Background/Purpose: Accuracy of ocular alignments is emphasized in laser refractive surgery. We evaluate pupil centroid shift and cyclotorsion and the correlation between both eyes in bilateral wavefront-guided laser refractive surgery.

Methods: A retrospective study was performed to analyze pupil centroid shift and cyclotorsion using an iris registration system of Zyoptix 100 platform in 186 eyes of consecutive 93 patients at National Taiwan University Hospital. Pearson’s correlation analysis was used.

Results: The mean pupil centroid shift was $0.179 \pm 0.096$ mm, and 42.2% of eyes had more than $0.2$ mm shift between wavefront measurement with dilated pupil and laser ablation with undilated pupil. When the pupil was pharmacologically dilated, pupil centers predominantly shifted to inferonasal direction (59% of eyes). The vertical shift was larger than the horizontal shift. The correlations between both eyes in horizontal and vertical shifts were statistically significant, indicating a symmetric mirror pattern. A good opposite correlation of pupil centroid shifts was observed between in wavefront measurement and in laser treatment. The mean amount of cyclotorsion between the seated and supine positions was $3.22 \pm 2.53^\circ$ with a maximum of $13.51^\circ$. A total of 112 eyes (60.2%) had cyclotorsion $>2^\circ$, while 39 eyes (21.0%) had cyclotorsion $>5^\circ$. Moderate correlation was observed between cyclotorsion of both eyes and was statistically significant.

Conclusion: Inferonasal pupil centroid shift as the pupil pharmacologically dilated and a significant amount of cyclotorsion with good correlation between both eyes was observed in refractive surgery and could be compensated by iris registration.

Copyright © 2012, Elsevier Taiwan LLC & Formosan Medical Association. All rights reserved.
Introduction

Accurately ocular alignments are important for good results in the refractive surgery, including the determination of center of ablated zone and the direction of astigmatic axis. The center of the pupil is usually used as an anatomic landmark or adjusted with the visual axis as the center for laser ablation. However, the pupil center may shift when pupil diameter changes because the pupil does not dilate concentrically. Moreover, cyclotorsion can occur between the time of preoperative measurement and the time of laser surgery. Position-induced cyclotorsion between seated and supine positions is thought to be one of the sources of torsional misalignment. As the emergence of customized wavefront-guided laser refractive surgery, accurate alignment is more emphasized to reduce higher-order aberrations (HOAs) as well as correct sphere and cylinder because laser ablation is better applied to the exact area where the aberration was measured by the preoperative wavefront measurement. However, wavefront-guided ablation is usually based on the aberration measured preoperatively over a dilated pupil at a seated position to correct the refraction errors over an undilated pupil at a supine position. The possible centration error and torsional misalignment between these two conditions are supposed to decrease the accuracy of alignment and lead to residual astigmatism or HOAs. To compensate the shift of the pupil center and torsional misalignment during refractive surgery, iris registration method was developed to determine the extent of the center shift and the degree of cyclotorsion between measurement and surgery. The two sets of iris images during wavefront measurement and refractive surgery were compared with each other using infrared cameras. After matching the multiple reference points on iris, the rotational amount was calculated from image-based alignment methods. This iris registration can provide more objective and accurate measurement. In this retrospective study, we used iris registration to evaluate the patterns of pupil centroid shift and cyclotorsion and the correlation between both eyes in patients with bilateral wavefront-guided laser refractive surgery. We would like to compare our results to others and discuss the differences.

Patients and methods

A retrospective, nonrandomized study was done in consecutive patients who had bilateral wavefront-guided laser refractive surgery in the Department of Ophthalmology of the National Taiwan University Hospital between September 2004 and December 2007. This study was conducted in accordance with the Declaration of Helsinki and approved by institutional review board. These consecutive patients underwent bilateral wavefront-guided laser in situ keratomileusis (LASIK) or photo-refractive keratectomy with an iris registration system performed by four surgeons (Chen WL, Hou YC, Hu FR, and Wang IJ) using the Technolas 217z laser system (Bausch & Lomb, Salt Lake City, UT, USA). If patients received conventional or only unilateral wavefront-guided refractive surgery, then they were excluded in this study.

Calculating pupil centroid shift and cyclotorsion

All patients were seated in front of the Zyoptix 100 platform (Bausch & Lomb) and received aberrations measurement by a Hartmann-Shack wavefront sensor (Zywave aberrometer, Bausch & Lomb) on both eyes. Zywave aberrometer uses infrared cameras to take the images of the iris features and measures the size of pupils with its pupillometer subsystem. Iris registration system in Zywave aberrometer used the limbus as the reference because the limbus was a static landmark. A circle was fit to inner boundary of iris and the pupil radius and center coordinates were determined with respect to the center of the limbus. After aligning the subject to the apparatus, the technician centered the pupil in the video monitor by adjusting the acquisition head and the image of iris was in best focus. The iris/pupil imaging was first performed in undilated pupils (> 4 mm) under room light conditions, then in pharmacologically dilated pupils (> 6 mm) with a drop of phenylephrine 0.5% and tropicamide 0.5%. Zywave examination comprised two examinations with an undilated pupil and five examinations with a dilated pupil, all in a seated position. Two experienced technicians performed all examinations. Head position was kept straight and unchanged as much as possible in each measurement. An undilated iris/pupil image was used as the baseline. One of the five dilated measurements was chosen to compare with the undilated measurement. The paired chosen measurements at undilated and dilated pupils were depended on each operator’s preference according to the concern of quality of wavefront images, scores of HOAs, and manifested refraction.

Iris recognition was processed using the image alignment algorithm. Through the iris recognition between two images of the dilated and the undilated pupils in seated position, we acquired two data in wavefront measurements. One was pupil centroid shift from seated-undilated state to seated-dilated state, measured by the horizontal and vertical change of the center. Another was the rotational angle from seated-undilated pupil to seated-dilated pupil, which was obtained by the torsional change of the iris pattern through the comparison of the two iris images (angle A). Besides, pupil diameters in undilated and dilated states were also recorded.

The information of dilated measurement from Orbscan II corneal topography and Zywave aberrometer were translated into a treatment plan using Zylink software and copied to a floppy disk. All the data were exported to the Technolas 217z100 excimer laser system for treatment by inserting the floppy disk and a Zyoptix card. An iris image was captured from an infrared laser mounted on the laser system before laser ablation when patients with undilated pupil were in supine position. This iris image of the supine-undilated pupil was compared with the image of the seated-dilated pupil in wavefront measurement using the iris-recognition function. We obtained pupil centroid shift from the seated-dilated pupil to the supine-undilated pupil and the rotational angle from the seated-dilated state to the supine-undilated state (angle B).

Because position-induced cyclotorsion between seated and supine position is one of the main causes of cyclotorsion in refractive surgery, we calculated the rotational angle (angle C) from the seated-undilated state to the
supine-undilated state by the summation of angles A and B to avoid the influence by pupil dilatation:

\[
\text{Angle } A = (\text{seated-dilated state}) - (\text{seated-undilated state})
\]

\[
\text{Angle } B = (\text{supine-undilated state}) - (\text{seated-dilated state})
\]

\[
\text{Angle } C = (\text{supine-undilated state}) - (\text{seated-undilated state}) = \text{Angle } A + \text{Angle } B
\]

**Statistical analysis**

Two-tailed \( t \) test was used to compare the magnitudes of the horizontal and vertical shifts of the pupil center in all eyes. Pearson’s correlation analysis was performed to assess the relationship between both eyes in the pupil centroid shift and cyclotorsion and the relationship between the magnitude of the pupil centroid shift and pupil diameter change. A \( p \) value < .05 was considered statistically significant. All of the statistical analyses were performed using STATA 8.2 software (StataCorp LP, College Station, TX, USA).

**Results**

After chart review, a total of 93 participants (186 eyes) were enrolled for analysis of position-induced cyclotorsion, but only 90 participants (180 eyes) were included in the pupil centroid shift study because the data of pupil centroid shift between both eyes was marginally significant with correlation coefficient \( r = 0.322, p = 0.025 \). However, there was no significant correlation between the vector shifts of pupil center and the amount of the pupil diameter changes with correlation coefficient \( r = 0.10, p = 0.188 \) in all 180 eyes.

**Pupil centroid shift**

We analyzed the pupil centroid shift between seated-dilated state during wavefront measurement and supine-undilated state during laser ablation. The mean horizontal shifts of pupil centers were \(-0.059 \pm 0.106 \) mm and \(0.036 \pm 0.106 \) mm in the right and left eyes. The nasal side in the right eye and temporal side in the left eye were defined to be positive in a horizontal direction. The mean vertical shifts were \(0.109 \pm 0.118 \) mm and \(0.128 \pm 0.119 \) mm in the right and left eyes. The vector shift was calculated as the square root of sum of the squares of the horizontal and vertical shifts. The mean vector shift of pupil center in all 180 eyes was \(0.179 \pm 0.096 \) mm (range: 0.013–0.466 mm). Seventy-six of the 180 eyes (42.2%) had more than a 0.2 mm shift.

To focus on the effect of topical pupil-dilating agents in pupil centroid shift, we also compared the pupil status between seated-undilated state and seated-dilated state during wavefront measurement in 90 patients, 180 eyes. The mean pupil diameters were \(5.73 \pm 0.74 \) mm and \(7.14 \pm 0.53 \) mm in undilated and dilated statuses, respectively. The distribution of pupil centroid shifts as the pupils pharmacologically dilated is shown in Fig. 1. The mean horizontal shifts of pupil centers were \(0.062 \pm 0.105 \) mm and \(-0.032 \pm 0.102 \) mm in the right and left eyes, respectively. The mean vertical shifts were \(-0.109 \pm 0.105 \) mm and \(-0.128 \pm 0.123 \) mm in the right and left eyes, respectively. The mean magnitudes of horizontal and vertical shifts were \(0.096 \pm 0.075 \) mm and \(0.131 \pm 0.089 \) mm (right eyes) and \(0.084 \pm 0.065 \) mm and \(0.147 \pm 0.100 \) mm (left eyes), respectively. The mean magnitude for the vertical shift of pupil center was significantly larger than that in the horizontal shift (\( p < 0.001 \)). The mean vector shift of pupil center in all 180 eyes was \(0.18 \pm 0.091 \) mm (range, 0.01–0.47 mm). The direction of the pupil centroid shift as the pupils pharmacologically dilated tended to be inferonasal with 64.4% in the right eyes and 55.5% in the left eyes. The correlation of the pupil centroid shift between both eyes was also evaluated. The correlations between both eyes in horizontal and vertical shifts were both statistically significant with correlation coefficient \( r = -0.322, p = 0.002 \) and correlation coefficient \( r = 0.236, p = 0.025 \), respectively. The correlation of the magnitude of vector shift between both eyes was marginally significant with correlation coefficient \( r = 0.190, p = 0.073 \). However, there was no significant correlation between the vector shifts of pupil center and the amount of the pupil diameter changes with correlation coefficient \( r = 0.10, p = 0.188 \) in all 180 eyes.

![Figure 1](image) Distribution of the pupil centroid shift as the pupils were pharmacologically dilated with a drop of phentylephrine 0.5% and tropicamide 0.5% in both eyes of 90 patients. OD = right eye; OS = left eyes.
The analysis of pupil centroid shift in two different conditions (between seated-dilated and supine-undilated state and between seated-undilated and seated-dilated state) was also compared (Table 1). The horizontal and vertical shifts of the pupil center from the seated-dilated pupil to the supine-undilated pupil had all significantly negative correlation with the pupil centroid shift from the seated-undilated pupil to the seated-dilated pupil. The vector shifts in these two conditions had significantly positive correlation.

Cyclotorsion

The rotational angle from seated-dilated state to the supine-undilated state (angle B) was used to correct cyclotorsion in wavefront-guided laser refractive surgery. To evaluate the influence of positional change in cyclotorsion and exclude the influence of pupil dilatation, we analyzed the data of rotational angle from the seated-undilated state to the supine-undilated state (angle C) instead of angle B. The distribution of angle C for right and left eyes in the study is shown in Fig. 2A. According to the default definition, positive value indicates a clockwise rotation, and negative value indicates a counterclockwise rotation. A positive value in the right eyes indicates incyclotorsion, while a positive value in the left eyes indicates excyclotorsion. Excyclotorsion was observed more frequently than incyclotorsion in both eyes (51 eyes vs. 42 eyes on the right and 62 eyes vs. 31 eyes on the left). The mean value of cyclotorsion was $-0.42 \pm 3.84^\circ$ (range, $-10.87$ to 10.01') in right eyes and $1.74 \pm 3.97^\circ$ (range, $-6.40$ to 13.51') in left eyes. The correlation of cyclotorsion between both eyes was statistically significant (correlation coefficient $= 0.418$, $p < 0.001$). This is shown in Fig. 2B. Overall, the distribution of the absolute values of angle C for all 186 eyes is depicted in Fig. 3. The mean absolute value was $3.22 \pm 2.53^\circ$ (right eye, $3.04 \pm 2.37^\circ$; left eye, $3.40 \pm 2.68^\circ$). A total of 112 eyes (60.2%) had torsional misalignment > 2°, and 39 eyes (21.0%) had torsional misalignment > 5°.

We analyzed the data of the rotational angle from the seated-undilated state to the seated-dilated state (angle A). Fig. 4 demonstrated the distribution of absolute values of angle A in all 186 eyes and the mean absolute value was $1.15 \pm 0.91^\circ$ (right eyes, $1.15 \pm 0.93^\circ$; left eyes, $1.16 \pm 0.89^\circ$). A total of 156 eyes (67.7%) were within 2°. Unlike angle C, the correlation of cyclotorsion between both eyes was not statistically significant. We also analyzed the possibility of the measurement errors in these dilated measurements and found no statistically significant difference in rotational angle between the selected dilated measurements and other non-selected dilated measurements ($p = 0.479$).

Discussion

In the laser refractive surgery, aberration measurements are usually performed in pupil dilatation with cycloplegic or mydriatic agents, or simply under mesopic condition in a seated position, but are surgically corrected over an undilated pupil in a supine position. Shifts of the pupil center between different pupil diameters and cyclotorsion between measurement and laser ablation are considered to be the potential sources of residual refractive error and HOAs after laser refractive surgery.5–9 The range and direction of pupil centroid shift and positional cyclotorsion have been reported with wide variation. The variation in each other may be due to the examination under different conditions or using different measurement methods.

Pupil centroid shift

Wavefront-guided laser refractive surgery tries to correct some of HOAs and requires higher accuracy of pupil centration than conventional spherocylindrical corrections only. Several studies have shown that decentrations as small as 0.2 mm significantly increase HOAs after laser refractive surgery.6–8 Wang and colleagues3 and Porter and others4 calculated the presumed residual wavefront aberrations induced by clinically measured decentration on eyes treated with iris recognition system. Increased aberration was related to increased centration error, especially the third- and fifth-order coma, and decentration causes more theoretical impact on residual HOAs than rotational error. In our study, 42.2% of eyes with more than 0.2 mm pupil centroid shift were observed between wavefront measurement and laser ablation. If pupil center is used as the only reference point for laser ablation without correction of the pupil centroid shift, more than 40% of cases may theoretically increase residual HOAs and decrease the postoperative visual quality due to decentration.

Several investigators have attempted to measure the amount of pupil centroid shifts between different conditions using a high-resolution infrared camera. Due to

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Correlation of the horizontal, vertical, and vector shifts of the pupil center between wavefront measurement and laser surgery.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Undilated to dilated pupils (wavefront measurement), mm</td>
</tr>
<tr>
<td>Horizontal shift</td>
<td>OD: $0.062 \pm 0.105$</td>
</tr>
<tr>
<td></td>
<td>OS: $-0.032 \pm 0.102$</td>
</tr>
<tr>
<td>Vertical shift</td>
<td>OD: $-0.109 \pm 0.105$</td>
</tr>
<tr>
<td></td>
<td>OS: $-0.128 \pm 0.123$</td>
</tr>
<tr>
<td>Vector shift</td>
<td>$0.18 \pm 0.091$</td>
</tr>
</tbody>
</table>

OD = right eyes; OS = left eyes.
different study design and diameters of pupil dilatation, the amount and direction of pupil centroid shift in those studies were varied, but the shifts were indeed observed, especially in pharmacologically dilated pupils (Table 2).\textsuperscript{1,4,10,11} Several studies reported that most of direction of pupil centroid shift were inferotemporal or temporal from photopic to mesoptic or scotopic conditions with the mean shift ranged from 0.086 to 0.37 mm.\textsuperscript{1,3,10,12–14} However, the pupil centroid shift tended to the superotemporal direction from natural to pharmacologically dilated pupils (using cyclopentolate 1%) with the range of the mean shift from 0.15 to 0.18 mm.\textsuperscript{1,4,10,11} Porter and colleagues\textsuperscript{4} reported that 92.3% of eyes displayed the pupil centroid shift in the inferonasal direction when the pupils were dilated with phenylephrine 2.5%.\textsuperscript{4} In our study, the mean shift of pupil center was 0.18\textsuperscript{68} to 0.10 mm with a tendency of the inferonasal direction (58.9%) using 0.5% phenylephrine and 0.5% tropicamide. The varied direction of pupil centroid shifts under different conditions may be due to the effect of using different mydriatic agents. Chang and coauthors\textsuperscript{15} found that fibers of the iris sphincter muscle are arranged in a circular pattern and contract

---

**Figure 2**  (A) Distribution of cyclotorsion between seated and supine positions; (B) correlation of position-induced cyclotorsion between both eyes. OD = right eyes; OS = left eyes.

**Figure 3** Distribution of absolute value of position-induced cyclotorsion in all 186 eyes. OD = right eyes; OS = left eyes.

**Figure 4** Distribution of absolute value of cyclotorsion between dilated and undilated pupils in all 186 eyes. OD = right eyes; OS = left eyes.
uniformly to constrict pupil, but radiating fibers of the iris dilator muscle can contract independently to produce uneven dilatation of pupil. Phenylephrine and Neo-Synephrine are sympathomimetic agents and can induce contraction of the iris dilator muscle, while cyclopentolate and tropicamide are anticholinergic agents and can relax the iris sphincter muscle. Pupil dilatation is more even and concentric with cyclopentolate than with phenylephrine. Porter et al. have proposed that if the distribution of drug on the ocular surface is uneven, the contraction of dilator muscle or the relaxation of the sphincter muscle may be not uniform and pupil centroid shift may occur. The distribution of mydriatic agents may be relatively higher in the inferonasal area of ocular surface because of gravity and the tendency of tear flow to the punctum. The iris dilator muscle could be stimulated more in the inferior and nasal portion and cause pupil centroid shift to inferonasal direction after receiving eyedrops of phenylephrine or Neo-Synephrine. Carkeet and associates found that the position of pupil dilated with 2.5% phenylephrine was 0.14 mm more nasal and 0.20 mm more inferior than 1% cyclopentolate. Comparing our results with these previous studies, we believed that the direction of pupil centroid shift after pharmacologic dilatation was associated with what the type of mydriatics were used and sympathomimetic agents might have stronger effect than anticholinergic agents in pupil centroid shift. We also found a symmetric mirror pattern in the inferonasal direction and a good correlation between both eyes in the pupil centroid shift. However, the magnitude of the pupil centroid shift was not related with the pupil diameter change. It meant that the direction and magnitude of pupil centroid shift after dilatation with pharmacological agents was similar in both eyes in each individual, but the magnitude of individual shift was widely varied and independent of pupil diameter change.

Pupil centroid shift may possibly influence the result of aberration measurement. Carkeet and colleagues found significant difference of aberrometry results between cyclopentolate and phenylephrine pupil dilatation, which might be due to different locations of pupil center and different lens status under cycloplegic and noncycloplegic pupil dilatation. Preoperative wavefront assessment over a pharmacologically dilated pupil may set the ablation center in a deviated position from natural pupil, and lead to inappropriate correction of HOAs in customized wavefront-guided laser refractive surgery without iris registration. Our study showed a good opposite correlation between pupil centroid shifts from the seated-undilated pupils to the seated-dilated pupils in wavefront examination and that from the seated-dilated pupils to the supine-undilated pupils in laser refractive surgery. The slight difference in the magnitude of pupil centroid shift between each other may be related to the different pupil diameters under the different illumination. This suggests that the pupil centers shifted in almost the same amount and opposite directions in these two conditions, just as we expected. Iris registration in our settings indeed can reliably detect and compensate most of pupil centroid shift between different pupil diameters and may theoretically decrease HOAs induced by pupil centroid shift in wavefront-guided refractive surgery. However, further studies about the actual clinical outcomes are needed to prove its efficacy.

### Cyclotorsion

Cyclotorsion was another potential cause of undercorrection and residual HOAs after laser refractive surgery. Many factors can cause cyclotorsion in laser refractive surgery, including rotation of the head and body, position-induced cyclotorsion, unmasking of a cyclophoria, distortion of the globe by application of a lid speculum and dynamic torsional movement. Cyclotorsion caused by position change is a major concern in refractive surgery. Many investigators measured the amount of position-induced cyclotorsion by various kinds of methods. Among these studies, some of them reported a minimal cyclotorsion between seated and supine positions without significant changes, and others reported a significant cyclotorsional change. Iris registration method can measure pupil centroid shift and cyclotorsion more objectively and accurately than these methods because iris registration recognized and compared the detailed images of the iris of an individual’s eye, then subtle changes in the rotational orientation can be measured very accurately.

The impact of cyclotorsion in laser refractive surgery has been reported in several studies. More degree of torsional misalignment results in more undercorrection of astigmatism. Theoretically, a 16° misalignment will result in undercorrection of up to 50% in astigmatism, which is clinically unacceptable. With respect to customized laser corrections, the required accuracy of rotational alignment is more emphasized. Significant postsurgical aberrations

---

**Table 2** Studies of the pupil centroid shift from natural to pharmacologic conditions.

<table>
<thead>
<tr>
<th>Pupil status</th>
<th>Change of pupil diameters (mm)</th>
<th>Magnitude of the shift (mm)</th>
<th>Direction of the shift</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photopic to dilated (cyclopentolate 1%)</td>
<td>NA</td>
<td>0.15 ± 0.12</td>
<td>Slight tendency for superotemporal</td>
<td>Walsh 1988</td>
</tr>
<tr>
<td>Photopic to dilated (cyclopentolate 1%)</td>
<td>4.06 ± 0.70 to 7.58 ± 0.82</td>
<td>0.183 ± 0.093</td>
<td>Superotemporal</td>
<td>Porter 2006</td>
</tr>
<tr>
<td>Photopic to dilated (phenylephrine 2.5%)</td>
<td>6.41 ± 1.19 to 8.47 ± 0.72</td>
<td>0.29 ± 0.141</td>
<td>Inferonasal</td>
<td>Yang 2002</td>
</tr>
<tr>
<td>Photopic to dilated (cyclopentolate 1%)</td>
<td>4.55 ± 0.64 to 7.53 ± 0.75</td>
<td>0.149 ± 0.080</td>
<td>Inferonasal</td>
<td>Erdem 2008</td>
</tr>
<tr>
<td>Photopic to dilated (phenylephrine 0.5% and tropicamide 0.5%)</td>
<td>5.73 ± 0.74 to 7.14 ± 0.53</td>
<td>0.18 ± 0.091</td>
<td>Inferonasal</td>
<td>Our study</td>
</tr>
</tbody>
</table>

NA: non-available.
could be induced in > 2° rotational misalignment.\textsuperscript{5} Increased residual aberration was related to increased torsional misalignment, especially the second-order astigmatism.\textsuperscript{7} Moreover, to achieve a diffraction-limited retinal image in 95% of the normal eyes within a 7.0 mm pupil, alignment of wavefront-guided treatments would have to be performed with a torsional precision of approximately 1° or better.\textsuperscript{6}

Most studies using iris registration showed a mean from 2–3° of position-induced cyclotorsion and a maximum up to 17.5° (Table 3). Greater than 50% of eyes had cyclotorsion exceeding 2°. Our study involving 186 eyes showed a mean of 3.22 ± 2.53° of torsional misalignment between seated-undilated status and supine-undilated status, with a maximum of 13.5°. Cyclotorsion was > 2° in 60.2% eyes and > 5° in 21.0% eyes. Such an amount of torsional misalignment can have a theoretically significant negative effect on the outcome of laser refractive surgery if the rotation is not corrected, especially when dealing with high astigmatism and high-order aberrations. Considering the orientation of position-induced cyclotorsion, most studies reported that excyclotorsion was predominant when patients’ position changed from seated to supine.\textsuperscript{14,25–27} In our study, this tendency of excyclotorsion was also noted in 54.8% of the right eyes and 66.7% of the left eyes. However, we found a moderate correlation of cyclotorsion between both eyes when the position changed. It indicated that both right and left eyes tended to rotate toward the same direction, clockwise or counterclockwise. This finding suggested that some degrees of torsional misalignment were possibly contributed with a small-degree head tilt between seated status in wavefront measurement and supine status in laser ablation in our study cases.

In our study, the absolute value of the rotational angle from seated-undilated to seated-dilated status (angle A) was approximately 1° in average. This change of rotational alignment may be due to the torsional or shifting change of iris features after dilatation when using iris registration, position changes of head between each measurement at different times, or measurement error in each measurement. Head tilt is the less likely cause because of the no directional correlation between the alignment change of the right and left eyes. Measurement error is also unlikely because of no significant difference in all dilated measurements.

Limbal marking and subsequent eye astigmatic axis alignment have been proved to improve the refractive outcome of laser astigmatic treatment, especially in high astigmatic eyes.\textsuperscript{28} Iris registration method is widely used in current laser refractive surgery and has shown that it can improve the outcome for astigmatism correction compared with control group without iris registration in wavefront-guided laser ablation.\textsuperscript{29} Although both limbal markings and iris registration are effective for correction of myopic astigmatism,\textsuperscript{30} wavefront-guided LASIK with iris registration has shown better visual outcomes than conventional or wavefront guided LASIK with manual marking in correcting mixed astigmatism.\textsuperscript{31}

Studies about pupil centroid shift and torsional misalignment have shown their impact to postoperative visual outcome in laser refractive surgery. Our study showed that 42.2% had more than 0.2 mm pupil centroid shift, and 60.2% had torsional misalignment more than 2°, which were indeed significant and should not be overlooked. The use of mydriatic drugs for pupil dilatation in wavefront measurement is thought to be the major cause of pupil centroid shift. Positional change from seated to supine condition is thought to be the major cause of torsional misalignment in refractive surgery. Iris registration can compensate these two alignment errors and is beneficial to customized wavefront-guided laser ablation. Because of limitations of equipment in our study, we could not evaluate dynamic cyclotorsion change during laser ablation. With the newly developed real-time iris registration, torsional misalignment can be detected not only before laser ablation but also during the period of laser

Table 3  Studies of positional static cyclotorsion.

<table>
<thead>
<tr>
<th>Eyes, N</th>
<th>Mean absolute magnitude (°)</th>
<th>Eyes (%)</th>
<th>Maximum of cyclotorsion (°)</th>
<th>Ex-cyclotorsion (%)</th>
<th>Measurement method</th>
<th>Study</th>
</tr>
</thead>
</table>
| 240     | 4.1 ± 3.7                   | 65% eye > 2°  
28% eye > 6°  
16 NA | Marking at limbus Swami 2002\textsuperscript{24} |
| 1019    | 4.05 ± 2.9                  | 68% eye > 2°  
21.6% eye > 5°  
17.5 72.6 9.5 79.2 | Marking at limbus Ciccio 2005\textsuperscript{27}  
Iris registration Chernyak 2005\textsuperscript{25} |
| 51      | ~ 2                         | 68% eye > 2°  
21.6% eye > 5°  
56% eye > 2°  
9.5 79.2 | Iris registration Wang 2008\textsuperscript{23}  
Iris registration Kim 2008\textsuperscript{26} |
| 58      | 2.5 ± 2.0  
58 NA  
140     | 2.59 ± 1.91  
13.0% eye > 5°  
8.7 9.5 54.3 54.6 | Iris registration Park 2009\textsuperscript{14}  
Iris registration  
Swami 2002  
Limbal marking Limbal marking \textsuperscript{24}  
Eyes (%) Ex-cyclotorsion (%) Measurement Study |
| 183     | 2.58 ± 1.56  
(in-cyclotorsion)  
11.5% eye > 5°  
2.94 ± 1.87 (ex-cyclotorsion)  
7.8 54.6 | Iris registration  
Park 2009\textsuperscript{14}  
Iris registration  
Kim 2008\textsuperscript{26}  
Iris registration Neuhann 2010\textsuperscript{31}  
Iris registration  
Febbraro 2010\textsuperscript{12}  
Iris registration  
Febbraro 2010\textsuperscript{12}  
Iris registration  
Chernyak 2005\textsuperscript{25}  
Iris registration  
Wang 2008\textsuperscript{23}  
Iris registration  
Ciccio 2005\textsuperscript{27}  
Iris registration  
Swami 2002\textsuperscript{24} |

NA = not available.
ablation. Several studies have shown that the amplitude of dynamic cyclotorsion was significant during laser ablation and was not ignorable when compared with that of static cyclotorsion.\textsuperscript{12-14} Active cyclotorsion error correction can increase the accuracy of cylinder correction and reduce the induced HOAs in LASIK.\textsuperscript{33,34} The impact of pupil centroid increase the accuracy of cylinder correction and reduce the factors being controlled.

Consideration when we do refractive surgery. Iris registration has been well documented. However, other factors such as size of optical zone, ablation programs, wound healing, corneal biomechanical change and different methods of flap creation could also affect the postoperative uncorrected visual acuity, residual aberrations and contrast sensitivity. All of them need to be taken into consideration when we do refractive surgery. Iris registration is a good method to compensate pupil centroid shift and cyclotorsion in the refractive surgery, but the clinical advantage should still be validated by studies with other factors being controlled.

References