Highlights for improving cyclotorsional eye-tracking success rate in femtosecond laser-assisted LASIK with WaveLight EX500 excimer laser

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PURPOSE: To present novel techniques for improving the success rate of cyclotorsional eye-tracking and visual and refractive outcomes following LASIK with an IntraLase 150-kHz femtosecond and WaveLight EX500 excimer laser.

SETTING: Universal Eye Center, Zhongli, Taoyuan, Taiwan.

METHODS: A total of 84 eyes of 47 patients with myopia or myopic astigmatism were enrolled. If patients had dense opaque bubble layers (OBLs) and gas accumulation through the pocket in the perilimbal area impeding cyclotorsional eye-tracking, gentle scraping of the surface with a flap lifter was used to decrease OBL density and gas in the perilimbal area. The flap lifter was also used to cover the gas in the perilimbal area and simulate an enlarged circle delineating the corneal periphery for comparison with reference images. Adequate adjustment of illumination and infrared light facilitated cyclotorsional eye-tracking. Preoperative and postoperative uncorrected distance visual acuity (UDVA), corrected distance visual acuity (CDVA), manifest sphere and cylinder were analyzed.

RESULTS: Eye-tracking was successfully performed in all eyes. The mean ± SD preoperative spherical equivalent (SE) refraction was −5.43 ± 2.28 diopters (D). Three months postoperatively, all eyes maintained or had improved CDVA. UDVA was 20/20 or better in 85%, and 20/40 or better in 100% of the eyes. Overall, 75% and 93% of the eyes had SE refraction within ±0.5 D and ±1.0 D, respectively. The mean magnitude of cyclotorsion was 2.40 degrees ± 1.89 (range 0.0 to 9.0 degrees).

CONCLUSION: The novel methods improved eye registration success and cyclotorsional eye-tracking using the WaveLight EX500 excimer laser.

J Emmetropia 2016; 2: 85-93

Femtosecond lasers have become a commonly used technology for the creation of corneal flaps during refractive surgery.

Submitted: 6/19/2016
Accepted: 7/23/2016

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Financial Disclosure: The authors have no proprietary or commercial interest in any of the materials discussed in this article.

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The advantages of femtosecond lasers over mechanical microkeratomes for flap creation include greater predictability of flap thickness and diameter, improved astigmatic neutrality, decreased incidence of flap injury, and stronger flap adhesion1-3.

Femtosecond lasers create corneal flaps using photodisruption, in which each laser pulse creates a gas bubble within the corneal stroma. An opaque bubble layer (OBL), creating a diffuse opacity, may form in the corneal stroma if the collection of gas bubbles becomes trapped. The reported incidence of OBL ranges from 5% to 56.4%4-6. Gas situated in the pocket between the hinge and limbus in the perilimbal area is often seen beneath the corneal flaps created using IntraLase femtosecond laser (Abbott Medical Optics), and may interrupt the eye registration process.

The development of cyclotorsional eye-tracking systems has led to major advances in excimer laser procedures. Eyes can move and cyclorotate from the upright to supine position and also during the excimer laser ablation. Cyclotorsion of the eye during laser in situ keratomileusis (LASIK) can lead
to decreased correction of astigmatism and worsen visual and refractive outcomes8. Cyclotorsional eye-tracking systems have been shown to improve refractive predictability and efficacy9.

However, dense OBL that masks pupil or iris characteristics could cause failure of iris registration and subsequent cyclotorsional tracking. Furthermore, gas accumulation in the perilimbal area through the pocket may obscure the architectural landmarks of the iris and prevent the automatic iris detection from working, thereby interrupting the excimer laser surgery. The efficacy of LASIK for the correction of visual acuity and refractive cylinders may be decreased when the cyclotorsional eye trackers are inactive during the procedure8.

In the present study, we describe novel techniques for overcoming intraoperative failure of cyclotorsional tracking while using an IntraLase 150-kHz femtosecond and EX500 excimer laser, and their utility in improving postoperative visual acuity and refraction.

**PATIENTS AND METHODS**

In this retrospective study, consecutive patients undergoing LASIK with femtosecond laser flap creation from March 2014 to May 2014 at Universal Eye Center, Zhongli, Taoyuan, Taiwan were evaluated. All patients received a thorough explanation of the risks and benefits of LASIK, including a discussion of nonsurgical alternatives. The present study was approved by the Institutional Review Board of Antai Tian-Sheng Memorial Hospital (15-026-B1).

**Inclusion–Exclusion Criteria**

All patients enrolled in the present study had no history of previous ocular surgery and had discontinued contact lens use (if present) for at least 1 week. Prior to intervention, a complete preoperative ophthalmologic evaluation ensured the absence of current or previous ocular pathology other than refractive error. Additional inclusion criteria were as follows: minimum age of 18 years and planned residual stromal bed thickness of at least 275 μm.

Exclusion criteria for LASIK were as follows: systemic or ocular diseases, history of corneal dystrophy or herpetic eye disease, topographic evidence of ectatic corneal disorder/keratoconus, corneal warpage from contact lens use, glaucoma, severe dry eye, and collagen vascular diseases.

All patients underwent a baseline ophthalmic examination that included measurements of uncorrected distance visual acuity (UDVA) and corrected distance visual acuity (CDVA), manifest and cycloplegic refraction, keratometry (K), corneal topography (OPD-Scan III, Nidek) and tomography (Allegro Topolyzer Vario, WaveLight, Alcon Laboratories), corneal pachymetry (Allegro Topolyzer Vario, WaveLight, Alcon Laboratories), pupil size (OPD-Scan III, Nidek), intraocular pressure (Nidek), slit lamp biomicroscopy, and dilated fundus examination. UDVA, manifest refraction and slit lamp biomicroscopy were repeated at 1-week, 1-month, and 3-month postoperative visits.

**Surgical technique**

All eyes underwent myopic LASIK surgery performed by the same surgeon (HYL). Corneal flaps were created with a 150-kHz IntraLase femtosecond laser (Abbott Medical Optics). The attempted flap thickness was 100 μm. The elliptical flap diameter was 9.00 × 8.65 mm. Other laser parameters were temporal hinge, angle of 60 degrees, mean bed energy of 0.95 μJ, spot separation of 7 μm, line separation of 7 μm, side-cut energy of 1 μJ, side-cut angle of 110 degrees, pocket width of 0.25 mm, initial pocket depth of 230 μm, and pocket tangent and radial spot separation of 7/7 μm.

Excimer laser ablation was performed using a WaveLight EX500 excimer laser (WaveLight, Alcon Laboratories) at a pulse repetition rate of 500 Hz. The eye tracker scanning rate of the EX500 was 1050 Hz, synchronized to the 500-Hz repetition rate of the scanning spot, with a latency time of 2 milliseconds. Ablation was centered on 70% of the distance from the pupil center to the apex (which was a misnomer in the EX500 that in fact meant corneal vertex). The Custom-Q profile with a plano refraction target was used in all patients, and treatment was based on manifest refraction. Cyclotorsional eye registration was attempted in all patients.

**Novel methodology for improving cyclotorsional eye-tracking success rate**

**Preoperative**

The Allegro Topolyzer Vario captured two-dimensional images of the anterior segment that included the cornea, pupil, and iris. The pupil center and limbus locations were also determined. Some patients demonstrated “Too few suitable iris structures detected” that could lead to a decreased tracking success rate (Figure 1).

Operators selected the best reference image for registration and paid close attention to keratometry values and axis, iris images, pupil diameter, and pupil center coordinates relative to the apex (expressed as “Pupil Dec. X/Y” in the EX500) (Figure 2).

**Intraoperative**

After flap creation and lifting, the following three steps were required for successful cyclotorsional eye-tracking.

**Step 1. Automatic limbus fit: Measurement of iris size**

OBL in the perilimbal area might cause the EX500 excimer laser to erroneously detect the iris as smaller and return the “Difference of iris size between diagnostic
Figure 1. Normal photo capture in the right eye. The “Too few suitable iris structures detected” error was shown during examination of the left eye with the Topolyzer Vario.

Figure 2. Selection of a good reference image for registration with consideration of keratometry values and axis, iris images, pupil diameter, and pupil center coordinates relative to the apex (expressed as “Pupil Dec. X/Y” in the EX500).
image and current image is too large” error message. Gentle scraping of the stromal surface with a flap lifter could decrease OBL density and gas accumulation in the perilimbal area (Figure 3).

The initial use of a flap lifter might increase the automatic iris size (white-to-white) detection rate. If the previous method failed, and the same error message occurred, the flap lifter was used to cover the gas accumulation in the perilimbal area, simulating an enlarged circle delineating the corneal periphery, to allow successful comparison with the reference iris image (Figure 4).

**Figure 3.** Left-upper panel shows an example of the “Difference of the iris size between diagnostic image and current image is too large” error. After gentle scraping of the surface with the flap lifter (right-upper panel) to decrease the density of the gas in the perilimbal area (red arrow in left-lower panel), the iris size (white-to-white) can be successfully detected.

**Figure 4.** The flap lifter can be used to cover the gas accumulation in the perilimbal area (red arrow in right-upper panel) to simulate an enlarged circle delineating the corneal periphery (green arrows in right-upper panel) to allow successful comparison with the reference iris image if the “Difference of the iris size between diagnostic image and current image is too large” error occurs.
Step 2. Adapt pupil size: Pupil diameter matching
The diameter of the pupil was continuously measured under the laser and controlled by adjusting the illumination level to match the reference pupil image as closely as possible.

Step 3. Adjust PCS/CC: Pupil center shift compensation and cyclotorsion alignment
On beginning step 3, the most common issue was the inability to detect the “CTA angle” with the bottom column showing “Confirm with OK.” This issue might result for several reasons. First, dense OBL would obscure the iris from being imaged. Second, a different pupil size from the reference image could change the iris characteristic markers. Third, too few suitable iris structures detected with the Topolyzer Vario (Figure 1) would cause CTA angle detection failure. Adjusting the infrared light level could enhance the contrast of the iris image and overcome the interference of OBL (Figure 5). A proper illumination level helped to obtain the intraoperative pupil size similar to the reference one, and retain the iris characteristic markers. However, failure to detect suitable iris structures with the Topolyzer Vario would make the determined pupil margin on the monitor become yellow and CTA angle detection invalid (Figure 6). This situation represents registration failure.
The locations of the photopic pupil center and apex were determined preoperatively with the Topolyzer Vario. During PCSC, the difference between the live location of the pupil center to the limbus and the one recorded with the Topolyzer Vario was measured and expressed in Cartesian coordinates. The angle of cyclotorsion was calculated and shown in degrees. If the PCSC (X, Y) distances were less than 100 microns, their values were then added to the distance between the pupil center and apex (pupil shift compensation) measured with the Topolyzer Vario. If the distances were greater than 100 microns, the values were not added to the distance between the pupil and apex (Figure 7). We then set the center of ablation at 70% of the distance from the pupil center to apex. Finally, the excimer laser was applied as usual.

Statistical analyses

Descriptive statistics for each variable were calculated. The preoperative and postoperative visual acuity and astigmatism profiles are presented as means ± SD. All data were analyzed using PSPP 0.8.4 (Free Software Foundation) and Microsoft Excel 2013 (Microsoft).

### Results

#### Baseline patient demographics

Table 1 shows the demographic data of all treated eyes. The study consisted of 25 female and 22 male patients. There were 42 right eyes and 42 left eyes. Mean patient age was 32.4 ± 7.6 years (range, 18 to 46 years). Mean preoperative spherical error was −4.95 ± 2.24 D (range, −0.75 to −9.50 D). Mean preoperative cylindrical error was −0.95 ± 0.82 D (range, 0 to −4.25 D). Mean preoperative spherical equivalence (SE) was −5.43 ± 2.28 D (range, −1.00 to −10.25 D).

#### Intraoperative eye registration

Intraoperative cyclotorsional eye registration was successful in 84 eyes (100%). All eyes were matched to preoperative diagnostic images. Ablation center shift to 70% of the distance from the pupil center to the apex and cyclotorsion alignment was successfully accomplished in all patients. The mean absolute value of the CTA angle in the present study was 2.40 ± 1.89 degrees (range, 0 to 9 degrees). No patient in the present study encountered failure of cyclotorsional eye-tracking due to too few suitable iris structures being detected during the preoperative period.

#### Efficacy and safety

Figure 8, A shows the efficacy expressed as Snellen visual acuity. A preoperative CDVA of 20/20 was observed in 74 of the 79 eyes (94%). A postoperative UDVA of 20/20 or better at 3 months was observed in 70 eyes (85%). A preoperative CDVA of 20/40 was observed in 100% of the eyes. A postoperative UDVA of 20/40 or better was observed in all eyes at 1 month and 3 months.

Figure 8, B shows no eyes (0%) lost CDVA, 4 eyes (5%) gained 1 line, and 1 eye (1%) gained 2 lines at 3 months.
Refractive predictability and stability

The attempted versus achieved SE refraction for all eyes is shown in Figure 8, C. At 3 months, 63 eyes (75%) were within 0.5 D of the attempted refractive change and 78 eyes (93%) were within 1.0 D (Figure 8, D).

Seventy-six eyes (90%) had residual astigmatism within 0.5 D and 82 eyes (98%) within 1.0 D (Figure 8, E). The mean postoperative SE was $-0.12 \pm 0.59$ D (range, $+1.50$ to $-2.00$ D) at 1 month and $-0.20 \pm 0.53$ D (range, $+1.25$ to $-1.75$ D) at 3 months (Figure 8, F).
DISCUSSION

Cyclotorsional movement is defined as the rotational movement of the eye around the visual axis. The mean cyclotorsional movements observed during refractive surgery procedures have been reported to be approximately 3 degrees\(^\text{10}\). The mean absolute value of the CTA angle in the present study was 2.41 ± 1.90 degrees (range, 0 to 9 degrees). Iris registration has been successful as a potential method to compensate cyclotorsional misalignments\(^\text{11}\), and may be useful in ensuring that ablation is delivered to the intended location to improve postoperative visual acuity and decrease astigmatism\(^\text{9,12,13}\).

Photodisruption generated by the femtosecond laser creates gas bubbles that dissipate throughout the cornea resulting in a cleavage plane. The expanding gas bubbles migrate through the path of least resistance within the cornea and may occasionally be retained as OBL. OBL tends to form under conditions such as a thickened cornea, hard-docking, or a steeper cornea, possibly attributable to increased corneal rigidity and resistance in these situations\(^\text{4,6}\). The incidence of OBL has been reported to be 56.4\% and 52.5\% using the IntraLase 15-kHz and 60-kHz femtosecond laser systems, respectively\(^\text{5,6}\). Jung et al.\(^\text{4}\) reported a lower incidence of OBL of 5\% using the newer Visumax 500-kHz femtosecond laser.

Dense OBL and gas accumulation in the perlimbal area may interfere with the cyclotorsional eye-tracking system during excimer laser ablation\(^\text{5}\). The EX500 excimer laser attempts to match the iris size (white-to-white) with the preoperative eye images from the first step of eye registration. Gas situated in the pocket between the hinge and limbus in the perlimbal area may interrupt the eye registration process and thereby inactivate the eye tracker in the following excimer laser ablation. As maintained activation of the cyclotorsional eye tracker can improve postoperative visual acuity and astigmatism correction results\(^\text{1,4,14}\), there is a clinical need to overcome interruption of the eye tracker by dense OBL or gas accumulation in the perlimbal area.

The present study highlights the importance of selecting a good reference image preoperatively. Several measurements are taken and provide information on pupil diameter, keratometry values and axes, and location with respect to the apex. The intraoperative key points are as follows:

1. Gentle scraping of the stromal surface with a flap lifter can decrease OBL density and gas accumulation in the perlimbal area. The initial use of a flap lifter may increase the automatic iris size (white-to-white) detection rate.

2. Using a flap lifter to cover the gas accumulation in the perlimbal area can be used to simulate an enlarged circle delineating the corneal periphery for comparison with the reference image.

3. Adjustment of the illumination to ensure pupil diameters are as close as possible to the reference pupil image.

4. Adequate infrared light to enhance the contrast of the captured iris characteristic markers for matching with the reference image.

Adjustment of illumination to ensure live pupil diameter values are as close as possible to the reference pupil image, and adequate infrared lighting to optimize intraoperative imaging of the iris characteristic markers and facilitate the registration process are important during the second and third steps of eye registration.

With the use of novel methodology to improve cyclotorsional eye-tracking success rates, we achieved a higher eye-tracking success rate of 100\%. Previous studies have reported eye-tracking success rates ranging from 57\% to 90.5\% with the IntraLase 60-kHz femtosecond and Zyoptix 100-Hz excimer laser systems\(^\text{7,15,16}\). In the present study, we demonstrated refractive efficacy, safety, and predictability in correcting visual acuity and myopic astigmatism comparable to the results achieved using different excimer laser platforms reported by previous studies\(^\text{1,13-19}\).

In conclusion, in patients in whom OBL or gas accumulation in the perilimbal area interferes with the eye tracker, initial gentle scraping of the surface with the flap lifter decreases OBL density and gas accumulation in the perilimbal area and increases the automatic iris size (white-to-white) detection rate. Using a flap lifter to cover the gas accumulation in the perilimbal area can simulate an enlarged circle delineating the corneal periphery, improving the success rate of eye registration and subsequent tracking. Adjustment of illumination and infrared light can be used to control pupil diameter and enhance captured iris characteristic markers for matching with the reference image. Good postoperative visual acuity and astigmatism results were obtained in the present study that were comparable to previous studies.

REFERENCES


