Long-Term Stability of Femtosecond Astigmatic Keratotomy After Treatment of High Postkeratoplasty Astigmatism

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Purpose: The purpose of this study was to assess long-term stability and outcomes of femtosecond astigmatic keratotomy (FSAK) after treatment of high postkeratoplasty astigmatism.

Methods: This retrospective study included patients who underwent FSAK for high astigmatism (≥4 D) after penetrating keratoplasty or deep anterior lamellar keratoplasty. Main outcome measures were corneal astigmatism, uncorrected visual acuity, and best-corrected visual acuity (BCVA) at 1 month and 1, 5, and 10 years.

Results: Overall, 61 eyes of 61 patients (mean age 56 ± 19 years, 54.1% male) were included in this study. Preoperative corneal astigmatism ranged from 4 to 25 D. One month after FSAK, mean corneal astigmatism was significantly reduced from 9.02 ± 3.97 D to 4.86 ± 3.10 D ($P < 0.001$). Thereafter, corneal astigmatism remained stable at all visits up to 10 years ($P < 0.05$ for all compared with baseline). After FSAK, there was a significant improvement in logMAR uncorrected visual acuity from 1.21 ± 0.48 to 0.87 ±0.54 ($P < 0.001$) and logMAR BCVA from 1.03 ± 0.55 to 0.49 ± 0.45 ($P < 0.001$) which remained stable up to 10 years. A mild reduction in BCVA improvement was seen between 1 month and 1 year.

Conclusions: Femtosecond astigmatic keratotomy was effective and stable at reducing very high magnitudes of postkeratoplasty astigmatism over the long term. The procedure also had a stable effect on visual acuity, albeit some reduction in the degree of BCVA improvement was seen over the early postoperative period.

Key Words: astigmatic keratotomy, arcuate keratotomy, AK, femtosecond, FSAK, keratoplasty, DALK, PKP, deep anterior lamellar keratoplasty, penetrating keratoplasty, astigmatism, long-term, stability

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Postkeratoplasty astigmatism is often challenging to treat because of its high magnitude and irregular characteristics which affect visual outcomes and patient satisfaction.[1–3] Femtosecond astigmatic keratotomy (FSAK) enables the formation of precise deep arcuate stromal incisions which are effective in reducing the magnitude of high postkeratoplasty astigmatism.[4,5]

One potential issue associated with deep stromal incisions is their long-term refractive stability. For example, radial keratotomy (RK) stromal incisions which have been used in the past for the correction of myopic refractive errors were associated with significant long-term instability.[6] Böhringer et al[7] evaluated longer-term outcomes of manual astigmatic keratotomy (AK) and found an increase of keratometric astigmatism after the procedure by 0.3 D/year, equalizing the surgical effect after 10 years. The authors concluded that it may be interesting to check whether the use of a femtosecond laser makes FSAK more stable than manual arcuate keratotomy over a longer follow-up time.

Although FSAK has been shown to be effective in the short term, data on long-term efficacy and stability are lacking. The purpose of this study was to assess long-term outcomes and stability of FSAK after treatment of high postkeratoplasty astigmatism.

METHODS

This retrospective study included patients who underwent FSAK for the treatment of high astigmatism (≥4 D)

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after penetrating keratoplasty (PKP) or deep anterior lamellar keratoplasty (DALK) between 2007 and 2014. Cases of significant irregular astigmatism with no discernible steep axis where AK was not performed were excluded from the study. In cases where an additional refractive procedure was performed after FSAK, data were included in the study up to the point when the additional procedure was performed. The procedures were performed at the Toronto TLC Laser Center (Toronto, ON, Canada) by 2 corneal surgeons. This study received Research Ethics Board approval from the University of Toronto and from the University Health Network and adhered to the tenets of the Declaration of Helsinki.

The primary outcome measure was corneal astigmatism. Secondary outcome measures were uncorrected and best-corrected visual acuity (UCVA, BCVA). Corneal astigmatism was obtained using the OPD Scan II ARK 10000 topographer (NIDEK, Tokyo, Japan). Data were obtained from the preoperative examination and postoperatively from follow-ups performed at 1 month and 1 year (±3 months), 5 years (±1 year), and 10 years (±2 years).

Surgical Technique

Complete removal of all graft sutures was required at least 3 months before the procedure, with verification of refractive stability. The steep astigmatism axis was determined using corneal topography.

Arcuate keratotomy was performed using the iFS IntraLase system (Johnson and Johnson Vision, Jacksonville, FL) under topical anesthesia (proparacaine 0.5%). Our FSAK technique has been previously described.[4,5,8] In brief, the horizontal and steep axes were marked under the Visx laser (Johnson and Johnson Vision) using the reflection of the circular light on the tear film. The eyelids were prepared with Betadine sponges. Ultrasound pachymetry was performed (Corneo-Gage; Sonogage Inc, Cleveland, OH) to determine graft thickness at the position of the proposed incision. Paired symmetric arcuate incisions were centered around the graft center and on the topographic location of the steep axis. The incisions were positioned 0.5 mm anterior to the graft–host junction with the incision depth set at 90% of the thinnest measured ultrasound pachymetry. Incision angles (arc length of the incisions) were set according to the following nomogram: 6 to 8 D of corneal astigmatism was treated with 30-degree to 45-degree arc length, 8 to 10 D with 45-degree to 65-degree arc length, 10 to 15 D with 70-degree to 75-degree arc length, and greater than 15 D with 90-degree arc length. The laser's limbal suction ring was then applied and the cone positioned so that the fluid meniscus was beyond the graft–host junction. Once the procedure was complete, the suction was released, and the ring was removed.

Postoperatively, patients received topical tobramycin and dexamethasone (TobraDex, Alcon, Mississauga, ON, Canada) 4 times daily for 1 week. Thereafter, they were placed back on their antirejection topical steroid maintenance dose.

Data were recorded in Microsoft Excel (2016) and analyzed using Minitab Software, version 17 (Minitab Inc, State College, PA). Visual acuity values were obtained with a Snellen chart and converted into logMAR. Normality of the data was assessed by the Kolmogorov–Smirnov test. A repeated measures analysis of variance (ANOVA) was performed to compare postoperative continuous outcomes at different time points. The Bonferroni correction was applied for multiple comparison. Astigmatism vector analysis was performed at the corneal plane (vertex of 12 mm) using the Alpins method.[9] All tests were 2-tailed, and the threshold for statistical significance was defined as a P-value <0.05.

RESULTS

Overall, 61 eyes of 61 patients were included. The mean age was 56 ±19 years, with 33 male patients (54.1%). Main indications for keratoplasty were keratoconus (n = 21) and corneal ulcer (n = 9) (Table 1). Type of keratoplasty performed was PKP (n = 48, 78.7%) and DALK (n = 13, 21.3%). Preoperative corneal astigmatism ranged from 4 to 25 D. Follow-up data availability was n = 61 at 1 month, n = 44 at 1 year, n = 32 at 5 years, and n = 16 at 10 years.

Corneal and Manifest Astigmatism

Compared with preoperative corneal astigmatism, the postoperative corneal astigmatism was significantly lower at every time point ($P < 0.001$). Corneal astigmatism decreased from 9.02 ±3.97 D preoperatively to 4.86 ±3.10 D at 1 month after the procedure ($P < 0.001$). This effect remained stable at 1 year (4.76 ±5.34 D, $P < 0.001$), 5 years (5.43 ±3.99 D, $P = 0.004$), and 10 years (4.95 ±3.40 D, $P = 0.02$) (Fig. 1).

Manifest astigmatism was −6.48 ±2.50 D preoperatively (n = 40). Postoperative manifest astigmatism at 1 month (n = 51), 1 year (n = 24), and 5 years (n = 4) was −3.89 ±2.07 D, −3.06 ±2.07 D, and −1.31 ±2.15 D, respectively. There were no available manifest refraction data at 10 years.

Visual Acuity

There was a significant improvement in UCVA compared with baseline ($P = 0.001$). Mean UCVA improved from 1.21 ±0.48 logMAR preoperatively (Snellen equivalent ~20/324) to 0.87 ±0.54 logMAR (Snellen equivalent ~20/148) at 1 month ($P < 0.001$), 0.95 ±0.58 logMAR (Snellen equivalent ~20/178) at 1 year ($P = 0.10$), 0.91 ±0.70

TABLE 1. Indications for Keratoplasty

	n = 61
Keratoconus	21 (34.4%)
Corneal ulcer	9 (14.8%)
Bullous keratopathy	5 (8.2%)
Trauma	4 (6.6%)
Fuch dystrophy	3 (4.9%)
Failed graft	1 (1.6%)
Granular dystrophy	1 (1.6%)
Unknown	17 (27.9%)

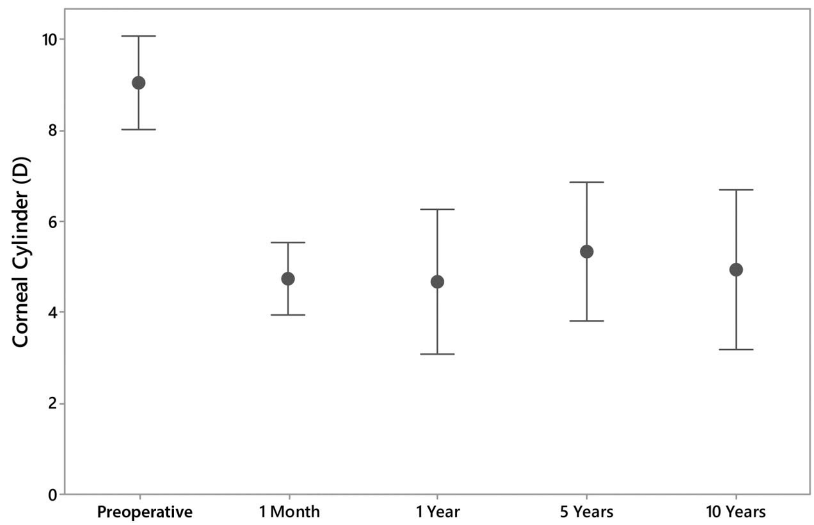

FIGURE 1. Corneal cylinder preoperatively and at 1 month and 1 year, 5 years, and 10 years after the procedure (whiskers represent SD).

logMAR (Snellen equivalent ~20/163) at 5 years (P = 0.55), and 0.86 ±0.73 logMAR (Snellen equivalent ~20/145) at 10 years (P = 0.86) (Fig. 2).

There was a significant improvement in BCVA compared with baseline ($P < 0.001$). Mean BCVA improved from 1.03 ±0.55 logMAR preoperatively (Snellen equivalent ~20/214) to 0.49 ±0.45 logMAR (Snellen equivalent ~20/62) at 1 month ($P < 0.001$), 0.77 ±0.59 logMAR (Snellen equivalent ~20/118) at 1 year (P = 0.08), 0.73 ±0.66 logMAR (Snellen equivalent ~20/107) at 5 years (P = 0.17), and 0.67 ±0.68 logMAR (Snellen equivalent ~20/94) at 10 years (P = 0.57) (Fig. 3).

Alpins Vector Analysis

At 1 month, the mean SIA was 7.70 ± 5.05 D with a difference vector (DV) of 5.01 ± 3.18. The mean correction index (CI) was 0.85 ± 0.50 with an index of success (IOS) of 0.57 ± 0.31. There was no significant change in any of these parameters at 1, 5, or 10 years ($P > 0.05$ for all) (Table 2). Figure 4 depicts preoperative astigmatism versus astigmatism reduction at 1 month and 1 year, 5 years, and 10 years after FSAK.

Additional Astigmatic Procedures After FSAK

Additional corneal astigmatic procedures performed after FSAK included 1 FSAK incision resuturing because of overcorrection (2 years postoperatively), 3 topography-guided photorefractive keratectomy procedures (2, 3, and 4 years postoperatively), and 1 PKP regraft (8 years postoperatively). Five eyes underwent cataract extraction (2 eyes at 2 years, 2 eyes at 3 years, and 1 eye at 7 years postoperatively). One eye underwent implantation of a piggyback intraocular lens 2 years after FSAK.

DISCUSSION

Although the short-term efficacy and safety of FSAK in the management of postkeratoplasty astigmatism is well-

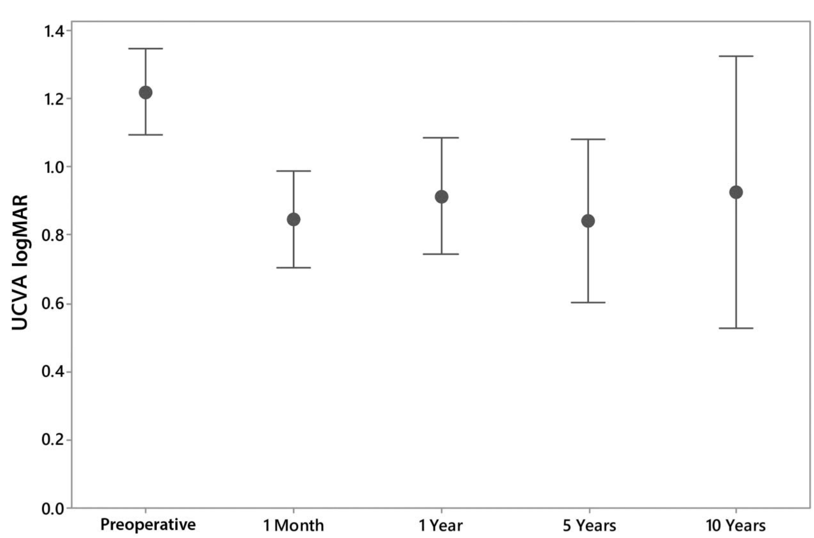

FIGURE 2. UCVA preoperatively and at 1 month and 1 year, 5 years, and 10 years after the procedure (whiskers represent SD).

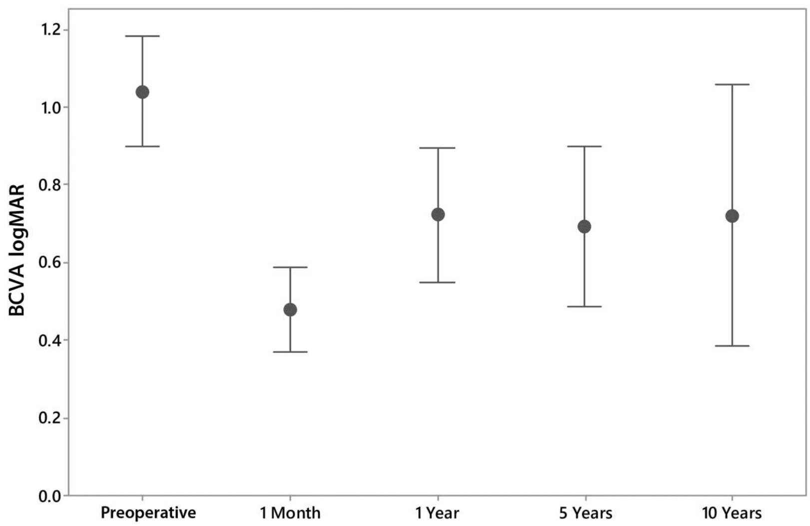

FIGURE 3. BCVA preoperatively and at 1 month and 1 year, 5 years, and 10 years after the procedure (whiskers represent SD).

established in recent literature,[4,5,10–14] there are no published data on its long-term stability. This study investigated the long-term stability of FSAK in eyes with high postkeratoplasty astigmatism, showing a significant reduction in corneal astigmatism which remained stable throughout the 10-year follow-up.

RK has been used in the past to correct ametropia.[15] Although early results were acceptable, and the procedure had been widely used as an incisional refractive procedure, long-term outcomes showed reduced stability with some patients suffering from progressive hyperopic shift and significant diurnal refractive variations which pose a significant management challenge for clinicians to this day.[16–18] AK is in some ways similar to RK because it is based on the creation of deep stromal incisions, albeit different because the incisions are tangential/arcuate rather than radial. Although the concern was that AK arcuate incisions might produce instability similar to the one occurring after radial incisions, most clinicians have not found such an instability to exist after AK. This study confirms the clinical notion that FSAK is stable in the long-term. The tangential/arcuate vector of the incisions, performed within the graft and parallel to the wound, preserves the biomechanical integrity of the cornea in a manner sufficient to maintain long-term biomechanical stability. Our group previously investigated femtosecond-assisted Descemet membrane endothelial keratoplasty (F-DMEK), where the femtosecond laser is used to create a complete circular posterior stromal incision which extends 100 μm into the posterior stroma.[19–22] One concern was that such an incision would induce refractive instability of the recipient cornea. However, the F-DMEK procedure was found to be refractively stable over longer-term follow-up, supporting the theory of tangential/arcuate incisions associated with long-term refractive stability.[20]

Böhringer et al[7] examined long-term stability of manual AK and found the procedure to be acceptably stable but with an annual treatment regression rate of 0.3 D per year (or 3 D per decade). This seems significantly different than FSAK stability outcomes reported in our current study. Although accurate comparisons cannot be made between the cohorts of this study and the one by Böhringer et al, the apparent differences in long-term stability between FSAK and manual AK should be further investigated in future comparative studies. Femtosecond incisions have been previously shown to promote faster and stronger wound healing because of better apposition of the wound edges and postoperative subclinical inflammatory processes which induce adhesion.[23,24] The keratotomy wound is primarily filled with epithelium until fibroblasts synthesize new collagenous fibers within the gap leading to a contraction of the wound and a change of its architecture over time.[25] It may be that a more significant inflammatory reaction shortly after femtosecond incision leads to a faster fibroblastic reaction which reduces epithelial filling of the gap and architectural changes over time. These mechanisms may contribute to increased stability of FSAK compared with manual AK.

Stability of FSAK's refractive effect is essential in cases of high postkeratoplasty astigmatism because in many such cases, FSAK needs to be sequentially combined with an additional refractive procedure. FSAK has limited

TABLE 2. Alpins Vector Analysis at 1 Month and 1, 5, and 10 years

	1 Month	1 Year	5 Years	10 Years
TIA (D)	9.17 ± 3.92	9.60 ± 4.63	8.92 ± 4.87	8.53 ± 2.93
TIA axis (°)	88.4 ± 56.9	86.0 ± 54.1	89.9 ± 44.8	84.8 ± 48.5
SIA (D)	7.70 ± 5.05	9.99 ± 7.13	7.30 ± 4.53	8.50 ± 3.41
SIA axis (°)	71.8 ± 54.4	75.0 ± 48.8	92.0 ± 44.3	79.5 ± 57.0
DV (D)	5.01 ± 3.18	5.63 ± 5.11	5.30 ± 4.01	4.88 ± 3.71
DV axis (°)	89.9 ± 55.5	111.2 ± 55.4	90.2 ± 49.1	70.4 ± 34.9
Angle of error (°)	1.4 ± 15.8	0.7 ± 13.8	2.0 ± 15.7	−5.2 ± 29.0
Correction index	0.84 ± 0.50	1.08 ± 0.63	0.89 ± 0.53	1.03 ± 0.33
Index of success	0.57 ± 0.31	0.62 ± 0.44	0.57 ± 0.36	0.63 ± 0.49

D, diopter; °, degrees; TIA, target-induced astigmatism; SIA, surgically induced astigmatism; DV, difference vector; correction index, SIA/TIA; index of success, DV/TIA.

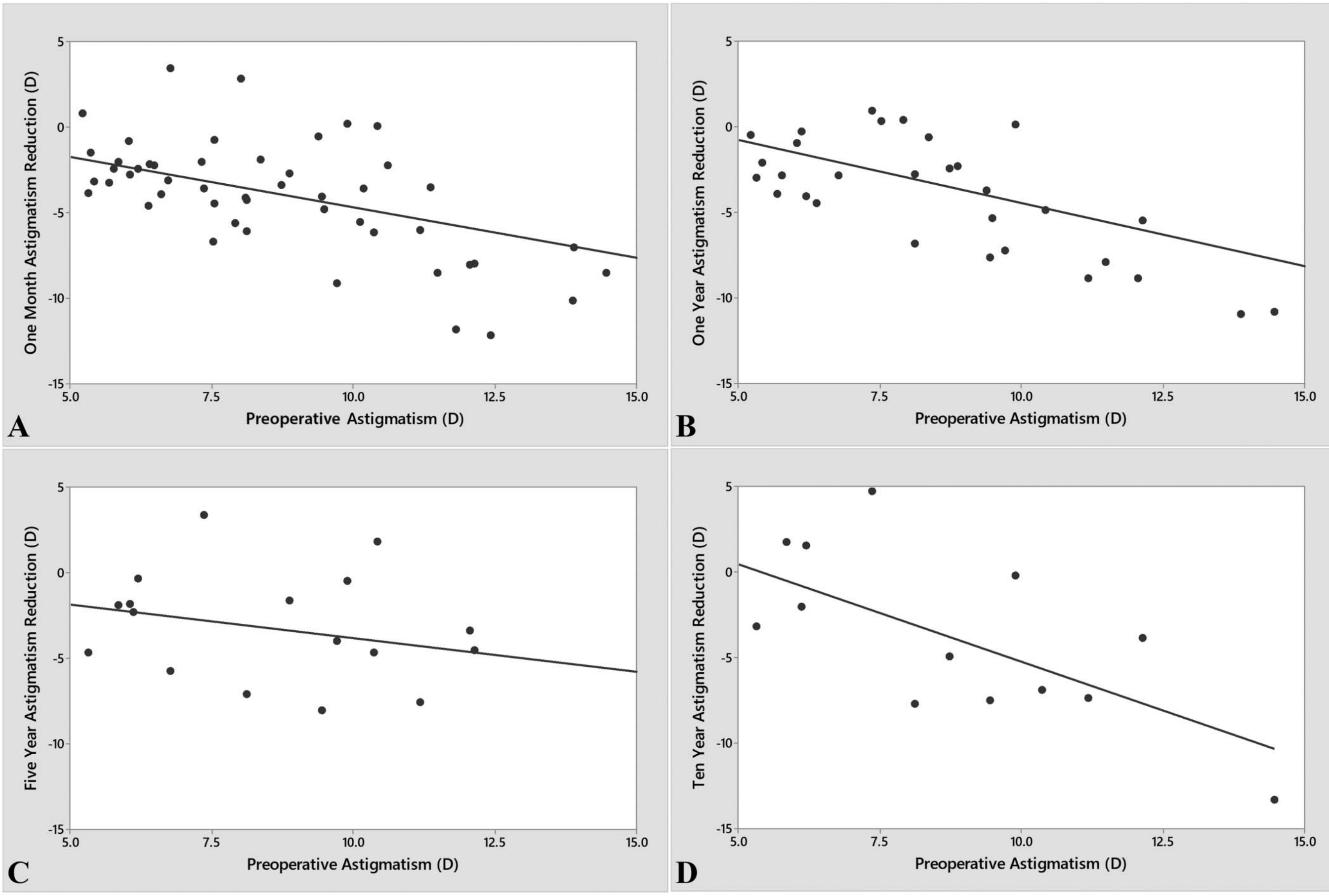

FIGURE 4. Preoperative astigmatism versus astigmatism reduction at (A) 1 month ($P < 0.001$) and (B) 1 year ($P = 0.004$), (C) 5 years ($P < 0.001$), and (D) 10 years ($P = 0.02$) after femtosecond astigmatic keratotomy.

predictability and is often used to "debulk" astigmatism magnitude to allow better sequential use of more precise astigmatic procedures such as toric intraocular lens implantation or photorefractive keratectomy.[8] This study suggests that combining FSAK with additional astigmatic procedures in these challenging cases can be beneficial in the long term.

This study is limited by its retrospective nature and relatively small sample size. Nevertheless, this is, to the best of our knowledge, the first study to describe long-term outcomes of FSAK in patients with high postkeratoplasty astigmatism.

In conclusion, femtosecond astigmatic keratotomy was effective and stable at reducing very high magnitudes of postkeratoplasty astigmatism over the long term. The procedure also had a stable effect on visual acuity, albeit some reduction in the degree of corrected visual acuity improvement was seen over the early postoperative period.

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