Int Ophthalmol (2022) 42:2633–2642
https://doi.org/10.1007/s10792-021-02090-8

ORIGINAL PAPER

Refractive outcomes of femtosecond laser-assisted cataract surgery with arcuate keratotomy and standard phacoemulsification with toric intraocular lens implantation

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Received: 6 June 2021 / Accepted: 21 October 2021 / Published online: 16 November 2021

Abstract
Purpose Femtosecond laser arcuate keratotomy (FS-AK) and toric intraocular lens (IOL) implantation are effective for the correction of eyes with corneal astigmatism. In this study, the postoperative refractive outcomes of patients receiving femtosecond laser-assisted cataract surgery (FLACS) with FS-AK and patients receiving standard phacoemulsification with toric IOL implantation were evaluated.

Methods This retrospective study reviewed the postoperative outcomes of patients undergoing FLACS with FS-AK (the FS-AK group) and patients undergoing standard phacoemulsification with toric IOL implantation (the toric IOL group). The main outcome measures were uncorrected and corrected visual acuities, keratometric and refractive astigmatism, and vector analysis.

Results The FS-AK group included 41 eyes with preoperative keratometric astigmatism of -1.64 ± 0.42 diopters (D), and the toric IOL group included 53 eyes with preoperative keratometric astigmatism of -2.29 ± 0.91 D ($P < 0.001$). Postoperative

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10792-021-02090-8.

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refractive astigmatism was comparable between the two groups. Compared with the FS-AK group, postoperative uncorrected visual acuity was significantly better ($P = 0.005$) and corrected visual acuity was marginally better in the toric IOL group ($P = 0.051$). The absolute angles of error were 9.95° ± 9.57° and 5.08° ± 4.94° ($P = 0.02$) in the FS-AK and the toric IOL groups, respectively.

Conclusion Both FLACS with FS-AK and standard phacoemulsification with toric IOL implantation are safe and effective methods for astigmatism correction during cataract surgery. Standard phacoemulsification with toric IOL implantation achieves better visual acuity than FLACS with FS-AK at the 6-month follow-up.

Keywords Arcuate keratotomy · Astigmatism · Femtosecond laser · Toric intraocular lens

Background

Cataract surgery has recently been considered a type of refractive surgery. An increasing number of patients started demanding for better visual quality rather than just a safe cataract surgery. Postoperative residual astigmatism is one of the leading causes of ordinary visual outcomes and poor patient satisfaction [1]. The incidence of preoperative corneal astigmatism was estimated to be 87%, and 22.2% of them were ≥ 1.50 diopters (D) [2]. Therefore, corneal astigmatism correction has now become common during cataract surgery, and techniques thereof include limbal relaxing incision, peripheral corneal incision, and toric intraocular lens (IOL) implantation [3, 4]. With advances in femtosecond laser technology, femtosecond laser arcuate keratotomy (FS-AK) has also been used to correct astigmatism [5].

A femtosecond laser provides superior accuracy and predictability in customized corneal cutting compared with the traditional manual technique [6, 7]. To correct high postkeratoplasty astigmatism, FS-AK displays better alignment outcomes than mechanized arcuate keratotomy (AK) [8, 9]. Ruckl et al. [10] reported the initial results of FS-AK in treating corneal astigmatism before a planned cataract surgery, which revealed a significant improvement in manifest cylinder, topographic cylinder, and bare vision. Furthermore, Chan et al. reported the stability and efficacy of penetrating FS-AK after 2 years of surgery [11]. Phacoemulsification with a toric IOL implantation has been widely used to correct corneal astigmatism and has been effective and safe in various toric IOL models [12, 13]. The main concern regarding toric IOL implantation is potential postoperative IOL rotation and misalignment.

Yoo et al. [14] compared the refractive outcomes of patients receiving FS-AK after standard phacoemulsification and patients receiving simultaneous standard phacoemulsification and toric IOL implantation, and they reported comparable results between the two methods. However, few studies have compared the refractive outcomes of patients receiving femtosecond laser-assisted cataract surgery (FLACS) with FS-AK and patients receiving standard phacoemulsification with toric IOL implantation. The present study compared the refractive outcomes of these two methods for correcting low to moderate regular astigmatism.

Methods

This retrospective study reviewed the case records at the Department of Ophthalmology, Shuang Ho Hospital, Taiwan. Between October 2015 and December 2016, patients with cataract and coexisting corneal astigmatism between − 1.5 and − 4.5 D were recommended for simultaneous cataract surgery and astigmatism correction. We divided the patients into two groups: one group received FLACS with FS-AK, and the other group received standard phacoemulsification with toric IOL implantation. Because age and astigmatism type affect accuracy in predicting the outcomes of FS-AK [15], we selected age- and astigmatism type-matched patients who underwent standard phacoemulsification with toric IOL implantation during the study period in the toric IOL group. The Joint Institutional Review Board Committee of Taipei Medical University approved the study protocol. This study was conducted in accordance with the tenets of the Declaration of Helsinki. All patients underwent thorough preoperative ophthalmologic assessment, including manifest refraction, uncorrected visual acuity (UCVA) and best-corrected distant visual acuity (BCVA), noncontact tonometry (NT530P;NIDEK, Gamagori, Japan), slit-lamp fundus examination, automated keratometry (KR-8900;Topcon, Tokyo, Japan), axial length, biometry (IOLMaster; Carl Zeiss Meditec, Dublin, California, USA), and corneal topography (Keratograph 4; Oculus, Washington, USA). With different postoperative target refraction, postoperative UCVA was defined as the best achieved distant, intermediate, or near UCVA. Patients with severe corneal disorders, irregular astigmatism, active ophthalmic disease, or refractive surgery history were excluded.

Surgical techniques

All surgeries were performed by a single surgeon (Y.D.S.) under topical anesthesia with 0.5% proparacaine hydrochloride (Alcon Laboratories, Fort Worth, Texas, USA).

In the FS-AK group, patients were examined before surgery with the head fixed and chin rested on the slit lamp, and two points at 3 and 9 o'clock were marked on the limbus, with the patient sitting upright. The patients were then transferred to a femtosecond laser platform (LENSAR, Orlando, Florida, USA). A pair of AK incisions were made in the steep meridian, which was determined using a topographic map. The incision depth of the AK extended from 100 μm above the endothelium to the surface of the epithelium with a 90° side-cut angle. The optical zone diameter was set at 8 mm. The angular arc length of the AK incision ranged between 30° and 80°, according to the surgeon's nomogram, which was modified from the December 2011 version of the Woodcock LenSx astigmatic nomogram [16]. The suction ring was docked on the patient's eye and centered on the pupil center mark. A femtosecond laser was then used to perform anterior capsulotomy, lens fragmentation, and AK consecutively. After removal of the docking cone and suction ring, the main incision for phacoemulsification was created at 210° in the right eye and at 30° in the left eye by using a 2.2-mm disposable blade (Alcon Laboratories). A paracentesis was created using a microvitreoretinal blade (Alcon Laboratories) at 60° from the main corneal incision. Phacoemulsification and implantation of a foldable aspheric IOL (TECNIS, Abbott Medical Optics, Santa Ana, California, USA) were then performed. At the end of surgery, the pair of keratotomies was dissected with a blunt spatula to ensure full separation of the incisions.

In the toric IOL group, the IOL power and alignment axis were calculated using an online calculator (https://www.raytrace.rayner.com). Surgically induced astigmatism (SIA) of the main corneal incision was set at 0.25 D. Furthermore, the steep corneal meridian was determined through topography and marked by the surgeon using the Neuhann one-step toric marker (ASICO, Illinois, USA) with patients sitting upright. The main incision and paracentesis were created in the same locations as those in the FS-AK group by using a 2.2-mm disposable blade and microvitreoretinal blade, respectively (Alcon Laboratories). Standard phacoemulsification was performed using a foldable IOL (T-flex aspheric Toric; Rayner, UK) implanted into a capsular bag through a Monarch II injector with a C-cartridge (Alcon Laboratories). The corrected IOL alignment was verified at the end of surgery. Stromal hydration of the main incision was performed to form an anterior chamber.

Postoperatively, patients were prescribed topical eye drops of tobradex suspension, which contained 0.1% dexamethasone and 0.3% tobramycin (Alcon Laboratories), four times a day for 1 month. Postoperative examinations were performed at 1 day, 1 week, 1 month, 3 months, and 6 months after surgery. Postoperative examinations included manifest refraction, UCVA, BCVA, noncontact tonometry, automated keratometry, and topography.

Vector analysis

Astigmatic analysis was performed using the Alpins method [17] to evaluate the effective correction of astigmatism. The target-induced astigmatism (TIA) vector is the planned surgically induced astigmatic change after surgery, which is equivalent to preoperative corneal astigmatism. SIA is the actual surgically induced astigmatic change. The difference vector (DV) is the induced astigmatic change that would enable the intended goal of the initial surgery to be achieved, which is equivalent to postoperative astigmatism. The magnitude of error (ME) is the arithmetic difference between 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 ratio of SIA to TIA. CI of > 1 and < 1 indicate overcorrection and undercorrection, respectively. The index of success (IOS) is the ratio of DV to TIA (the ideal value is 0). The flattening index (FI) is the proportion of SIA required to reduce astigmatism at the intended meridian. SAS 9.3 (SAS, Cary, NC, USA) was used for statistical analyses. A paired *t* test was used to compare preoperative and postoperative continuous variables. An independent-samples *t* test or Fisher's exact test was used to compare the data between the two groups. $P < 0.05$ was considered statistically significant.

Results

During the 15-month study period, combined FLACS and FS-AK were performed in 41 eyes of 36 patients, and standard phacoemulsification with toric IOL implantation was performed in 53 eyes of 47 patients. We assumed the two-sided alpha value of 0.05 and power of 0.8 to calculate the sample size that the power achieved for our outcome measures, UCVA, and absolute AE. The mean difference of UCVA was 0.13 ± 0.21; the required sample size was 42 per group, yielding a power of 0.79. The mean differences of absolute AE and its standard deviation were 4.8 and 7.2, respectively; the required sample size was 37 per group, yielding a power of 0.86.

In the FS-AK and toric IOL groups, the preoperative age was 67.0 ± 13.3 years and 67.2 ± 11.4 years ($P = 0.92$), axial lengths were 24.3 ± 2.0 mm and 24.6 ± 2.2 mm ($P = 0.47$), and against-the-rule astigmatism was 79.3% and 61.1% ($P = 0.18$), respectively (Table 1). In the FS-AK and toric group, the mean preoperative refractive astigmatism were –2.33 ± 1.43 D and –3.44 ± 1.72 D ($P = 0.005$); the mean preoperative corneal astigmatism were – 1.64 ± 0.42 D and –2.29 ± 0.91 D ($P < 0.001$); the mean postoperative refractive astigmatism were –0.98 ± 0.61 D and –0.92 ± 0.72 D ($P = 0.41$); and the mean postoperative corneal astigmatism were –0.69 ± 0.51 D and –2.41 ± 0.89 D ($P < 0.001$) respectively (Table 2). Preoperative UCVA and BCVA (logarithm of the minimum angle of resolution) were not significantly different between the two groups. In the FS-AK and the toric IOL groups at 6 months after surgery, postoperative UCVA was 0.25 ± 0.32 and 0.12 ± 0.11 ($P = 0.005$), and postoperative BCVA was 0.16 ± 0.17 and 0.08 ± 0.09 ($P = 0.051$), respectively. This finding implies that postoperative UCVA was significantly better and that BCVA was marginally better in the toric IOL group than in the FS-AK group. Our results revealed comparable postoperative refractive astigmatism at the 1-month and 6-month follow-up between these two groups. A postoperative reduction in corneal astigmatism was observed in the FS-AK group, but no significant reduction in corneal astigmatism was observed in the toric IOL group.

Table 3 presents the results of refractive vector analysis. TIAs were 2.26 ± 1.21 D and 3.31 ± 1.69 D ($P = 0.005$), and SIAs were 1.78 ± 1.34 D and 3.02 ± 1.64 D in the FS-AK and toric IOL groups, respectively ($P = 0.001$). The between-group difference in the mean AE was not significant ($P = 0.12$), which indicates that the average achieved correction axis was close to the intended axis. However, the absolute AEs were 9.95° ± 9.57° and 5.08° ± 4.94° in the FS-AK and toric IOL groups ($P = 0.02$), respectively, indicating that the alignment in the toric IOL group was better than that in the FS-AK group. MEs were − 0.50 ± 0.83 D and − 0.30 ± 0.89 D in the FS-AK and toric IOL groups, respectively ($P = 0.31$), indicating undercorrection in both groups. The CI was 0.87 ± 0.60 and 0.97 ± 0.37 in the FS-AK and toric IOL groups, respectively. In the FS-AK group, 65.4% of patients had undercorrection and 34.6% had overcorrection. In the toric IOL group, 60.4% had undercorrection, 3.8% had CI of 1, and 35.8% had overcorrection. Among 53 eyes with preoperative keratometric astigmatism in the toric IOL group, 10 eyes had significant misalignment (nine eyes had 15 > absolute AE > 10; one eye had

Table 1 Baseline parameters of the FS-AK and toric IOL groups

Variable	FS-AK	Toric IOL	*P* value*
Number of eyes (*n*)	41	53	–
Age (years)	67.0 ± 13.3	67.2 ± 11.4	0.917
Axial length (mm)	24.3 ± 2.0	24.6 ± 2.2	0.471
Astigmatism type			0.177
With-the-rule (*n*)	1 (3.4%)	2 (3.7%)	
Oblique (*n*)	5 (17.2%)	19 (35.2%)	
Against-the-rule (*n*)	23 (79.3%)	33 (61.1%)	

Data are presented as mean ± standard deviation

FS-AK femtosecond laser arcuate keratotomy, *IOL* intraocular lens

*Independent-samples *t* test or Fisher's exact test

Table 2 Changes in visual acuities, astigmatism, and keratometry of the FS-AK and toric IOL groups

Parameter	FS-AK	Toric IOL	*P* value*
UCVA (logMAR)			
Preoperative	0.92 ± 0.41	0.67 ± 0.52	0.206
Postoperative 1 month	0.23 ± 0.23	0.13 ± 0.12	0.053
Postoperative 6 months	0.25 ± 0.32	0.12 ± 0.11	0.005
BCVA (logMAR)			
Preoperative	0.57 ± 0.26	0.54 ± 0.33	0.658
Postoperative 1 month	0.17 ± 0.16	0.09 ± 0.10	0.009
Postoperative 6 months	0.16 ± 0.17	0.08 ± 0.09	0.051
Refractive cylinder (D)			
Preoperative	− 2.33 ± 1.43	− 3.44 ± 1.72	0.005
Postoperative 1 month	− 1.00 ± 0.56	− 0.88 ± 0.53	0.322
Postoperative 6 months	− 0.98 ± 0.61	− 0.92 ± 0.72	0.405
Keratometric cylinder (D)			
Preoperative	− 1.64 ± 0.42	− 2.29 ± 0.91	< 0.001
Postoperative 1 month	− 0.67 ± 0.43	− 2.13 ± 0.97	< 0.001
Postoperative 6 months	− 0.69 ± 0.51	− 2.41 ± 0.89	< 0.001
Mean corneal keratometry (D)			
Preoperative	44.1 ± 1.5	45.1 ± 1.6	0.005
Postoperative 1 month	43.7 ± 1.7	44.9 ± 1.4	0.004
Postoperative 6 months	43.5 ± 1.5	45.5 ± 1.6	0.003

All values are expressed as mean ± SD

FS-AK femtosecond laser arcuate keratotomy, *IOL* intraocular lens, *VA* best-corrected visual acuity, *UCVA* uncorrected visual acuity, *logMAR* logarithm of the minimum angle of resolution, *SD* standard deviation, *D* diopters

*Independent-samples *t* test

Table 3 Refractive vector analysis of the FS-AK and toric IOL groups

Parameter	FS-AK	Toric IOL	*P* value*
SIA (D)	1.78 ± 1.34	3.02 ± 1.64	0.001
SIA axis (°)	92.70 ± 35.62	99.96 ± 48.03	0.489
TIA (D)	2.26 ± 1.21	3.31 ± 1.69	0.005
TIA axis (°)	99.44 ± 32.94	99.44 ± 32.94	0.900
AE (°)	3.76 ± 13.28	1.37 ± 6.95	0.382
Absolute AE (°)	9.95 ± 9.57	5.08 ± 4.94	0.016
ME (D)	− 0.50 ± 0.83	− 0.30 ± 0.89	0.310
Radians	− 0.23 ± 1.01	0.01 ± 0.35	0.116
FI	0.67 ± 0.63	0.67 ± 0.63	0.026
Correction index	0.87 ± 0.60	0.97 ± 0.37	0.342
DV (D)	1.09 ± 0.66	1.03 ± 0.65	0.696
DV axis (°)	88.26 ± 43.60	81.91 ± 46.67	0.557
IOS	0.66 ± 0.62	0.41 ± 0.52	0.062

All values are expressed as mean ± SD

FS-AK femtosecond laser arcuate keratotomy, *IOL* intraocular lens, *SIA* surgically induced astigmatism, *TIA* target-induced astigmatism, *AE* angle of error, *ME* magnitude of error, *FI* flattening index, *DV* difference vector, *IOS* index of success, *D*: diopter, *SD* standard deviation, *CI* confidence interval

*Independent-samples *t* test

absolute AE of 18). However, none of the patients in either group expressed dissatisfaction with the results; thus, no re-incisions in the FS-AK group or re-rotations in the toric IOL group was implemented.

Table 4 shows the results of the keratometric vector analysis. In the FS-AK and toric IOL groups, the absolute AE was 10.70° ± 10.23° in the FS-AK group. CIs were 0.65 ± 0.35 and 0.35 ± 0.47 ($P = 0.007$), IOSs were 0.44 ± 0.42 and 1.01 ± 0.29 ($P < 0.001$), and FIs were 0.45 ± 0.41 and 0.15 ± 0.48 ($P = 0.006$), respectively. No cases of corneal perforation or epithelial ingrowth were detected during the study period. Tables S1 and S2 present the percentage of eyes with refractive astigmatism preoperatively and postoperatively in the FS-AK and toric IOL groups, respectively.

Figures 1 and 2 illustrate a double-angle plot of refractive astigmatism in the FS-AK and toric IOL groups, respectively. The mean values of preoperative and postoperative refractive astigmatism were − 2.33 ± 1.43 D and − 0.98 ± 0.61 D, respectively ($P < 0.001$) in the FS-AK group and − 3.44 ± 1.72 D and − 0.92 ± 0.72 D, respectively ($P < 0.001$) in the toric IOL group. In both methods under investigation, compared with preoperative dots,

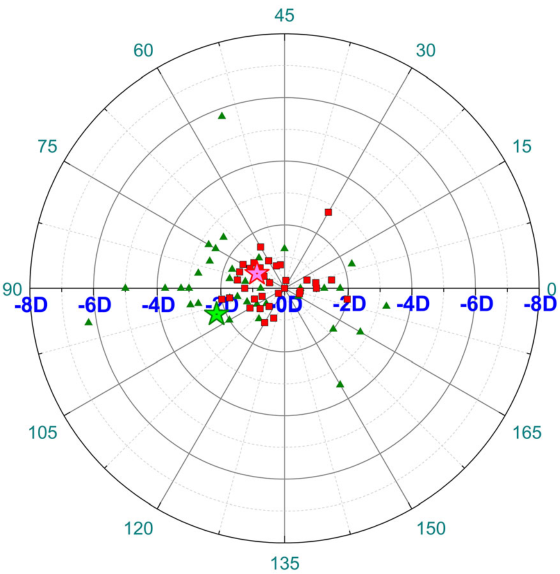

Fig. 1 Double-angle plot of refractive astigmatism before (Δ) and after (☐) FLACS with FS-AK. The green Δ represents preoperative refractive astigmatism. The green star represents the mean preoperative astigmatism vector (− 2.33 ± 1.2 D). The red ☐ represents postoperative refractive astigmatism. The pink star represents the mean postoperative astigmatism vector (− 0.98 ± 0.61 D; $P < 0.001$). The mean astigmatism vector was closer to the null position after surgery, and the standard deviation was reduced

Table 4 Keratometric vector analysis of the FS-AK and toric IOL groups

Parameter	FS-AK	Toric IOL	P value*
SIA (D)	1.10 ± 0.61	0.70 ± 0.85	0.034
SIA axis (°)	0.50 ± 0.67	105.36 ± 42.89	< 0.001
TIA (D)	1.55 ± 0.88	2.31 ± 0.94	0.001
TIA axis (°)	105.54 ± 38.01	106.02 ± 47.39	0.964
AE (°)	6.43 ± 50.74	− 0.67 ± 44.98	0.518
Absolute AE (°)	10.70 ± 10.23	30.88 ± 33.12	0.006
ME (D)	− 0.23 ± 0.72	− 1.61 ± 1.24	< 0.001
Radians	− 0.13 ± 0.39	− 0.02 ± 1.57	0.693
FI	0.45 ± 0.41	0.15 ± 0.48	0.006
Correction index	0.65 ± 0.35	0.35 ± 0.47	0.007
DV (D)	0.69 ± 0.49	2.26 ± 0.99	< 0.001
DV axis (°)	100.65 ± 51.15	92.62 ± 47.89	0.515
IOS	0.44 ± 0.42	1.01 ± 0.29	< 0.001

All values are expressed as mean ± SD

FS-AK femtosecond laser arcuate keratotomy, *IOL* intraocular lens, *SIA* surgically induced astigmatism, *TIA* target-induced astigmatism, *AE* angle of error, *ME* magnitude of error, *FI* flattening index, *DV* difference vector, *IOS* index of success, *D* diopter, *SD* standard deviation, *CI* confidence interval

*Independent-samples t test

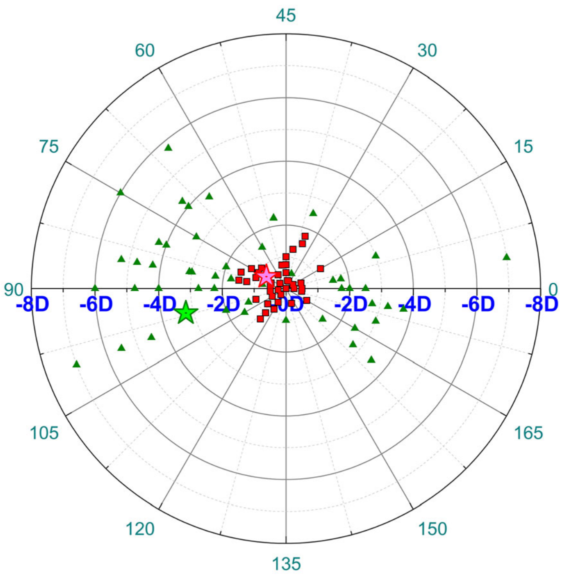

Fig. 2 Double-angle plot of refractive astigmatism before (Δ) and after (□) standard phacoemulsification with toric IOL implantation. The green Δ represents preoperative refractive astigmatism. The green Δ represents the mean preoperative astigmatism vector (− 3.44 ± 1.72 D). The red □ represents postoperative refractive astigmatism. The pink star represents the mean postoperative astigmatism vector (− 0.92 ± 0.72, $P < 0.001$). The mean astigmatism vector was found closer to the null position after surgery, and the standard deviation was reduction

postoperative astigmatism dots were distributed closer to null points, and standard deviations were decreased.

Discussion

This study indicated that the difference in postoperative astigmatism values between the FS-AK and toric groups was not significant. The outcome of UCVA was significantly better ($P = 0.01$) and that of BCVA was marginally better ($P = 0.051$) in the toric IOL group than in the FS-AK group at 6 months after surgery. Our study is the first to compare the refractive outcomes of patients receiving FLACS with FS-AK and patients receiving standard phacoemulsification with toric IOL implantation. Yoo et al. compared the refractive outcomes of patients who underwent FS-AK after standard phacoemulsification and patients who underwent standard phacoemulsification and toric IOL implantation. They observed that the outcomes of FS-AK were effective and comparable to those of toric IOL implantation for correcting postoperative refractive astigmatism and improving visual acuities at 5 months after surgery. They also demonstrated that AE was not significantly different between the two methods; however, they did not provide data on absolute AE [14]. Our study result is similar to that of Yoo et al. and indicates that both FS-AK and toric IOL are effective surgical methods for astigmatism correction.

Alignment is a crucial factor that determines the success of astigmatism correction. In previous studies, FS-AK appeared to induce more absolute AE than toric IOL implantation. In a study of FLACS with penetrating FS-AK, the absolute AE was 14.0° ± 15.5° after 2 years of follow-up [11]. In a randomized controlled study, Hoffart et al. compared penetrating FS-AK with manual AK for correcting postkeratoplasty astigmatism [8], where the keratometric absolute AE of FS-AK was 11.67° ± 17.95°. The rotation of the Rayner T-flex toric IOL has been reported to be 3.4° [18] and 5.54° ± 4.65° [19]. In the current study, we observed significantly higher refractive absolute AE with greater deviation, which suggests more induced misalignment in the FS-AK group than in the toric IOL group ($P = 0.03$). Increased misalignment consequently resulted in unfavorable outcomes for FI, IOS, UCVA, and BCVA in the FS-AK group compared with the toric IOL group.

Although the femtosecond laser can provide a more consistent corneal incision depth and arc length than manual blade AKs [20], FS-AK is still associated with higher misalignment relative to toric IOL implantation. This misalignment might be related to interindividual variations in wound healing and nomograms, which require refinement with large samples specific to penetrating or intrastromal FS-AK. A study on the wound-healing process of penetrating FS-AK corneal incisions revealed epithelial ingrowth inside the wound initially, and fibrotic scarring developed consequentially [9], which might lead to uncertainty in postoperative refractive outcomes. Although we ensured full separation of incisions during dissection, wound healing might vary among individuals. In the nomogram for intrastromal FS-AK, Day et al. observed that corneal biomechanical parameters were an independent predictor of FS-AK efficacy, even after adjusting for AK arc length, AK start depth, and preoperative corneal cylinder [15]. In addition, penetrating or intrastromal incisions and the diameter of the incisions might affect the results. Therefore, the incorporation of individualized biomechanical parameters to create a customized treatment protocol and nomogram may enhance the precision of astigmatism correction through the FS-AK technique.

Numerous studies have investigated the visual outcomes of FLACS and conventional phacoemulsification cataract surgery. A Cochrane review of 16 randomized controlled trials found little evidence of any crucial difference in postoperative visual acuity between FLACS and standard phacoemulsification. A meta-analysis of 15 randomized controlled trials and 22 observational cohort studies, including 14,567 eyes, found no significant difference in UCVA, BCVA, and mean absolute error between patients receiving FLACS or manual cataract surgery [21]. Therefore, the difference in visual outcomes of the current study may be attributed to the superior alignment of the toric IOL compared with FS-AK, regardless of the cataract extraction method.

During cataract surgery, toric IOL implantation has inherent advantages over FS-AK. Toric IOL implantation is less surgically demanding, does not require special instruments, and does not increase the duration of phacoemulsification [22]. Furthermore, astigmatism correction with toric IOL implantation does not require additional corneal incisions as in FS-AK, which contributes to increased postoperative high-order aberrations [11, 23, 24] and weakening of the corneal structure. Nevertheless, our data indicate that FS-AK provides efficacious and stable visual improvement even 6 months after surgery and that it may be an effective procedure for correcting residual astigmatism after cataract surgery or keratoplasty.

This study has some limitations. First, the sample size was small. Second, we neglected the SIA of main incisions in designing FS-AK incisions. Third, the incision depth was not proportional to the entire corneal thickness; consequently, the outcome may have deviated from the expected outcome. Fourth, in the present study, the against-the-rule astigmatism was 79.3% and 61.1% in the FS-AK and toric IOL groups, respectively, and the percentage of against-the-rule astigmatism in the FS-AK group was higher than that previously documented [25]. This might be attributed to that we only measured the anterior corneal astigmatism with autorefraction and topography. Posterior corneal astigmatism may affect the outcome of astigmatic surgical interventions that are based on anterior corneal measurements only. Failure to account for a vertically steep posterior corneal curvature will cause overcorrection in eyes having with-the-rule astigmatism and undercorrection in eyes having against-the-rule astigmatism [26] The planned astigmatism correction in the current study was based on anterior corneal measurement, and it may explain the reason why the postoperative residual astigmatism is -0.98D and -0.92D in the FS-AK and toric IOL groups, respectively. Finally, the preoperative corneal astigmatism in the FS-AK (-1.64 ± 0.42 D) and toric IOL (-2.29 ± 0.91 D) groups was significantly different. Initially, we divided patients in the toric IOL group into subgroups with low corneal astigmatism (> -2 D, with an average astigmatism of -1.63 ± 0.38 D) and moderate corneal astigmatism (< -2 D, with an average astigmatism of -3.05 ± 0.72), and we compared the outcome with that of the FS-AK group. Although the toric IOL low-astigmatism subgroup and the FS-AK group had comparable corneal astigmatism (-1.63 ± 0.38 D versus -1.64 ± 0.42 D, $P = 0.84$), their absolute AE was still significantly different ($P = 0.024$). Because the sample sizes were relatively small (n = 41, 28, and 25 in the FS-AK group, low-astigmatism toric IOL subgroup, and moderate-astigmatism toric IOL group, respectively), we decided to analyze the toric IOL group without subgrouping.

Conclusions

Both FLACS with FS-AK and standard phacoemulsification with toric IOL implantation were effective for correcting eyes with preexisting corneal astigmatism. The 6-month outcomes in this study indicate that standard phacoemulsification with toric IOL implantation achieves better visual outcomes than FLACS with FS-AK.

Acknowledgements This manuscript was edited by Wallace Academic Editing.

Author contributions LMY performed data collection. LMY, HYT, and LIC conceived and drafted the manuscript. LMY, SYD, HYT, WIJ, and LIC contributed to the study design. LMY performed the statistical analysis and LIC contributed to data interpretation. All authors have read and approved the final manuscript.

Funding This study did not receive any funding.

Data availability The datasets used and/or analyzed in the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest All authors have read and approved the final manuscript and do not have any financial interest. The authors declare that they have no competing or proprietary interests.

Ethics approval The Joint Institutional Review Board Committee of Taipei Medical University approved the study protocol (TMU-JIRB N201802025).

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