Arcuate Keratotomy for High Postoperative Keratoplasty Astigmatism Performed With the IntraLase Femtosecond Laser

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ABSTRACT

PURPOSE: To evaluate the refractive and keratometric effect of arcuate keratotomy performed using the IntraLase femtosecond laser (Abbott Medical Optics) in patients with high postoperative keratoplasty astigmatism.

METHODS: Nine eyes of nine patients (mean age 45±7.5 years; mean spherical equivalent refraction +2.50 to +3.60 diopters [D]) who had undergone a penetrating keratoplasty were considered. The subjective refraction was measured, and corneal thickness and keratometric parameters were calculated by the Pentacam (Oculus Optikgeräte). All uncomplicated surgeries were performed with the IntraLase femtosecond laser. Paired 70° arc length incisions were performed at 80% depth of the corneal thickness. The mean optical zone was 5.9 mm. The side cut was 90°. All incisions were performed in the graft itself. Mean change in best spectacle-corrected visual acuity (BSCVA), refractive and keratometric astigmatism, and spherical equivalent refraction was evaluated. Follow-up was 3 months. Refractive and keratometric data were analyzed using vector analysis as described by Alpins. A paired Student t test was used to compare preoperative and 3-month postoperative data. A P value <.05 was considered significant.

RESULTS: Mean preoperative BSCVA was 20/30, increasing to 20/25 postoperatively (P=.05). The mean refractive astigmatism decreased by 6.00 D (P<.05), whereas the mean keratometric value decreased by 4.60 D (P<.05). The mean spherical equivalent refractive astigmatism did not change significantly. The surgical vectors in the refractive and keratometric analysis were calculated, showing good predictability.


Penetrating keratoplasty often induces high astigmatism, which represents a significant limiting factor in the visual rehabilitation of patients. Several surgical techniques were proposed to treat postoperative keratoplasty astigmatism: excimer laser custom ablation,1,2 implantation of toric intraocular lenses,3 compression sutures, lamellar keratotomy, and astigmatic keratotomy.4 Merlin5 reported the efficacy of arc-shaped relaxing incisions performed in the corneal stroma to correct astigmatism. The arcuate incisions are commonly used to treat high astigmatism defects that cannot be corrected with spectacles or contact lenses.

The femtosecond solid-state laser6 has been used successfully in several corneal surgical procedures. This technology consists of an infrared Nd:Glass laser beam focused at a desired corneal depth that induces an optical breakdown (ie, photodisruption) without thermal or shockwave damage to the surrounding tissue, especially improving the predictability and optical quality of lamellar surgery.7,8 The femtosecond laser technology of the 60 kHz, the last version recently commercially introduced by the IntraLase system (Abbott Medical Optics, Santa Ana, Calif), enables flap creation in LASIK; the creation of channels for intracorneal rings; the preparation of donor and host tissue in anterior, posterior, and penetrating keratoplasty; and also enables the performance of arcuate incisions, theoretically increasing the precision, reproducibility, and safety of the cuts.

In this preliminary study, we evaluated the refractive and keratometric effect of arcuate keratotomy performed with In-
traLase in patients with high astigmatism after keratoplasty.

**PATIENTS AND METHODS**

Any experimental investigation reported in the manuscript was performed with informed consent and following all guidelines for experimental investigation with human subjects required by the institution with which all authors are affiliated. All surgeries and follow-up were performed at the Hospital “Casa Sollievo della Sofferenza,” San Giovanni Rotondo, Italy. Inclusion criteria in this retrospective study were high postoperative keratoplasty astigmatism and myopia, complete removal of sutures at least 10 months prior, contact lens intolerance, and a clear lens.

The study cohort comprised nine eyes of nine patients (mean age 45 ± 7.5 years; mean spherical equivalent refraction −2.50 ± 3.60 diopters [D]) who had undergone penetrating keratoplasty. The refractive parameters were measured by subjective refraction, corneal thickness, and keratometric parameters using the Pentacam (Oculus Optikgeräte, Wetzlar, Germany) (Fig 1). Corneal irregular astigmatism changes were evaluated by some of the Pentacam indices that indicate the regularity of the corneal surface: index of surface variance, value of curvature variation from the mean curvature; the index of vertical asymmetry, value of curvature symmetry comparison of the upper and lower area; and the index of height decentration, value of the decentration of height data in the vertical direction.

All surgeries were performed under topical anesthesia using a 60 kHz IntraLase femtosecond laser loaded with the IntraLase Enabled Keratoplasty computer program without complication.

The IntraLase requires placement of a suction ring and applation lens. After a proper vacuum seal was obtained, the applation lens was applied to provide a uniform reference plane for the laser, and the laser procedure was performed. Only the “side-cut” function was used. No reference mark was performed.

Two simultaneous opposite incisions were created. Because the IntraLase software allows only one depth measure to be set for both simultaneous incisions, the cut depth was calculated at 80% of the thinnest corneal point measured by the Pentacam over the optical zone diameter.

The mean depth of incisions was 475 ± 59 µm. The mean optical zone was 5.9 mm (range: 4.8 to 6.8 mm). The optical zone was always centered on the pupil and its diameter was chosen to avoid the impact intersection of the femtosecond laser beam with the graft scar. The optical zone diameter decreased as a function of the amount of the astigmatic defect. Paired 70° arc length incisions were made and centered on the steep keratometric axis, as determined by the corneal topography, and the side cut was 90°. All incisions were performed in the graft itself. Immediately after treatment, the surgeon opened the full length of the side cut in an attempt to verify the effect of the femtosecond laser and thoroughly cleaned the area with balanced salt solution (BSS) using a 30-gauge cannula. All eyes

\[ \text{Figure 1. Comparison of A) preoperative and B) 3-month postoperative keratometric and sagittal anterior maps taken by the Pentacam (Oculus Optikgeräte). The panel on the right shows the difference calculated for each map between A minus B.} \]
received topical dexamethasone 0.1% and netilmicin 0.3% six times a day for 1 week, four times a day for 1 week, and two times a day for 1 week.

Mean change in best spectacle-corrected visual acuity (BSCVA), refractive and keratometric astigmatism, and spherical equivalent refraction were evaluated preoperatively and 3 months postoperatively.

The refractive and keratometric data were analyzed using vector analysis as described by Alpins\textsuperscript{10,11} that evaluated the effective change in astigmatism, with consideration of change in the astigmatic axis, measuring three vectors and different relationships among them: the target induced astigmatism vector (TIA), defined as the astigmatic change by magnitude and axis the surgery was intended to induce; the surgically induced astigmatism vector (SIA), defined as the amount and axis of astigmatic change the surgery actually induced; and the difference vector (DV), defined as the induced astigmatic change by magnitude and axis that would enable the initial surgery to achieve its intended target (it is an absolute measure of success and is preferably zero). Related to SIA are: the correction index, calculated by determining the ratio of the index of success and correction index 0.45 to 0.52 and index of success 0.38 to 0.59 and index of success 0.45 to 0.80 and index of success 0.20 to 0.29.

A paired Student \( t \) test was used to compare the preoperative and 3-month postoperative data. A \( P \) value <.05 was considered statistically significant. Because keratometric and refractive data showed different degrees of skew, the geometric mean for each value of the index of success and correction index was computed. Therefore, by taking the logarithm of data and back-transforming, we obtained the following asymmetrical 95% confidence intervals: keratometric correction index 0.46 to 0.52, index of success 0.38 to 0.44, and index of success 0.45 to 0.60. Spherical equivalent refraction was 2.30 to 6.00 D; the spherical equivalent value was 9.80 to 13.00 D; the postoperative mean value was 3.10 to 1.50 D; and the postoperative mean value was 2.50 to 6.00 D.

The refractive and keratometric vectors were calculated for each eye (Tables 1 and 2). The mean refractive vectors were: TIA 9.1, SIA 6, DV 3.1, AE −33, ME −3.1, correction index 0.6, and index of success 0.3. The mean keratometric vectors were: TIA 9.8, SIA 5.2, DV 4.5, AE −49, ME −4.6, correction index 0.5, and index of success 0.4.

Preoperative index of surface variance, index of vertical asymmetry, and index of height decentration values resulted in the pathological range. Postoperatively, in individual cases, index of vertical asymmetry and index of height decentration decreased as a function of the optical zone diameter and incision depth, for optical zone larger than 6.0 mm and arcuate keratotomy deeper than 500 µm. In all other cases, postoperative indices got worse.

\textbf{RESULTS}

Mean BSCVA preoperatively was 20/30 and postoperatively was 20/25. The change was not statistically significant (\( P > .05 \)). Without regard to the axis, the preoperative mean subjective cylinder was 9.10 to 3.90 D (range: 5.00 to 13.00 D) and the postoperative mean value was 3.10 to 1.50 D; the cylinder error significantly decreased by 6.00 D (\( P < .05 \)). Without consideration of the axis, the mean preoperative keratometric value was 9.80 to 1.90 D and postoperatively was 5.20 to 1.50 D, with a statistically significant reduction by 4.60 D (\( P < .05 \)). The preoperative mean spherical equivalent refraction was −2.50 to 6.00 D and the postoperative mean value was −2.30 to 0.90 D (range: 1.25 to 3.50 D); the spherical equivalent refraction did not show significant change (\( P > .05 \)).

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\textbf{DISCUSSION}

High astigmatism after penetrating keratoplasty is a common complication\textsuperscript{12} and many surgical procedures have been developed to correct it.\textsuperscript{1-5} Several studies reported the efficacy of arcuate keratotomy in correcting astigmatic errors with minimal changes in spherical equivalent refraction.\textsuperscript{4,13,14} Arcuate keratotomy, popularized by Merlin,\textsuperscript{5} is defined as one or more curved relaxing incisions performed in the corneal stroma or graft–host interface, perpendicular to the steep meridian of astigmatism. An arcuate incision produces a relative flattening of the cornea in the axis of the incision with relative steepening at 90° of the incision. This effect, called coupling effect, avoids a significant change in spherical equivalent refraction. Several elements influence the effect of arcuate keratotomy: number, depth, optical zone, and length.

Wilkins et al\textsuperscript{4} found that in postoperative keratoplasty eyes, the change in the magnitude of astigmatism induced by a pair of 60° arc length arcuate keratotomies performed with an optical zone of 6.0 mm for 600 µm depth, was proportional to the preoperative magni-
Recently, Zuberbuhler et al.\textsuperscript{15} proposed a modified Ruiz procedure for reducing high astigmatism after penetrating keratoplasty. Two paired 60° arc length arcuate keratotomies with an optical zone ranging from 3.0 to 5.0 mm were performed within the graft and four radial cuts were made. All incisions were planned at 90% to 95% of the central corneal thickness. The preoperative mean subjective cylinder was 8.75 \pm 3.05 D and, without consideration of cylinder axis and its changes, the mean postoperative cylinder was 5.31 \pm 3.12 D. The reduction in cylinder of 3.44 D was statistically significant. This procedure resulted in decreased postoperative keratoplasty astigmatism, but the refractive outcome did not appear predictable with the method of vector analysis of Alpins (mean correction index was 1.95 and mean index of success was 1.27).

In this preliminary study, we evaluated the refractive and keratometric effect of arcuate keratotomy performed with IntraLase in patients with high postoperative keratoplasty astigmatism (Fig 2).

We found an increase in BSCVA that was not statistically significant and a statistically significant reduction

\begin{table}
\centering
\caption{Individual Keratometric Data Analyzed Using Vector Analysis}
\begin{tabular}{|l|c|c|c|c|c|c|c|c|c|c|}
\hline
Keratometric Analysis & Patients & \multicolumn{9}{|c|}{Patients} \\
\hline
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
Target induced astigmatism, TIA & 9.9 & 11.8 & 10.5 & 7.1 & 10.4 & 9.5 & 8.4 & 12.2 & 8.9 \\
Surgically induced astigmatism, SIA & 4.3 & 5.9 & 3.9 & 4.1 & 6.1 & 5.6 & 6.1 & 6.5 & 4.8 \\
Difference vector, DV & 5.6 & 5.9 & 6.6 & 3 & 4.3 & 3.9 & 2.3 & 5.7 & 4.1 \\
Magnitude of the error, ME & -5.6 & -5.9 & -6.6 & -3 & -4.3 & -3.9 & -2.3 & -5.7 & -4.1 \\
Correction index & 0.4 & 0.5 & 0.4 & 0.6 & 0.4 & 0.6 & 0.7 & 0.5 & 0.5 \\
Index of success & 0.6 & 0.4 & 0.6 & 0.4 & 0.4 & 0.4 & 0.3 & 0.5 & 0.5 \\
\hline
\end{tabular}
\end{table}

\begin{table}
\centering
\caption{Individual Refractive Data Analyzed Using Vector Analysis}
\begin{tabular}{|l|c|c|c|c|c|c|c|c|c|c|}
\hline
Refractive Analysis & Patients & \multicolumn{9}{|c|}{Patients} \\
\hline
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
Target induced astigmatism, TIA & 5 & 12 & 13 & 6.5 & 12 & 7.6 & 7.8 & 10.8 & 7.2 \\
Surgically induced astigmatism, SIA & 3.5 & 8 & 10.5 & 1.5 & 6.4 & 5.5 & 6.2 & 6.4 & 6.1 \\
Difference vector, DV & 1.5 & 4 & 2.5 & 5 & 5.6 & 2.1 & 1.6 & 4.4 & 1.1 \\
Angle of error, AE & 0 & -95 & 0 & -35 & -28 & 0 & -55 & -11 & -78 \\
Magnitude of the error, ME & -1.5 & -4 & -2.5 & -5 & -5.6 & -2.1 & -1.6 & -4.4 & -1.1 \\
Correction index & 0.7 & 0.7 & 0.8 & 0.2 & 0.5 & 0.7 & 0.8 & 0.6 & 0.8 \\
Index of success & 0.3 & 0.3 & 0.2 & 0.8 & 0.5 & 0.3 & 0.2 & 0.4 & 0.1 \\
\hline
\end{tabular}
\end{table}

\begin{table}
\centering
\caption{Mean Refractive and Keratometric Data Analyzed Using Vector Analysis}
\begin{tabular}{|l|c|c|}
\hline
 & Refractive Analysis & Keratometric Analysis \\
\hline
Target induced astigmatism, TIA & 9.1 & 9.8 \\
Surgically induced astigmatism, SIA & 6.0 & 5.2 \\
Difference vector, DV & 3.1 & 4.5 \\
Angle of error, AE & -33 & -49 \\
Magnitude of the error, ME & -3.1 & -4.6 \\
Correction index & 0.6 & 0.5 \\
Index of success & 0.3 & 0.4 \\
\hline
\end{tabular}
\end{table}
in refractive and keratometric astigmatism. The lack of a significant change in spherical equivalent refraction was due to the coupling effect. In individual cases, we found that the corneal irregular astigmatism amount was less with a larger optical zone and deeper incisions.

We also evaluated the predictability of the astigmatic correction using the method of vector analysis of refractive and keratometric data. Both refractive and keratometric analysis showed an undercorrection of the astigmatism with correction index values of 0.6 for refraction and 0.5 for keratometry. The negative magnitude of the error values, where the mean SIA magnitude is less than the mean TIA magnitude, confirmed a trend of undercorrection for the group.

The analysis of astigmatic correction suggested that the treatment was off axis clockwise, indicating a misalignment. The examination of the angle of error showed a less favorable outcome on alignment for the keratometric mean. The angle of error changes could be partially correlated to variable factors such as healing or alignment, as well as to the surgical procedure. The optical zone was always centered on the pupil because the IntraLase suction procedure makes it difficult for exact alignment of the applanation cone to the corneal apex, whereas the center of the pupil can be determined after cone docking using the options of the computer program. The procedure could induce a virtual decentration due to tilt of the cone. No reference mark was performed. Although the vacuum suction of the IntraLase maintains a constant position of the eye during the treatment, an axis mark will be necessary to optimize the procedure. All incisions were planned on the center of the steep keratometric axis as determined by corneal topography.

Several authors observed the high precision of IntraLase in corneal lamellar surgery, reporting the quality and precision of the latest femtosecond laser engine that permits a tight spot/line separation using low energy. The 60 kHz IntraLase femtosecond laser loaded with IntraLase Enabled Keratoplasty computer program makes it possible to use femtosecond technology in arcuate keratotomy using only the “side cut” function. The side-cut angle is the angle that the cylindrical side cut makes with the corneal surface (90° is perpendicular to the corneal anterior surface). The IntraLase creates corneal arcuate incisions whose length, depth, and optical zone diameter can be planned for each individual eye. Because the IntraLase software allows only one depth measure to be set for both simultaneous incisions, we calculated the cut depth at 80% of the thinnest corneal point measured by the Pentacam over the optical zone diameter. However, in an attempt to preserve the same residual corneal stroma thickness for each arcuate keratotomy, the surgeon could perform two distinct treatments, setting different stromal depth values. The effect of this approach was not evaluated by our study.

The use of the IntraLase femtosecond laser for the correction of high postoperative keratoplasty astigmatism seems to provide good refractive and keratometric results, better than those achieved by other authors who performed the incisional surgery with smaller optical zones and deeper incisions usually calculated at 90% to 95% of the corneal thickness. Our findings suggest that arcuate keratotomy performed with the IntraLase could reduce the risk of corneal perforation as well as the delayed changes in corneal curvature and the increased separation of the edges of the original wound occasionally observed after incisional surgery, hopefully producing a greater stability of the refractive effect.

One of the advantages related to the IntraLase technology is that, with proper spacing of the laser spots, no significant morphologic tissue bridges are present. This element could also provide a better and more stable wound healing process after arcuate keratotomy. With standardized arcuate keratotomy, the healing begins with an epithelial plug filling the gaping wound and it can take as long as 5 years for the plug to be replaced with disorganized hypercellular scar tissue. This preliminary study evaluated a small sample of patients with a brief follow-up; however, our findings suggest that a nomogram adjustment could be derived by the SIA magnitude that could represent the nominal value of TIA. In fact, a refractive and keratometric TIA of 9.00 D (the mean TIA value calculated in this study) appears as a nonrealistic surgical goal with the femtosecond laser. Alternatively, the SIA magnitude...
of approximately 6.00 D could be considered as the TIA, then as the amount of postoperative keratoplasty astigmatism that could really be corrected with the IntraLase.

These findings suggest that simultaneous arcuate keratotomy performed with the IntraLase femtosecond laser could be an effective and safe surgical procedure in the treatment of high postoperative keratoplasty astigmatism. The 3-month follow-up showed a good predictability of the procedure. However, more patients and longer follow-up are needed to confirm these early results and to improve treatment nomograms.

AUTHOR CONTRIBUTIONS

Study concept and design (L.B.); data collection (L.B., G.P., A.L., E.M., M.G.); interpretation and analysis of data (L.B., G.P., P.V.); drafting of the manuscript (L.B.); critical revision of the manuscript (G.P., A.L., E.M., P.V., M.G., P.V.)

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