. The manual posterior limbal approach was chosen to exclude any astigmatic impact of the cataract incision on the corneal curvature. The precut anterior capsule disc was gently removed and the 6 sectioned nucleus pieces aspirated using a high-fluidic setting of the phaco machine (OS4 + easyTip2.2; Oertli Instruments, Berneck, Switzerland) with the minimum use of ultrasound energy, followed by a coaxial cortical clean-up and implantation of an intraocular lens. At the end of surgery, the Femto AK incisions were opened manually by gently pulling the inner lip of the AI centrally with a blunt spatula and inspected for remaining tissue bridges.

• **DATA ANALYSIS:** CA_{ant} was measured in 43 eyes of 43 patients using Placido disc–based imaging. CA_{post} and CA_{tot} were measured in addition in 35 eyes of 35 patients (ID 8-43) using SS-OCT. Vector analysis with the Alpins method was performed to determine postoperative changes in CA_{ant}, CA_{post}, and CA_{tot}.[19] The target-induced astigmatism vector (TIA), defined as the astigmatic change the surgery was intended to induce, was not equal to the preoperatively measured CA_{ant}, CA_{post}, and CA_{tot}, as the

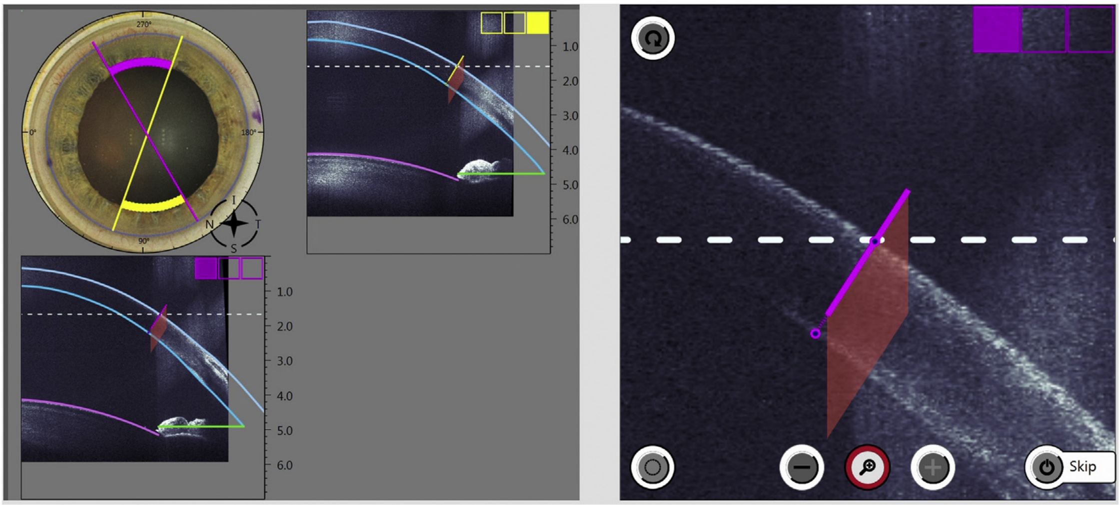

FIGURE 4. Positioning of the arcuate incisions on the LDV Z8 display: the local cornea pachymetry is automatically measured at 3 locations for each planned arcuate incision (center and at both ends). The cut depth target is then automatically adapted along the planned cut.

targeted residual astigmatism was defined case-wise to be between 0.3 and 0.5 D after surgery. Additionally, the magnitude of error, the difference vector (DV), and the surgically induced astigmatism vector (SIA) were calculated, which define the induced astigmatic change that would enable the initial surgery to achieve its intended target and the amount and axis of astigmatic change the surgery actually induced, respectively. The absolute angle of error, described by the vectors of achieved correction (SIA) vs the intended correction (TIA), was also calculated. HOA measurements of the 3.0-mm zone were obtained from 43 patients from ATLAS corneal topography after 1 month, 3 months, and 1 year. With-the-rule (WTR) astigmatism and against-the-rule (ATR) astigmatism were defined as having steep corneal meridians at 67.5 to 112.58 and either 0 to 22.58 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 CA measurements (Figure 5).

• **STATISTICAL ANALYSIS:** Descriptive statistics and 95% confidence intervals for the mean values were computed for the variables of interest for the different time points and the different examination devices separately. In order to assess the correlation between TIA and SIA, Pearson correlation coefficients and *P* values based on the Fisher transformation were used. Paired *t* tests were used to assess whether the DV and CA changed significantly over time. As *P* values serve only descriptive purposes, no multiplicity correction was applied and *P* values of $<.05$ were considered statistically significant. Statistical analysis was performed using SPSS 23 (IBM Corp, Armonk, New York, USA) and R 3.6.3.[21]

RESULTS

A TOTAL OF 43 EYES (24 RIGHT AND 19 LEFT) OF 43 PATIENTS with a mean age of 73 ± 11 years were included in the study. Surgery in all eyes was uneventful. No corneal perforation occurred. No residual tissue bridges were detected in the AKs upon inspection at the conclusion of surgery.

All patients were seen 1 month (30 ± 3 days), 3 months (87 ± 8 days), and 1 year (370 ± 31 days) after surgery. All patients presented after 1 month; 1 patient (1 eye) did not show up for the 3-month follow-up and 4 (4 eyes) for the 1-year control, resulting in 39 out of 43 complete visits over the 1-year follow-up period.

CA_{ant} preoperatively was 1.62 ± 0.49 D and was significantly reduced, to 0.66 ± 0.38 D ($P < .001$) 1 year after surgery. CA_{tot} was also significantly reduced, from 1.58 ± 0.44 D preoperatively to 0.50 ± 0.30 D ($P < .001$) 1 year after surgery (Figure 6). However, CA_{post} was not significantly reduced, from 0.31 ± 0.19 D preoperatively to 0.31 ± 0.13 D ($P = .732$) 1 year after surgery.

Table 1 shows the results of vector analysis according to the Alpins method, including TIA, SIA, DV, magnitude of error, and absolute angle of error comparing preoperative with postoperative changes in CA_{ant} and CA_{tot}. SIA showed no statistically significant difference postoperatively from 1 month to 3 months, 3 months to 1 year, or 1 month to 1 year. *P* values were .806, .203, and .116 for $CA_{ant,}$ and .220, .413, and .417 for CA_{tot}.

Preoperatively we observed 17 eyes with WTR astigmatism, 21 eyes with ATR astigmatism, and 5 eyes with oblique astigmatism. Tables 2 and 3 show vector analysis of WTR and ATR astigmatism. There was no statistically

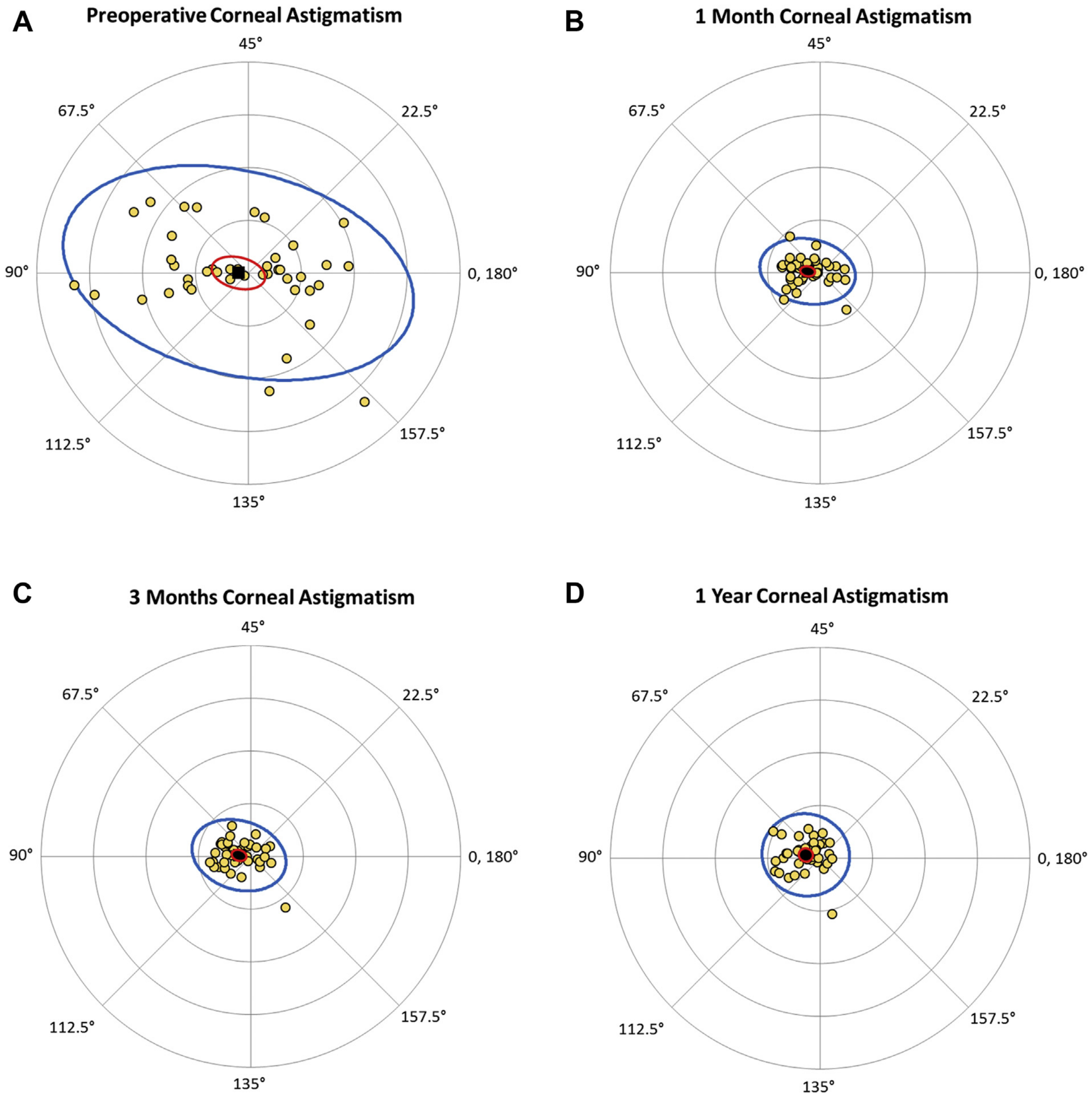

FIGURE 5. Double-angle plot of preoperative (A) and postoperative anterior corneal astigmatism at 1 month (B), 3 months (C) and 1 year (D). Centroid A: 0.28 diopters (D) @ 89° ± 2.27 D; Centroid B: 0.36 D @ 87° ± 0.64 D; Centroid C: 0.34 D @ 87° ± 0.65 D; Centroid D: 0.42 D @ 84° ± 0.66 D. The inner ellipse represents the 95% confidence ellipse of the centroid and the outer ellipse represents the 95% confidence ellipse of the dataset. Each ring equals 1.50 D.

significant difference observed in DV between WTR and ATR astigmatism after 12 months ($P = .32$). Moreover, we observed no difference when comparing the change in DV from 1 month to 12 months postoperatively between the 2 groups ($P = .18$).

Furthermore, we analyzed slit lamp–based marks (9 eyes) and computer-guided marks (34 eyes) separately. We observed no significant difference in DV after 12 months ($P = .86$) or a significant change in DV from 1 month to 12 months ($P = .09$) between the marking methods (Tables 4 and 5). Double-angle plots of preoperative and postoperative CA are shown in Figure 5.

FSL cuts could be measured 1 year after Femto AK with the CASIA2 anterior segment OCT in 39 of 43 eyes (90%). In 4 eyes the corneal cuts could not be detected in the OCT image. Mean corneal cut depth was 513.93 ± 31.51 μm, remaining depth was 132.60 ± 14.44 μm, and total corneal depth was 646.52 ± 37.77 μm. The average corneal cut depth corresponds to 79.49% of the total corneal depth.

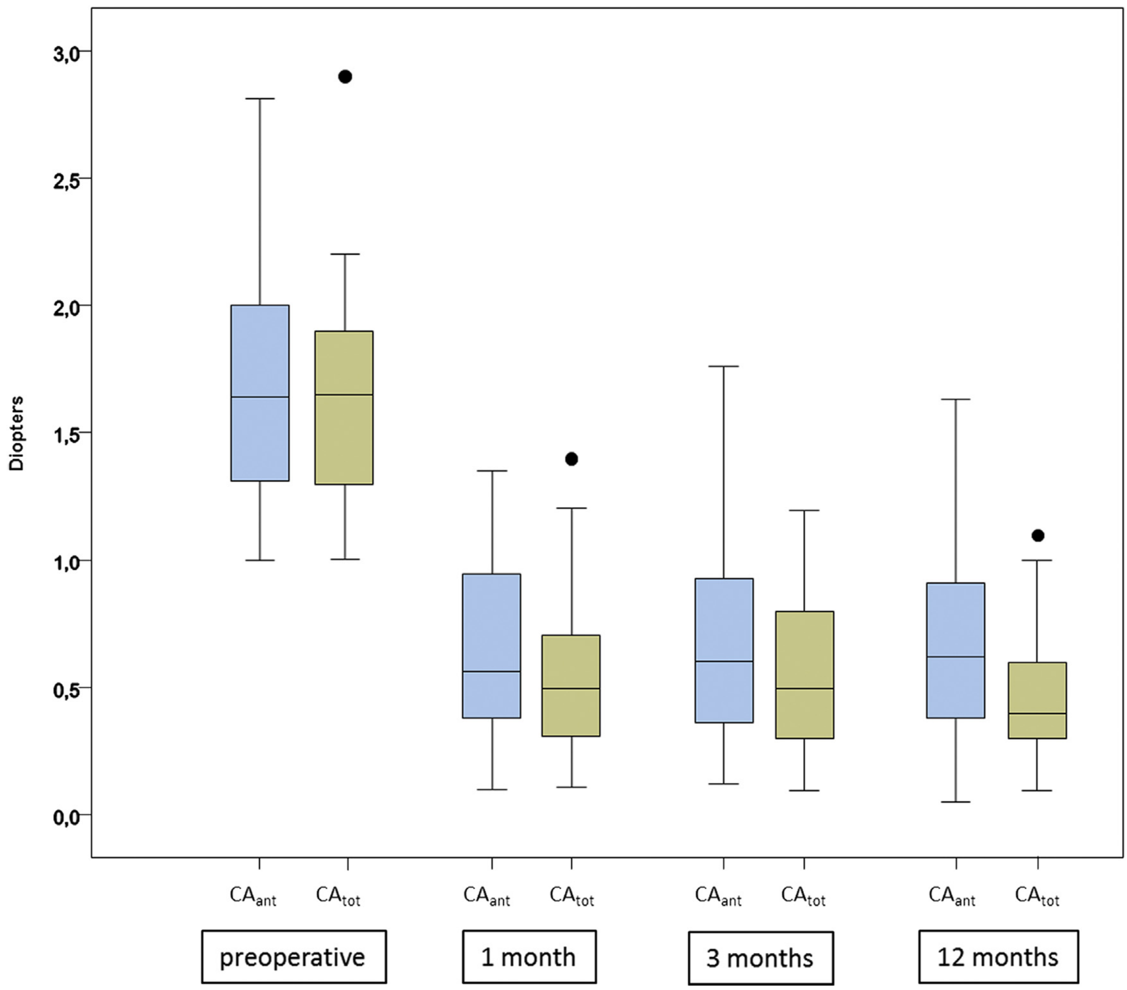

FIGURE 6. Astigmatism analysis of corneal astigmatism anterior curvature (CA_{ant}) and total corneal refractive power astigmatism (CA_{tot}) from preoperative to 1 month, 3 months, and 12 months.

Total corneal HOAs decreased significantly after Femto AK ($P < .001$) and showed no significant changes in the follow-up period from 1 month to 1 year ($P = .073$). Spherical aberrations increased 1 month after Femto AK, from 0.25 ± 0.11 to 0.30 ± 0.14 ($P = .01$), but after 3 months and 1 year no longer showed a significant difference compared with preoperative values ($P = .187$ and $P = .451$). There was no statistically significant difference in preoperative to postoperative vertical and horizontal coma (Table 6).

Best-sphere corrected visual acuity (in logMAR) was 0.26 ± 0.17 preoperatively and increased to 0.06 ± 0.13, 0.04 ± 0.12, and 0.03 ± 0.12 after 1 month, 3 months, and 1 year.

DISCUSSION

THE CORRECTION OF LOW-TO-MODERATE CA AT THE TIME of cataract surgery can be achieved by modifying the corneal incision, performing AK, or implanting a tIOL.[2,3,22] A small amount of astigmatism is known to reduce uncorrected visual acuity. This is particularly the case in eyes with multifocal intraocular lenses. An oblique residual astigmatism of 0.5 can reduce high-contrast visual acuity by a 1 logMAR line.[19] On the other hand, such a small amount may increase depth of field when 1 axis is emmetropic and the other myopic (astigmatismus myopicus simplex).[23] However, this is only true for WTR and ATR residual astigmatism increase.[24] Implantation of a tIOL is not an available option for such cases of low CA because the available tIOL diopter range usually starts with 1.0 D.[25,26] AK is considered a feasible option to correct very low to medium astigmatism.[2] The use of FSL adds precision in depth and repeatability to AK, making surface-penetrating Femto AK a procedure with more predictable results.[13] However, as the cornea is a biomechanical entity, regression of the corrective effect owing to healing has been observed.[4,27,28] As opposed to manual AK or limbal relaxing incisions, the corrective effect of

TABLE 1. Vector Analysis of Keratometric Astigmatic Correction After Femtosecond Laser–Assisted Arcuate Keratotomy Using the Alpins Method: All Cases

	1 Month N = 43	3 Months N = 42	1 Year N = 39
TIA			
Arithmetic mean ± SD (D)		1.24 ± 0.46 D[b]	
		1.10 to 1.37[a]	
Range[a] (D)		1.20 ± 0.47 D[c]	
		1.04 to 1.36[a]	
SIA			
Arithmetic mean ± SD (D)	0.96 ± 0.53[b]	0.96 ± 0.44[b]	0.95 ± 0.48[b]
	0.80 to 1.12	0.83 to 1.09	0.80 to 1.10
Range[a] (D)	1.00 ± 0.44[c]	1.01 ± 0.47[c]	1.07 ± 0.41[c]
	0.85 to 1.15	0.85 to 1.16	0.92 to 1.22
DV			
Arithmetic mean ± SD (D)	0.59 ± 0.30[b]	0.60 ± 0.33[b]	0.68 ± 0.37[b]
	0.50 to 0.68	0.50 to 0.70	0.56 to 0.80
Range[a] (D)	0.60 ± 0.47[c]	0.51 ± 0.29[c]	0.53 ± 0.35[c]
	0.45 to 0.76	0.41 to 0.60	0.41 to 0.66
ME			
Arithmetic mean ± SD (D)	−0.28 ± 0.35[b]	−0.29 ± 0.34[b]	−0.28 ± 0.39[b]
	−0.39 to −0.18	−0.39 to −0.18	−0.41 to −0.16
Range[a] (D)	−0.20 ± 0.29[c]	−0.20 ± 0.31[c]	−0.13 ± 0.34[c]
	−0.30 to −0.10	−0.31 to −0.10	−0.25 to 0.00
Absolute AE			
Arithmetic mean ± SD (D)	25.86 ± 30.14[b]	23.24 ± 24.80[b]	25.08 ± 24.75[b]
	16.85 to 34.87	15.65 to 30.83	17.21 to 32.95
Range[a] (D)	26.91 ± 22.24[c]	20.49 ± 20.50[c]	19.23 ± 21.88[c]
	19.55 to 34.28	13.49 to 27.48	11.41 to 27.06

AE = angle of error; DV = difference vector; ME = magnitude of error; SIA = surgically induced astigmatism; TIA = target−induced astigmatism.

[a]95% confidence interval.

[b]Anterior corneal curvature.

[c]Total corneal power.

low-pulse-energy Femto AK proved to be stable and permanent for a 1-year follow-up, in our study. This may be also attributable to the minimal collateral tissue damage and inflammatory response induced by the low-energy laser used compared with other high-pulse-energy lasers.[29] The optimally accurate nomogram for Femto AK for low-energy FSL AKs is still to be developed. As with tIOL implantation, however, not only the anterior but also the total corneal power including the posterior curvature should be considered as the nomogram input to reach the optimal outcome.[14,30]

Our study is the first to investigate the effect of performing Femto AK with a low-energy FSL device in preoperative regular CA in up to 3 D at the time of cataract surgery, and also considering the total corneal refractive power.

In our study, we evaluated the CA_{ant} by measuring eyes with a Placido disc–based corneal topographer and used an SS-OCT-based tomographer to evaluate CA_{tot}. The 2 measurements led to similar results. We reached a reduction of mean preoperative astigmatism of 59% and 68% of CA_{ant} and CA_{tot}, after 1 year. In 2 studies evaluating CA_{ant} after surface-penetrating Femto AK with a high-pulse-energy femtosecond laser device (Victus; Bausch & Lomb Inc) a reduction of 50% and 35% was reported with lower preoperative astigmatism mean values of 1.35 D and 1.33 D, respectively.[9,13] In another study that investigated the reduction of low preoperative astigmatism, mean values of 0.97 D showed a reduction of 35% when using another high-pulse-energy FSL device (LenSx; Alcon).[14]

These studies reported a lower reduction of CA values than ours, even though they included lower mean preoperative astigmatism values of 1.35 D (CA_{ant}) and 0.97 D (CA_{tot}) than those in our study (1.62 D and 1.58 D). Our favorable results may be attributable to the low-energy

TABLE 2. Vector Analysis of Keratometric Astigmatic Correction After Femtosecond Laser–Assisted Arcuate Keratotomy Using the Alpins Method: With-the-Rule Astigmatism

	1 Month N = 17	3 Months N = 16	1 Year N = 16
TIA			
Arithmetic mean ± SD (D)		1.16 ± 0.38D[b]	
		0.98 to 1.34[a]	
Range[a] (D)		1.05 ± 0.25 D[c]	
		0.91 to 1.18[a]	
SIA			
Arithmetic mean ± SD (D)	0.90 ± 0.55[b]	0.92 ± 0.40[b]	1.00 ± 0.40[b]
	0.65 to 1.17	0.72 to 1.11	0.81 to 1.20
Range[a] (D)	0.92 ± 0.40[c]	0.97 ± 0.48[c]	1.14 ± 0.27[c]
	0.70 to 1.14	0.70 to 1.24	0.98 to 1.30
DV			
Arithmetic mean ± SD (D)	0.72 ± 0.30[b]	0.78 ± 0.36[b]	0.75 ± 0.49[b]
	0.58 to 0.86	0.60 to 0.95	0.51 to 0.99
Range[a] (D)	0.53 ± 0.28[c]	0.51 ± 0.24[c]	0.59 ± 0.39[c]
	0.35 to 0.82	0.37 to 0.64	0.35 to 0.82
ME			
Arithmetic mean ± SD (D)	−0.25 ± 0.43[b]	−0.25 ± 0.39[b]	−0.17 ± 0.39[b]
	−0.39 to −0.18	−0.39 to −0.18	−0.41 to −0.16
Range[a] (D)	−0.12 ± 0.31[c]	−0.08 ± 0.34[c]	−0.10 ± 0.23[c]
	−0.30 to −0.10	−0.31 to −0.10	−0.25 to 0.00
Absolute AE			
Arithmetic mean ± SD (D)	37.65 ± 28.31[b]	40.38 ± 29.26[b]	38.44 ± 28.43[b]
	24.19 to 51.11	26.04 to 54.71	24.51 to 52.37
Range[a] (D)	29.92 ± 21.45[c]	26.42 ± 21.78[c]	29.91 ± 26.25[c]
	18.26 to 41.58	14.09 to 38.74	14.39 to 45.42

AE = angle of error; DV = difference vector; ME = magnitude of error; SIA = surgically induced astigmatism; TIA = target-induced astigmatism.

[a]95% confidence interval.

[b]Anterior corneal curvature.

[c]Total corneal power.

technology of the laser system (LDV Z8; Ziemer Ophthalmic Systems), which allows for smooth corneal cuts without the formation of tissue bridges, less stromal cell death, and less inflammatory response.[29,31,32]

However, not only were different FSL devices used in these studies, but also different nomograms. In the first 2 studies a pre-set 450-μm cut depth for AIs in the 8.0-mm OZ modified from the Wallace limbal relaxing incision nomogram was used. In the third study mentioned, a cut depth to 80% of the measured corneal thickness was set and the cuts located in the 9.0-mm OZ, pursuant to Wang and associates.[2] We chose to follow Hoffmann's[15] FSL-specific modification of the nomogram by Oshika[1] for AK after cataract surgery, placing AIs in the 8.5-mm OZ and setting cut depth to 80% of corneal thickness. Our results suggest a high accuracy of target-induced astigmatism using this nomogram with low-energy FSL-assisted AK, resulting in only minor undercorrection. Adjustment of the nomogram should be considered.

Although our Femto AK results achieved the intended reduction of astigmatism accurately, we observed a relatively high standard deviation of the SIA vector. The variance may be partly attributable to keratometry deviations or a result of the individual tear film structure. Our results are comparable with other studies investigating the effect of Femto AK, showing a similar variability of astigmatism change.[6,13,14] When investigating the angle of error, we saw a counterclockwise mean axis shift of 26 ± 30° in CA_{ant} and 27 ± 22° in CA_{tot} 1 month after surgery that remained stable over the 1-year follow-up period. These results indicate a long-lasting stable effect of the low-energy Femto AK, and we believe the axis shift can be further improved by advances in centration and on-axis positioning of the AKs during the planning and cutting phases with the laser handpiece docked. When analyzing cases after slit lamp–based marking compared with computer-guided marks, we observed no significant difference in DV with a tendency to a lower absolute

TABLE 3. Vector Analysis of Keratometric Astigmatic Correction After Femtosecond Laser–Assisted Arcuate Keratotomy Using the Alpins Method: Against-the-Rule Astigmatism

	1 Month N = 21	3 Months N = 21	1 Year N = 18
TIA			
Arithmetic mean ± SD (D)		1.33 ± 0.52 D[b]	
		1.11 to 1.55[a]	
Range[a] (D)		1.34 ± 0.58 D[c]	
		1.07 to 1.62[a]	
SIA			
Arithmetic mean ± SD (D)	1.00 ± 0.55[b]	0.98 ± 0.51[b]	0.87 ± 0.38[b]
	0.76 to 1.23	0.76 to 1.21	0.61 to 1.13
Range[a] (D)	1.05 ± 0.50[c]	1.08 ± 0.47[c]	0.97 ± 0.45[c]
	0.82 to 1.29	0.85 to 1.31	0.74 to 1.19
DV			
Arithmetic mean ± SD (D)	0.47 ± 0.28[b]	0.47 ± 0.22[b]	0.62 ± 0.24[b]
	0.35 to 0.59	0.37 to 0.59	0.51 to 0.72
Range[a] (D)	0.57 ± 0.56[c]	0.44 ± 0.25[c]	0.49 ± 0.26[c]
	0.30 to 0.83	0.32 to 0.56	0.36 to 0.62
ME			
Arithmetic mean ± SD (D)	−0.33 ± 0.27[b]	−0.36 ± 0.30[b]	−0.43 ± 0.38[b]
	−0.45 to −0.22	−0.49 to −0.23	−0.60 to −0.25
Range[a] (D)	−0.28 ± 0.27[c]	−0.28 ± 0.30[c]	−0.35 ± 0.31[c]
	−0.41 to −0.16	−0.43 to −0.14	−0.50 to −0.19
Absolute AE			
Arithmetic mean ± SD (D)	15.05 ± 31.30[b]	8.80 ± 5.96[b]	18.06 ± 36.30[b]
	1.66 to 28.44	6.19 to 11.41	1.28 to 34.83
Range[a] (D)	18.47 ± 19.47[c]	10.63 ± 14.30[c]	10.40 ± 16.01[c]
	9.09 to 27.85	3.62 to 17.63	2.30 to 18.50

AE = angle of error; DV = difference vector; ME = magnitude of error; SIA = surgically induced astigmatism; TIA = target-induced astigmatism.

[a]95% confidence interval.

[b]Anterior corneal curvature.

[c]Total corneal power.

axis shift after slit lamp–based marking. However, owing to an inhomogeneous sample size between the groups we could not draw a reliable conclusion regarding the limbal marking methods.

Our results showed no statistically significant change in the magnitude of CA_{post}, coinciding with the results of another study evaluating the effect of Femto AK on the CA_{post} with a high-energy FSL device.[14] CA_{post} is clinically relevant when correcting low-to-moderate astigmatism, but when evaluating only its magnitudes this does not seem to be influenced by Femto AK.[33] Nevertheless, the CA_{post} vector should be considered when calculating the CA_{tot} vector preoperatively and planning Femto AK.

Clear corneal incisions are known to also induce corneal flattening, influencing CA.[34] In contrast to all the other studies mentioned on Femto AK, we chose to create a 2.2-mm posterior limbal incision to measure only the effect of the Femto AK on CA change.

We observed a higher DV in preoperative WTR astigmatism compared to preoperative ATR astigmatism 1 year after Femto AK. However, no statistically significant different magnitude of response as a function of the location of the AIs between preoperative WTR and ATR astigmatism was observed. Additionally, the corrective effect of Femto AK stayed equally stable in both groups over a time period of 1 year.

SIA_{ant} as well as SIA_{tot} after Femto AK were stable over the 1-year period, showing no statistically significant change in our study. This indicates that the effect of Femto AK does not regress in the long term as a consequence of corneal wound healing.

TABLE 4. Vector Analysis of Keratometric Astigmatic Correction After Femtosecond Laser–Assisted Arcuate Keratotomy Using the Alpins Method: Computer-Guided Marking of Axes

	1 Month N = 34	3 Months N = 32	1 Year N = 29
TIA			
Arithmetic mean ± SD (D)		1.19 ± 0.48 D[b]	
		1.03 to 1.35[a]	
Range[a] (D)		1.57 ± 0.44 D[c]	
		0.63 to 1.14[a]	
SIA			
Arithmetic mean ± SD (D)	0.95 ± 0.55[b]	0.98 ± 0.46[b]	0.97 ± 0.51[b]
	0.77 to 1.14	0.76 to 1.21	0.78 to 1.16
Range[a] (D)	0.99 ± 0.44[c]	0.99 ± 0.46[c]	1.08 ± 0.42[c]
	0.84 to 1.13	0.82 to 1.13	0.92 to 1.23
DV			
Arithmetic mean ± SD (D)	0.58 ± 0.30[b]	0.58 ± 0.33[b]	0.68 ± 0.38[b]
	0.47 to 0.68	0.47 to 0.70	0.55 to 0.82
Range[a] (D)	0.60 ± 0.48[c]	0.52 ± 0.29[c]	0.53 ± 0.36[c]
	0.44 to 0.76	0.42 to 0.61	0.40 to 0.66
ME			
Arithmetic mean ± SD (D)	−0.24 ± 0.34[b]	−0.22 ± 0.31[b]	−0.21 ± 0.38[b]
	−0.35 to −0.13	−0.33 to −0.12	−0.35 to −0.07
Range[a] (D)	−0.21 ± 0.29[c]	−0.21 ± 0.31[c]	−0.11 ± 0.34[c]
	−0.30 to −0.11	−0.32 to −0.10	−0.23 to 0.01
Absolute AE			
Arithmetic mean ± SD (D)	28.12 ± 33.00[b]	26.09 ± 27.00[b]	28.41 ± 26.65[b]
	16.95 to 39.29	16.74 to 35.45	18.72 to 38.11
Range[a] (D)	26.91 ± 22.57[c]	20.91 ± 20.68[c]	19.86 ± 21.99[c]
	19.32 to 34.50	13.74 to 28.07	11.86 to 27.86

AE = angle of error; DV = difference vector; ME = magnitude of error; SIA = surgically induced astigmatism; TIA = target-induced astigmatism.

[a]95% confidence interval.

[b]Anterior corneal curvature.

[c]Total corneal power.

The literature reports that manual AK and limbal relaxing incisions lead to a regression of astigmatism, which might suggest that Femto AK performs similarly.[4,28,35–37] In fact, in the early stage of Femto AK technology, reliability and predictability was uncertain owing to a lack of reproducibility in incision depth, effective length without tissue bridges, and alignment.[38,39] With the introduction of OCT image–guided FSL technology, the precision of the incision has improved.[40]

Our study results demonstrate a very precise execution of the planned arcuate cuts with a low-energy FSL device reaching effectively 79.49% of corneal thickness average cut depth, when 80% was planned, 1 year after the procedure, with only minimal scarring. This high accuracy of the incision depth, which would be impossible to consistently achieve in manual AK, and the absence of tissue bridges as well as the minimal collateral tissue damage, may explain the good predictability and stability of the corrective effect observed in our study.

Contrary to another study group that evaluated HOAs after Femto AK,[13] we found a statistically significant reduction of HOAs from 1 month to 1 year after surgery. Different from their methods, we cut the AIs in the 8.5-mm OZ rather than in the 8.0-mm OZ and used a different laser system cutting at considerably lower pulse energy levels with a smaller spot size, resulting in smoother incisions without tissue bridges.[41] Spherical aberration was statistically significantly higher 1 month after surgery but decreased to preoperative levels after 3 months to remain unchanged through the 9 months to follow.

The optical quality of the cornea was preserved. Coma remained unchanged, as did spherical aberrations after a transient increase at 1 month. HOAs even improved during the 1-year follow-up.

TABLE 5. Vector Analysis of Keratometric Astigmatic Correction After Femtosecond Laser–Assisted Arcuate Keratotomy Using the Alpins Method: Manual Marking of Axes

	1 Month N = 9	3 Months N = 9	1 Year N = 9
TIA			
Arithmetic mean ± SD (D)		1.44 ± 0.37 D[a]	
Range[a] (D)		1.11 to 1.55	
SIA			
Arithmetic mean ± SD (D)	0.97 ± 0.49[a]	0.90 ± 0.42[a]	0.89 ± 0.37[a]
Range[a] (D)	0.65 to 1.30	0.67 to 1.13	0.65 to 1.13
DV			
Arithmetic mean ± SD (D)	0.66 ± 0.30[a]	0.64 ± 0.34[a]	0.66 ± 0.39[a]
Range[a] (D)	0.46 to 0.86	0.42 to 0.86	0.40 to 0.91
ME			
Arithmetic mean ± SD (D)	−0.44 ± 0.38[a]	−0.51 ± 0.37[a]	−0.52± 0.37[a]
Range[a] (D)	−0.69 to −0.19	−0.75 to −0.27	−0.76 to −0.28
Absolute AE			
Arithmetic mean ± SD (D)	17.33 ± 10.57[a]	13.11 ± 10.06[a]	14.33 ± 13.34[a]
Range[a] (D)	10.43 to 24.24	6.54 to 19.68	5.52 to 23.05

AE = angle of error; DV = difference vector; ME = magnitude of error; SIA = surgically induced astigmatism; TIA = target-induced astigmatism.

[a]Anterior corneal curvature.

TABLE 6. Higher-Order Aberrations Before and After Femtosecond Laser–Assisted Arcuate Keratotomy

	Preoperative	1 Month	3 Months	1 Year	*P* Value[b]
Spherical aberration	0.25 ± 0.11	0.30 ± 0.14	0.27 ± 0.12	0.25 ± 0.13	.103
	P value[a]	.01	.187	.451	
Vertical coma	−0.07 ± 0.28	−0.06 ± 0.32	−0.07 ± 0.21	−0.03 ± 0.34	.682
	P value[a]	.987	.495	.663	
Horizontal coma	−0.04 ± 0.17	0.00 ± 0.19	0.00 ± 0.25	0.02 ± 0.30	.938
	P value[a]	.118	.138	.232	
Total RMS HOA	1.84 ± 0.58	1.42 ± 0.39	1.35 ± 0.42	1.48 ± 0.47	.073
	P value[a]	<.001	<.001	<.001	

HOA = higher-order aberration; RMS = root mean square.

[a]Comparision between preoperative and postoperative follow-up.

[b]Comparision between postoperative 1 month to 1 year follow-up.

In conclusion, our results indicate that surface-penetrating Femto AK with a low-energy FSL at the time of cataract surgery is safe, and effectively and predictably reduces low-to-moderate astigmatism in a 1-year follow-up by about 1 D, to within ±0.5 D of the targeted value. In contrast to reported results after manual AIs, a loss of corrective efficacy was not observed in the 1-year observation period.

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