# Detection of static cyclotorsion and compensation for dynamic cyclotorsion in laser in situ keratomileusis

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**PURPOSE:** To evaluate the degree of static and dynamic cyclotorsion using a rotational eye tracker in laser in situ keratomileusis (LASIK) to correct myopic astigmatism.

**SETTING:** Rothschild Foundation, Paris, France.

**DESIGN:** Cohort study.

**METHODS:** Laser in situ keratomileusis with active iris registration using a Zyoptix 100 Hz excimer laser with Advanced Control Eyetracking was performed in eyes with myopic astigmatism. In all cases, iris registration was used to evaluate the degree of static cyclotorsion preoperatively and the degree of dynamic cyclotorsion and intraoperatively. The direction, mean values, and ranges of static and dynamic cyclotorsion were recorded. The amplitude of intraoperative cyclotorsion was reported.

**RESULTS:** The study included 74 consecutive eyes (38 patients). The direction of cyclotorsion was not statistically significant. The mean static cyclotorsion was 3.08 degrees $\pm$ 2.68 (SD) (range $-7.0$ to 14.0 degrees) and the mean dynamic cyclotorsion, 3.39 $\pm$ 2.94 degrees (range $-10.3$ to 13.5 degrees). During photoablation, the mean amplitude of cyclotorsion was 2.69 $\pm$ 1.63 degrees (range 0.0 to 9.2 degrees). The magnitude of dynamic cyclotorsion was less than 5 degrees in 66% of eyes, 5 degrees or more in 34% of eyes, and 10 degrees or more in 4% of eyes.

**CONCLUSIONS:** Static and dynamic cyclotorsion was detected with a dynamic eye tracker in eyes having LASIK. Rotational movements were mainly static but had significant amplitude during photoablation.

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Different types of unexpected ocular movements can occur during excimer laser refractive surgery. Vertical and horizontal eye movements are the most common, and to a certain extent, they are easily managed by efficient dynamic eye trackers. Rotational movements have also been reported.[1–3] These can happen before surgery when the patient switches from between the upright position and the seated position as well as during the photoablation. These torsional movements, called static and dynamic, respectively, can compromise the refractive outcome, especially in wavefront-guided photoablations and eyes with astigmatism.[4,5]

Wavefront-guided treatments are delivered by small- or variable-spot laser beams with a random photoablation pattern. This delivery system requires an efficient eye-tracking component to optimize the placement of laser pulses and prevent the induction of higher-order aberrations (HOAs) or irregular astigmatism.[3,6]

The results of photoablation for mild to more significant degrees of astigmatism are reported to be excellent.[7–9] The refractive outcome of the cylinder correction depends on the accuracy of the axis treatment. For example, a 10-degree axis shift decreases the efficiency of the desired cylinder correction by more than 30%. Even minimal meridional errors can have significant negative refractive consequences, particularly in cases of moderate to high astigmatism.[7] In

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these cases, manual compensation techniques, such as preoperative limbal marks aligned to the ocular reticule of the laser microscope, are recommended at the time of surgery.[1–3] More recently, rotational eye trackers were developed and are now used as an alternative way to compensate for rotation. Most rotational eye-tracking systems can detect and compensate for static cyclotorsion; some also compensate for dynamic cyclotorsion. Several studies[5,6,8] report satisfactory refractive results with these technologies.

In this study, we report the results of static cyclotorsion and dynamic cyclorotation in eyes having laser in situ keratomileusis (LASIK). Measurements were taken with a dynamic cyclotorsion eye-tracker module incorporated in the excimer laser platform.

## PATIENTS AND METHODS

The study evaluated consecutive eyes that had LASIK surgery for myopia and astigmatism between July and December 2008. The same surgeon (J.L.F.) performed all LASIK procedures at Rothschild Laser Vision Center, Rothschild Foundation, Paris, France.

### Patient Examinations

The preoperative ocular examination included manifest and cycloplegic refractions, corrected distance visual acuity (CDVA), slitlamp biomicroscopy, tonometry, and dilated retinal evaluation. Corneal topography and pachymetry were measured with an Orbscan II scanning-slit system (Bausch & Lomb). Wavefront analysis was performed with a Zywave aberrometer (Bausch & Lomb) under mesopic luminance conditions with a minimum pupil diameter of 6.0 mm. Results of the scanning-slit and aberrometry examinations were uploaded into the laser platform computer and used to set the treatment mode and to allow compensation of static and dynamic cyclotorsion.

Postoperative examinations were performed at 1 week and 1, 3, and 6 months. The examinations included uncorrected distance visual acuity (UDVA), CDVA, slitlamp biomicroscopy, scanning-slit topography, and aberrometry.

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### Surgical Technique

The LASIK procedures were performed using a Zyoptix 100 Hz excimer laser (software version 4.33, Bausch & Lomb) and the incorporated eye-tracking system (Advanced Control Eyetracking). In all cases, the lamellar cut was created with an IntraLase 60 kHz femtosecond laser (IntraLase Corp.). The bed energy was 1.2 μJ with a pulse separation of 6 × 6. The side-cut energy was 2 μJ with a 70-degree angle. The flap was set at 9.2 mm diameter and 120 μm thickness. To eliminate stromal bubbles, the lamellar cuts were created in both eyes first, starting with the right eye, after which iris registration and ablation were performed in the same order.

The eye-tracking system includes an active $x$–$y$ tracker, a passive $z$ tracker, and a static and dynamic rotational eye tracker. The rotational module works independently of $x$–$y$–$z$ tracking, and the static and dynamic tracking systems can function independently. The active $x$–$y$ tracker works at 240 Hz with a range of $\pm$1.5 mm. The eye-tracking system is based on an iris-registration function, which records 3962 data points. The active rotational tracker works at 25 Hz with a range of $\pm$15 degrees; the latency for the last valid image is 0.8 seconds and the angle of resolution, 0.7 degrees.

The static rotational eye tracker was used to evaluate and compensate for rotation between the upright position and supine position. Static cyclotorsion was measured under the laser after the lamellar dissection, before the flap was lifted and the ablation performed. The degree of cyclotorsion is obtained by comparing the 2 iris images acquired with the iris-registration function; the first image is captured with the aberrometer with the patient upright and the other, under the laser. It was often necessary to lift and reposition the flap to dissipate the opaque bubble layer left by the femtosecond lamellar dissection.

The rotational eye tracker was used to evaluate and compensate for intraoperative cyclotorsion during ablation. Dynamic cyclotorsion was measured after the flap was lifted at the beginning of the ablation. The starting dynamic cyclotorsion value corresponds to the mean angle of error of the static cyclotorsion. The angle of error is the magnitude of cyclotorsional error recorded during the ablation and is displayed graphically on the laser screen. The angle of error values recorded were the mean, the maximum cyclotorsional shift in each direction, and the amplitude (absolute sum of the minimum and maximum values). Angles displayed in the laser correspond to the upright-sitting image at the wavefront analyzer. The angles follow polar coordinates, as in topographic systems; the 0-degree meridian corresponds to the 3 o'clock position of the eye. Clockwise rotation is recorded as negative errors of angle, and counterclockwise rotation is recorded as positive errors of angle. In right eyes, positive values (counterclockwise) indicate excyclotorsion and negative values (clockwise) indicate incyclotorsion. In left eyes, positive values (counterclockwise) indicate incyclorotation and negative values (clockwise) indicate excyclotorsion.

The eye-tracking system can be used with tissue-saving, aspheric, and wavefront-guided excimer laser ablation patterns. The treatment program for each eye in this study was selected based on the concordance of wavefront and subjective manifest refractions, the amount of HOA, residual stromal bed (RSB) thickness, and corneal asphericity (Q factor). An optical zone of 6.0 mm or more and an estimated RSB close to 300 μm were considered a priority in all cases.

Wavefront-guided ablation was chosen when the subjective manifest refraction and wavefront refraction were within $\pm$0.75 diopter (D) for sphere, 0.50 D for magnitude of cylinder, and 15 degrees for axis and when the HOA reached 0.35 μm or more. The wavefront ablation was performed with the wavefront axis, 90% cylinder magnitude, and 100% sphere magnitude. The laser manufacturer's nomogram was used without physician adjustments.

Aspherical treatment was preferred if wavefront and subjective refractions did not match and if the Q factor was greater than −0.25. The tissue-saving program was used if wavefront and subjective refractions were not close and if the RSB was less than 300 μm with the 2 other treatment modes.

### Rotation Data

Rotational data recorded included the iris-registration success rate; the mean, lowest, and highest static cyclotorsion measurement; the mean, lowest, and highest dynamic cyclotorsion measurement; and the amplitude of the dynamic cyclotorsion measurement. The direction of cyclotorsion was also evaluated. For static movements, the percentage of right eyes and left eyes separately that had cyclotorsion clockwise and counterclockwise was recorded. For dynamic cyclotorsion, the percentage of right eyes and left eyes separately that rotated clockwise, counterclockwise, or in both directions was recorded.

### Statistical Analysis

Preoperative and 6-month postoperative refractive outcomes are reported. For statistical analysis, the Student *t* test was used for static cyclotorsion, dynamic cyclotorsion, and cyclotorsion amplitude. The Pearson correlation factor was used to assess the correlation between static cyclotorsion measurements and dynamic cyclotorsion amplitude.

## RESULTS

### Preoperative and Surgical Data

The study included 74 eyes of 38 patients (29 women). The mean age of the patients was 29.6 years (range 20 to 42 years). The mean manifest spherical equivalent (SE) was −4.26 D ± 1.98 (SD) (range −1.25 to −7.50 D); the mean manifest sphere, −3.85 ± 1.94 D (range 0.50 to −7.25 D); and the mean manifest cylinder, −0.89 ± 0.59 D (range −0.25 to −3.25 D). Wavefront-guided ablation was performed in 60 eyes, tissue-saving treatment in 12 eyes, and aspheric treatment in 2 eyes.

### Postoperative Refraction

At the 6-month follow-up visit, the mean manifest SE was 0.12 ± 0.31 D (range 0.50 to −0.75 D); the mean manifest sphere, 0.31 ± 0.29 D (range 0.50 to –0.75 D); and the mean manifest cylinder, −0.29 ± 0.29 D (range 0.00 to −1.00 D). In terms of efficacy, all eyes had a UDVA of 20/40 or better and 66 eyes (89%), of 20/20 or better. In terms of predictability, all eyes were within ±1.00 D of emmetropia, 68 eyes (92%) were within ±0.50 D, and 64 eyes (86%) were within ±0.25 D. Two eyes required an enhancement procedure at 3 months for mild myopic residual refractive errors. No eye lost more than 1 line of CDVA.

### Cyclotorsion

**Iris-Registration Success Rate** The iris-registration function was systematically performed under the laser in all eyes. Static rotational eye tracking was unsuccessful in 4 eyes (5%). Dynamic rotational eye tracking failed in the same 4 eyes. Of the 4 eyes, 2 had a pupil diameter larger than 7.0 mm, one had oval pupil dilation under the laser, and the other had remnants of significant superficial stromal bubbles after flap lifting and several iris-image capture attempts.

**Static Cyclotorsion** The mean static cyclotorsion was 3.08 ± 2.68 degrees (range −7.0 to 14.1 degrees), which was statistically significantly greater than 0 degrees ($P<.01$). The cyclotorsion was less than 5.0 degrees in 53 eyes (71%), 5.0 to 9.9 degrees in 19 eyes (26%), and 10.0 degrees or more in 2 eyes (3%) (Figure 1).

Static incyclotorsion occurred in 22 eyes (31%); the mean rotation was 2.9 degrees (range 0.7 to 7.0 degrees). Excyclotorsion occurred in 42 eyes (60%); the mean rotation was 3.6 degrees (range 0.7 to 14.1 degrees). There was no cyclotorsion in 6 eyes (9%).

Of the 37 right eyes, 7 (19%) had incyclotorsion (mean rotation −3.2 degrees; range −0.7 to −7.0 degrees), 28 (76%) had excyclotorsion (mean rotation 3.9 degrees; range 0.7 to 14.1 degrees), and 2 (5%) had no rotation. Of the 33 left eyes, 14 (42%) had excyclotorsion (mean rotation −3.0 degrees; range −0.7 to −7.0 degrees), 15 (46%) had incyclotorsion (mean rotation 2.8 degrees; range 0.7 to 6.3 degrees), and 4 (12%) had no rotation.

**Dynamic Cyclotorsion** The mean dynamic cyclotorsion was 3.39 ± 2.94 degrees (range −10.3 to 13.5 degrees), which was statistically significant ($P<.05$). As noted above, the zero or starting point for calculating the dynamic cyclotorsion values was the static rotational eye-tracker value for each eye (static angle of error). The mean amplitude of dynamic cyclotorsion was 2.69 ± 1.63 degrees (range 0.0 to 9.2 degrees), which was statistically significant ($P<.01$). The rotation was 2 degrees or more in 55 eyes (74%) and 5 degrees or more in 3 eyes (4%) (Figure 2).

The dynamic rotation was less than 5 degrees in 49 eyes (66%), between 5.0 degrees and 9.9 degrees in 22 eyes (30%), and 10 degrees or more in 3 eyes (4%) (Figure 3).

Dynamic incyclotorsion occurred in 16 eyes (23%), excyclotorsion in 11 eyes (16%), mixed cyclotorsion, including incyclotorsion and excyclotorsion, in 43 eyes (61%). Of the 37 right eyes, 26 (70%) had mixed rotation, 7 (19%) had excyclotorsion, and 4 (11%) had incyclotorsion. Of the 33 left eyes, 17 (52%) had mixed rotation, 4 (12%) had excyclotorsion, and 12 (36%) had incyclotorsion.

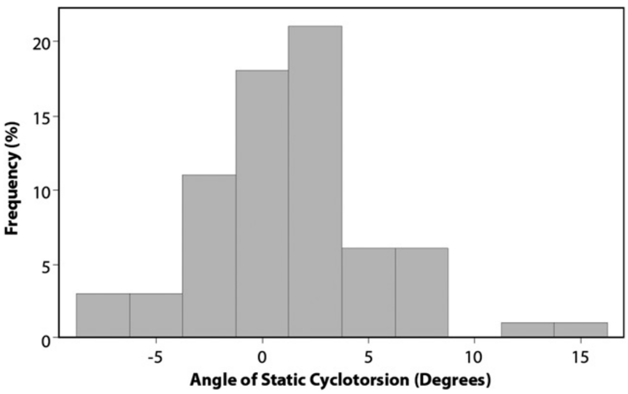


**Figure 1.** Distribution of static cyclotorsion.

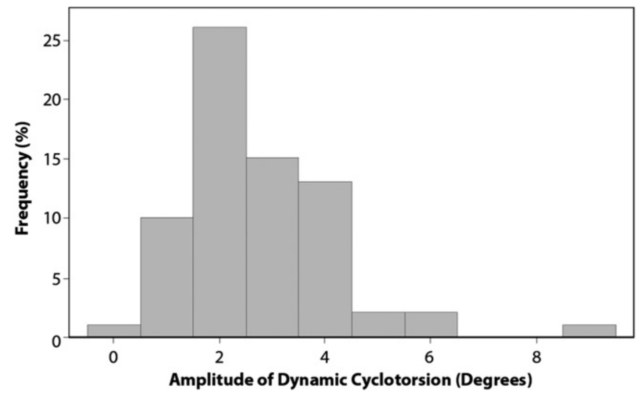


**Figure 2.** Dynamic cyclotorsion amplitude of angle of error.

Considering the mean values of dynamic rotation, incyclotorsion was recorded in 35 eyes (50%); the mean absolute value was 1.11 degrees (range 0.1 to 5.3 degrees). Excyclotorsion was recorded in 29 eyes (41%); the mean absolute rotation was 0.97 degrees (range 0.1 to 3.0 degrees). There was no rotation in 6 eyes (9%).

Of the 37 right eyes, 13 (35%) had incyclotorsion (mean rotation −1.42 degrees; range −0.1 to −5.3 degrees), 19 (51%) had excyclotorsion (mean rotation 0.77 degrees; range 0.1 to 2.8 degrees), and 5 (14%) had no rotation. Of the 33 left eyes, 22 (67%) had incyclotorsion (mean rotation 0.92 degrees; range −0.2 to 3.5 degrees), 10 (30%) had excyclotorsion (mean rotation −1.33 degrees; range −0.7 to 3.0 degrees), and 1 (3%) had no rotation.

There were no statistically significant correlations between static cyclotorsion and dynamic cyclotorsion (Figure 4).

## DISCUSSION

This study showed that static cyclotorsion and dynamic cyclotorsion occurred during LASIK and that they were reliably detected and compensated for by an active rotational eye-tracking system, as shown in other studies.[5,9] In the majority of eyes (66%), the magnitude of dynamic cyclotorsion was less than 5 degrees. However, rotation of at least 5 degrees was found in 34% of eyes and of 10 degrees or more in 4%. Studies[6,8–13] show that rotation of 5 degrees or more can induce significant undercorrection of the astigmatic component of the refraction and that undercorrection is more noticeable as the degree of astigmatism increases.

Regarding refractive outcomes, results in studies evaluating the benefits of stationary rotational eye trackers are discordant.[10,12–18,A] Moshirfar et al.[17] found effective, safe, and predictable refractive results with a static cyclotorsional registration system. However, there was no statistical difference in UDVA, astigmatism correction, or induced HOAs eyes treated with static iris registration and eyes in which it was not used.[17] On the other hand, Kohnen et al.[6] report lower lower-order aberrations and HOAs in patients treated with a static eye tracker. We are aware of 2 peer-reviewed studies[5,13] that evaluated outcomes of dynamic eye tracking. Bharti and Bains[13] found better

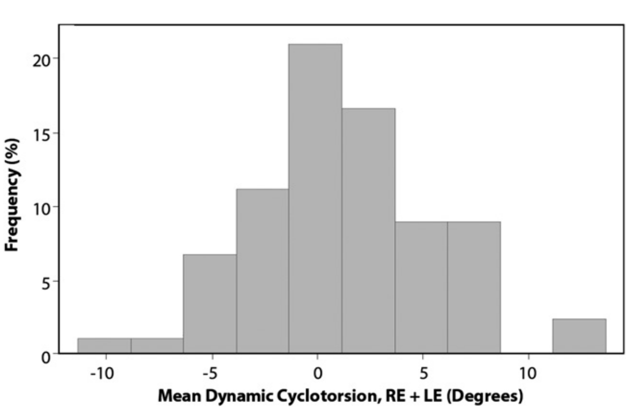


**Figure 3.** Distribution of dynamic cyclotorsion (RE = right eye; LE = left eye).

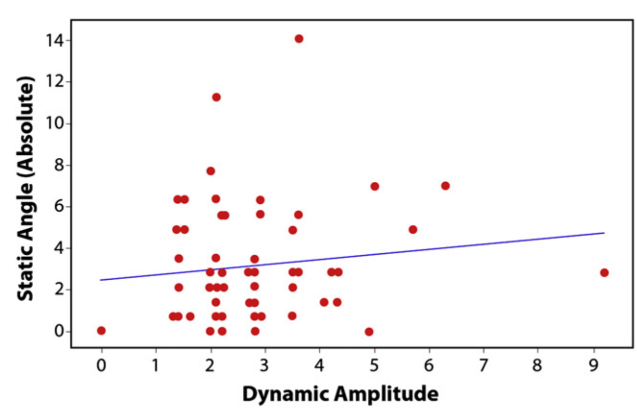


**Figure 4.** Correlation between static cyclotorsion and dynamic amplitude (degrees).

UDVA in patients treated with a dynamic eye-tracking system. Bharti and Bains also found better refractive results in eyes with myopic astigmatism treated with an active cyclotorsion eye tracker.

The refractive outcomes in our study compare favorably with those in the literature; however, we were not able to compare the results obtained with iris registration and without iris registration because the study did not include eyes treated without cyclotorsional compensation. The clinical relevancy and correlation of cyclotorsion with the efficacy and the predictability of the refractive results, with a particular focus on the astigmatic component, will be the subject of future studies.

In our study, cyclotorsional movements were unpredictable. In fact, the eye treated for the highest degree of astigmatism (−3.25 D) had one of the highest static rotational shifts. The rotational eye tracker compensated for a 12-degree angle of error with a satisfactory 20/15 postoperative UDVA. Using theoretic calculations, treatment without rotational compensation would have resulted in residual astigmatism of −1.30 D and residual sphere of 0.65 D.[17]

The mean static cyclorotation was 3.08 degrees. This angle of error is comparable to values in other studies using different laser platforms. Swami et al.,[3] Ciccio et al.,[14] Fea et al.,[16] and Moshirfar et al.[17] report a mean degree of rotation close to 4 degrees. These cyclotorsion values refer to static axis errors and do not consider the dynamic cyclorotation that may have occurred during photoablation.

In our study, the mean dynamic cyclotorsion magnitude was 3.39 degrees. This value, which was statistically significant ($P < .05$), included the mean static rotation and intraoperative rotation; most rotational errors were static.

The mean intraoperative rotation (0.31 degrees) (the average of values registered from the starting point of the mean static rotation [3.08 degrees] to the end of ablation) was not significantly different from 0 degree. However, the mean amplitude of dynamic rotation per eye (mean of maximum deviation in each direction [2.69 degrees]) was statistically significant. An intraoperative deviation of 5 degrees or more was recorded in 4% of eyes and reached 9.2 degrees in 1 eye.

Chang[5] evaluated cyclorotation with a similar dynamic eye-tracking system. He found some degree of intraoperative cyclotorsion, with a mean total cyclotorsion close to 2 degrees. Seven percent of eyes rotated at least 4 degrees, and 4% rotated more than 10 degrees. The amplitude of intraoperative cyclotorsion could reach 13.3 degrees. Chang stated that small intraoperative axis shifts could compromise the accuracy of the placement of each pulse. Other studies[7,17] found that even small axis shifts (2 degrees) can increase the induction of HOAs by 50%.

In our study, most torsional eye movements were static and corresponded to cyclorotation from the seated to supine position. However, the amplitude of intraoperative cyclotorsion was clinically significant. In addition to the mean and the extremes of intraoperative shifts, it would be interesting to measure more precisely the duration and timing of these significant rotations to better understand their potential refractive impact.

We did not find a correlation between static cyclotorsion and the amplitude of dynamic cyclotorsion. As for static cyclotorsion, intraoperative rotational movements are unpredictable and may predominate in a minority of patients. For these reasons, we believe that dynamic rotational eye-tracking systems are a valuable technological improvement and may be a better alternative to more subjective marking methods. Because cyclotorsion occurs before and during photoablation, we believe that static and dynamic rotational modules are more appropriate for optimally compensating for rotational movements.

The version of dynamic eye-tracking technology used in our study necessitated a 2-step procedure to activate static and dynamic iris registration. Future developments should improve the ergonomics of such sophisticated technology and allow friendlier and faster use of the whole eye-tracking system.

Limitations of our study include that we did not compare outcomes in eyes with and without dynamic cyclotorsional tracking, we did not report changes in HOAs in these eyes, and we did not evaluate the impact of dynamic tracking on shifts in the pupil centroids. Wang and Koch[19] show that with static registration systems, accurate centration may be a more important benefit than precise cyclotorsional alignment. Static rotational eye-tracker measurements would be more precise if they were captured just before the ablation. A limitation of our study is that static cyclotorsion measurements were acquired before the flap was lifted and additional rotational error may have occurred because of the flap lifting. Nevertheless, the mean rotation linked to flap lifting was 0.9 ± 1.1 degrees, which is smaller than the static and dynamic cyclotorsion values.

In conclusion, dynamic cyclotorsion eye trackers found static and dynamic rotational movements during LASIK. Static cyclotorsion was more prevalent, although intraoperative cyclotorsion was also detected and had clinically meaningful amplitude not correlated with static movements. Based on our results, we recommend the systematic use of a dynamic rotational eye-tracking system because cyclotorsion greater than 10 degrees can occur in a minority of patients in an unpredictable manner.

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