ORIGINAL RESEARCH

Vector Analysis and Prognostic Factors for Femtosecond Arcuate Keratotomy in Post-Keratoplasty Astigmatism

Bayan A Alsaif[1],*, Abdulaziz Al Somali ⓘ[2],*, Sumayah H Banaji[1], Askar K Alshaibani[3]

[1]Department of Ophthalmology, College of Medicine, King Fahd Hospital of the University, Imam Abdulrahman Bin Faisal University, Dammam, Saudi Arabia; [2]Department of Ophthalmology, College of Medicine, King Faisal University, Al-Ahsa, Saudi Arabia; [3]Ophthalmology, Dhahran Eye Specialist Hospital, Dhahran, Saudi Arabia

*These authors contributed equally to this work

Correspondence: Askar K Alshaibani, Email Asker0908@gmail.com

Purpose: To analyze different tomographic and refractive parameters for predicting successful visual outcome following femtosecond laser-assisted arcuate keratotomy (FSAK) for post-keratoplasty astigmatism.

Design: Retrospective.

Methods: Retrospective study evaluating patients with astigmatism following penetrating keratoplasty (PKP) or deep anterior lamellar keratoplasty (DALK) who underwent FSAK. Vector analysis using the Alpins method was done to calculate surgically induced astigmatism (SIA). An improvement of 3 lines of Early Treatment Diabetic Retinopathy Study (ETDRS) lines was used for successful outcome. Outcome was measured at 3 months and 17 months.

Results: This study included 106 eyes from 104 patients (65 males and 39 females). Mean age was 31.8±8.6 years, and 89.4% (*n*=93) of cases were keratoconus (KC), 3.8% (*n*=4) scar, 3.8% (*n*=4) granular dystrophy, 1.9% (*n*=2) post-LASIK ectasia, and 1.0% (*n*=1) macular dystrophy. Uncorrected visual acuity (UCVA) improved from 1.02±0.53 logarithm minimal angle of resolution (logMAR) to 0.87±0.49 logMAR (*p*=0.01) at 3 months and to 0.92±1.08 logMAR (*p*=0.57) at 17 months. Best spectacle-corrected visual acuity (BSCVA) improved from 0.41±0.30 logMAR to 0.31±0.19 logMAR (*p*<0.01) at 3 months and to 0.23±0.27 logMAR (*p*<0.01) at 17 months. Success was achieved in 50% (*n*=53) and 49% (*n*=52) at 3 and 17 months follow-up, respectively. Success group showed worse preoperative UCVA (1.21±0.56 vs 0.83±0.44 logMAR; *p*<0.01), worse preoperative BSCVA (0.50±0.36 vs 0.33±0.19 logMAR; *p*=0.01). Preoperative UCVA had an area under the curve of 0.721 (95% CI: 0.622–0.820; *p*< 0.01). The Youden's optimal cutoff point was 0.90 logMAR (equivalent Snellen 20/159) with 76.9% sensitivity and 35.2% specificity. Flattening index (FI) was 87% in DALK and 73% in PKP (*p*=0.14). Correction index (CI) was 99% and 86% (*p*=0.18) for DALK and PKP, respectively. Success of the astigmatic surgery for DALK and PKP was 44% vs 42% (*p*=0.29), respectively.

Conclusion: Improvement of at least three lines was achieved in 49% of patients who underwent FSAK following PKP or DALK; this improvement was achieved in patients who had a worse preoperative UCVA.

Keywords: DALK, PKP, femtosecond arcuate keratotomy, astigmatic keratotomy, keratoplasty astigmatism, vector analysis

Introduction

Post-keratoplasty astigmatism is a major confounding factor for the visual outcome. When keratoplasty results in high astigmatism, limited options are available to address the large amount of astigmatism as corneal based refractive procedures such as topography-guided custom ablation (T-CAT) photorefractive surgery are limited by a safe residual stromal bed thickness beyond which it cannot be used, or toric implantable collamer lens (ICL) which also has a maximum treatment limit. Alone or in combination, several interventions have been employed to address this issue, such as arcuate keratotomy, compression sutures, and the aforementioned procedures. Arcuate keratotomy is either made with a keratome or with the assistance of a femtosecond laser (FSAK). Femtosecond laser provides precise incision depth with safer and more

predictable outcomes compared with arcuate keratotomy made with a keratome.[1,2] However, AK remains unpredictable to some extent, especially in highly irregular astigmatic grafted corneas, further prolonging the visual rehabilitative journey of post-keratoplasty patients. In a retrospective data of 89 cases of post-keratoplasty astigmatism it has been found that 33% of the accuracy of post-keratoplasty astigmatism correction cannot be attributed to a known cause, with the remaining 67% being attributed to the amount of astigmatism preoperatively, arc length, depth, and incision diameter.[3] Prognostic factors for the visual outcome post-keratoplasty astigmatism using AK are poorly studied and to our knowledge only one study had looked into some possible prognostic factors in which they have found that preoperative cylinder more than 6.75 D is associated with effective treatment.[4] However, it had not been followed up beyond 6 months, and other possible factors such as corneal surface irregularity or posterior corneal astigmatism have never been addressed before. Hence we aimed at including more topographic parameters and a larger sample size and performing the vector analysis of early (less than 6 months) and late (beyond 6 months) results of FSAK.

Methods

This retrospective study had Research Ethics Board approval from Dhahran eye specialist hospital, and was conducted in accordance with the tenets of the Declaration of Helsinki. The requirement for informed consent was waived by the Research Ethics Board of Dhahran eye specialist hospital because this is a minimal risk retrospective chart review in which no patient interaction will occur, data were collected from 2014, in addition to the large number of patients. The data were maintained with confidentiality among authors in the study.

Study Participants

This study included patients that underwent FSAK for treating high regular astigmatism that could not be corrected with spectacles or intolerance to hard contact lenses following a suture-less PKP or DALK at the Dharana eye specialist.

Patients who only had poor vision explained by post-keratoplasty astigmatism were included. Those who had other ocular pathologies such as glaucoma, other corneal pathology, retinal pathology, cataract, optic neuropathy, or amblyopia were excluded. Different indications for keratoplasty were included, namely keratoconus, therapeutic keratoplasty, corneal dystrophies (granular and macular), post-LASIK ectasia, corneal scar. Furthermore, patients who had interventions before or during follow-up period, such as T-CAT or other corneal surface-based refractive procedures, placement of ICL, toric intraocular lens (IOL) that could affect visual outcome, were excluded. For the purpose of isolating the effect of FSAK only, patients who had had compression sutures or suturing of gaping wounds, or graft–host opening to account for excessive astigmatism were excluded. Also, patients who had a repeat FSAK were followed up until the first AK only. Data for patients who underwent FSAK to address high regular astigmatism post-PKP or DALK done from 2014 to 2021 at Dhahran eye specialist hospital were collected after at least 6 months from removing all sutures of keratoplasty.

Data Collection

Data collected included baseline demographics (age, sex). Preoperative and postoperative data include uncorrected visual acuity (UCVA), best spectacle-corrected visual acuity (BSCVA), manifest cylinder, manifest sphere, autorefractometer measurements of sphere and cylinder (Tonoref II ARK-510A autorefractometer; Nidek Inc., Aichi, Japan). Corneal topography was obtained using the Pentacam-HR (Oculus GmbH, Wetzlar, Germany), and data included: k max, flat k, steep k, anterior corneal cylinder, posterior corneal cylinder, presence of peripheral steepening defined as a steepening of ≥48 D in 6–8 mm zone on axial curvature, presence of complete ring defined as the former present in 360° of the cornea, keratometry power deviation (KPD), index of surface variance (ISV), index of height asymmetry (IHA), index of vertical asymmetry (IVA), index of height decentration (IHD), keratoconus index (KI), minimum radius of curvature (Rmin), central keratoconus index (CKI), and topographic keratoconus classification (TKC). Data were obtained preoperatively and early postoperatively within 1–5 months, and late within 6–57 months postoperatively.

Outcome Measure

Improvement in UDVA or BSCVA post-AK by three lines of ETDRS lines (doubling of the visual angle, ≥0.3 logMAR) a definition adopted by a previous study.[4] Safety index was calculated as (postoperative BSCVA/preoperative BSCVA),

and efficacy index was calculated as (postoperative UDVA/preoperative BSCVA). Alpins vector analysis[5,6] was carried out using VECTrAK, v.2.3.0 (ASSORT Pty Ltd, Cheltenham, Victoria, Australia) of topographic corneal astigmatism with the following measures: Target-induced astigmatism (TIA), which is the astigmatic change in magnitude and axis intended for treatment to fully correct the astigmatism. Surgically induced astigmatism (SIA), which is the actual change in astigmatism magnitude and axis by the surgery. Correction index (CI), calculated by dividing the actual effect (SIA) by the intended effect (TIA); it has an ideal value of 1. Magnitude of error (ME) arithmetic deviation of SIA from TIA in magnitude and axis; positive value for over-correction and negative value for under-correction. Difference vector (DV) ideally zero, index of success (IOS) calculated as DV/TIA and is ideally zero, flattening effect (FE) calculated as (SIA Cos2 × AE), and flattening index calculated as (FE/TIA) and is preferably 1.

Statistical Analysis

Quantitative data were summarized with mean, standard deviation, and range, while qualitative data were summarized with count and percentages. The normality of data was checked with Shapiro–Wilk. Qualitative data were compared with the chi-square test. Factors associated with success were assessed by binary logistic regression with back elimination. Independent non-normally distributed data were compared with Mann–Whitney U-test. Dependent non-normally distributed data were compared with Wilcoxon signed ranks test. Missing data were replaced by expectation maximization. Visual acuity was converted to a logarithm of the minimum angle of resolution (logMAR) for analysis. Statistical analysis was performed with IBM SPSS for Windows (v.22; IBM Corp, Armonk, NY, USA). All figures were constructed with Microsoft Excel (2019, Microsoft Corp., USA). A P-value less than 0.05 was considered statistically significant.

Surgical Technique

FSAK was created using iFS laser (Advanced Medical Optics, Inc.). Before going to the procedure room, the subject was seated upright and corneal marking was done along the horizontal meridian and along the topographic steep axis. After that, in the procedure room, the case was started with cleaning using povidone iodine 5% (Betadine) then anesthetized using topical benoxinate hydrochloride 0.4% (BNX, Alcon Laboratories, Inc.). Paired cuts centered on the steep axis based on topographic axial curvature map of the Pentacam-HR were made, corneal thickness at intended AK cuts 0.5 mm inside host graft junction was determined using ultrasonic pachymeter, and incision depth, arch length, and optical zone were determined using the Hanna nomogram for post-keratoplasty astigmatism.[7] After completion of procedure, incisions were opened using a Sinskey hook. Subjects were then treated with moxifloxacin 0.5% (Vigamox, Alcon Laboratories, Inc.) four times daily for 1 week and prednisolone acetate 1% drops (Pred Forte; Allergan, Irvine, CA), one drop four times daily with tapering dose weekly until kept on a maintenance dose according to their needs.

Results

A total of 106 eyes from 104 patients (65 males and 39 females) were included in this study. The mean age was 31.8±8.6 years (13.0–70.0 years). Altogether 89.4% (n=93) eyes were diagnosed with KC, 3.8% (n=4) with scar, 3.8% (n=4) with granular dystrophy, 1.9% (n=2) with post-LASIK ectasia, and 1.0% (n=1) with macular dystrophy. The UCVA improved from 1.02±0.53 logMAR at baseline to 0.87±0.49 logMAR (p=0.01) at 3 months and to 0.92±1.08 logMAR (p=0.57) at 17 months. The BSCVA improved from 0.41±0.30 logMAR at baseline to 0.31±0.19 logMAR (p<0.01) at 3 months and to 0.23±0.27 logMAR (p<0.01) at 17 months. The front corneal astigmatism improved from 9.01±2.88 D at baseline to 5.47±4.53 D (p<0.01) at 3 months and to 5.04±2.76 D (p<0.01) at 17 months. The back corneal astigmatism improved from 1.85±4.58 D at baseline to 1.01±0.61 D (p<0.01) at 3 months and to 0.92±0.54 D (p<0.01) at 17 months. In total, 37.7% (n=40) of the eyes were post-DALK, and 62.3% (66) were post-PKP.

In subjects who underwent DALK, UCVA changed from 1.01±0.54 logMAR to 0.92±0.59 logMAR (p=0.43) at 3 months and to 1.06±0.67 logMAR (p=0.94) at 17 months postoperatively. BSCVA changed from 0.36±0.28 logMAR to 0.30±0.19 logMAR (p=0.25) at three months and to 0.20±0.32 logMAR (p<0.01) at 17 months postoperatively. Front corneal astigmatism reduced from 8.33±3.23 D to 4.55±3.68 D at 3 months (p<0.01) and to 4.55±2.72 D (p<0.01) at 17 months postoperatively.

In subjects who underwent PKP, UCVA changed from 1.02±0.53 logMAR to 0.83±0.42 logMAR (*p*<0.01) at 3 months and to 0.84±1.26 logMAR (*p*=0.45) at 17 months postoperatively. BSCVA changed from 0.44±0.31 logMAR to 0.31±0.19 logMAR (p<0.01) at 3 months to 0.24±0.23 logMAR (*p*<0.01) at 17 months postoperatively. Front corneal astigmatism reduced from 9.42±2.59 D to 6.03±4.93 D at 3 months (*p*<0.01) and to 5.34±2.76 D (*p*<0.01) at 17 months postoperatively.

Table 1 compares preoperative parameters for eyes between success and non-success groups at early (3 months) postoperative time. The early success group had worse UCVA (1.25±0.54 vs 0.78±41 logMAR; *p*<0.01) and worse BSCVA (0.50±0.36 vs 0.32±0.18 logMAR; *p*<0.01). Table 2 compares preoperative parameters between success and non-success groups at late (17 months) postoperative time. The late success group had worse UCVA (1.21±0.56 vs 0.83 ±0.44 logMAR; *p*<0.01) and worse BSCVA (0.50±0.36 vs 0.33±0.19 logMAR; *p*=0.01).

Table 3 depicts the results of binary logistic regression with back elimination performed to assess the combinations of factors associated with early and late success. Worse UCVA was a significant factor associated with early (*p*<0.01) and late (*p*=0.03) success. Also, worse BSCVA was a significant factor associated with early (*p*=0.02) and late (*p*=0.03) success.

Figure 1 shows the ROC curve of preoperative UCVA and BSCVA as early success predictors. The area under the curve was 0.765 (95% CI: 0.675–0.855; p<0.01) for preoperative UCVA and 0.642 (95% CI: 0.537–0.746; *p*=0.012) for

Table 1 Comparisons of Preoperative Parameters Between Success and Non-Success Groups Three Months Postoperatively

Parameter	Success (*n*=53) Mean±SD	Non-success (*n*=53) Mean±SD	Odds Ratio (95% CI)	P-value
Age (years)	31.92±9.13	31.51±7.88	0.99 (0.95–1.04)	0.80
Gender, males (%)	49.3	50.7	0.92 (0.42–2.03)	0.84
Surgery, DALK (%)	45.0	55.0	0.73 (0.33–1.59)	0.42
UCVA (LogMAR)	1.25±0.54	0.78±0.41	0.21 (0.08–0.51)	<0.01
Manifest sphere (D)	−1.16±3.63	−1.27±4.07	0.99 (0.90–1.10)	0.87
Manifest cylinder (D)	−5.02±6.68	−6.12±2.23	0.94 (0.82–1.07)	0.33
Autoref. sphere (D)	−1.45±5.66	−2.15±5.47	0.98 (0.91–1.05)	0.52
Autoref. cylinder	−5.24±11.44	−7.24±5.22	0.97 (0.93–1.02)	0.27
BSCVA (logMAR)	0.50±0.36	0.32±0.18	0.08 (0.01–0.41)	<0.01
Kflat (D)	41.38±2.70	42.12±3.15	1.09 (0.95–1.25)	0.20
Ksteep (D)	50.84±5.07	49.76±3.60	1.01 (0.90–1.13)	0.92
Front c. astigmatism (D)	9.32±3.17	8.70±2.56	0.93 (0.81–1.06)	0.27
Back c. astigmatism (D)	2.35±6.45	1.35±0.42	0.61 (0.27–1.39)	0.24
Total c. 4 mm astigmatism (D)	6.82±7.73	7.68±4.72	1.02 (0.96–1.09)	0.49
Total c. 5 mm astigmatism (D)	5.91±7.42	5.16±3.84	0.98 (0.91–1.05)	0.51
ISV	101.52±38.75	89.73±27.38	0.99 (0.98–1.00)	0.08
IHA	38.92±40.83	45.83±52.40	1.00 (1.00–1.01)	0.45
IVA	0.71±0.35	0.66±0.32	0.62 (0.19–1.95)	0.41
IHD	0.08±0.05	0.09±0.06	3.53 (0.01–2428)	0.71
KI	0.96±0.16	0.99±0.13	3.55 (0.24–52.5)	0.36
Rmin	5.97±0.45	5.90±0.56	0.74 (0.35–1.59)	0.44
CKI	0.97±0.04	0.97±0.04	0.09 (0–289)	0.42
KPD	1.47±0.33	3.99±14.08	2.05 (0.79–5.30)	0.14
Optical zone (mm)	6.16±0.16	6.19±0.18	2.59 (0.28–24.04)	0.40
Angular length, 60° (%)	0	3.8		
Angular length, 70° (%)	28.3	28.8		
Angular length, 80° (%)	71.7	67.3		

Abbreviations: SD, standard deviation; D, diopter; UCVA; uncorrected visual acuity; BSCVA; best corrected visual acuity; autoref, autorefraction; c, corneal; K, keratometry; ISV, index of surface variance; IHA, index of height asymmetry; IHD, index of height decentration; IVA, index of vertical asymmetry; KI, keratoconus index; Rmin, minimum radius of curvature; CKI, central keratoconus index; KPD, keratometric power deviation.

Table 2 Comparisons of Preoperative Parameters Between Success and Non-Success Cases 17 Months Postoperatively

Parameter	Success (*n*=52) Mean±SD	Non-success (*n*=54) Mean±SD	Odds Ratio (95% CI)	*P*-value
Age (years)	32.87±9.27	30.61±7.59	0.97 (0.92–1.02)	0.18
Gender, males (%)	50.7	49.3	1.20 (0.55–2.65)	0.65
Surgery, DALK (%)	50.0	50.0	1.06 (0.48–2.33)	0.88
UCVA (logMAR)	1.21±0.56	0.83±0.44	0.21 (0.08–0.51)	<0.01
Manifest sphere (D)	−1.20±3.48	−1.23±4.18	1.00 (0.90–1.10)	0.97
Manifest cylinder (D)	−6.57±8.71	−5.93±9.17	0.97 (0.89–1.06)	0.52
Autoref. sphere (D)	−1.57±5.27	−2.02±5.85	0.99 (0.92–1.06)	0.67
Autoref. cylinder	−6.57±8.71	−5.93±9.17	1.01 (0.97–1.05)	0.71
BSCVA (logMAR)	0.50±0.36	0.33±0.19	0.11 (0.02–0.53)	0.01
Kflat (D)	41.52±2.90	41.97±2.98	1.05 (0.92–1.20)	0.43
Ksteep (D)	50.80±3.25	49.83±3.90	0.90 (0.80–1.01)	0.09
Front c. astigmatism (D)	9.52±3.20	8.52±2.47	0.88 (0.77–1.01)	0.08
Back c. astigmatism (D)	1.52±0.52	2.18±6.41	1.04 (0.0.92–1.18)	0.52
Total c. 4 mm astigmatism (D)	6.53±7.53	7.95±5.02	1.04±0.97–1.10)	0.26
Total c. 5 mm astigmatism (D)	6.19±7.10	4.91±4.41	0.96 (0.89–1.03)	0.28
ISV	100.15±35.08	91.28±32.47	0.99 (0.98–1.00)	0.18
IHA	46.55±47.90	38.36±45.97	1.00 (0.99–1.00)	0.37
IVA	0.71±0.35	0.66±0.33	0.61 (0.19–1.93)	0.40
IHD	0.09±0.06	0.08±0.06	0.13 (0–0.92.71)	0.13
KI	0.97±0.13	0.98±0.16	1.49 (0.10–21.49)	0.77
Rmin	5.90±0.48	5.96±0.53	1.27 (0.59–2.71)	0.54
CKI	0.97±0.04	0.97±0.04	0.11 (0–15,556)	0.65
KPD	1.89±3.17	3.54±13.66	1.02 (0.96–1.09)	0.48
Optical zone (mm)	6.15±0.16	6.20±0.18	5.55 (0.57–54.27)	0.14
Angular length, 60° (%)	50.0	50.0		
Angular length, 70° (%)	36.7	63.3		
Angular length, 80° (%)	54.8	45.2		

Abbreviations: UCVA, uncorrected visual acuity; BSCVA, best corrected visual acuity; autoref., autorefraction; c, corneal; K, keratometry; ISV, index of surface variance; IHA, index of height asymmetry; IHD, index of height decentration; IVA, index of vertical asymmetry; KI, keratoconus index; Rmin, minimum radius of curvature; CKI, central keratoconus index; KPD, keratometric pattern deviation.

Table 3 Analysis of Factors Associated with Success Cases

Postoperative Time	Factor	Odds Ratio	*P*-value
Early (3 months)			
	UCVA	0.14 (0.05–0.39)	<0.01
	BSCVA	0.11 (0.02–0.74)	0.02
Late (17 months)			
	UCVA	0.25 (0.10–0.63)	0.03
	BSCVA	0.16 (0.03–0.86)	0.03

Abbreviations: UCVA, uncorrected visual acuity; BSCVA, best corrected visual acuity.

preoperative BSCVA. Preoperative UCVA has a bigger area under the curve. The Youden's optimal cutoff point was 0.85 logMAR (Snellen 20/142) with 83.0% sensitivity and 39.6% specificity. Figure 2 shows the ROC curve of preoperative UCVA and BSCVA as predictor factors for late success. The area under the curve was 0.721 (95% CI: 0.622–0.820; p< 0.01) for preoperative UCVA and 0.605 (95% CI: 0.497–0.713; *p*=0.063) for preoperative BSCVA. Preoperative UNCVA
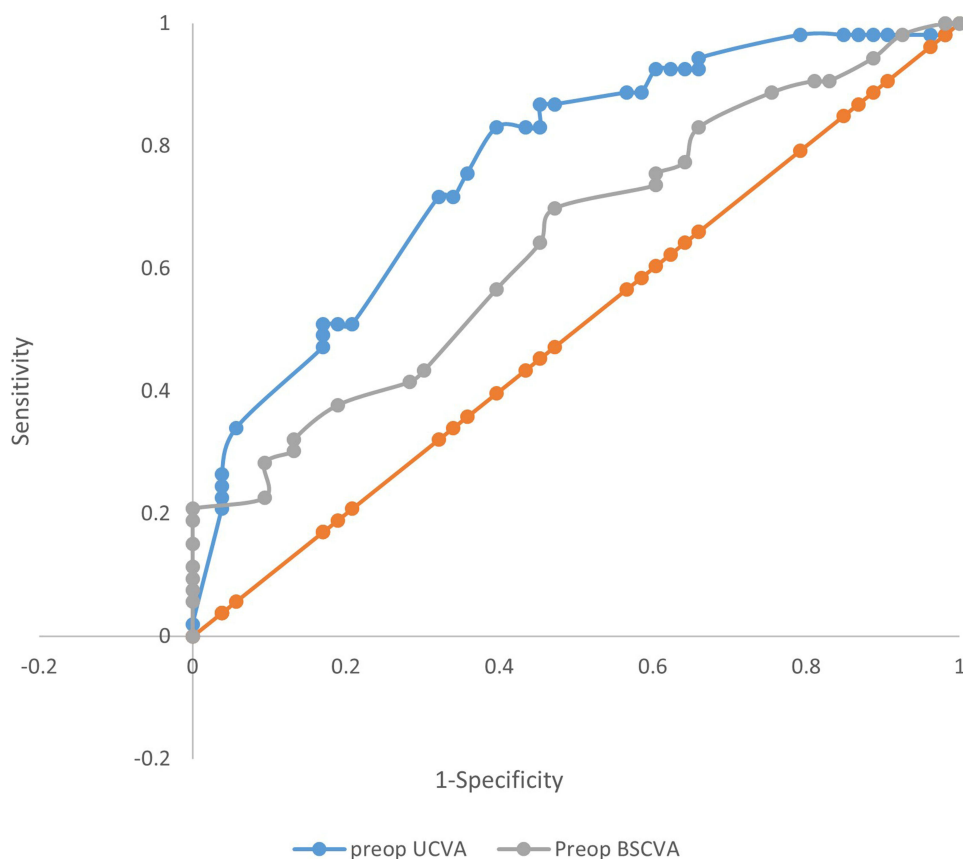
Figure 1 ROC Curve for Best Corrected and Uncorrected Visual Acuity Predicting Early success.

has a bigger area under the curve that is statistically significant. The Youden's optimal cutoff point was 0.90 logMAR (Snellen 20/159) with 76.9% sensitivity and 35.2% specificity.

Table 4 compares SIA between DALK and PKP at early and late postoperative times per length of the incision. For an incision length of 70°, the SIA was greater in DALK compared with PKP (7.23±4.20 vs 4.52±3.40; p=0.04), while there was no significant difference in SIA between the two surgeries for an incision length of 80° at early 3 months postoperative time. At late 17 months postoperative time, there was no significant difference between the two surgeries for 70° and 80° (p>0.05 for all).

Table 5 compares safety and efficacy indices and vector analysis between DALK and PKP at early 3 months. There was no significant difference between the two surgeries in terms of safety and efficacy. The TIA was significantly lower in DALK than in PKP (8.34±3.24 D vs 9.43±2.63 D; p=0.01). There was a systemic error of magnitude toward under-correction for DALK and PKP (−1.21±4.35 D vs −3.44±7.56 D; p=0.04). FI indicates that flattening at the intended steep meridian was 84% in DALK compared with 53% in PKP (p=0.01). From CI, the correction of astigmatism was under-corrected (90% in DALK and 65% in PKP; p=0.03). The success of astigmatic surgery, (1-IOS) *100, was 46% for DALK and 32% for PKP (p=0.43). COA suggests that for future FSAK the astigmatism should be adjusted by 1.91 and 2.95 for DALK and PKP, respectively (p=0.05).

Table 6 compares safety and efficacy indices and vector analysis between DALK and PKP at the late 17 months. There was no significant difference between the two surgeries in terms of safety and efficacy. The TIA was lower in DALK compared with PKP (8.22±3.27 vs 9.21±2.77; p=0.01). There was a systemic error in the angle in DALK and PKP (−4.28° vs −1.69°; p=0.38) where the achieved correction was clockwise to the intended axis. FI indicates that flattening at the intended steep meridian was 87% in DALK compared with 73% in PKP (p=0.14). From CI, the
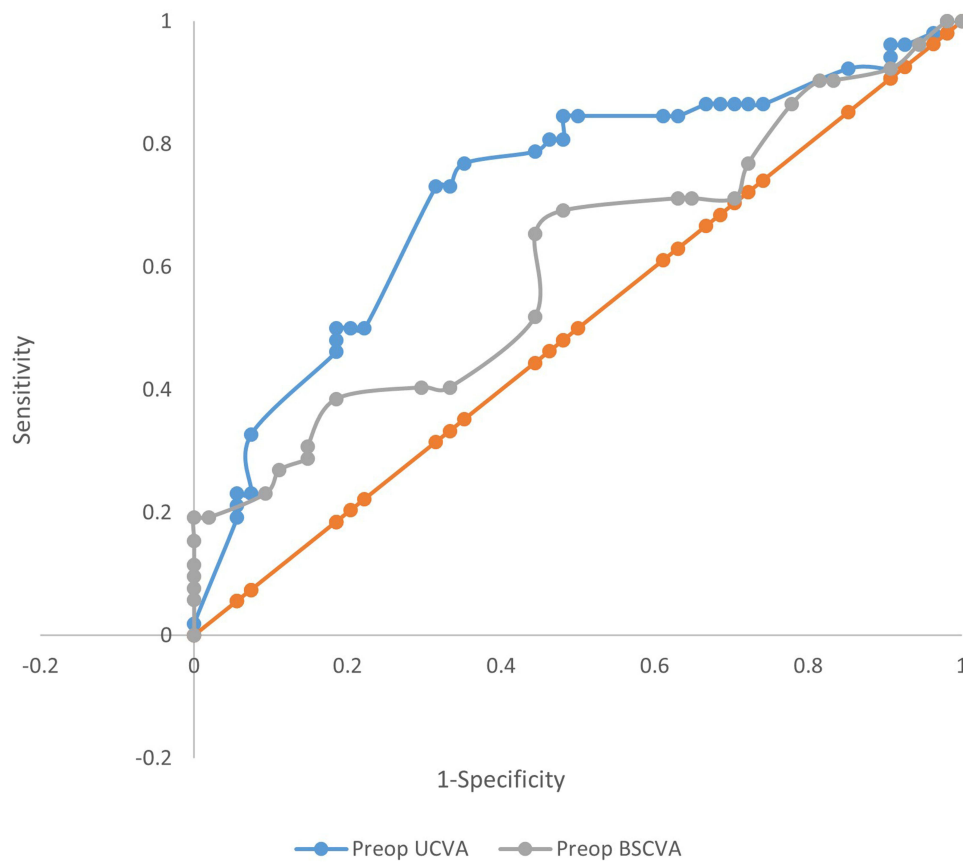
Figure 2 ROC Curve for Best Corrected and Uncorrected Visual Acuity Predicting Late Success.

correction of astigmatism was under-correction in DALK and PKP (99% vs 86%; p=0.18). The success of the astigmatic surgery for DALK and PKP was 44% vs 42%; p=0.29).

COA suggests that for future FSAK the astigmatism should be adjusted by 1.40 and 1.50 for DALK and PKP, respectively (p=0.61).

The complications of FSAK were as follows: 9.4% (n=10) had repeated FSAK, 0.9% (n=1) had regraft, 0.9% (n=1) had a recurrence of dystrophy, and 88.7% (n=94) had none.

Discussion

In this study subjective refraction and tomographic and topometric parameters have been analyzed for the possible predictive value of a successful visual outcome in patients who underwent PKP or DALK for different reasons over

Table 4 Surgically Induced Astigmatism Stratified by Surgery, Length of the Incision, and Postoperative Time

Postoperative Time	Incision Length	DALK		PKP		P-value
		N	SIA	N	SIA	
Early (3 months)						
	70°	15	7.23±4.20	15	4.52±3.40	0.04
	80°	23	8.11±3.57	50	6.67±7.08	0.44
Late (17 months)						
	70°	15	7.36±3.65	15	5.58±3.48	0.20
	80°	23	8.98±4.89	50	8.78±4.91	0.78

Abbreviations: SIA, surgically induced astigmatism; DALK, deep anterior lamellar keratoplasty; PKP, penetrating keratoplasty.

Table 5 Comparison of Outcomes Between DALK and PKP 3 Months Postoperatively

Parameter	Level	DALK	PKP	P-value
Visual outcomes				
	Safety index	1.38±1.13	1.76±1.74	0.27
	Efficacy index	0.47±0.44	0.68±0.95	0.17
Vector analysis				
	TIA (D)	8.34±3.24	9.43±2.63	0.01
	SIA (D)	7.23±4.54	6.43±6.75	0.34
	ME (D)	−1.21±4.35	−3.44±7.56	0.04
	AE (D)	1.10±16.34	0.04±22.63	0.81
	DV (D)	4.60±4.15	6.32±5.51	0.01
	FI	0.84±0.54	0.53±0.88	0.01
	CI	0.90±0.48	0.65±0.74	0.03
	IOS	0.54±0.44	0.68±0.51	0.04
	COA	1.91±3.19	2.95±5.66	0.05

Abbreviations: TIA, target induced astigmatism; SIA, surgically induced astigmatism; ME, the magnitude of error; AE, angle of error; DV, difference vector; FI, flattening index; CI, correction index; IOS, index of success; CoA, coefficient of adjustment; DALK, deep anterior lamellar keratoplasty; PKP, penetrating keratoplasty.

Table 6 Comparison of Outcomes Between DALK and PKP 17 Months Postoperatively

Parameter	Level	DALK	PKP	P-value
Visual outcomes				
	Safety index	2.98±9.03	2.20±2.40	0.43
	Efficacy index	0.48±0.68	0.81±1.35	0.12
Vector analysis				
	TIA (D)	8.22±3.27	9.21±2.77	0.01
	SIA (D)	7.90±4.85	8.00±4.76	0.87
	ME (D)	−0.41±4.90	−1.34±4.42	0.15
	AE (°)	−4.28 ±14.90	−1.69 ±22.04	0.38
	DV (D)	4.55±2.75	5.39±2.83	0.07
	FI	0.87±0.62	0.73±0.54	0.14
	CI	0.99±0.60	0.86±0.48	0.18
	IOS	0.56±0.39	0.58±0.33	0.29
	COA	1.40±1.53	1.50±2.09	0.61

Abbreviations: TIA, target induced astigmatism; SIA, surgically induced astigmatism; ME, the magnitude of error; AE, angle of error; DV, difference vector; FI, flattening index; CI, correction index; IOS, index of success; CoA, coefficient of adjustment; DALK, deep anterior lamellar keratoplasty; PKP, penetrating keratoplasty.

a median follow-up period of 17 months (range from 6–57 months). The pure effect of FSAK on post-keratoplasty astigmatism was assured by excluding any prior interventions, including the use of compression sutures or sutures addressing gaping wounds, corneal based interventions such as, but not limited to, topo-guided PRK, implantation of intracolumnar lens, and Toric intraocular lens. In this study we have found that a worse preoperative UCVA was associated with more visual acuity improvement, with a cut-off value of 0.85 logMAR (Snellen equivalent of 20/142). Until today, scarce data are available for predicting a successful outcome following arcuate keratotomy whether it be femtosecond assisted or mechanical AK (Table 7). One study by Mimouni et al[4] retrospectively reviewed 56 eyes over a follow-up period of 6 months and found that a higher preoperative manifest cylinder and a worse UCVA were

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Table 7 Previous studies with arcuate keratotomy

Author	Type of Study	Year	Number of Eyes	Follow-up Period (Months)	Type of Keratoplasty	Reason for Surgery	Predictors of VA Improvement or Worsening	Definition of Improved VA	BCVA Improvement Mean±SD (logMAR)	UCVA Improvement Mean±SD (logMAR)	Corneal Astigmatism Reduction Mean±SD (D) (R, Refractive; C, Corneal)	Nomogram	Use of Corneal Sutures Or Intervention Affecting Visual Outcome
Elzarga et al[9]	Prospective interventional cohort	2019	17	12	PKP	Not mentioned	None	None	Yes 0.58±0.04 to 0.44±0.059 P=0.040	Yes 0.96±0.019 to 0.81±0.059 P=0.078	No, C 5.85±0.74 to 4.241±0.73 P=0.95	Hanna	
Fadlallah et al[10]	Retrospective case series	2015	62	28	PKP	KC, PBK, Fuchs, scar	None	Gain of one or more line	Yes 0.51±0.26 logMAR to 0.40±0.22 logMAR P<0.01	Yes 0.98±0.24 logMAR to 0.60±0.2 logMAR P<0.01	Yes, C 7.1±1.72 to 3.5±3.1 (P<0.001)	Author decided treatment based on topography and manifest refraction	Cases needing suturing excluded
Nubile et al[11]	Prospective non-comparative interventional case series	2009	12	6	PKP DALK	Infectious keratitis, KC	None	None	Yes 0.25±0.16 logMAR to 0.11±0.12 logMAR P=0.011	Yes 1.05±0.18 logMAR to 0.55±0.34 logMAR (P=0.002)	Yes, R 7.16±3.07 to 2.39±1.62	Treatment adopted from a previous trial[14]	
Hoffart et al[1]	**Prospective, randomized study**	2009	10	6	Not mentioned	KC Bullous keratopathy Trauma Infectious keratitis	None	None	No 0.35±0.25 to 0.25±0.12 P=0.168	No 0.68±0.27 to 0.69±0.24 P=0.735	Yes, C 7.01±3.02 to 3.97±2.38 P=0.021	Hanna	
Anis et al[15]	Interventional prospective	2021	15	6	DALK PKP	Not mentioned	None	None	Not mentioned	Yes 0.72±1.00 to 0.38±0.1 P<0.001	Yes, C 8.18±2.11 to 4.00±1.29 P<0.001	Protocol of the University of Toronto	

Table 7 (Continued).

Author	Type of Study	Year	Number of Eyes	Follow-up Period (Months)	Type of Keratoplasty	Reason for Surgery	Predictors of VA Improvement or Worsening	Definition of Improved VA	BCVA Improvement Mean±SD (logMAR)	UCVA Improvement Mean±SD (logMAR)	Corneal Astigmatism Reduction Mean±SD (D) (R, Refractive; C, Corneal)	Nomogram	Use of Corneal Sutures Or Intervention Affecting Visual Outcome
Mimouni et al[4]	Retrospective study	2022	16	10	DALK PKP	Corneal ulcer Bullous keratopathy Trauma Fuchs' dystrophy Failed graft Granular dystrophy KC	None	None	Yes 1.03±0.55 to 0.67±0.68 P=0.57	No 1.21±0.48 to 0.86±0.73 P=0.86)	Yes, C 9.02±3.97 to 4.95±3.4 P=0.02	Described by author	One case underwent incision resuturing for overcorrection Three cases underwent T-CAT Five cases underwent cataract surgery One case had piggyback intraocular lens
Kumar et al[13]	Retrospective pilot study	2010	37	7	PKP	KC, PBK Corneal scar Fuchs' dystrophy	None	No	Yes 0.45±0.27 to 0.37±0.27 P=0.018	Yes 1.08±0.34 to 0.80±0.42 P=0.0016	Yes, C 7.46±2.70 to 4.77±3.29 (P=0.0001)	Described by the author	Eyes requiring suturing for overcorrection were excluded
Al-Qurashi et al[16]	Retrospective	2019	52	6 months at least Not specified	PKP DALK	KC, post-LASIK ectasia, PBK, microbial keratitis, scar	No	No	Yes 0.30±0.18 to 0.20±0.14 P=0.014	Yes 0.90±0.43 to 0.60±0.39 =0.001	Yes, C 6.73±2.49 to 4.35±3.83 P=0002	Nordan nomogram	
Al Sabaani[17]	Retrospective	2016	52	13	PKP LKP	KC, corneal scar, PBK	No	No	Yes 0.30±0.18 to 0.20±0.14 P=0.014	Yes 0.90±0.43 to 0.60±0.39 P=0.001	Yes, C 6.73±2.49 to 4.35±3.83 P=0.002	Nordan	One case needed suturing of AK wound
Wetterstrand et al[8]	Prospective interventional	2013	16	3	PKP	KC, Fuchs dystrophy Lattice dystrophy	Yes Worse CDVA Greater improvement postoperatively in CDVA	No	Yes 0.50±0.29 to 0.32±0.23 P=0.016	Not mentioned	Yes, C 9.49±4.78 to 4.41±2.14 P=0.001	Described by author	One case needed suturing of AK wound

Loriaut et al[2]	Retrospective	2015	20	17	Not mentioned	KC, Fuchs' dystrophy, bacterial keratitis	No	No	Yes 0.5±0.3 to 0.3±0.2 $P=0.004$	Not mentioned	Yes, C 9.45±2.97 to 4.64±2.79 $P=0.001$	Hanna	
anNakhli and Khattak[18]	Retrospective	2017	50	6	DALK PKP	KC Post-refractive surgery keratectasia Corneal ulcer Corneal scar Granular dystrophy	No	No	No DALK 0.57±0.48 to 0.38±0.29 $P=0.100$ PKP 0.44±0.37 to 0.38±0.33 $P=0.317$	Yes for DALK 0.97±0.33 to 0.59±0.55 $P=0.016$ No for PKP 0.88±0.47 to 0.95±0.44 $P=0.280$	Yes PKP 7.63±2.56 to 4.29±2.33 $P<0.001$ DALK 8.15±3.02 to 5.08±4.03 $P=0.012$	Not specified	Photorefractive keratectomy in one case
Sorkin et al[19]	A retrospective, comparative, pairwise-matched case series	2021	75	Not mentioned	PKP DALK	KC Herpetic keratitis, Bullous keratopathy, Failed graft, Trauma, Corneal scarring, Stromal dystrophy Fuchs' dystrophy, Corneal ulcer	No	None	Yes 0.55±0.27 to 0.41±0.37 $P<0.001$	Yes 1.16±0.45 to 0.89±0.51 $P<0.001$	Yes, C 9.40±2.80 to 4.80±3.20 $P<0.001$	Described by the author	Suturing done in 6 cases for overcorrection

Abbreviations: PBK, pseudophakic bullous keratopathy; LKP, lamellar keratoplasty.

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predictors of a visual improvement following FSAK. However, in their cohort there were five cases (8.9%) that underwent suturing of AK incisions to address overcorrection. Also Wetterstrand et al[8] conducted a prospective study of 16 eyes and found a significant correlation between having a worse preoperative CDVA and the outcome result of more improvement in postoperative CDVA. In agreement with previous studies, we have found that FSAK resulted in a significant improvement of UCVA over a median follow-up of 3 months.[4,9–13] Also in accordance with previous studies the BSCVA improved at 3 months and results were maintained at 17 months.[4,9–11,13] Corneal astigmatism significant reduction has been also demonstrated as in previous studies[4,10,12,13] over 3 months and maintained over 17 months. Although Wetterstrand et al used different incision planning with a fixed non-penetrating length of incision that was 90°, 90% depth of incision, different incision diameters of 6.0 mm, 6.5 mm, and 7 mm, they demonstrated a comparable mean reduction of 5.1±4.7 D of anterior corneal cylinder to our mean reduction of 5.04±2.76 D. They have also found a mean reduction of posterior cylinder by 0.7±0.6 D comparable to what we found, 0.92±0.54 D.

We have found a higher safety index for PKP and DALK compared with previous reports. Safety index was 2.98 and 2.20 for DALK and PKP, respectively, with no difference, compared with Mimouni et al[4] with a safety index of 1.45 and 1.66 for DALK and PKP, respectively (p=0.45) and anNakhli and Khattak [18] with a safety index of 1.50 and 1.27 for DALK and PKP, respectively (p=0.325). For the efficacy index, results were conflicting between Mimouni et al who found a statistically significant higher efficacy for PKP 0.74 compared with DALK 0.33 (p<0.001) and anNakhli and Khattak who found a statistically significant higher efficacy for DALK 1.00 compared with PKP 0.31 (p=0.001).[4,18] In our study, although PKP showed a relatively higher efficacy index compared with DALK (0.8 vs 0.48), respectively, we did not find a difference between them, p=0.12.

**In the early follow-up period (range 1–5 months, median of 3 months), DALK showed better results than PKP in terms of vector analysis with statistical significance evident from higher correction index 0.9 vs 0.65, more flattening effect along the steep meridian 0.84 vs 0.53, and a lower magnitude of error −1.21 vs −3.44. However, this superiority was not maintained over a longer follow-up period with a median of 17 months when PKP correction index improved to 0.86 and the flattening index along the steep meridian increased to 0.73, and the magnitude of error reduced to −1.34. The continuous change with improvement in PKP vector analysis, could be explained by the different vectorial powers created by the new limbus at the host graft junction of a penetrating keratoplasty that might influence wound healing with late changes in corneal curvature.

Although PKP had a higher mean TIA, the surgical effect of FSAK was statistically insignificant between DALK and PKP evident from a relatively similar index of success between both procedures, 0.56±0.39 and 0.58±0.33 for DALK and PKP, respectively. Moreover, both procedures exhibited a trend toward undercorrection, although statistically insignificant, the correction index for DALK was closer to ideal ratio of 1 compared with PKP (0.99 vs 0.86). Although anNakhli and Khattak[18] found a statistically significant better performance of FSAK with DALK compared with PKP in terms of vector analysis, their follow-up period was limited to the first 6 months following FSAK. On the other hand Mimouni et al's[4] analysis uggested PKP as a favorable prognostic factor of visual outcome compared with DALK. But in their study they have included keratoconus cases only, and the follow up was limited to 6 months after FSAK. Furthermore, there were 23.8% cases in Mimouni et al's[4] study in which they needed suturing due to overcorrection in the DALK group; it was also not mentioned when the suturing done was to address the effect of FSAK alone and to account for the final outcome and wound stability that might extend beyond 6 months. Healing of FS created keratotomy starts with epithelial plug formation that fills the wound with subsequent regression of that epithelial plug and replacement by a loose fibrotic scar formation. After 6 months following FSAK, the AK wounds were still found to be occupied with epithelium along the upper one third of the wound.[11] Furthermore, although in agreement with Mimouni et al.[4] DALK showed a significantly higher SIA for an incision length of 70° compared with PKP over a 6 month follow-up period, this statistical difference was no longer demonstrated over a longer follow-up median of 17 months in our cohort; it is worth mentioning that Mimouni et al have also demonstrated this difference over a follow-up period of 6 months.

Conclusion

FSAK is an effective, safe procedure for post-keratoplasty astigmatism over a median follow up of 17 months with a gain of vision noted in 65% and nearly one third gaining more than 3 lines. A worse preoperative UCVA with a cut-off value of 20/159 Snellen was found to be a predictor of improvement in vision by at least 3 lines of ETDRS lines over a follow-up median of 17 months. This study has shown no differences in vector analysis between DALK and PKP over an extended follow-up period

beyond 6 months. It had also shown no correlation between type of surgery, refractive, topometric or tomographic corneal parameters and visual improvement after FSAK. Limitations to our study include its retrospective nature.

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Disclosure
The authors declare no conflict of interest in this work.

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