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Long-Term Outcomes of Post-Penetrating Keratoplasty Astigmatic Keratotomy Performed Using 30 kHz Femtosecond Laser Flap Mode Software *vs* 150 kHz Femtosecond Laser Enabled Astigmatic Keratotomy Software

Priyanka Chhadva[1], **Florence Cabot**[1,2,3], **Victor Hernandez**[3], **Mukesh Taneja**[3,4], **Yu-Cherng Chang**[3,5], **Vasilios Diakonis**[1,2] **and Sonia H. Yoo**[1,2,3*]

[1]*University of Miami Miller School of Medicine, Miami, FL, USA*

[2]*Department of Ophthalmology, Anne Bates Leach Eye Hospital, FL, USA*

[3] *Department of Ophthalmology, Ophthalmic Biophysics Center, Miami, FL, USA*

[4]*L.V. Prasad Eye Institute, Hyderabad, India*

[5]*University of Miami College of Engineering, Coral Gables, FL, USA*

[*]**Corresponding author:** Sonia H. Yoo, Bascom Palmer Eye Institute, 900 NW 17th Street, Miami, FL 33136, USA, Tel: 305-626-6322; Fax: 305-326-6337; E-mail: syoo@med.miami.edu

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Abstract

Purpose: To assess the long-term outcomes of astigmatic keratotomy (AK) performed with two different techniques in patients with post-penetrating keratoplasty (post-PK) residual astigmatism.

Methods: This retrospective comparative case series was performed at Bascom Palmer Eye Institute, University of Miami Miller School of Medicine, Miami, FL, USA. Patients who underwent post-PK AK performed using either 30 kHz femtosecond laser flap mode software (IntraLase/AMO, Irvine, CA)-Group 1-or using 150 kHz femtosecond laser enabled AK software (IntraLase/AMO, Irvine, CA)-Group 2-to create two anterior arcuate corneal incisions were included in this study. Preoperative and long-term postoperative follow-up data, including uncorrected distance visual acuity (UDVA), corrected distance visual acuity (CDVA), and spherical equivalence (SE) were analyzed.

Results: In group 1 (n=5), the difference in pre- and post-operative UDVA (0.97 ± 0.29 LogMAR to 0.68 ± 0.40 LogMAR, p=0.13), CDVA (0.28 ± 0.27 LogMAR to 0.47 ± 0.48 LogMAR, p=1), SE (-2.0 ± 3.0 diopters (D) to -1.8 ± 1.8 D, p=0.88) were not statistically significant, although UDVA and SE showed clinical improvement. In group 2 (n=6), the difference in pre- and post-operative UDVA (1.20 ± 0.14 LogMAR to 0.82 ± 0.62 LogMAR, p=0.19), CDVA (0.58 ± 0.32 LogMAR to 0.34 ± 0.31 LogMAR, p=0.25), SE (-2.3 ± 4.7 D to -2.9 ± 4.4 D, p=0.25) were not statistically significant. There was no statistical difference regarding postoperative UDVA (p=0.85), CDVA (p=0.93), SE (p=0.51) and surgically induced astigmatism (p=0.13) between the 2 groups.

Conclusion: AK performed with both techniques is a safe procedure to correct post-PK residual astigmatism. Both techniques yielded comparable results.

Keywords: Penetrating keratoplasty; Astigmatism; Astigmatic keratometry; Femtosecond laser

Introduction

Astigmatism can hinder visual rehabilitation in patients who have undergone an otherwise successful penetrating keratoplasty (PK) procedure. Patients with mild degrees of astigmatism can achieve greater visual acuity with the use of spectacles contact lenses; however, moderate to severe degrees of astigmatism may require surgical correction [1,2]. Such surgical procedures include laser in situ keratomileusis (LASIK), photorefractive keratectomy (PRK), toric intraocular lens placement in cataract surgery candidates, and more commonly arc-shaped corneal relaxing incisions or astigmatic keratotomy (AK), done either manually or with a femtosecond laser [1-5]. The manual incisions of AK tend to lack uniformity, reproducibility, and predictability, which can negatively affect visual outcome. On the other hand, the femtosecond laser, a new technology used for many corneal procedures, provides precise and reproducible incisions [1,6,7]. The first generation of femtosecond laser assisted AK was performed with slow frequency femtosecond laser and flap mode software used for LASIK. However, with advancement in technology, AK is now created using a higher frequency femtosecond laser and AK enabled software. This study assesses the long-term outcomes of femtosecond laser assisted AK performed with these two different techniques: 30 kHz femtosecond laser flap mode software versus 150 kHz femtosecond laser enabled astigmatic keratotomy software in patients with post-penetrating keratoplasty (post-PK) residual astigmatism.

Methods

Study population

This study is a retrospective study performed at Bascom Palmer Eye Institute, Miami, FL with approval from the Institutional Review Board of the University of Miami. Patients with post-PK residual astigmatism, who underwent femtosecond laser assisted AK, were included. Patients who underwent manual AK were excluded, as well as those who underwent femtosecond laser assisted AK for naturally occurring astigmatism or post-lamellar keratoplasty residual astigmatism. Patients were divided in two groups: Group 1 included patients who underwent post-PK AK performed using 30 kHz femtosecond laser flap mode software (IntraLase/AMO, Irvine, CA) and Group 2 included patient who underwent post-PK AK using 150 kHz femtosecond laser enabled AK software (IntraLase/AMO, Irvine, CA).

In both groups, the following evaluations were collected preoperatively and at the most recent postoperative visit: uncorrected visual acuity (UDVA), corrected distance visual acuity (CDVA), and slit-lamp examination. Additionally, corneal topography using Tomey TMS-4 (Tomey Corporation, Nagoya, Japan) was performed preoperatively and postoperatively, and the following parameters were recorded: keratometric readings, spherical equivalence (SE), average keratometry (avgK), and corneal cylinder (Cyl).

Surgical techniques

All the AK procedures were performed under topical anesthesia by the same surgeon. Central and peripheral corneal thickness was measured by ultrasonic pachymetry prior to surgery. Paired symmetric incisions were centered on the steep axis according to topography.

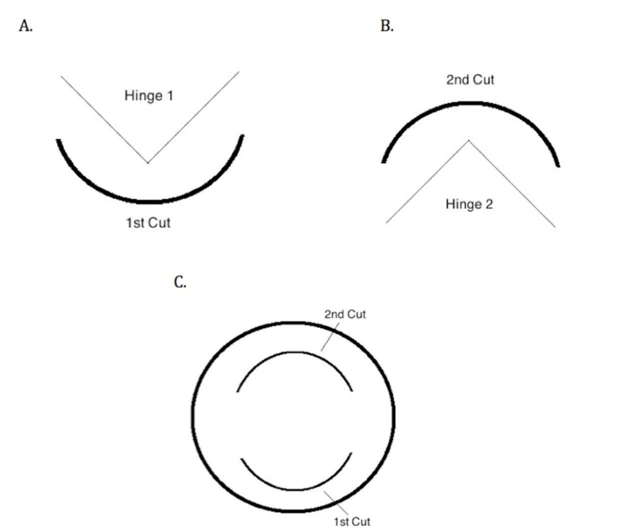

Figure 1: Depiction of how incisions are made using the 30 kHz femtosecond flap mode software. The hinge angle is increased to create semicircular arcuate incisions. **(A)** The first incision with specified hinge angle is made **(B)** the second incision with specified hinge angle is made **(C)** two anterior arcuate corneal incisions in the corneal stroma are created.

Group 1: 30 kHz femtosecond laser flap mode software: The hinge angle was set to be 360 degrees minus the desired arcuate length. The side-cut angle was set at 70 or 80 degrees, the flap diameter was set from 6.00 to 6.7 mm, and the flap thickness was set at 400 µm. After entering these parameters in the Intralase flap mode software of the 30 kHz femtosecond laser, the suction ring was applied and the cone was positioned. The first arcuate incision was created by the femtosecond laser. Then, a second applanation was performed, using the same parameters, except the position of the hinge that was set was located 180 degrees apart from the first one (Figure 1) [2].

Group 2: 150 kHz femtosecond laser enabled AK software: The angular arc length of all incisions was 90 degrees and the side-cut angle was set at 30 degrees. The optical zone diameter was set at 7 mm. The posterior incision depth was calculated by subtracting 100 µm from the thinnest ultrasound pachymetry value measured at the optical zone. After entering these parameters in the Intralase Enabled Keratoplasty mode window of the femtosecond laser, the suction ring was applied and the cone was positioned. The 150 kHz femtosecond laser used an energy setting of 1.8mJ and a spot/line separation of 3 µm × 3 µm. After AK completion, suction was released, and the position of the cuts was checked with a microscope.

Postoperatively, patients from both groups were treated with lubricating eye drops, and a combination of topical steroids and antibiotics 4 times daily for 2 weeks.

Vector analysis and statistical analysis

The SIA Calculator (version 2.1) was used to analyze astigmatism as a vector [8]. This calculator produced preoperative and postoperative amplitude of astigmatism from the difference in respective keratometric values (steep and flat meridians). The direction of this vector pointed toward the steeper keratometric meridian for each value. Additionally, data was analyzed using Cartesian coordinates according to Holladay's methodology [9]. The Cartesian-based data was converted to astigmatic vector form (i.e. magnitude of astigmatism and angle) using Microsoft Office Excel 2010 (Microsoft, Redmond, WA). This vector information was plotted with a custom program using MATLAB (Mathworks, Natick, MA). The polar coordinates were scaled to allow for angles ranging across pi radians to be plotted along a full 2pi radial graph. This plotting in vector form allowed calculation of the centroid, which is the true mean astigmatism value, and calculation of surgically induced astigmatism (SIA). Bunching of points on these plots indicates a uniform group with a highly predictive centroid value.

Non-parametric Wilcoxon rank sum test was used to compare the two groups and non-parametric Wilcoxon signed rank test was used for paired analysis of preoperative versus postoperative data within groups. Statistical significance was set at $p<0.05$.

Results

No intraoperative complications were noted using either technique. The mean age of patients at the time of surgery in Group 1 (n=5) was 75 years, the mean follow up time was 1.9 years, and all patients were male. The mean age of patients at the time of surgery in Group 2 (n=7) was 64 years, the mean follow up time was 3.5 years, and there were 6 females and 1 male (Table 1). There was no statistically significant difference between age at the time of surgery (p=0.3), and years of follow-up (p=0.21) when comparing patients of these two groups. Additionally, there was no statistically significant difference between these groups with regards to preoperative UDVA (p=0.13), preoperative CDVA (p=0.15), preoperative SE (p=0.13), preoperative AvgK (p=1), or preoperative Cyl (p=0.64).

	Total Group 1	Total Group 2
Number of Eyes	5	7

Number of Patients	5	7
Age, mean (SD) [range]	75, (15.4) (55-93)	64, (19.5) (32-82)
Gender: Male, n (%)	5 (100%)	1 (14.3%)
Female, n (%)	0 (0%)	6 (85.7%)
Eye: Right, n (%)	3 (60%)	2 (28.6%)
Left, n (%)	2 (40%)	5 (71.4%)

Table 1: Patient Demographics.

In Group, postoperative UDVA showed clinical, but not statistically significant, improvement (0.97 ± 0.29 logMAR improving to 0.68 ± 0.40 logMAR, p=0.13) (Tables 2 and 3). The differences between preoperative and postoperative SE (p=0.88), AvgK (p=0.31), and Cyl (p=0.06) were not statistically significant. Similarly, in Group 2, the differences between preoperative and postoperative UDVA and CDVA showed clinical improvement, even though the difference between values was not statistically significant (p=0.19 and p=0.25 respectively). The differences between preoperative and postoperative SE (p=0.25), AvgK (p=0.13) and cyl (0.06) were also not statistically significant (Table 3).

Group 1	Patient Number	Preop UCVA	Postop UCVA	Preop BCVA	Postop BCVA	Preop Cyl	Postop Cyl
	1	1.00	0.60	0.00	0.18	11.33	6.31
	2	1.18	1.30	0.60	1.00	6.40	11.30
	3	1.00	1.00	0.18	0.10	4.03	2.97
	4	1.18	0.40	0.54	1.00	8.06	7.83
	5	0.48	0.10	0.10	0.10	11.59	7.07
Group 2							
	6	1.00	0.54	0.70	0.30	6.70	2.79
	7	1.30	0.10	0.30	0.00	9.20	3.21
	8	1.18	1.18	0.30	0.30	6.86	1.49
	9	1.30	1.82	1.00	0.18	8.35	0.67
	10	1.30	0.48	0.48	0.30	9.67	5.46
	11	1.00	0.30	0.30	1.00	8.53	2.21
	12	1.30	1.30	1.00	0.30	16.46	5.74
Uncorrected visual acuity (UCVA) in logMAR; Best-corrected visual acuity (BCVA) in logMAR; Corneal cylinder (Cyl) in Diopters							

Table 2: Individual changes in UCVA, BCVA, and Cyl.

	Preop UDVA	**Postop UDVA**	**p value**	**Preop CDVA**	**Postop CDVA**	**p value**			
Group 1 (logMAR)	0.97 (0.29)	0.68 (0.40)	0.13	0.28 (0.27)	0.47 (0.48)	0.15			
Group 2 (logMAR)	1.20 (0.14)	0.82 (0.62)	0.19	0.58 (0.32)	0.34 (0.31)	0.25			
	Preop SE	Postop SE	p value	Preop Avg K	Postop Avg K	p value	Preop Cyl	Postop Cyl	p value
Group 1 (D)	-2 (3)	-1.8 (1.8)	0.88	46 (2.4)	48 (2.1)	0.31	8.3 (3.2)	7.1 (3)	0.06
Group 2 (D)	-2.3 (4.7)	-2.9 (4.4)	0.25	45 (1.8)	55.5 (23)	0.13	9.4 (3.3)	3.1 (1.9)	0.06
All values are mean (+/-SD); Uncorrected distance visual acuity (UDVA); corrected distance visual acuity (CDVA); Spherical equivalence (SE); Average keratometry (Age K); Corneal cylinder (Cyl)									

Table 3: Visual Acuity Outcomes.

With regards to the postoperative comparison between group 1 and group 2, there was no statistically significant difference in postoperative UDVA (p=0.85), postoperative CDVA (p=0.93), postoperative SE (p=0.51), or postoperative AvgK (p=0.69), but there was a statistically significant difference in postoperative corneal cylinder (Cyl; p=0.02). However, 3 patients in group 1 and 3 patients in group 2 showed improvement in UDVA postoperatively. Moreover, 3 patients in group 1 and all patients in group 2 showed improvement in Cyl postoperatively (Table 2).

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	Group 1	Group 2	p value
Mean preoperative amplitude	7.9 (3.6)	9.2 (2.7)	0.06
Mean postoperative amplitude	5.1 (3.7)	2.9 (2.1)	0.23
Mean SIA amplitude	7.8 (5.4)	9.5 (3.6)	0.13
All values are mean diopters (± SD); SIA (surgically induced astigmatism)			

	Group 1	Group 2	
Mean preoperative centroid	5.2 × 167°	2.3 × 95°	
Mean postoperative centroid	3.5 × 151°	2.3 × 86°	
Mean SIA centroid	2.6 × 91°	0.75 × 44°	
Measured in Diopters x degrees; SIA: Surgically induced astigmatism			

Table 4: Amplitude of Astigmatism and Centroids.

The preoperative amplitude of astigmatism in group 1 was 7.9 D ± 3.6, while group 2 was higher at 9.2 ± 2.2 D (p=0.06) (Table 4). Postoperative amplitude of astigmatism was higher in group, 5.1 ± 3.7 D, than in group 2, 2.9 ± 2.1 D. However, the surgically induced astigmatism (SIA) was lower in group, 7.8 ± 5.4, than in group 2, 9.5 ± 3.6 D (p=0.13) (Table 4). With regards to the analysis of astigmatism using vector analysis, preoperative and postoperative values are detailed for group, group 2, and SIA (Figures 2-4). These double angled plots do not exhibit clustering, which implies low predictive value of the centroid.

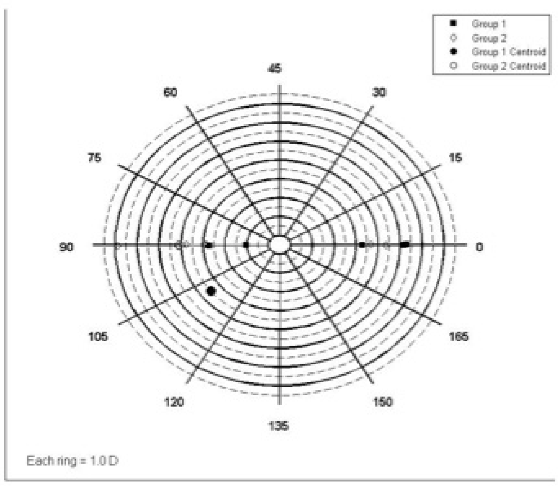

Figure 2: Vector Analysis; Pre-operative vector analysis of group 1 and group 2. This figure details the pre-operative vector of astigmatism in each patient, and the predicted centroid (true mean astigmatism value) of each group.

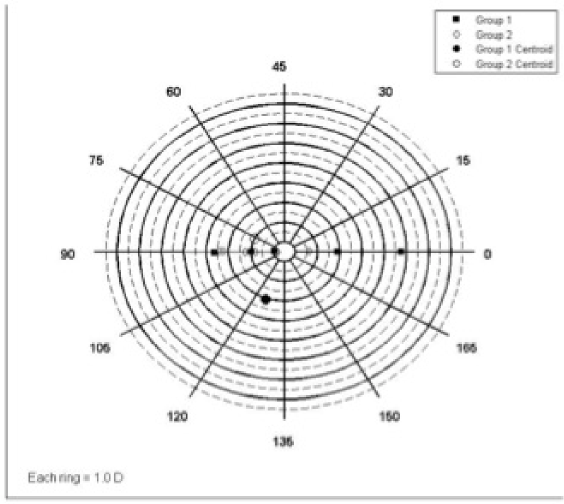

Figure 3: Vector Analysis; Post-operative vector analysis of group 1 and group 2. This figure details the post-operative vector of astigmatism in each patient, and the predicted centroid (true mean astigmatism value) of each group.

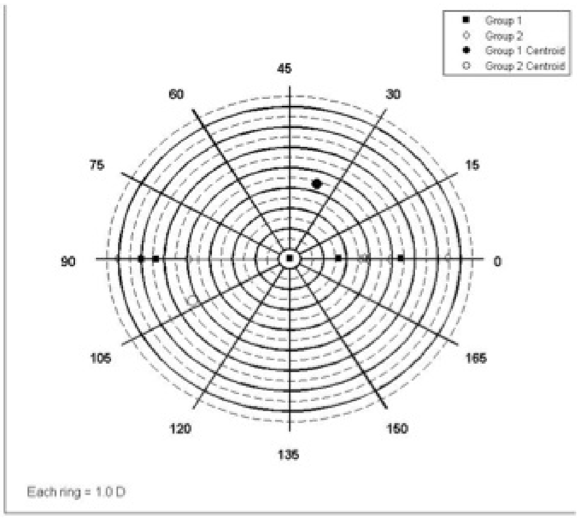

Figure 4: Double Angled Plot; Surgically induced astigmatism vector analysis of group 1 and group 2 with predicted value of each group.

Discussion

This study, to our knowledge, is the first comparing 2 femtosecond laser methods and platforms (flap mode in 30 kHz *vs* keratoplasty mode in 150 kHz) for treating post-PK residual astigmatism with AK. Such astigmatism can be caused by many factors, including astigmatism of the donor eye, irregular wound healing, and incorrect corneal suture tension, placement, and depth. Spectacles and contact lenses are an option for visual rehabilitation. Around 10-30% of patients who are post-PK wear contact lenses and 25-50% of patients do so far post-PK keratoconus correction [10]. However, contact lenses can cause peripheral neovascularization, which increases the risk of graft rejection [11,12]. Surgical options are available for patients with post-PK astigmatism, and include AK.

Traditional methods using manual free-hand techniques and mechanized using Hanna arcitome are now being replaced by the femtosecond laser. The femtosecond laser uses near-infrared pulses to manipulate tissue with minimal collateral damage [13]. It is a safe technology which is mainly used for creating anterior corneal flaps in LASIK, however, it has the ability to produce different wound configurations with defined control of incision dimensions such as in AK, corneal biopsy, tunnel creation of intrastromal ring segments and cutting donor buttons in endothelial keratoplasty [13,14].

Looking at manual AK in post-PK eyes, a study by Poole et al. demonstrated a reduction in mean Cyl postoperatively (9.13D to 4.85D, p<0.001) and an increase in SE (-3.65D to -3.73D) [15]. A similar reduction in Cyl and increase in SE was seen in our study's Group 2 patients using a femtosecond laser (Cyl 9.4 ± 3.3 to 3.1 ± 1.9, p=0.0004; SE -2.3 ± 4.7 to -2.9 ± 4.4, p=0.81). A study by Wilkins et al. also showed a reduction of mean cylinder (-10.99 ± 4.26 D to -3.33 ± 2.18 D) and no significant change in SE (-3.77 D to -3.15 D) using manual technique [6].

Comparing this manual technique to laser-assisted AK in post-PK eyes, a study by Behar et al. reported the outcomes of manual and Intralase-enabled AK in 39 patients, with 20 eyes in each group. Both groups showed an improvement in UDVA and CDVA; however, only the group operated on with the femtosecond laser achieved statistically significant improvement. UDVA improved from 1.14 ± 0.42 to 0.82 ± 0.44 logMAR (p=0.004) and CDVA improved from 0.52 ± 0.38 to 0.29 ± 0.26 log MAR (p=0.01) in the Intralase enabled-AK group [16]. This study provides insight into the comparison between lasers versus manual AK, and noted a complication in 3 cases of corneal perforation requiring resuturing of the AK wound after manual AK [16].

The use of the femtosecond laser for AK allows for precision and reproducibility [17]. The surgeon is able to set the laser parameters such as depth, length, and width of the incision. The 30 kHz femtosecond laser flap mode software used in Group 1 uses a raster beam pattern to make side cuts one at a time (two separate applanations and incisions), and has a maximum depth of incision of 400 microns. Abbey et al. reported an improvement in UDVA of counting fingers to 20/50 in the right eye, and 20/200 to 20/30 in the left eye, of one patient using the Intralase 30 kHz femtosecond laser with flap mode software in eye with naturally occurring astigmatism [2]. A similar trend in improvement was seen in our patients who underwent this technique of post-PK AK, however the difference between preoperative visual acuity and postoperative visual acuity was not statistically significant (UDVA 20/180 to 20/50). Results of a more precise laser, the 60 kHz Intralase femtosecond laser enabled AK, were shown by Kook et al. They reported an improvement in UDVA of 20/370 to 20/260 and mean corneal astigmatism from 9.3D to 6.5 D in 10 eyes with post-PK astigmatism [18].

With advancing technology, the 150 kHz laser was subsequently developed. New technology with updated software now allows greater flexibility and automated creation of the AK incisions using spiral laser beam patterns. The 150 kHz femtosecond laser enabled astigmatic keratotomy software used in Group 2 of this study requires only one applanation to perform both arcuate incisions, which are done simultaneously.

Regarding the analysis of astigmatism, there was a reduction in the amplitude of astigmatism in both groups, however only in group 2 was this difference statistically significant (Table 4). Similarly, a study by Kumar at al. analyzed post-PK AK done with a 60 kHz Intralase laser and found a decrease in the mean absolute value of astigmatism at 3 months postoperatively (7.46 ± 2.70 D to 4.77 ± 3.19 D, p=0.0001) [19]. Further, there was no difference in SIA between both groups of our study, indicating that in this study, both methods yielded comparable results.

Although AK is one option for reducing post-PK astigmatism, other methods exist and have been shown to be effective. Using PRK to correct post-PK astigmatism and myopia, Bilgihan et al. found a reduction of Cyl from −5.62 ± 2.88 D to −3.23 ± 1.70 D (p<0.05) in 16 eyes [11]. Similarly, LASIK to treat post-PK astigmatism has been demonstrated. A study by Hardten et al. showed an improvement in astigmatism from 4.67 ± 2.18 D to 1.94 ± 1.35 D 2 years post-op in 28 patients [20]. Although this study looks at AK as a method of treating post-PK astigmatism, LASIK and PRK may be considered as valuable options even though they involve treating the visual axis. Another technique described to help reduce post-PK astigmatism is suture adjustment. McNeill et al. found that suture adjustment after PK surgery reduced astigmatism by 25.4% (1.2 D) at least 12 months after suture removal compared to patients with no suture adjustment (p=0.01) [21].

The limits of our study include its retrospective design and a limited number of patients that may be the cause of the non-statistical significance of the difference between preoperative and postoperative data. The interpretation of the vector analysis of this study was also difficult due to the limited number of patients in both groups. Looking at the DAP displayed in Figure 4, the SIA values of each group do not exhibit clustering, implying low predictive value of the centroids. Thus, the variability in results did not allow us to extrapolate a trend or prediction. Prospective comparative studies with larger sample sizes are needed to support the outcomes of this study.

In conclusion, the creation of arcuate incisions using femtosecond laser technology has evolved to provide precision in creating incisions of desired radius, length, depth, and shape, with minimal surrounding tissue damage. The 30 kHz flap mode software method, even though a 2-step procedure, provided similar outcomes with regards to visual acuity when compared to the more recent generation of femtosecond laser (150 kHz). Our study showed that AK performed using 30 kHz femtosecond laser flap mode software versus 150 kHz femtosecond laser enabled AK software are both effective in treating post-PK residual astigmatism.

Conflict of Interest Statement

Dr. Sonia H. Yoo is a consultant for Abbott Medical Optics (AMO, Santa Ana, CA, USA). All other authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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