This article has been amended to include a factual correction. An error was identified subsequent to its original printing (J Refract Surg. 2012;28(5):358-362), which was acknowledged in an erratum (J Refract Surg. 2012;28(7):449). The online article and its erratum are considered the version of record.

Effect of Limbal Marking Prior to Laser Ablation on the Magnitude of Cyclotorsional Error

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ABSTRACT

PURPOSE: To evaluate the residual registration error after limbal-marking-based manual adjustment in cyclotorsional tracker-controlled laser refractive surgery.

METHODS: Two hundred eyes undergoing custom surface ablation with the iVIS Suite (iVIS Technologies) were divided into limbal marked (marked) and non-limbal marked (unmarked) groups. Iris registration information was acquired preoperatively from all eyes. Preoperatively, the horizontal axis was recorded in the marked group for use in manual cyclotorsional alignment prior to surgical iris registration. During iris registration, the preoperative iris information was compared to the eye-tracker captured image. The magnitudes of the registration error angle and cyclotorsional movement during the subsequent laser ablation were recorded and analyzed.

RESULTS: Mean magnitude of registration error angle (absolute value) was 1.82°±1.31° (range: 0.00° to 5.50°) and 2.90°±2.40° (range: 0.00° to 13.50°) for the marked and unmarked groups, respectively ($P<.001$). Mean magnitude of cyclotorsional movement during the laser ablation (absolute value) was 1.15°±1.34° (range: 0.00° to 7.00°) and 0.68°±0.97° (range: 0.00° to 6.00°) for the marked and unmarked groups, respectively ($P=.005$). Forty-six percent and 60% of eyes had registration error >2°, whereas 22% and 20% of eyes had cyclotorsional movement during ablation >2° in the marked and unmarked groups, respectively.

CONCLUSIONS: Limbal-marking-based manual alignment prior to laser ablation significantly reduced cyclotorsional registration error. However, residual registration misalignment and cyclotorsional movements remained during ablation. [*J Refract Surg*. 2012;28(5):358-362.]
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Incorrect placement of the ablation due to ocular cyclotorsion during laser refractive surgery has been identified to cause undercorrection, or even induction of astigmatism and/or higher order aberrations, leading to deterioration of the postoperative optical quality of the eye.[1] Ocular cyclotorsion may result from body movement, such as shifting from seated to supine positions, head tilting, head rotation, autorotation, and distortion of the globe by the lid speculum.[2,3] Manual limbal marking and subsequent eye and laser astigmatic-axis alignment have been used to ameliorate cyclotorsional misalignment. Some studies have shown this technique improved the outcome of astigmatic correction,[4] whereas others have shown no effect.[1]

Iris-recognition technology has recently been introduced[5] and implemented into cyclotorsional eye trackers that continuously scan the iris for preoperatively acquired landmarks and adjust the placement of the laser beam to match those landmarks. Such a system was applied in the current study to evaluate the magnitude of cyclotorsional registration error in eyes with and without previous limbal-marking-based manual adjustment. In addition, we quantified the magnitude of cyclotorsional error that takes place during the laser ablation to evaluate the necessity for dynamic cyclotorsional eye tracking.

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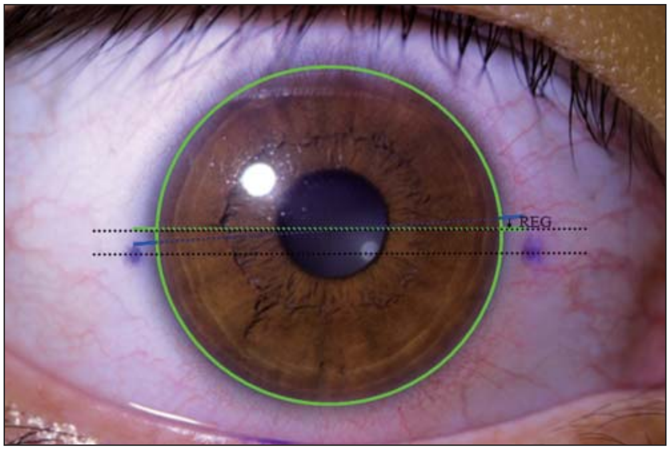

Figure 1. Registration (REG) angle represents the rotational angle from the blue line (the cyclotorsional position acquired during preoperative Precisio examination) to the green line (the cyclotorsional position at the moment registration is achieved); blue line being used as 0 point.

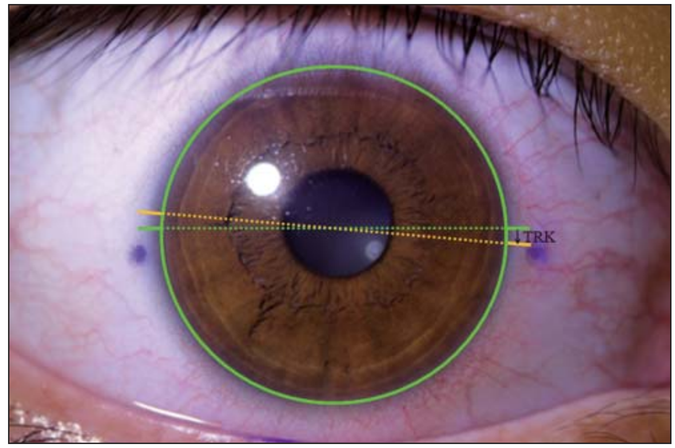

Figure 2. Dynamic tracking (TRK) angle represents the rotational angle from the green line (the cyclotorsional position at the moment registration is achieved) to the yellow line (cyclotorsional position during laser ablation); green line being used as 0 point.

PATIENTS AND METHODS

Two hundred eyes from 100 consecutive patients who underwent the topography-guided custom transepithelial "no-touch" technique (cTEN) for correction of refractive error were observed. The iVIS Suite integrated system (iVIS Technologies, Taranto, Italy) consisting of a Scheimpflug-based topo/tomographer (Precisio), dynamic pupillometer (pMetrics), ablation planning software (Corneal Interactive Programmed Topographic Ablation), and excimer laser (iRES) was used for treatments. Patients were randomly assigned to limbal-marked (marked group, 100 eyes from 50 patients) and non-limbal-marked (unmarked group, 100 eyes from 50 patients) groups using a randomization table generated by an online randomizer. This study was approved by the regional ethics committee of north Norway and adhered to the tenets of the Declaration of Helsinki.

Preoperative iris-pattern images were acquired from all eyes by the Precisio topo/tomographer along with corneal topo/tomography for use in custom ablation planning. Preoperatively, reference marks for the horizontal axis in the marked group were placed on the limbus at the 3- and 9-o'clock positions (Fig 1), with patients in a sitting position and their right and left eyes leveled to the same height. A slit-lamp, with its slit rotated to the horizontal position, was used to define the points to be marked. The marked patients were then moved under the laser to a supine position, and the limbal marks were aligned with the horizontal line of the projected laser cross by adjusting the patient's head tilt. Neither limbal marking nor adjustment of the head position was performed in the unmarked group. Automatic cyclotorsional registration of the iris pattern acquired by the laser camera was performed on all eyes prior to laser ablation. During the registration procedure, the cyclotorsional-tracker software compared the iris pattern acquired during the preoperative examination to the current live image to identify the eye. It also calculated the angular difference in cyclotorsional position, using the preoperative data as a 0 point (see Fig 1). The angular difference is displayed as "REG" (registration) angle with "+" as clockwise cyclotorsional error (incyclotorsion for the right eye and excyclotorsion for the left eye), and "−" as counterclockwise cyclotorsional error.

After registration, the active online cyclotorsional eye tracker continuously monitored the cyclotorsional movements and compensated for the error throughout the laser ablation. The magnitude of cyclotorsion during the ablation was displayed as "TRK" (dynamic tracking) angle (Fig 2), and used the cyclotorsional position of the eye at the moment of the initial registration as 0 (reference) point. The maximum value was recorded for each direction and the amplitude of the TRK was calculated.

The current eye tracking system includes an active x-y tracker, a passive z tracker, and a cyclotorsional tracker. The cyclotorsional eye tracker uses a separate computer and works independently of the x-y and z tracking system. To minimize pupillary centroid shift, the illumination device automatically adjusts the illumination of the surgical field to induce constriction or dilation of the pupil to match the pupil size of the reference image. Cyclotorsion of the eye is recognized as a change of angular position of the iris structure encircling the pupil, and is actively followed by the cyclotorsional eye tracker with an angle resolution of 0.5°.

Statistical Analysis

Statistical analysis was performed using Microsoft Office Excel 2003 (Microsoft Corp, Redmond, Washington) and SPSS 13.0 (SPSS Inc, Chicago, Illinios).

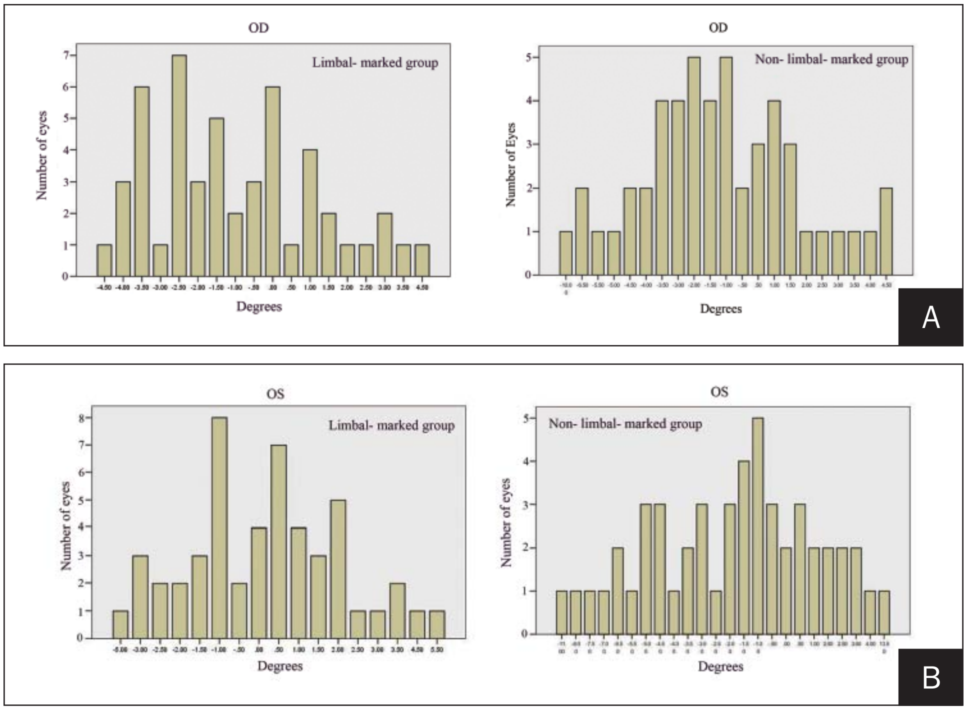

Figure 3. Frequency distribution of REG angle in **A)** right (OD) eyes and **B)** left (OS) eyes in the limbal-marked and non-limbal-marked groups.

Absolute values were used when analyzing the magnitude of the cyclotorsional movement. Results were expressed as mean±standard deviation. Student *t* test was used for comparisons of the data sample means and $P \leqslant .05$ was considered statistically significant.

RESULTS

Preoperative Patient Demographics

Mean patient age was 35.12±8.81 years (range: 20 to 57 years) for the marked group and 33.08±6.88 years (range: 20 to 50 years) for the unmarked group. Mean manifest spherical error was −2.47±1.60 diopters (D) (range: −7.75 to +1.75 D) and −2.58±1.59 D (range: −6.25 to +0.50 D) for the marked and unmarked groups, respectively. Mean manifest cylindrical error was −0.80±0.63 D (range: −3.25 to 0.00 D) and −0.61±0.42 D (range: −1.75 to 0.00 D) for the marked and unmarked groups, respectively.

Registration Error

Mean magnitude (absolute value) of REG angle was 1.82°±1.31° (range: 0.00° to 5.50°) and 2.90°±2.40° (range: 0.00° to 13.50°) for the marked and unmarked groups, respectively ($P < .001$). In the marked group, 34% of eyes exhibited incyclotorsional error, 56% exhibited excyclotorsional error, and 10% did not demonstrate any cyclotorsional error (Fig 3). In the unmarked group, 52% of eyes displayed incyclotorsional error, 46% displayed excyclotorsional error, and 2% did not demonstrate any cyclotorsional error (see Fig 3). Forty-six percent of eyes presented cyclotorsion >2° and 2% of eyes presented cyclotorsion >5° in the marked group compared to 60% and 16%, respectively, in the unmarked group.

Cyclotorsion During Laser Ablation

The absolute value of the TRK angle at the moment of the onset of laser ablation was 0.64°±0.66° (range: 0.00° to 3.00°) and 0.56±0.64° (range: 0.00° to 3.50°) for the marked and unmarked groups, respectively ($P = .387$). During ablation, mean maximum cyclotorsional angle was 1.15°±1.34° (range: 0.00° to 7.00°) and 0.68°±0.97° (range: 0.00° to 6.00°) for the marked and unmarked groups, respectively ($P = .005$). In the marked group, 22% of eyes rotated >2° during ablation and 3% rotated >5°. In comparison, 10% rotated >2° and 1% rotated >5° in the unmarked group.

Total Cyclotorsion

The sum of REG and TRK angle values represents the total cyclotorsional error during ablation using preoperative cyclotorsional position data as 0 point. Maximum absolute cyclotorsion values were 2.66°±1.55° (range: 0.50° to 7.00°) and 3.46°±2.48° (range: 0.50° to 13.50°) for the marked and unmarked groups, respectively ($P = .007$). In the marked group, 69% and 9% of eyes experienced cyclotorsion >2° and >5°, respectively, whereas 75% and 23% of eyes in the unmarked group experienced cyclotorsion >2° and >5°, respectively (Fig 4).

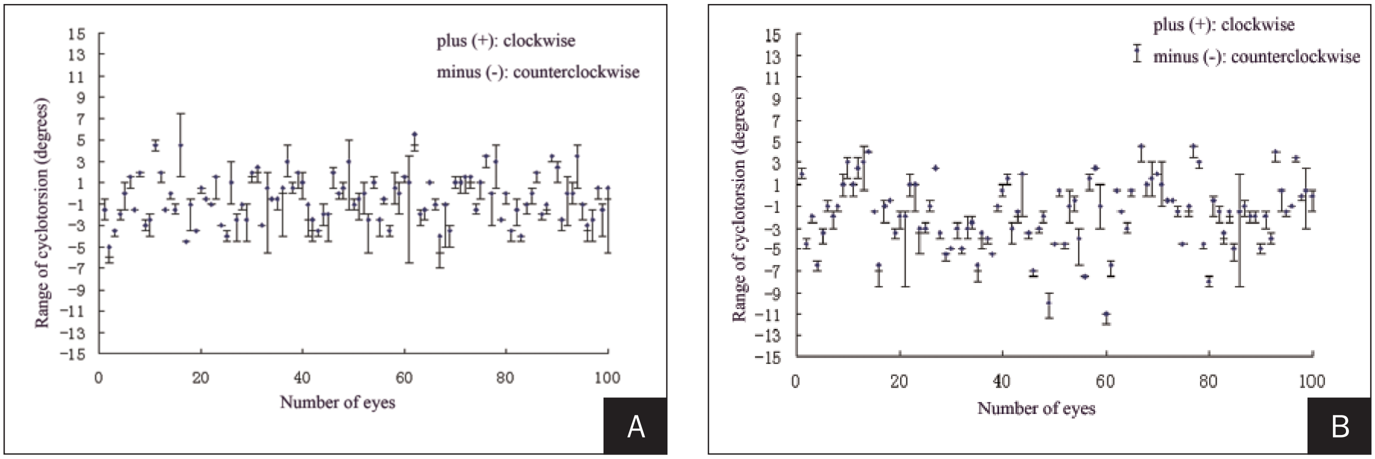

Figure 4. Distribution of total cyclotorsion error in the **A)** limbal marked group and **B)** non-limbal-marked group.

DISCUSSION

As the ablation patterns used in laser treatments become more complex and specific to the eye of the treated individual, the importance of precise registration of those patterns on the cornea increases. Before the iris registration technique was developed, most lasers had an eye tracker device that measured the eye positional movements and adjusted the laser pulse placement in the x-, y-plane. Orthogonal centration is, however, only one requirement for accurate laser delivery. The other is the ability to address cyclotorsional misalignment.[6] Some studies reported significant cyclotorsional errors of $>5°$ or even $>10°$.[3,7] Large cyclotorsional errors can lead to significantly worse outcomes after treatment for astigmatism,[8] as a misaligned ablation can induce astigmatism and higher order aberrations postoperatively. The amount of induced astigmatism is proportional to both the magnitude and frequency of cyclotorsional movements during ablation. Theoretically, the residual astigmatism can be calculated using the formula $C = 2F \times \sin \alpha$, where C is the residual astigmatism, F is the original astigmatic power in diopters, and α is the amount of axis misalignment.[9] Using this formula, a difference of 4°, 6°, and 10° would result in a 14%, 20%, and 35% undercorrection of astigmatism, respectively.

For induction of higher order aberrations, the effect of a displaced ablation is different for each aberration.[10] Guirao et al[10] claimed laser delivery must account for cyclotorsion to an accuracy within 3°. In the majority of cases, the greatest magnitude of cyclotorsion occurs with change from upright to supine position and from binocular to monocular condition.[8,11] To prevent cyclotorsional errors due to positional changes of the body, some surgeons use limbal marking and a subsequent alignment technique.[4] However, the marks can fade and manual methods are prone to human errors. Moreover, even with perfect marking and realignment, dynamic eye rotation, which cannot be addressed by any preoperative adjustment, occurs during the excimer laser ablation procedures. Our study showed that although the REG angle value in the marked group was significantly smaller than in the unmarked group, some residual cyclotorsional registration error remained.

The difference in cyclotorsional eye position between the time of preoperative iris information capture and limbal marking may be one source of error. Incorrect limbal marking and improper eye alignment before the registration are other sources of error. Additionally, inappropriate eye leveling during the preoperative iris information acquisition may lead to a wrong starting point for cyclotorsional error adjustment. These may explain different outcomes in laser astigmatic treatments utilizing limbal marking.[1,4] Similarly, in cases where manifest refraction is used as the basis for treatment of astigmatism, discrepancy between the cyclotorsional position upon subjective refraction (determining the astigmatism axis) and upon iris image capture, may lead to registration error even with an otherwise perfect cyclotorsional-tracking system. This may explain why some studies showed that iris registration and cyclotorsional tracking significantly increased the predictability of astigmatism correction and reduced the induction of higher order aberrations,[12] whereas others showed no significant difference between the outcomes with and without cyclotorsional tracking,[13] or between automated cyclotorsional tracking and manual limbal marking.[14]

Similar to other studies,[15-19] we found that cyclotorsional eye movements caused registration and tracking errors even in limbal-marked and manually compensated eyes. Iris-registration–based eye trackers detect and correct the cyclotorsional errors automatically. However, proper caution must be taken in keeping the same cyclotorsional eye position during preoperative refractive data acquisition and iris pattern acquisition. This is especially important when the treatment of the astigmatism axis is based on subjective refraction.

The current study demonstrated that the limbal marking technique reduces cyclotorsional registration error, implying that it would be beneficial when automated cyclotorsional tracking is not available or in the event the iris-registration technology fails.

AUTHOR CONTRIBUTIONS

Study concept and design (X.C., A.S.); data collection (X.C., F.S., H.O.); analysis and interpretation of data (X.C., J.R.E., S.R., T.P.U.); drafting of the manuscript (X.C., F.S., T.P.U.); critical revision of the manuscript (X.C., A.S., J.R.E., S.R., H.O., T.P.U.); statistical expertise (X.C.); administrative, technical, or material support (X.C.); supervision (A.S., T.P.U.)

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