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ORIGINAL PAPER

Vector analysis of femtosecond laser-assisted astigmatic keratotomy after deep anterior lamellar keratoplasty and penetrating keratoplasty

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Abstract
Purpose To compare the refractive and keratometric changes induced by femtosecond laser astigmatic keratotomy (AK) for suture-out post-keratoplasty astigmatism in deep anterior lamellar keratoplasty (group I) and penetrating keratoplasty (group II).
Setting Dhahran Eye Specialist Hospital, Dhahran, Saudi Arabia.
Design Retrospective, comparative, interventional study.
Methods This study comprised 15 eyes in group I and 35 eyes in group II. All eyes underwent femtosecond AK for suture-out post-keratoplasty astigmatism. The refractive and keratometric measurements were evaluated before and 6 months after AK. The Alpins method for vector analysis was used to evaluate the keratometric changes induced by AK.
Results The astigmatic correction was 99 and 110% in group I and group II, respectively ($p = 0.743$) and the success of AK was 43 and 51% in group I and group II ($p = 0.966$). There was a trend in the magnitude of error toward overcorrection with increased surgically induced astigmatism ($r = 0.80$ with $p < 0.001$ in group I and $r = 0.70$ with $p < 0.001$ in group II). There was no systemic misalignment in either group. The safety indices were 1.50 (0.19–26.67) and 1.27 (0.12–13.33) in group I and group II, respectively ($p = 0.325$). The efficacy indices were 1.00 (0.05–24.00) and 0.31 (0.04–2.50) in group I and group II, respectively ($p = 0.001$).
Conclusions Femtosecond laser AK has similar safety for correcting suture-out post-DALK and PKP astigmatism; however, it is more effective for DALK. There is a positive correlation between surgically induced astigmatism and magnitude of error.

Keywords Arcuate keratotomy · Astigmatic keratotomy · Femtosecond laser · Deep anterior lamellar keratoplasty · Penetrating keratoplasty · Alpins method

Introduction

Postoperative astigmatism may contribute significantly to poor visual outcome in an otherwise successful keratoplasty procedure. The etiology of post-keratoplasty astigmatism includes intraoperative causes such as dull, tilted, or eccentric trephination; oversized and small grafts, disparity in graft–host thickness and postoperative causes such as non-uniform peripheral changes in donor tissue, irregular

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or vascularized recipient bed, and poor wound healing [1]. Mild postoperative astigmatism can be addressed with spectacles or contact lenses yet; high astigmatism may require astigmatic keratotomy (AK), wedge resection, laser refractive surgery, or toric intraocular lenses [1].

There has been significant research on femtosecond laser AK for suture-out post-keratoplasty astigmatism [2, 3]. It is now considered a better alternative to manual AK [4, 5] due to the increased accuracy of depth and alignment, increased effectiveness, and decreased complications [6, 7]. However, the predictability of femtosecond laser AK is limited [8–11]. Additional procedures are often required to improve the final outcome, including lengthening of the AK incisions for under-correction or compression sutures for overcorrection with significantly gaping wounds [12].

Alexander et al. found that corneal hysteresis and the corneal resistance factor are independent predictors of the efficacy of femtosecond laser AK [13]. However, deep anterior lamellar keratoplasty (DALK) results in normal corneal hysteresis and resistance factor values compared to reduced values after penetrating keratoplasty (PKP) [14–17]. Therefore, the efficacy of AK might differ between DALK and PKP. Kubaloglu et al. [18] compared manual AK after DALK and PKP and found that it was safe and effective allowing similar reduction in refractive cylinder.

In this study, we compare the refractive and keratometric changes induced by femtosecond laser AK for suture-out post-DALK (group I) and PKP (group II) astigmatism using the Alpins method. To the best of our knowledge, this is the first study evaluating the performance of femtosecond laser AK for astigmatism after DALK and PKP.

Subjects and methods

This retrospective study compared the refractive and topographic data of eyes that had undergone femtosecond laser AK for suture-out post-DALK or PKP corneal astigmatism greater than 3D. DALK, PKP, and femtosecond laser AK were performed by the second author (AK). Indications for DALK were keratoconus ($n = 14$) and keratectasia post-refractive surgery ($n = 1$); and indications for PKP were keratoconus ($n = 27$), corneal scar (6), corneal ulcer ($n = 1$), and granular dystrophy ($n = 1$). The initial indications for femtosecond AK were high or irregular astigmatism. Femtosecond laser AK was performed between March 2012 and October 2015 at Dhahran Eye Specialist Hospital, Dhahran, Saudi Arabia. Experienced optometrists measured visual acuity, refractive data and keratometry using index of 1.3375 from corneal topography (Pentacam-HR, Oculus Gmbh, Wetzlar, Germany) with index 1 month prior to AK and 6 months after AK.

This study was approved by Institutional Review Board at Dhahran Eye Specialist Hospital, and the study adhered the tenets of the Declaration of Helsinki. All patients underwent an informed consent procedure for AK including an explanation of the risk and benefits of femtosecond AK.

Astigmatic keratotomy was performed with the iFS laser (Advanced Medical Optics, Inc.) under topical anesthesia. Before the procedure, the cornea was marked at the horizontal meridian and the steep axis to reduce the error induced by cyclotorsion in the supine position. Topical anesthesia, benoxinate hydrochloride 0.4% (BNX, Alcon Laboratories, Inc), was instilled in the eye. Pachymetry was obtained well within the graft–host interface at the intended site of the AK incisions with an ultrasonic pachymeter. The AK specifications were determined using an AK nomogram previously used for femtosecond laser-assisted AK. The laser parameters for performing AK were reviewed thoroughly before the procedure. The cornea was docked with the laser's docking system, and 2 paired AK incisions were placed along the steep axis of the cornea within the optical zone, inside donor tissue. The incisions were then opened by Sinskey hook. All surgeries were completed uneventfully. The patient was started on moxifloxacin 0.5% eyedrops (Vigamox, Alcon Laboratories, Inc) 4 times daily for 2 weeks.

Vector analysis

The method described by Alpins et al. [19–23] was used to compare all astigmatic vectors and indices between groups including: *Target Induced Astigmatism* (TIA) defined as the same magnitude of corneal astigmatism but opposite in direction for this study; *Surgically Induced Astigmatism* (SIA); *Difference Vector* (DV) defined as the magnitude and angle to

enable the initial AK to achieve the target in second attempt; *Magnitude and Angle of Error* (ME&AE) by which the SIA deviated from TIA; *Flattening Effect* (FE) at the intended meridian by SIA; *Torque or Rotational Effect* of SIA on the preoperative steep meridian which rotates the steep meridian either clockwise or counterclockwise; *Spherical Effect* which is the shift (change) in mean keratometry; *Ocular Residual Astigmatism* (ORA) which is the non-corneal part of the total refractive astigmatism; *Correction Index* (CI) which is the ratio of SIA to TIA; *Coefficient of Adjustment* (CA) is the inverse of CI and is used to refine future treatment; *Index of Success* (IOS) which is the ratio of DV to TIA; *Flattening Index* (FI) which is the ratio of SIA component at the steep meridian to TIA; *Coupling Ratio* (CR) which is the change in corneal power at the opposite meridian to that at the treatment meridian; *Coupling Constant* (CC) which is ratio of change in mean keratometry to the difference in corneal power at the treatment and opposite meridians. For AK, the coupling adjustment is equal to the coupling constant. The coupling adjustment is the spherical adjustment per diopter of cylinder of astigmatic treatment that has to be incorporated into the spherical part of the treatment. The overall astigmatic correction is CI $\times$ 100. The astigmatic correction at intended axis is FI $\times$ 100. The success of astigmatism surgery is (1.0 $-$ IOS) $\times$ 100 [4]. In addition to the Alpins terms above, we calculated the *absolute magnitude of error* (AME) to reveal any cancelation due to opposite directions of errors.

Calculations of Alpins parameters and the residual ocular astigmatism, coupling ratio and constant, were performed with Excel (Office 2013; Microsoft Corp., Redmond, WA, USA) and verified with a vector calculator (VECTrAK, v.2.3.0; ASSORT Pty Ltd, Cheltenham, Victoria, Australia) and the ASSORT free web calculators (http://www.assort.com).

Statistical analysis

The safety index was calculated as the ratio of the postoperative BCVA to the preoperative BCVA. The efficacy index was calculated as the ratio of the postoperative UCVA to the preoperative BCVA. The paired *t* test was used to compare the preoperative and postoperative measurements when the unpaired t-test was used to compare group I and group II measurements. The normality of the data was assessed by the Shapiro–Wilk test. Non-normally distributed data such as indices were tested with the Mann–Whitney U nonparametric test for independent groups (group I vs. group II) and Wilcoxon signed rank test for dependent measurements (preoperative vs. post-operative data); the median and range of data were reported. Also for non-normally distributed data, Spearman's Rho correlation was calculated. Chi-squared test was used for categorical data. Missing data are imputed by the method of Expectation Maximization. A p value < 0.05 was considered statistically significant. Statistical analysis was performed with IBM SPSS for windows (v.22; IBM Corp, Armonk, NY, USA).

Results

The study sample was comprised of 50 patients (34 males and 16 females). The median age of the study sample was 31.1 (range 15.7–71.8 years) years. There were 15 patients (8 males and 7 females) in group I of median age 29.2 (range 15.7–71.8 years) years. Group II was comprised of 35 patients (26 males and 9 females) with median age 33.5 (18.8–69.7 years) years ($p = 0.305$). There were no significant differences in the AK femtosecond laser settings between groups ($p > 0.05$ for all parameters) (Table 1).

Safety and efficacy

The BCVA did not change significantly for group I and group II; however, the UCVA improved 6 lines in group I and did not change significantly in group II. The median safety index was 1.50 (range 0.19–26.67) for group I and 1.27 (range 0.12–13.33) for group II ($p = 0.325$). The median (range) efficacy index was 1.00 (0.05–24.00) for group I and 0.31 (0.04–2.50) for group II ($p = 0.001$).

Refractive and topographic measurements

Table 2 compares refractive and topographic measurements between groups prior to and after femtosecond laser AK. There was a steepening in median keratometry of 1.64 D in group I ($p = 0.017$). There was a reduction in the median corneal astigmatism of 3.55 D in group I ($p = 0.012$) and 2.88 D in group II

Table 1 Femtosecond laser setting for astigmatic keratotomy in group I and group II cases

	Surgery				*p* value
	Group I		Group II		
	Mean		Mean		
No. of incision	2.00 ± 0.00		2.00 ± 0.00		–
Post-depth (μm)	397.3 ± 32.0		410.2 ± 36.0		0.24
	400 (340–444)		413 (320–500)		
Diameter (mm)	6.17 ± 0.24		6.20 ± 0.32		0.804[a]
	6.00 (6.00–6.70)		6.00 (5.50–7.00)		
Energy (μJ)	1.50 ± 0.00		1.51 ± 0.05		0.513[a]
	1.50 (1.50–1.50)		1.50 (1.50–1.80)		
Cut angle 1					
60°	13.3%		5.7%		0.497[b]
65°	26.7%		31.4%		
70°	26.7%		34.4%		
80°	26.7%		28.6%		
85°	6.7%		0.0%		
Cut angle 2					
60°	13.3%		5.7%		0.440[b]
65°	26.7%		31.4%		
70°	26.7%		40.0%		
80°	26.7%		22.9%		
85°	6.7%		0.0%		
Side cut angle (°)	75.00 ± 5.67		75.86 ± 2.84		0.320[a]
	75.0 (60–90)		75 (75–90)		
Spot separation (μm)	3.00	0.00	3.00	0.00	–
Layer separation (μm)	3.00	0.00	3.00	0.00	–
Depth in glass (μm)	50.00	0.00	50.00	0.00	–

DALK deep anterior lamellar keratoplasty, *PKP* penetrating keratoplasty, *SD* standard deviation, [a]Wilcoxon Singed Rank test was used, [b]Chi-squared test was used, group I DALK, group II PKP

($p < 0.001$). Figure 1 shows the preoperative and postoperative corneal astigmatism in both study groups. There was a reduction in the median refractive cylinder of 1.25 D in group I ($p = 0.055$) and 2.00 D in group II ($p < 0.001$). Figure 2 shows the preoperative and postoperative refractive cylinder in both study groups. There was a reduction in the median ORA of 2.42D in group I ($p = 0.244$) and 1.38 D in group II ($p = 0.512$).

Flattening, rotational, and spherical effects

Table 3 presents the comparison of the flattening/rotational/spherical effects of femtosecond laser AK between groups. Two cases in group I had an increase in astigmatism; in these 2 cases, the effective cut positions were 57° clockwise and 70° counterclockwise to the intended positions.

The coupling ratios and coupling constants

The median coupling ratio (CR) was 1.19 and 1.08 D of change in corneal power at the opposite meridian per 1 D change in the treatment meridians for group I and group II, respectively ($p = 0.626$). The median coupling constant was − 0.06 and − 0.08 in group I and group II, respectively ($p = 0.966$) (Table 3).

Precision

Table 4 compares the errors in magnitude and angle between groups. The magnitude of error in both groups was trivial that there was no systematic error; however, the absolute magnitude of error was 2.30 and 2.44 D in group I and group II, respectively ($p = 0.824$). There were some errors in individual eyes, but they negated each other because the errors

Table 2 Comparisons of preoperative and postoperative refractive and topographic measurements of femtosecond laser AK for astigmatism in group I and group II

	Group I ($n = 15$)		p value	Group II ($n = 35$)		p value
	Preoperative	Postoperative		Preoperative	Postoperative	
BCVA (LogMAR)						
Mean ± SD	0.57 ± 0.48	0.38 ± 0.29	0.100[a]	0.44 ± 0.37	0.38 ± 0.33	0.317[a]
Median (range)	0.40 (0.10–1.82)	0.30 (0.05–0.90)		0.40 (0.02–1.82)	0.30 (0.00–1.52)	
UCVA (LogMAR)						
Mean ± SD	0.97 ± 0.33	0.59 ± 0.55	0.016[a]	0.88 ± 0.47	0.95 ± 0.44	0.280[a]
Median (range)	1.00 (0.52–1.52)	0.40 (0.13–2.30)		0.82 (0.29–2.30)	0.90 (0.22–2.00)	
Average keratometry (D)						
Mean ± SD	46.37 ± 2.94	48.07 ± 2.61	0.017[a]	45.99 ± 2.89	46.52 ± 3.53	0.055[a]
Median (range)	46.65 (39.55–50.18)	48.29 (43.20–53.02)		45.52 (40.46–53.77)	45.83 (41.55–56.35)	
Corneal astigmatism (D)						
Mean ± SD	8.15 ± 3.02	5.08 ± 4.03	0.012[a]	7.63 ± 2.56	4.29 ± 2.33	< 0.001[a]
Median (range)	7.80 (3.10–13.70)	4.25 (0.60–15.00)		6.80 (4.00–14.20)	3.92 (0.63–12.80)	
Refractive cylinder (D)						
Mean ± SD	− 4.55 ± 2.52	− 3.17 ± 1.68	0.055[a]	− 5.88 ± 2.90	− 3.49 ± 1.69	< 0.001[a]
Median (range)	− 4.50 (− 9.50 to 0.00)	− 3.25 (− 6.00 to 0.00)		− 5.50 (− 12.50 to 0.00)	− 3.50 (− 6.00 to 0.00)	
ORA (D)						
Mean ± SD	5.95 ± 3.82	4.98 ± 4.34	0.244[a]	4.35 ± 3.29	3.63 ± 3.05	0.512[a]
Median (range)	5.94 (2.23–16.53)	3.52 (0.60–15.72)		3.89 (0.06–13.21)	2.51 (0.01–13.93)	
Spherical equivalent (D)						
Mean ± SD	− 4.34 ± 3.78	− 4.77 ± 3.72	0.560	− 5.18 ± 4.48	− 4.54 ± 4.84	0.257
Median (range)	− 3.75 (− 11.00 to 1.00)	− 4.75 (− 13.25 to 0.13)		− 4.75 (− 17.38–4.00)	− 5.00 (− 14.75 to 5.00)	

BCVA best corrected visual acuity, *UCVA* uncorrected visual acuity, *ORA* ocular residual astigmatism, *DALK* deep anterior lamellar keratoplasty, *PKP* penetrating keratoplasty, *AK* astigmatic keratotomy, [a]Wilcoxon Signed Ranks test was used, group I DALK, group II PKP

were in opposite directions. Such errors in magnitude may be responsible for 28.1 and 35.9% reduction in astigmatic correction with femtosecond laser AK in group I and group II, respectively. Figure 3 depicts SIA versus ME. There was a statistically significant correlation between SIA and ME of 0.80 in group I ($p < 0.001$) and 0.70 in group II ($p < 0.001$) (Spearman's ρ). Figure 4 depicts SIA versus AE. There was no systematic misalignment in both groups. The absolute angle of error differed, 4.00° in group I and 10.00° in group II ($p = 0.102$). These angles of error may be responsible for 1.0 and 6.0% reduction in astigmatic correction with femtosecond laser AK in group I and group II, respectively. The plot of SIA versus AE indicates no trend (Fig. 3). The correlation coefficient between SIA and AE was 0.020 in group I ($p = 0.944$) and 0.183 in group II ($p = 0.292$) (Spearman's ρ).

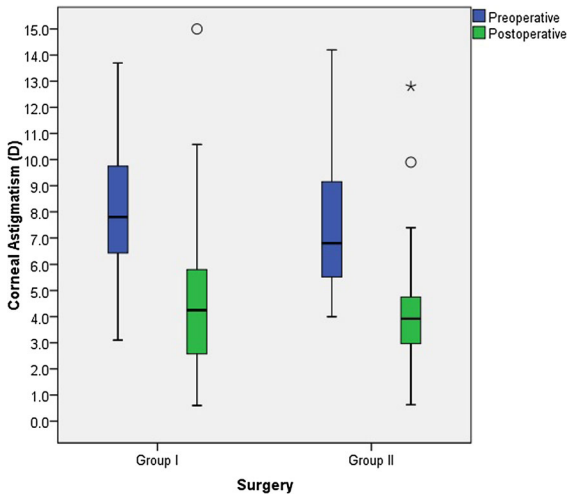

Fig. 1 Pre- and post-corneal astigmatism after femtosecond laser Astigmatic Keratotomy corneal astigmatism in group I and group II

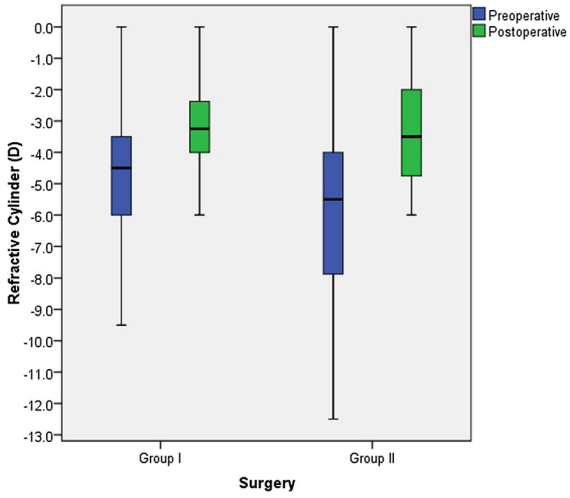

Fig. 2 Pre- and post-refractive cylinder after femtosecond laser Astigmatic Keratotomy corneal astigmatism in group I and group II

Correction, success, and refinement

The overall astigmatic correction was 99% in group I and 110% in group II ($p = 0.743$) (Fig. 5). Calculated from flattening index, the correction at the steep meridian was 98% in group I and 100% in group II ($p = 0.932$). The success of astigmatic surgery was 43% in group I and 51% in group II ($p = 0.966$). Coefficients of Adjustment (CA) were 1.01 and 0.91 in group I and group II ($p = 0.743$) which could be used to refine future femtosecond laser AK.

Complications and secondary procedures

There were no cases of microperforation, infectious keratitis, wound dehiscence, or any other adverse effect. In group II, one eye underwent photorefractive keratectomy to refine the final outcome, and another eye underwent DALK followed by photorefractive keratectomy for a failed graft 1 year after femtosecond laser AK.

Discussion

AK involves the use of 2 incisions along the steep meridian to create a flattening effect at this meridian and a corresponding steepening at the flat meridian due to coupling. The advent of the femtosecond laser has resulted in greater precision in the depth and architecture of AK [11, 24]. Although femtosecond laser AK reduces naturally occurring astigmatism and post-keratoplasty astigmatism [25], the cutting precision is dependent on the status of the cornea. For example, the biomechanics of a virgin cornea differ significantly from transplanted cornea. Hence, AK nomograms for congenital astigmatism are inaccurate for correcting post-keratoplasty astigmatism [26].

Recent studies have found that SIA due to femtosecond AK is dependent on the biomechanical properties of the cornea [13]. Additionally, several studies has reported that post-DALK corneas preserve the biomechanical properties to normal values compared to weaker biomechanics after PKP [14–17]. The differences may be due to preservation of the recipient Descemet Membrane in DALK. Alpins Method was utilized in the current study because it allows comprehensive analysis of astigmatic changes. We believe this method should be utilized for evaluating the effects of ablative and incisional procedures of any astigmatic treatments.

In this study, the safety indices were similar. These outcomes indicate a modest improvement in BCVA in both groups after AK which is consistent with Kubaloglu et al.'s study [18]. However, in the current study, group I resulted in a higher efficacy index with an improvement of 6 lines of UCVA, compared to group II ($p = 0.001$) regardless of similar reduction of

Table 3 Surgical effects of laser-assisted AK in group I and group II

	Surgery		*p* value
	Group I ($n = 15$)	Group II ($n = 35$)	
Target induced astigmatism (D)			
Mean ± SD	8.15 ± 3.02	7.63 ± 2.59	0.531
Median (range)	7.80 (3.10–13.70)	6.80 (4.00–14.20)	
Surgically induced astigmatism (D)			
Mean ± SD	8.18 ± 4.69	7.84 ± 3.52	0.780
Median (range)	6.65 (2.57–17.63)	8.26 (0.96–18.04)	
Correction index			
Mean ± SD	1.03 ± 0.46	1.07 ± 0.44	0.743[a]
Median (range)	0.99 (0.34–1.70)	1.10 (0.11–1.86)	
Coefficient of adjustment			
Mean ± SD	1.25 ± 0.77	1.35 ± 1.52	0.743[a]
Median (range)	1.01 (0.59–2.94)	0.91 (0.54–9.09)	
Flattening effect (D)			
Mean ± SD	6.94 ± 5.97	6.88 ± 3.87	0.975[a]
Median (range)	6.59 (− 3.09 to 17.24)	6.67 (0.49–17.87)	
Flattening index			
Mean ± SD	0.88 ± 0.62	0.92 ± 0.45	0.932[a]
Median (range)	0.98 (− 0.28 to 1.69)	1.00 (0.04–1.70)	
Rotational effect or torque (D)			
Mean ± SD	− 0.04 ± 2.54	− 0.033.28	0.711[a]
Median (range)	− 0.27 (− 3.67 to 4.65)	0.38 (− 8.87 to 4.73)	
Spherical effect (D)			
Mean ± SD	1.70 ± 2.40	0.53 ± 2.54	0.212[a]
Median (range)	0.95 (− 1.25 to 6.37)	0.35 (− 8.25 to 8.80)	
Coupling ratio			
Mean ± SD	3.27 ± 6.86	3.00 ± 9.28	0.626[a]
Median (range)	1.19 (− 9.41 to 20.73)	1.08 (− 11.43 to 30.44)	
Coupling constant			
Mean ± SD	0.16 ± 0.98	0.13 ± 1.71	0.966[a]
Median (range)	− 0.06 (− 0.62 to 2.59)	− 0.08 (− 1.31 to 9.77)	

DALK deep anterior lamellar keratoplasty, *PKP* penetrating keratoplasty, *AK* astigmatic keratotomy, [a]median (range) and nonparametric test (Mann–Whitney U) was used, group I DALK, group II PKP

corneal astigmatism in both groups; this outcome differs from Kubaloglu et al.'s study [18]. Fadlallah et al. [8] reported a safety index of 1.288 and an efficacy index of 0.81, at 6 months in the PKP group, which is a similar safety index but better efficacy index compared to group II in our study. Differing enrollment criteria and surgical technique may explain the differences between studies.

In the current study, the reduction in corneal astigmatism concurs with Kumar et al.'s study for the PKP group [11]. In our study, there was a corresponding reduction in refractive cylinder. Kubaloglu et al. [18] have attributed the greater reduction in refractive cylinder in PKP compared to DALK to higher preoperative refractive cylinder in the PKP group, which also explains the outcome in the current study. Notably, there was a reduction in ORA in both groups in our study which resulted in the similarities between the refractive cylinder and corneal astigmatism in magnitude and axis. In our study, the spherical equivalent changed by trivial amount in both groups. This was expected as astigmatic surgery does not change spherical equivalent significantly. However, many times patients did not accept the required high cylinder. This affected cylinder and spherical equivalent data.

Table 4 Precision of femtosecond laser AK in group I and group II

	Surgery		*p* value
	Group I ($n = 15$)	Group II ($n = 35$)	
Magnitude of error (D)			
Mean ± SD	0.03 ± 3.99	0.22 ± 3.39	0.824[a]
Median (range)	− 0.07 (− 7.67 to 6.90)	0.92 (− 11.78 to 4.01)	
Absolute magnitude of error (D)			
Mean ± SD	3.05 ± 2.45	2.71 ± 2.00	0.824[a]
Median (range)	2.30 (0.07–7.67)	2.44 (0.05–11.78)	
Angle of error (°)			
Mean ± SD	0.80 ± 25.76	− 0.60 ± 17.21	0.849[a]
Median (range)	3.00 (− 57.00 to 70)	− 1.00 (− 35.00 to 37.00)	
Absolute angle of error (°)			
Mean ± SD	11.04 ± 17.37	13.23 ± 10.79	0.102[a]
Median (range)	4.00 (0.57–70.00)	10.00 (1.00–37.00)	
Difference vector (D)			
Mean ± SD	4.87 ± 3.83	4.28 ± 2.33	0.680[a]
Median (range)	4.25 (0.60–15.00)	3.92 (0.63–12.80)	
Index of success			
Mean ± SD	0.60 ± 0.39	0.60 ± 0.32	0.966[a]
Median (range)	0.57 (0.08–1.43)	0.49 (0.07–1.46)	

DALK deep anterior lamellar keratoplasty, *PKP* penetrating keratoplasty, *AK* astigmatic keratotomy, [a]median (range) and nonparametric test of Mann–Whitney U was used, group I DALK, group II PKP

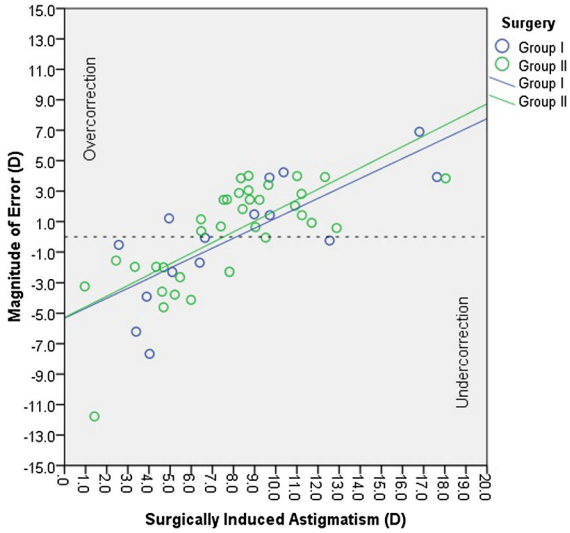

Fig. 3 Surgically induced astigmatism versus magnitude of error of femtosecond laser astigmatic keratotomy in group I and group II

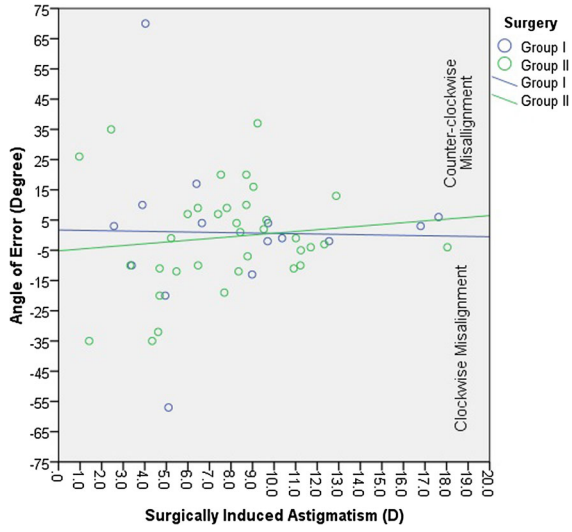

Fig. 4 Surgically induced astigmatism versus angle of error of femtosecond laser astigmatic keratotomy in group I and group II

The overall astigmatic correction in this study was 99 and 110% for and the astigmatic correction at the intended axis, correction at the steep meridian in this study, was 98 and 100% in group I and group II, respectively. In group II, there was about 110% over all overcorrection despite 100% correction at the intended axis. These results concur with the findings of a previous study of manual AK [18] which reported an overall correction of 97 and 117% in DALK group and PKP groups respectively ($p = 0.410$). In their study, Kubaloglu et al. [18] reported a 117% overall

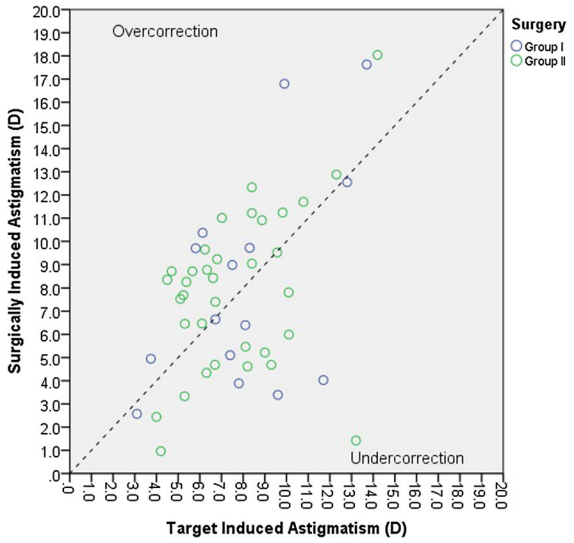

Fig. 5 Astigmatic correction of femtosecond laser astigmatic keratotomy in group I and group II

overcorrection in the PKP group. Additionally, Kubaloglu et al. [18] reported an under-correction at the intended axis of 77 and 75% after DALK and PKP, respectively ($p = 0.720$).

In case of AK, the CA is equal to CC [22]. In this study, CC values suggests that future femtosecond laser AK will not require spherical adjustment based in relatively small spherical effect or shift (change in mean keratometry) and corresponding change in spherical equivalent.

An evaluation of accuracy of femtosecond laser AK in our study indicated that there was a − 0.07 D under-correction and 0.92 D overcorrection in magnitude and 3° counterclockwise and − 1° clockwise change in group I and group II, respectively. This outcome indicates that there was no significant systematic over/under-correction or misalignment. These outcomes are similar to Kubaloglu et al.'s [18] observations. However, the observed AME (2.30 and 2.44 D) and the observed AAE (4° and 10°) for group I and group II, respectively, indicate that at an individual level there were some errors in magnitude and angle which could be due to the healing process. The ME in the current study correlated positively with SIA that is higher SIA was associated with higher ME. There was no observable trend in the AE (misalignment) with increased SIA.

Regardless of the correction values mentioned above, the success of femtosecond laser AK was 43 and 51% in group I and group II, respectively ($p = 0.966$) because the femtosecond laser AK did not completely eliminate the corneal astigmatism postoperatively; about 4.25 and 3.92 D of corneal astigmatism remained in group I and group II respectively. Thus, the success of surgery as per Alpins method is a better indicator of the success of astigmatic surgery compared to the correction percentage.

Femtosecond AK for post-keratoplasty was safe with no case of microperforation, infectious keratitis, or wound dehiscence in current study. However, a failed graft did occur at 1 year post-femtosecond laser AK which cannot be solely attributed to the AK procedure. Additionally photorefractive keratectomy was required in one case to enhance the correction of astigmatism. Hence, the femtosecond laser AK post-DALK and PKP is relatively safe in the short term and future studies are required to assess long term safety.

Our results are encouraging and should be validated in a larger cohort with equal number in both groups. A limitation of the current study is that we selected the target induced astigmatism to create a spherical cornea. Future studies could select to target with-the-rule astigmatism postoperatively, reduce ocular residual astigmatism and optimize the refractive cylinder and corneal astigmatism [27]. Additionally, future evaluations of incisional or ablative astigmatic surgeries should be evaluated in terms of correction at the intended meridian compared to overall correction, and success of surgery as defined by Alpins Method.

In summary, femtosecond AK has similar safety profile for the treatment of suture-out post-DALK and PKP astigmatism. However, it is more effective for post-DALK astigmatism. Moreover, there is a positive correlation between SIA and ME in both groups.

Compliance with ethical standards

Conflict of interest Fouad anNakhli and Ashbala Khattak declare that they have no conflict of interest.

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