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Evaluation of femtosecond laser intrastromal incision location using optical coherence tomography

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Abstract

Purpose—Using optical coherence tomography (OCT) to evaluate the femtosecond laser intrastromal (IS) incisions made during cataract surgery to reduce corneal astigmatism.

Design—Retrospective case series.

Subjects—77 eyes of 77 patients were included.

Methods—Paired IS incisions were created using the Catalys femtosecond laser (Abbott Medical Optics, Inc.). The planned IS incision parameters were 20% uncut anterior, 20% uncut posterior, midpoint depth of 50%, and 90° side cut angle. OCT scans were obtained three weeks or more postoperatively to assess these four parameters, and actual values were compared to intended values.

Main Outcome Measures—Percentages of uncut anterior and posterior tissue, midpoint depth, and degrees of side cut angle.

Results—The mean values were $17.2\% \pm 5.8\%$ (range 7.2% to 36.9%) for uncut anterior, $32.5\% \pm 8.8\%$ (range 6.0% to 57.9%) for uncut posterior, and $42.3\% \pm 6.6\%$ (range 25.5% to 65.4%) for midpoint depth, which were all significantly different from the planned parameters (all $P < 0.05$). The mean side cut angle was $88.5^\circ \pm 5.6^\circ$ (range 71° to 114°) and was significantly different from the planned side cut angle of 90° ($P < 0.05$). In 50 eyes that had paired IS incisions scanned by the OCT, there was no correlation between the paired incisions for midpoint depth and side cut angle (correlation coefficient $r = -0.063$ and -0.067 , respectively, $P > 0.05$).

Conclusions—The IS incision midpoint depth was significantly more anterior than the planned depth of 50%. The location of paired IS incisions in each eye were not correlated. Further improvements are needed to ensure the precise location of the IS incisions made with this device.

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Optical coherence tomography (OCT) is a non-invasive powerful imaging technology that can produce cross-sectional images of the anterior and posterior segments of the eye. Anterior segment OCT allows for the visualization of incisions made in the cornea and provides a means to analyze structural changes or precise location of these incisions. Using anterior segment OCT, several studies have been performed to assess the architectural changes of clear corneal incisions after cataract surgery.¹⁻⁷

Recently, femtosecond laser-assisted corneal incisions have been used to reduce corneal astigmatism during femtosecond laser-assisted cataract surgery. The incision may be placed in two ways: 1) penetrating incision, in which the incision penetrates the anterior corneal surface; and 2) intrastromal (IS) incision, in which the incision is placed in the stroma without penetrating the anterior and posterior corneal surfaces. The effectiveness of femtosecond-assisted penetrating arcuate keratotomy and IS astigmatic keratotomy combined with cataract surgery have been previously reported.⁸⁻¹⁰

Haque and colleagues¹¹ performed a video review of 28 consecutive eyes of 25 patients who underwent intrastromal limbal relaxing incisions using the Catalys laser (Abbott Medical Optics, Inc.) and reported a high incidence of anterior microperforation in planned intrastromal incisions. Cherfan and Melki¹² reported a case in which a planned intrastromal arcuate incision (20% below the epithelium and 20% above the endothelium) ended up with a full-thickness incision along the entire length of the incision. We are unaware of any published studies evaluating femtosecond laser IS incision location postoperatively using OCT. In this study, using an OCT device (RTVue, Optovue Inc, Fremont, CA), we assessed the location of the femtosecond laser-assisted IS incisions following cataract surgery and compared the actual location to the planned location.

PATIENTS AND METHODS

Subjects

Institutional review board approval was obtained for the study, which followed the tenets of the Declaration of Helsinki. Retrospectively, we reviewed consecutive patients who underwent Catalys femtosecond laser-assisted cataract surgery combined with IS incisions between July 2014 and July 2016. Inclusion criteria were patients who had: 1) paired IS incisions, and 2) at least one of the paired IS incisions was visualized and scanned by the OCT at 3 weeks or longer following the cataract surgery. One eye from each subject was included for analysis. If a patient had both eyes that met the inclusion criteria, the first eye that underwent cataract surgery was included in this study.

Intrastromal incisions

To determine the arc length of the IS incision, we used the Intrastromal AK nomogram calculator proposed by Julian Stevens (<http://femtoemulsification.com/>), and modified it to take into account posterior corneal astigmatism. The paired IS incision arc length ranged from 30–70°.

All procedures were performed by one surgeon (DDK) using the Catalys laser. The laser treatment steps in sequence were capsulotomy (4.8 mm diameter), lens fragmentation

(quadrants), and then the IS incisions at the intended meridian. The programmed IS incision parameters were 20% uncut anterior, 20% uncut posterior, and 90° side cut angle at a 8.0 mm optical zone (Figure 1 top left and top right).

Intrastromal incision location evaluation using anterior segment OCT

Three weeks or more postoperatively, the OCT was used to assess the location of the IS incision in the corneal stroma. OCT scans were performed by one of two examiners (LW and a research coordinator). With the RTVue device, the cross line scan mode was used to scan the IS incision. The cross line (6 mm in length) was first rotated to the IS incision meridian. For example, if paired IS incisions were placed at 120°, the cross line was rotated along the semimeridian of 120° to search for the IS incision with the center of the cross line aligned at the mid-periphery of the cornea. In the first few eyes, we scanned the center and at both ends of the incision, and we noted that the IS incision architecture was similar at the center and at both sides of the incision; therefore, for subsequent cases, we took scans near the center of the incision only. Three scans were taken for each IS incision, and the one with the clearest image of the IS incision was chosen for analysis.

Using RTVue's built-in calipers, we measured the distances between the following: 1) the anterior corneal surface to the most anterior aspect of the IS incision, 2) the most posterior aspect of the IS incision to the posterior corneal surface, and 3) the anterior corneal surface to the posterior corneal surface parallel to the IS incision (Figure 1 bottom left). Additionally, we also measured the side cut angle by: 1) placing a line overlapping the IS incision (IS incision line), 2) extending the IS incision line passing the anterior corneal surface, 3) placing a tangent line to the anterior cornea at the point where the IS incision line crosses the anterior corneal surface, and 4) measuring the angle between the IS incision line and the tangent line toward the center of the cornea (Figure 1 bottom right). One examiner (the research coordinator) performed the distance and angle measurements on all OCT scans.

Data Analysis

Parameters evaluated—Based on the measurements obtained from the OCT scans, four parameters were evaluated:

1. % uncut anterior: the percent of IS incision uncut anteriorly was calculated. The mean value was compared to the planned 20% uncut anterior;
2. % uncut posterior: the percent of IS incision uncut posteriorly was calculated. The mean value was compared to the planned 20% uncut posterior;
3. % midpoint depth: midpoint location depth of the IS incision from the anterior corneal surface was calculated. The mean value of the midpoint depth was compared to the planned value of 50%; and
4. Side cut angle: the angle of the IS incision in degrees was recorded and compared to the planned angle of 90 ° relative to the corneal surface.

For data analysis, all IS incisions scanned by the OCT were included in the whole group. In the subgroup, one IS incision from each eye was included. In eyes with both IS incisions

scanned, the first incision that was scanned by the OCT was included in this subgroup analysis.

Statistical analysis—SPSS for Windows (version 12.0) was used, and a probability of less than 5% ($P < 0.05$) was considered statistically significant. Data distribution for normality was confirmed. One sample t-test was used to assess if the mean values of % uncut anterior, % uncut posterior, % midpoint depth, and ° side cut angle were significantly different from their planned values. Correlation analysis was performed to investigate the association of % midpoint depth and ° side cut angle between the paired IS incisions in each eye. For this analysis, the IS incision located inferiorly, inferior-temporally, or temporally was defined as IS incision #1, and the other paired IS incision was deemed as IS incision #2.

RESULTS

We included 77 eyes of 77 patients. The mean age was 70 ± 8 years (range 47 to 85 years). Of the 77 eyes, 50 eyes had paired IS incisions visualized and imaged by OCT, and 27 eyes had only one IS incision scanned by the OCT.

In the whole group, 127 IS incisions were scanned by the OCT (two incisions from each of the 50 eyes and one incision from the 27 eyes). The mean values were $17.2\% \pm 5.8\%$ for uncut anterior, $32.5\% \pm 8.8\%$ for uncut posterior, and $42.3\% \pm 6.6\%$ for midpoint depth (Table 1). These mean values were all significantly different from their planned values (all $P < 0.05$). Figure 2 shows that the majority of eyes had a midpoint depth that was more anterior than the planned depth of 50%. The mean value for side cut angle was $88.5^\circ \pm 5.6^\circ$ and was significantly different from the planned value of 90° ($P < 0.05$). Figure 3 shows the distribution of the side cut angle.

In the subgroup with one IS incision from each eye, 77 IS incisions from the 77 eyes were scanned by the OCT. The mean values for uncut anterior, uncut posterior, and midpoint depth were all significantly different from their planned values (all $P < 0.05$). The mean value for side cut angle was not significantly different from the planned value of 90° ($P > 0.05$) (Table 1).

In eyes with paired IS incisions scanned by the OCT, there was no correlation between the paired IS incisions for midpoint depth and side cut angle (Pearson correlation coefficient $r = -0.063$ and -0.067 , respectively, both $P > 0.05$) (Figures 4 and 5).

DISCUSSION

The effectiveness of femtosecond-assisted penetrating arcuate keratotomy and IS astigmatic keratotomy combined with cataract surgery have been reported.^{8–10} To our knowledge, this is the first study to investigate the achieved IS incision depth postoperatively using anterior segment OCT and compare the achieved IS incision location postoperatively to the intended location.

Our results show that the IS incision midpoint depth was located significantly more anteriorly than the planned depth of 50% from the anterior corneal surface. The mean IS

incision midpoint depth was 42.3%, with a SD of 6.6%, indicating that approximately 95% of eyes had an IS midpoint depth between 29.1% and 55.6%, which was a statistically, and, we believe, clinically significant finding. On the other hand, although the achieved mean side cut angle of 88.5° in the whole group was statistically different from the planned value of 90°, we believe the deviation of 1.5° on average is not clinically significant. Results from the subgroup with one IS incision in each cornea were similar to the whole group, except that the mean side cut angle was not significantly different from the planned value. We also explored the association of the achieved location between the paired IS incisions in each eye. The midpoint depth and the side cut angle between the paired IS incisions in each eye were not significantly correlated.

In a video review of 28 consecutive eyes of 25 patients who underwent intrastromal limbal relaxing incisions using the Catalys laser, Haque and colleagues¹¹ evaluated the incidence of microperforations, which they defined as the appearance of one or more air bubbles either at the epithelial layer or in the overlying liquid interface. All intrastromal incisions were set within 0.5 mm of the limbus with planned depth of 20% of the cornea left uncut anteriorly and posteriorly. Of the 28 eyes, 19 had one IS incision and 9 had two IS incisions. Microperforations were noted in 19 of the 28 eyes. No posterior or full-thickness perforations were noted. Cherfan and Melki¹² reported the occurrence of a full-thickness incision in a case with planned parameters of 20% below the epithelium and 20% above the endothelium.

In eyes after penetrating keratoplasty, Wetterstrand and colleagues¹³ evaluated the correlation between the efficacy of femtosecond laser-assisted intrastromal relaxing incisions and the posterior depth of corneal incisions. Using the IntraLase femtosecond laser, paired IS arcuate incisions were made inside the graft stroma, leaving 90 µm of intact anterior cornea including epithelium. The programmed intact posterior corneal margin was 10% of the measured corneal thickness for 10 patients (10% group, presumably around 55 µm), and 125 µm for 10 patients (125-µm group). The refractive cylinder decreased by 34% in the 10% group, but did not change in the 125-µm group, presumably due to the shallower incision depth.

In our study, we did not evaluate the incidence of microperforations, but we did observe the appearance of air bubbles at the epithelial layer in some cases. For some incisions, OCT scans revealed that the distance between the anterior corneal surface to the top of the IS incision was around 50–60 µm, which is approximately the thickness of the corneal epithelium, indicating probable anterior microperforation of the IS incision. No eyes in our study had apparent posterior or full-thickness perforations.

We presume that it is critical to achieve precise IS incision depth to ensure consistent and accurate outcomes in corneal astigmatism reduction, but this needs careful study. Overall incision depth of penetrating femtosecond laser arcuate incisions has been reported as a factor contributing to effectiveness, with deeper incisions with less uncut posterior cornea providing more astigmatic correction.¹⁴ Additionally, these IS incisions may cause architectural changes of the cornea, due to wound repair or other factors. Subsequently, the architectural changes of the cornea may have potential impact on the deviation between the

actual location of IS incisions and the planned parameters. Further study is warranted in this area.

With the Catalys laser, OCT measurements for determining laser delivery for incisions are performed prior to initiating the entire laser treatment. We suspect that the liquid optics interface allows for slight relaxation of the pressure on the eye, allowing the eye to move slightly away from the laser and shift laterally. This would cause incisions to be placed more anteriorly than planned and would explain the lack of correlation between paired incisions in the same eye. The latest laser software provides continuous OCT monitoring but does not allow adjustment of the laser treatment based on the updated OCT imaging. We believe that it would be preferable to program the incisions using the OCT data obtained immediately prior to making them.

This study has certain limitations: 1) only OCT scans near the center of the IS incisions were taken. However, in a small sample of eyes, incision parameters at each end were essentially the same as centrally; 2) OCT scans could not be visualized and measured in one of the paired IS incisions in some cases. The majority of the incisions that could not be visualized were located superiorly and covered by the upper eye lid; no attempt was made to lift the upper eye lid during the OCT scan; 3) the built-in calipers from the OCT were used to manually measure the distances and angles, and interobserver/intraobserver reliability may contribute to errors, especially the angle measurements. In this study, one examiner (the research coordinator) performed the distance and angle measurements on all OCT scans; 4) we did not record intraoperatively the incidence of gas breakthrough, which would indicate intraoperative microperforations as defined by Haque and colleagues¹¹, and 5) we did not correlate incision findings to achieved astigmatic change.

In conclusion, evaluation with the anterior segment OCT revealed that the IS incisions were frequently placed more anteriorly than planned and varied among cases. There was no correlation between the paired incisions in each eye for midpoint depth and side cut angle. Further improvements are needed to ensure precise location of the IS incisions, and further studies are needed to investigate the correlation of IS incisional parameters to the induced astigmatic change.

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Synopsis

Femtosecond laser intrastromal incision midpoint depth was significantly more anterior than the planned depth of 50% and varied among cases.

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Figure 1. Planned parameters from the Catalys femtosecond laser (top left), optical coherence tomography (OCT) image from the femtosecond laser showing the planned intrastromal (IS) incision (top right), image from the OCT device postoperatively showing the achieved location of the IS incision and measurements of the uncut anterior and posterior (bottom left), and OCT image showing the measurement of side cut angle (bottom right).

Figure 2.
Distribution of intrastromal (IS) incision midpoint depth from the anterior corneal surface.
Dash line indicates the planned midpoint depth.

Figure 3. Distribution of intrastromal (IS) incision side cut angle. Dash line indicates the planned side cut angle.

Figure 4. Scatterplot of intrastromal (IS) incision midpoint depth from paired incisions in each eye (Pearson correlation coefficient $r = -0.063$, $P > 0.05$). The red circle represents the planned midpoint depth. The solid line is the equivalent line, and the dotted line is the linear trendline.

Figure 5.

Scatterplot of intrastromal (IS) incision side cut angle from paired incisions in each eye (Pearson correlation coefficient $r = -0.067$, $P > 0.05$). The red circle represents the planned side cut angle. The solid line is the equivalent line, and the dotted line is the linear trendline.

Table 1

Mean $\pm$ standard deviation (SD), minimum (min), and maximum (max) values for uncut anterior, uncut posterior, midpoint depth from the anterior corneal surface, and side cut angle.

	Uncut anterior (%)	Uncut posterior (%)	Midpoint depth (%)	Side cut angle (°)
Planned	20	20	50	90
Whole group (n=127)	17.2 $\pm$ 5.8 [*] 7.2 to 36.9	32.5 $\pm$ 8.8 [*] 6.0 to 57.9	42.3 $\pm$ 6.6 [*] 25.5 to 65.4	88.5 $\pm$ 5.6 [*] 71.0 to 114.0
Subgroup (n=77)	17.5 $\pm$ 5.6 [*] 7.2 to 36.9	31.5 $\pm$ 8.1 [*] 6.0 to 57.7	43.0 $\pm$ 6.2 [*] 28.3 to 65.4	89.1 $\pm$ 6.1 71.0 to 114.0

^{*} Significantly different from planned values (all $P < 0.05$).