# Femtosecond Laser-Assisted Astigmatic Keratotomy for Correction of Corneal Astigmatism During Phacoemulsification

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**ABSTRACT**

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

**Materials and Methods:** This study included patients who underwent combined femtosecond laser-assisted phacoemulsification and arcuate keratotomy between October 2016 and October 2018. Keratometric astigmatism and astigmatic changes were evaluated before and six months after the surgery by vector analysis based on Alpin's method.

**Results:** In total, 69 eyes of 69 patients (35 female and 34 male; mean age, 60.3 ±10.5 years) were included. The mean preoperative target induced astigmatism (TIA) was 1.55±0.46 diopters (D) and postoperative astigmatism (difference vector [DV]) was 0.83±0.41 D (P<.001). The mean surgically induced astigmatism (SIA) was 1.09±0.56 D. The magnitude of error (difference between SIA and TIA) was -0.28±0.65 D and correction index (SIA/TIA ratio) was 0.71±0.34, indicating a slight undercorrection. The angle of error was near 0 (22±16 degrees), indicating no significant systematic error of misaligned treatment. The index of success (IOS), which is the ratio of DV to TIA, was 0.54±0.27, indicating a success rate of 46% in the correction of astigmatism.

**Conclusion:** Combined phacoemulsification with FSAK appears to be a relatively easy and safe means for management of low-to-moderate corneal astigmatism in cataract surgery candidates.

**Keywords:** Cataract surgery, Corneal astigmatism, Femtosecond laser-assisted arcuate keratotomy.

## INTRODUCTION

Although the primary aim of modern cataract surgery is to improve vision, recent technological advances have resulted expectations of perfect vision in the patients Approximately 25–50% of patients referred for cataract surgery have astigmatism greater than 1 diopter (D) and 8–13% have astigmatism greater than 2 D.[1,2] Correcting astigmatism is becoming increasingly important to ensure postoperative emmetropia. In order to meet patient expectations, it is crucial to minimize spherical and cylindrical refractive error after surgery to achieve satisfactory visual outcomes.

Various methods have been recommended to correct astigmatism, which can cause unfavorable symptoms in the postoperative period such as halo, glare, monocular diplopia, and asthenopia. These include intraoperative methods such as toric IOL implantation, arcuate keratotomy (AK), limbal relaxing incisions (LRIs), and clear corneal incisions on the steep meridian, as well as postoperative excimer laser to correct residual astigmatism.[3-14]

In the present study, we evaluated the effectiveness of cataract surgery with femtosecond excimer laser-assisted arcuate keratotomy (FSAK) in cataract patients with low-to-moderate astigmatism.

## MATERIALS AND METHODS

All participants enrolled in this prospective study were

*Authors report no conflict of interest. The work has not been presented in any meeting.*

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**Received:** 11.09.2019
**Accepted:** 19.11.2019
*Glo-Kat 2020; 15: 85-91*
DOİ: 10.37844/glauc.cat.2020.15.17

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informed about the study in detail according to the Declaration of Helsinki. The study was approved by the Ethics Committee of Alaattin Keykubat University (No:5-10).

Prior to surgery, the patients were assessed using an autorefractor-keratometer (KR-8900; Topcon, Tokyo, Japan) to obtain ocular measurements and refraction values, and best visual acuity was recorded. Intraocular pressure was measured using Goldmann applanation tonometry, and endothelial count and morphology were analyzed using specular microscopy (Topcon SP-3000P, Topcon Corporation, Tokyo, Japan). In all patients, the pupils were dilated by instilling topical 0.05% tropicamide drops (Tropamid, Bilim Lab.Turkey) before cataract evaluation and fundus examination using a Volk's 90-D lens. Biometric measurements were made using IOLmaster (Carl Zeiss Meditec AG), while topographic measurements were made using the Sirius, a Scheimpflug-Placido disc-based system (Costruzione Strumenti Oftalmici, Italy).

The study participants were selected among patients aged 45–73 years who presented to the ophthalmology outpatient clinic with complaints of reduced vision. Patients with visual acuity ≤0.5 (Snellen) in either eye due to cataract, corneal astigmatism of 1.00–3.00 D (low to moderate), no corneal or retinal pathology in anterior or posterior segment examination, and no systemic diseases were enrolled in the study. Those with history of ocular surgery due to any reason and those with oblique and irregular astigmatism were not included in the study.

The amount and axis of astigmatism to be corrected by AK was determined by corneal topography and autorefractor-keratometry evaluation. The length of the AK and amount of astigmatism it would correct were calculated with a modified Donnenfeld LRI nomogram (Table 1).[15] Based on this modified nomogram, the range of the angular arc length of the keratotomy incision was between 30 and 80 degrees. With the patient seated at the biomicroscope, the corneal limbus was marked preoperatively at 0° and 180° degrees on the horizontal plane using a sterile marker. Femtosecond laser energy was set to 2.0 µJ, spot and layer separation was set to 3 µm. The AK was created with incision depth of 85% of the corneal thickness, side-cut angle of 90 degrees, and arc diameter of 9.0 mm. For all phacoemulsification procedures, the main corneal incisions were placed in tri-planar configuration with a width of 2.2 mm at the steeper corneal meridian. Side port incisions (1 mm in length) were made perpendicular to the right and left of the uniplanar main corneal incision. All surgeries were performed by the same surgeon (H.B.) in the Ekol Eye Hospital in Izmir, Turkey. In all patients, the main phacoemulsification incision in the steeper meridian was selected and a single AK was made in the area 180 degrees opposite to this incision using a modified Donnenfeld nomogram.

**Table 1.** *Nomogram for Femtosecond-Assisted Combined Phacoemulsification and Single Arcuate Keratotomy in Eyes With Low to Moderate Keratometric Astigmatism based on modified Donnenfeld's nomogram.*

| Intended Astigmatic Correction (Diopters) | Arc Length at 9 mm Optical Zone (Degrees) |
|---|---|
| 1.00-1.25 | 30 |
| 1.25-1.50 | 40 |
| 1.50-2.00 | 50 |
| 2.00-2.50 | 70 |
| 2.50-3.00 | 80 |

Prior to all cataract surgeries, mydriasis was induced by instilling 0.05% tropicamide (Tropamid, Bilim Lab.), 1% cyclopentolate hydrochloride (Sikloplejin, Abdi Ibrahim), 2.5% phenylephrine hydrochloride (Mydfrine, Alcon Lab.), and 0.1% nepafenac (Nevanac, Alcon Lab.) drops 3 times at 5 minute intervals. Patients were moved to the room where the LenSx device is located and the ocular surface was disinfected using 5% iodine solution. The LenSx device was used to perform 5-mm capsulotomy, nucleus fragmentation, a single AK incision, and the primary phacoemulsification incision and side incisions, in that order. After the femtosecond laser procedures were completed, the patient was transferred to another room in the operating theater for the phacoemulsification procedure, which involved the following stages: opening the LenSx incisions with a blunt spatula, injecting 1.8% sodium hyaluronate into the anterior chamber, removing the detached capsule, hydro-dissection, phacoemulsification, clearing the cortex by irrigation/aspiration, implanting a one-piece foldable aspheric IOL (SN60WF, AcrySof IQ, Alcon Surgical Inc.) in the capsular bag, hydrating and sealing the incisions, and finally, injecting 0.1 ml (1 mg) cefuroxime sodium (Aprokam, Thea Pharma.) into the anterior chamber. At all stages, 0.5% proparacaine HCl (Alcaine, Alcon Lab.) was used for topical anesthesia. None of the patients had complications such as open posterior capsule or anterior capsule tears. In addition, no suture was used to close the incisions, and none of the AK incisions opened postoperatively.

After the procedure, all patients were prescribed 0.5% moxifloxacin (Vigamox, Alcon Lab.) and dexamethasone (Maxidex, Alcon Lab.) drops 4 times a day for 1 month. The patients were examined on postoperative days 1 and

5 and at months 1, 3, and 6. The patients' data obtained at baseline and on postoperative month 6 were used to evaluate the efficacy of AK, which was the focus of this study.

### Statistical Analysis

Keratometric astigmatism was assessed using vector analysis based on Alpin's method.[16] Target induced astigmatism (TIA), surgically induced astigmatism (SIA), and the difference vector (DV) were calculated and the results were analyzed. In addition, to make our results clearer and consistent with the literature, we determined the following parameters: index of success (IOS) of astigmatism correction calculated as the DV/TIA ratio; correction index (CI) calculated as SIA/TIA and expressed as percentage (%) to indicate under- or overcorrection of astigmatism; magnitude of error (ME) calculated as the arithmetic difference between TIA and SIA (ME=TIA–SIA); and angle of error (AE), obtained by vectoral comparison of SIA and TIA.[16-18]

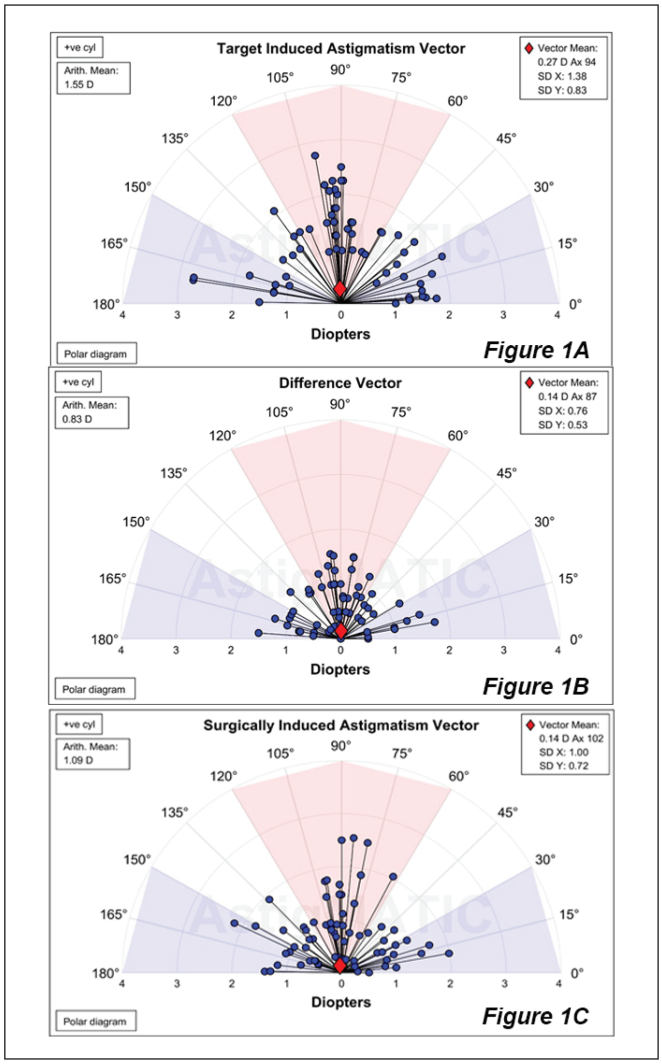
## RESULTS

This prospective study included 69 eyes of 69 patients (35 females and 34 males). The mean age of the patients was 60.3±10.5 (range: 45-73) years. The mean preoperative TIA was 1.55±0.46 D and the mean postoperative SIA was 0.83±0.41 D (P<.001). Preoperative spherical equivalent (SE) was -1.05±1.2 D, while postoperative SE was -0.95±1.01 D (P=0.665). TheTIA, SIA, and DV values in the patients are shown in Figures 1A, 1B, and 1C. Astigmatism correction is indicated by the change in the image of the point source from wide and distant preoperatively to a narrow image closer to the point source postoperatively. In addition, a box-plot chart showing TIA, SIA, and DV values with standard deviations are presented in Figure 2.

Keratometric vector analysis and TIA, SIA, and DV values were calculated using Alpin's vector analysis method, and these values were used to derive the ME, AE, CI, IOS, and flattening index (FI) values (Table 2).

CI values >1.00 were classified as overcorrection and values <1.00 as undercorrection; the CI in this study was 0.71±0.34 (minimal undercorrection). A box-plot chart showing the distribution of SIA and TIA values illustrates the distribution of patients with under- and overcorrection (Figure 3).

AE is calculated by evaluating TIA and SIA values as vectors and measuring the angle between them. The closer the value and magnitude of this angle are to zero, the more successful the preoperative astigmatism axis calculation




**Figures 1A, 1B, and 1C:** *The TIA (Figure 1A), DV (Figure 1B), and SIA (Figure1C) values of patients are shown. Target induced astigmatism (TIA), Surgically induced astigmatism (SIA), Difference vector (DV).*

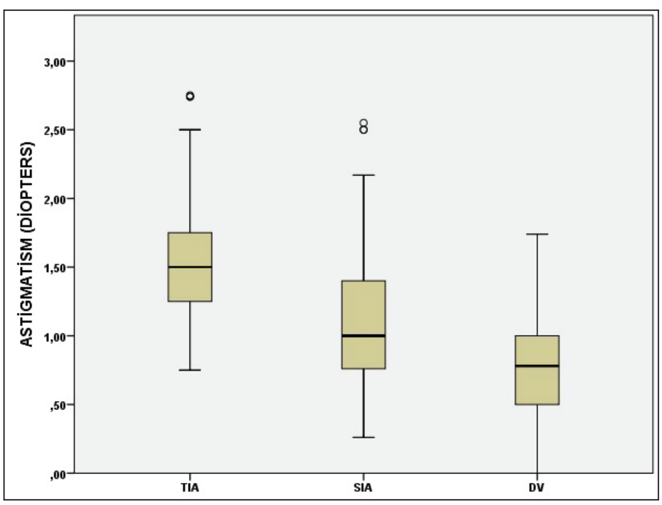



**Figure 2:** *A box-plot chart showing TIA, SIA, and DV value with standard deviation is presented. Target induced astigmatism (TIA), Surgically induced astigmatism (SIA), Difference vector (DV).*

**Table 2.** *Vector Analysis of Keratometric Astigmatic Correction After Femtosecond-Assisted Combined Phacoemulsification and Arcuate Keratotomy Using Alpin's Method.*

| | |
|---|---|
| **TIA** (diopters) | |
| Arithmetic mean± SD (Range) | 1.55±0.46 (0.9-2.75) |
| Angle | 87±50.8 |
| **SIA** (diopters) | |
| Arithmetic mean± SD (Range) | 1.09±0.56 (0.26-2.55) |
| Angle | 94.9±51.6 |
| **DV** (diopters) | |
| Arithmetic mean± SD (Range) | 0.83±0.41 (0.00-1.74) |
| Angle | 88,2±52,1 |
| **ME** (diopters) | |
| Arithmetic mean± SD (Range) | -0.28±0.65 (-0.11; -0,42) |
| **AE (Angle)** | |
| Arithmetic mean± SD (Range) | 22.5 ±19.2 (-1.05;1.49) |
| **CI** (diopters) | |
| Geometric mean± SD (Range) | 0.71±0.34 (0,15; 1,74) |
| **IOS** (diopters) | |
| Geometric mean± SD (Range) | 0.54±0.27 (0.00-1.52) |
| **FI** (diopters) | |
| Geometric mean± SD (Range) | 0.66±0.51 (0.00-2.10) |

**TIA:** target induced astigmatism; **SIA:** surgically induced astigmatism; **DV:** difference vector; **ME:** magnitude of error; AE: angle of error; **CI:** correction index; **IOS:** index of success; **FI:** flattening index; **IOS:** index of success; **SD:** standard deviation;

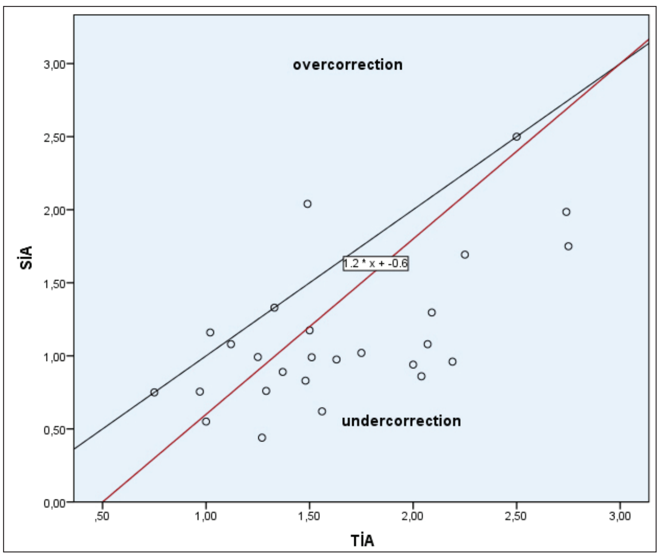



**Figure 3:** *A box-plot chart showing the distribution of SIA and TIA values illustrates the distribution of patients with under- and overcorrection. Target induced astigmatism (TIA), Surgically induced astigmatism (SIA), Difference vector (DV).*

and planning were. In this study, the mean AE was 22±16 (range: 0-44) degrees.

IOS value indicates the success of the procedure. The mean IOS value in this study was 0.54±0.27 (46% success). No corneal structural complications associated with AK (e.g., perforation, thinning, inflammation) were observed in any of the patients during the study.

## DISCUSSION

In the present study, we analyzed the outcomes of cataract surgery with FSAK in patients with low-to-moderate astigmatism. In the our study sample including 69 patients, the mean magnitude of preoperative astigmatism (TIA) was 1.55±0.46 D while the mean magnitude of postoperative astigmatism (DV) was 0.83±0.41 D and the magnitude of astigmatism corrected (SIA) was 1.09±0.56 D. Analysis of our study data showed that our success rate (IOS) with FSAK was 46% and the amount of astigmatism that could not be corrected (ME) was -0.28±0.65 D. Moreover, our results showed that we performed minimal undercorrection, as indicated by the CI of 0.71.

AK has been used as a method of correcting astigmatism since 1869, when German ophthalmologist Snellen[19] reported that incisions in the corneal surface can be used to correct keratometric astigmatism. Chan et al.[17] performed cataract surgery with FSAK to correct a mean moderate/low astigmatism of 1.33±0.57 D in 54 eyes. Vector analysis based on Alpin's method showed that the mean postoperative residual astigmatism was 0.87±0.56 D whereas the mean amount of corrected astigmatism was 1.20±0.68 D, the mean CI was 0.86±0.52, IOS was 62% (IOS), mean ME was 0.13±0.68, and mean AE was 17.56±19.2 degrees. In another study, Chan et al.[18] performed cataract surgery with FSAK in 50 eyes and vector analysis showed that the mean preoperative astigmatism of 1.35± 0.48 D decreased to 0.74±0.53 D at postoperative 2 years while the mean success rate was 51%, and the amount of residual astigmatism was 0.74±0.53 D. Wang et al.[20] performed cataract surgery with FSAK on 25 eyes and used vector analysis to determine that astigmatism decreased from 1.40±0.37 D to 0.70±0.29 D, with 1.22±0.46 D of correction and a success rate of 51%. They also reported a CI of 88%, indicating undercorrection, and an AE of 0.85±13.69. In their study including outcomes of FSAK from 16 eyes, Rückl et al.[21] reported that a mean astigmatism of 1.41±0.6 D decreased to 0.63±0.34 D at postoperative month 6, with overcorrection in 7 patients and undercorrection in 9 patients. Day et al.[22] analyzed cataract surgery with intrastromal FSAK in a large series of 319 eyes and reported a mean TIA of 1.24±0.44 D and mean SIA of 0.71±0.43, with postoperative astigmatism

(DV) reduced to 0.79±0.41 D. In addition to demonstrating the efficacy of AK, their study showed that the amount of preoperative astigmatism, the astigmatic meridian, and AK depth and length play important roles in the efficacy of AK. They also demonstrated that corneal hysteresis and corneal resistance factor, two corneal biomechanical parameters, are independent determinants of AK success. Byun et al.[23] analyzed the outcomes of cataract surgery with AK performed concurrently with cataract surgery in 89 eyes and demonstrated that the mean amount of astigmatism was 1.16 D preoperatively and decreased to 0.63 D postoperatively. In the same study, CI at 6 months was found to be 0.87±0.50 and it was demonstrated that whether astigmatism was with-the-rule or against-the-rule affected the biomechanical structure of the cornea (corneal hysteresis and corneal resistance factor) as well as the amount of correction achieved with FSAK, suggesting the need for a new nomogram for these different types of astigmatism. The results of our study were in agreement with findings of Chan[17,18], Wang[20], Day[22] and Byun[23] in terms of amount of astigmatism correction. Analysis of CI values revealed a minimal undercorrection in our study, which was similar to the outcomes of the studies by Chan[17,18] and Byun[23], and slightly better than the outcomes reported by Wang[20], Rückl[21]and Day[22]. The graphic summary of our study outcomes presented in Figure 3 illustrates that correction was closer to ideal as the amount of astigmatism approached 2.5–3.00 D, while less correction was seen as the amount of astigmatism decreased.

Differences in AK outcomes both in our study and in the literature may be due to several reasons. First, we used a modified Donnenfeld nomogram to plan AK in our study, whereas Chan et al.[17,18] used a modified Wallace nomogram and Wang et al.[20] used the Donnenfeld nomogram. Second, we made AK incisions at a depth corresponding to 85% of the corneal thickness, while Chen et al.[17,18] used a standard incision depth of 450 µm. Rückl et al.[21] used intrastromal incision through the entire cornea to within 100 µm of the epithelium and endothelium. Third, in our study the AK was made in the 9-mm optic zone, whereas the optic zone was 7.5 mm in the study by Rückl[21] and 8 mm in the study by Day et al.[22] Studies have shown that AK position, depth, and length affect the success of AK.[24,25] Fourth, biomechanical factors such as cornea hysteresis, which various studies have shown to be an independent risk factor, may have led to different outcomes even if the incision depth and length were the same.[22]

CI index was 0.71±0.34 in our study and values<1.00 was considered as undercorrection. Approach to the peripheral cornea, shallow or short incision of the arcuate incision and leaving intact epithelium was considered as the risk factors which may be related with undercorrection, besides the corneal biomechanical variations between the patients.[17,18,20,23] Also different nomograms for astigmatic correction may be related with undercorrection. Inter-individual variations of wound healing may interact with the under- or overcorrection of astigmatism.[22]

In a study using optic coherence tomography (OCT) to evaluate concordance between preoperative planned and postoperative actual AK position and depth, it was shown that incisions planned to start at a depth of 20% from both the epithelium and endothelium started at an average depth of 17.2% from the epithelium and 32.5% from the endothelium.[26] It was also stated that this deviation may be attributable to the calibration of the femtosecond laser device or the ambient temperature and humidity in the operating room, indicating that these factors can also impact the efficacy of AK. AK site and depth were not evaluated postoperatively using OCT in our study, but the daily equipment calibration, the humidity and temperature of the operating room were regulated by automated systems to eliminate such factors. Loffler et al.[27] performed AK using values obtained by topographical evaluation of both the anterior and posterior corneal surfaces and demonstrated that posterior corneal astigmatism did not affect postoperative outcomes. We did not evaluate posterior corneal astigmatism in this study.

Nejima et al.[28] increased visual acuity significantly in 6 patients with prior cataract surgery but >2.00 D corneal astigmatism by correcting a mean preoperative corneal astigmatism of 2.84±0.83 by 3.22±1.37 D (SIA) (overcorrection) using AK with 2 incisions of 80 degrees in a 8.5-mm optic zone. In another study comparing cataract surgery with FSAK performed in 43 eyes as an LRI according to the Donnenfeld nomogram and with AK according to the Day nomogram in 44 eyes, the amount of corneal astigmatism was 1.50±0.46 and 1.38±0.40 in LRI and AK, respectively, and these values decreased to 1.17 D (CI 48%) and 0.89 D (CI 73%) after the surgery.[29] The authors concluded that astigmatism correction was more successful using AK compared to LRI. High astigmatism is also common after keratoplasty. The mean correction achieved with FSAK in cases of regular or irregular astigmatism after penetrating keratoplasty has been reported as 3.23 D by Bahar et al.[30], 4.39 D by Nubile et al.[31], 2.69 D by Kumar et al.[32] and 4.55 D by Fadlallahet al.[33] The FSAK procedure is shown to be safe and effective in the correction of post-keratoplasty astigmatism.

## Study Limitations

In our study, we observed no complications related to the AK incision site in any of our patients during follow-up. After AK, incision healing and stabilization occurs in an average of 3 months.[34] Data from postoperative month 6 were used in our study in an attempt to eliminate factors related to wound healing. Limitations of our study include the smaller number of patients and the lack of certain measurements such as posterior corneal astigmatism and biomechanical factors such as corneal hysteresis. In addition, we did not assess agreement of location and depth between the AK planned preoperatively and the actual AK postoperatively using anterior segment OCT. Lack of control group, comparing the results of the same group with and without FASK incision is a another limitation to our study.

## CONCLUSION

Femtosecond laser-assisted AK has gained popularity in recent years because the experience and skills of the surgeon do not impact the procedure as they do in manual keratotomy, and it provides more predictable and effective outcomes. The results of this study indicate that this technique is effective in cataract patients with low-to-moderate astigmatism. FSAK can be recommended to cataract patients with low-to-moderate astigmatism in order to avoid postoperative reduced and blurred vision, halo, glare, and high-order aberrations associated with astigmatism.

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