

Effects of Cyclotorsion Orientation and Magnitude in Eyes with Compound Myopic Astigmatism on the Compensation Capacity of WaveLight EX500 Photorefractive Keratectomy

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Purpose: To investigate the clinical effects of different orientation and magnitude of cyclotorsion on the compensation capacity of the WaveLight EX500 photorefractive keratectomy (PRK) platform.

Methods: This retrospective study comprised 400 eyes of 200 patients who underwent bilateral simultaneous PRK due to compound myopic astigmatism. The subjects were separated according to the orientation of cyclotorsion into incyclotorsion and excyclotorsion groups, and by the magnitude of cyclotorsion into group 1 (0.50 to 2.50 degrees), group 2 (3.00 to 5.00 degrees), group 3 (5.50 to 7.50 degrees), and group 4 (8.00 to 9.50 degrees).

Results: The mean magnitude of cyclotorsion was 3.50 ± 2.4 degrees (0.50 to 9.50 degrees) in the incyclotorsion group and 3.32 ± 2.3 degrees (0.50 to 9.50 degrees) in the excyclotorsion group ($p = 0.617$). The postoperative refractive outcomes of the incyclotorsion and excyclotorsion groups were similar ($p > 0.05$ for all). The postoperative mean cylindrical refractive error was -0.32 ± 0.3 diopters (D, -1.25 to 0.00 D) in group 1, -0.47 ± 0.2 D (-2.00 to 0.00 D) in group 2, -0.62 ± 0.2 D (-1.00 to -0.25 D) in group 3, and -0.91 ± 0.2 D (-1.50 to -0.50 D) in group 4 ($p < 0.001$). Preoperative cylindrical refractive error was positively correlated with magnitude of cyclotorsion ($r = 0.125$ and $p = 0.013$), which was also positively correlated with postoperative cylindrical refractive error ($r = 0.600$ and $p < 0.001$).

Conclusions: Incyclotorsion and excyclotorsion can be equally compensable in the WaveLight EX500 PRK platform for compound myopic astigmatism. A value of ≤ 2.50 degrees cyclotorsion magnitude was observed to be more compensable than higher degrees of cyclotorsion magnitude. Preoperative high astigmatism was associated with high cyclotorsion magnitude, which was also associated with a high degree of postoperative astigmatism.

Key Words: Astigmatism, Lasers, Myopia, Photorefractive keratectomy, Refractive surgical procedures

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Cyclotorsional movements occur to maintain the natural orientation of the image on the retina in monocular viewing conditions and when an individual tilts head or lies down [1-3]. Incyclotorsion and excyclotorsion are two kinds of cyclotorsional movement distinguished by the orienta-

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tion. Incyclotorsion is defined as when the upper pole of the globe rotates to the nasal side with the effects of the inferior oblique and inferior rectus muscles. Excyclotorsion is defined as when the upper pole of the globe rotates to the temporal side with the effects of the superior oblique and superior rectus muscles [4]. There are two components of cyclotorsion: static and dynamic. The static cyclotorsion component is measured when the individual lies down before excimer laser surgery, while the dynamic cyclotorsion component is measured during excimer laser surgery.

The magnitude of cyclotorsional movements is variable in individuals in a few ranges. Cyclotorsional movement can be clinically important when an individual undergoes laser refractive surgery because it can cause axis misalignments during surgery, and can be a reason for astigmatism under-correction or induction [5]. The formula $C = 2F \times \sin\alpha$ allows the calculation of residual astigmatism (C) through original astigmatic power (F) and degree of axis misalignment (α) [6]. A 3-degree axis misalignment causes nearly 10% under-correction of astigmatism and a 6-degree axis error causes nearly 20% under-correction, depending on the original astigmatic power, which is directly proportional to the residual astigmatism. Therefore, according to the orientation and magnitude of cyclotorsion, ablation nomograms should be adjusted to the new position of the globe when the patient lies down.

In the past, compensatory cyclotorsional movements were generally provided manually via limbal marking. Limbal marking techniques, including slit-lamp markers, pendular markers, bubble markers, and tonometer markers, can be performed as a reference for alignment of the laser microscope reticule when the patient lies down. Adjustment of the ablation nomogram according to the orientation and magnitude of cyclotorsional movement is made manually. However, these techniques can result in 5.6-9.3 degrees rotational and 0.6-1.3 mm vertical misalignment [7]. To avoid irregular astigmatism caused by misalignments in the ablation zone, which could affect visual performance, many excimer laser platforms automatically measure these cyclotorsional movements and make adjustments via a static and/or dynamic rotational iris eye tracker and advanced software. Iris recognition is the standard used in measurements of cyclotorsional movements, due to the unique properties of the iris [8].

In the current literature, there have been few reports related to the clinical effects of automatically compensated

cyclotorsional movements, especially in the photorefractive keratectomy (PRK) platform. The WaveLight EX500 with Contoura (Alcon, Fort Worth, TX, USA) PRK platform is a very reliable device and is preferred by many excimer laser surgeons globally, as it enables automatic compensation for both static and dynamic cyclotorsion.

The primary aim of the present study was to investigate the clinical effects of different orientations and magnitudes of cyclotorsion on the compensation capacity of the WaveLight EX500 PRK platform. The relationship between refractive status and the magnitude of cyclotorsion was also investigated.

Materials and Methods

Ethics statement

This retrospective comparative observational study was conducted between January 2016 and January 2018 in the refractive surgery department of an eye hospital, with approval granted by the TOBB ETU Medicine Faculty Clinical Research Ethics Committee (KA EK-118/013). All procedures were performed in accordance with the ethical standards of the Helsinki Declaration for human subjects and informed consent was obtained from each patient before surgery after detailed explanation of the surgical procedures.

Study patients

The medical records of patients who underwent bilateral simultaneous PRK due to compound myopic astigmatism were investigated retrospectively. Patients who met the following criteria were included in the study: 1) age ≥ 18 and ≤ 45 years, 2) no systemic or ocular diseases except ≤ 8.00 diopters (D) myopic or ≤ 6 D astigmatic refractive error, 3) stable refractive error for the previous year, 4) best-corrected visual acuity ≥ 0.00 logarithm of the minimum angle of resolution, and 5) ≥ 0.50 - and ≤ 9.50 -degree cyclotorsional movement magnitude. Exclusion criteria were defined as a history of ocular surgery or trauma, manifest or latent strabismus, anisometropia, irregular astigmatism on corneal topography, estimated central stromal bed thickness of < 300 μm at the thinnest point, macular diseases, neuro-ophthalmological disease, pregnancy or lactation, or

systemic abnormalities such as diabetes mellitus, collagen vascular disease or autoimmune disease. Finally, 400 eyes of 200 patients who had a suitable medical record were enrolled in this study.

Clinical evaluation

Patient medical records included detailed ocular and general medical history, preoperative clinical evaluation, operation reports, and postoperative follow-up examinations. All preoperative evaluations were performed after contact lens discontinuation for at least 2 weeks.

On preoperative examination, manifest and objective refraction were determined, and uncorrected and best-corrected visual acuity were examined using a Snellen chart. Intraocular pressure was measured with a pneumotonometer. Anterior segment and dilated fundus examinations were performed with slit-lamp biomicroscopy. Curvature, elevation, and thickness maps were obtained with a Placido-based corneal topography Allegrato Topolyzer (ver. 1.59, Alcon).

As a reference for measurement of cyclotorsional movement, an image was captured by the Allegrato Topolyzer when the patient fixed the chin and forehead in the reference of the device and was looking at a primary orientation of the sight. On the operation table, after topical proparacaine hydrochloride 0.5% (Alcaine, Alcon) instillation and eyelid speculum placement, a second image was captured by the WaveLight EX500 excimer laser device to measure cyclotorsional movement in the supine position. This device takes fully automated static and dynamic cyclotorsion measurements based on the iris registration technique with a 35 Hz dynamic acquisition rate. This technique is known as "cyclo torsion alignment" and is applicable to topo-guided treatments. Two consecutive images in different positions are superimposed with the device and static cyclotorsional movement is measured by comparing the positions of reference points on the iris. The values are given from 0 to 10 degrees at 0.5 increments. No cyclotorsional movement is described as 0 degrees while ≥ 10 degrees is described as 10 degrees. Incyclotorsion is stated as a negative value and excyclotorsion as a positive value. The orientation and magnitude of cyclotorsion of each eye were recorded. In accordance with the instructions of the excimer laser platform, the patients were repeatedly repositioned if the magnitude of the static cyclo-

torsion was 10 degrees, as that is highly deviated from normal distribution. The operation was started after obtaining the minimum static cyclotorsion magnitude after a few attempts at repositioning, because the excimer laser device compensates automatically in cases with ≤ 10 degrees of static cyclotorsion magnitude. During excimer laser surgery, the system automatically rotates before each excimer laser pulse according to the concurrent dynamic cyclotorsion. Thus, the system compensates for both static and dynamic cyclotorsion.

A single experienced surgeon (KO) performed all surgeries using the same excimer laser device and aimed to achieve emmetropia for all eyes. After topical anesthesia and eyelid opening with a wire speculum, topical 5% povidone iodine was instilled for 3 minutes for antisepsis. The superficial epithelium was cut using an 8.5-mm diameter trephine and mechanically debrided with a spatula after exposure of the corneal surface to 20% ethyl alcohol solution for 30 seconds. Corneal ablation was performed with a wavefront-optimized ablation profile. If ablation depth was $>30 \mu\text{m}$, 0.02% mitomycin C was applied to the eye and then irrigated with room temperature balanced saline solution. The mitomycin C administration time was 30 seconds on average. No cases developed intraoperative complications.

After laser ablation, a Senofilcon A bandage contact lens (Acuvue; Johnson & Johnson, Jacksonville, FL, USA) was placed for 5 days. Postoperative medication was prescribed, consisting of topical moxifloxacin 0.5% (Vigamox, Alcon) 3 times a day for 1-week, topical dexamethasone (Maxidex, Alcon) starting after epithelial healing and tapered off over 3 weeks, and artificial tears every 2 hours for 2 months. No postoperative complications developed in any case. In the postoperative 3-month follow-up period, clinical examinations including manifest and objective refraction, the best corrected visual acuity, intraocular pressure, and clinical findings in anterior and posterior segment examinations with slit-lamp biomicroscopy were recorded.

Statistical analysis

Data obtained in the study were analyzed using the IBM SPSS Statistics ver. 24.0 (IBM Corp., Armonk, NY, USA). Descriptive data were presented as mean \pm standard deviation, minimum values, and maximum values. The chi-

square test was used to analyze the categorical variables. The subjects were first separated into two groups according to the orientation of cyclotorsion as incyclotorsion and excyclotorsion groups. The subjects were then subdivided into four groups according to the magnitude of cyclotorsion as group 1 (0.50 to 2.50 degrees), group 2 (3.00 to 5.00 degrees), group 3 (5.50 to 7.50 degrees), and group 4 (8.00 to 9.50 degrees). Normal distribution of the variables was checked using the Kolmogorov-Smirnov test. The Mahalanobis distance was checked for the variables not conforming to normal distribution, then the Student's *t*-test was used for comparison of the groups separated by the orientation of the cyclotorsion and one-way analysis of variance test was used for comparison of the groups separated by the magnitude of the cyclotorsion. Post-hoc tests (Tukey honestly significant difference) for pairwise comparisons were also performed. Pearson correlation tests were used to investigate the relationship between refractive status

and magnitude of the cyclotorsion. A value of $p < 0.05$ was accepted as statistically significant.

Results

The study included a total of 400 eyes as 200 right and 200 left eyes of 200 patients. The mean age of the patients was 26.9 ± 7.1 years (range, 18 to 45 years) and the male-to-female ratio was 92 : 108. The mean spherical and cylindrical refractive errors were -2.89 ± 2.0 D (-8.00 to -0.25 D) and -1.68 ± 1.3 D (-6.00 to -0.50 D), respectively.

Patients were grouped according to the orientation of cyclotorsion as incyclotorsion ($n = 255$) or excyclotorsion ($n = 145$). No significant differences were determined between the groups in terms of mean age of patients and male-to-female ratio ($p = 0.426$, and $p = 0.184$, respectively). The mean magnitude of the cyclotorsion was 3.50 ± 2.4

Table 1. Preoperative demographic and clinical characteristics of the patients grouped according to the orientation of cyclotorsion

	Incyclotorsion group (n = 255)	Excyclotorsion group (n = 145)	<i>p</i> -value
Age (yr)	25.1 \pm 4.7 (18 to 45)	27.2 \pm 6.1 (18 to 45)	0.426
Male : female	113 : 142	71 : 74	0.184
Magnitude of cyclotorsion (degree)	3.50 \pm 2.4 (0.50 to 9.50)	3.32 \pm 2.3 (0.50 to 9.50)	0.617
Spherical RE (D)	-2.80 \pm 2.0 (-8.00 to -0.25)	-3.05 \pm 2.0 (-8.00 to -0.25)	0.341
Cylindrical RE (D)	-1.72 \pm 1.4 (-6.00 to -0.50)	-1.60 \pm 1.2 (-5.50 to -0.50)	0.724
Cylinder axis (degree)	99.36 \pm 69.9 (1 to 180)	93.83 \pm 71.6 (1 to 180)	0.246
Spherical equivalent (D)	-3.66 \pm 2.0 (-9.50 to -0.75)	-3.85 \pm 2.1 (-9.13 to -0.75)	0.648
Flat keratometry (D)	42.85 \pm 1.6 (37.34 to 47.01)	43.00 \pm 1.4 (39.94 to 47.34)	0.632
Steep keratometry (D)	44.43 \pm 1.7 (38.14 to 48.84)	44.53 \pm 1.6 (41.06 to 48.28)	0.641
Central CT (μ m)	522.70 \pm 31.1 (438 to 593)	522.64 \pm 30.8 (453 to 585)	0.759
Residual CT (μ m)	398.78 \pm 44.6 (310 to 494)	400.55 \pm 44.3 (314 to 491)	0.606

RE = refractive error; D = diopter; CT = corneal thickness.

Table 2. Postoperative refractive outcomes of the groups according to orientation of cyclotorsion

	Incyclotorsion group (n = 255)	Excyclotorsion group (n = 145)	<i>p</i> -value
Spherical RE (D)	0.07 \pm 0.4 (-1.00 to 1.25)	0.15 \pm 0.4 (-0.75 to 1.25)	0.143
Cylindrical RE (D)	-0.46 \pm 0.3 (-2.00 to 0.00)	-0.49 \pm 0.3 (-1.25 to 0.00)	0.534
Cylinder axis (degree)	89.42 \pm 76.7 (1 to 180)	93.31 \pm 61.3 (1 to 180)	0.108
Spherical equivalent (D)	-0.16 \pm 0.5 (-1.50 to 0.88)	-0.10 \pm 0.4 (-1.13 to 0.75)	0.202

RE = refractive error; D = diopter.

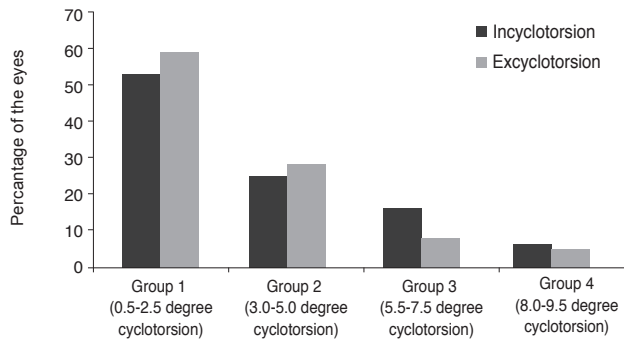


Fig. 1. Percentage of eyes in the incyclotorsion and excyclotorsion groups according to the magnitude of cyclotorsion.

degrees (0.50 to 9.50 degrees) in the incyclotorsion group and 3.32 ± 2.3 degrees (0.50 to 9.50 degrees) in the excyclotorsion group. The mean magnitude of cyclotorsion was similar in both groups ($p = 0.617$). Comparisons of the groups in respect to preoperative spherical and cylindrical refractive errors, cylinder axis, spherical equivalent, flat and steep keratomeries, central corneal thickness, and residual corneal thickness are shown in Table 1. No signifi-

cant differences were determined in these criteria ($p > 0.05$ for all). Comparisons of the 3-month postoperative refractive outcomes of the incyclotorsion and excyclotorsion groups are shown in Table 2. No significant differences were determined in these criteria ($p > 0.05$ for all).

The mean magnitude of cyclotorsion was 3.44 ± 2.4 degrees (0.50 to 9.50 degrees). The eyes were separated into four groups according to the magnitude of cyclotorsion (Fig. 1). The groups were similar in terms of mean age of the patients and male-to-female ratio ($p = 0.288$ and $p = 0.437$, respectively). The preoperative demographic and clinical characteristics of the four groups separated by magnitude of cyclotorsion are shown in Table 3 and there were no significant differences ($p > 0.05$ for all). The 3-month postoperative mean cylindrical refractive error was -0.32 ± 0.3 D (-1.25 to 0.00 D) in group 1, -0.47 ± 0.2 D (-2.00 to 0.00 D) in group 2, -0.62 ± 0.2 D (-1.00 to -0.25 D) in group 3, and -0.91 ± 0.2 D (-1.50 to -0.50 D) in group 4. The difference between the groups in terms of 3-month postoperative mean cylindrical refractive error was statistically significant ($p < 0.001$). Significant differences were

Table 3. Preoperative demographic and clinical characteristics of the groups according to the magnitude of cyclotorsion

	Group 1 (n = 220)	Group 2 (n = 104)	Group 3 (n = 52)	Group 4 (n = 24)	p-value
Magnitude of cyclotorsion (degree)	1.24 ± 0.9 (0.50 to 2.50)	3.85 ± 0.7 (3.00 to 5.00)	6.31 ± 0.7 (5.50 to 7.50)	9.25 ± 0.8 (8.00 to 9.50)	
Age (yr)	27.5 ± 6.9 (18 to 45)	28.0 ± 6.3 (18 to 45)	24.8 ± 5.7 (18 to 45)	25.3 ± 7.0 (18 to 44)	0.288
Male : female	101 : 119	49 : 55	23 : 29	11 : 13	0.437
Spherical RE (D)	-2.64 ± 1.8 (-8.00 to -0.25)	-3.06 ± 2.1 (-8.00 to -0.25)	-2.91 ± 2.1 (-8.00 to -0.25)	-2.93 ± 2.6 (-8.00 to -0.50)	0.340
Cylindrical RE (D)	-1.56 ± 1.2 (-6.00 to -0.50)	-1.64 ± 1.4 (-6.00 to -0.50)	-1.76 ± 1.2 (-6.00 to -0.50)	-2.27 ± 1.5 (-6.00 to -0.50)	0.062
Cylinder axis (degree)	96.45 ± 66.7 (1 to 180)	93.74 ± 69.7 (1 to 180)	89.86 ± 72.2 (2 to 180)	90.66 ± 73.4 (3 to 180)	0.298
Spherical equivalent (D)	-3.42 ± 1.8 (-9.38 to -0.75)	-3.88 ± 2.1 (-9.50 to -0.75)	-3.79 ± 2.1 (-9.50 to -0.75)	-4.06 ± 2.5 (-9.00 to -0.75)	0.185
Flat keratometry (D)	42.91 ± 1.5 (36.57 to 47.34)	42.93 ± 1.5 (39.15 to 46.49)	42.91 ± 1.9 (38.48 to 46.55)	42.49 ± 1.5 (38.88 to 45.12)	0.659
Steep keratometry (D)	44.40 ± 1.7 (37.13 to 48.70)	44.44 ± 1.8 (41.01 to 48.84)	44.53 ± 1.7 (40.56 to 47.47)	44.54 ± 1.3 (41.93 to 47.87)	0.900
Central CT (D)	522.16 ± 32.1 (424 to 593)	524.88 ± 30.1 (457 to 580)	526.77 ± 30.1 (453 to 587)	518.04 ± 30.5 (463 to 584)	0.541
Residual CT (D)	404.80 ± 42.1 (310 to 494)	400.70 ± 44.1 (314 to 482)	399.04 ± 48.3 (319 to 491)	380.96 ± 44.7 (316 to 485)	0.085

RE = refractive error; D = diopter; CT = corneal thickness.

Table 4. Postoperative refractive outcomes of the groups according to magnitude of cyclotorsion

	Group 1 (n = 220)	Group 2 (n = 104)	Group 3 (n = 52)	Group 4 (n = 24)	<i>p</i> -value
Spherical RE (D)	0.06 ± 0.4 (-0.75 to 1.25)	0.08 ± 0.4 (-0.75 to 1.00)	0.23 ± 0.5 (-0.75 to 1.00)	0.08 ± 0.6 (-1.00 to 1.25)	0.102
Cylindrical RE (D)	-0.32 ± 0.3 (-1.25 to 0.00)	-0.47 ± 0.2 (-2.00 to 0.00)	-0.62 ± 0.2 (-1.00 to -0.25)	-0.91 ± 0.2 (-1.50 to -0.50)	<0.001*
Cylinder axis (degrees)	88.21 ± 74.6 (1 to 180)	90.24 ± 72.2 (1 to 180)	91.63 ± 75.5 (1 to 180)	94.53 ± 64.8 (4 to 180)	0.346
Spherical equivalent (D)	-0.10 ± 0.4 (-1.25 to 0.75)	-0.15 ± 0.4 (-1.50 to 0.75)	-0.08 ± 0.5 (-1.00 to 0.88)	-0.37 ± 0.6 (-1.38 to 0.50)	0.900

RE = refractive error; D = diopter.

*Statistically significant. $p < 0.001$ in pairwise comparisons including group 1 vs. group 2, group 1 vs. group 3, group 1 vs. group 4, group 2 vs. group 3, group 2 vs. group 4, and group 3 vs. group 4.

Table 5. Relationship between refractive status and magnitude of cyclotorsion

	Magnitude of cyclotorsion	
	<i>r</i> -value	<i>p</i> -value
Preoperative value		
Magnitude of spherical RE	0.088	0.078
Magnitude of cylindrical RE	0.125	0.013*
Cylinder axis	0.424	0.312
Magnitude of spherical equivalent	0.107	0.032*
Postoperative value		
Magnitude of spherical RE	0.094	0.061
Magnitude of cylindrical RE	0.600	<0.001*
Cylinder axis	0.368	0.296
Magnitude of spherical equivalent	0.128	0.010*

RE = refractive error.

*Statistically significant.

determined between the groups in pairwise comparisons with post-hoc tests ($p < 0.001$ for all). The 3-month postoperative refractive outcomes of the groups separated by magnitude of cyclotorsion are shown in Table 4. When the relationship between refractive status and magnitude of cyclotorsion was investigated, the preoperative cylindrical refractive error and spherical equivalent values were significantly positively correlated with the magnitude of cyclotorsion ($r = 0.125$ and $p = 0.013$, and $r = 0.107$ and $p =$

0.032, respectively). The magnitude of cyclotorsion was significantly positively correlated with the postoperative cylindrical refractive error and spherical equivalent values ($r = 0.600$ and $p < 0.001$, and $r = 0.128$ and $p = 0.010$, respectively). Table 5 presents the relationships between the preoperative refractive status and magnitude of cyclotorsion, and between the magnitude of cyclotorsion and postoperative refractive status.

Discussion

Varying proportions of cyclotorsion orientation have been reported in different series and several reports in the literature have mentioned the predominance of incyclotorsion or excyclotorsion in eyes undergoing ocular surgery [9-12]. Zhao et al. [9] stated that incyclotorsion occurs more prevalently in left eyes and excyclotorsion occurs more prevalently in right eyes, which are the dominant eye for most subjects. However, various studies have reported no association between dominant eye and excyclotorsional movement. Hummel et al. [12] reported that incyclotorsion occurs more prevalently in both of the right and the left eyes. Zhao et al. [9] also reported that several factors, including age, sex, visual acuity, astigmatism degree or axis, and axial length, are not associated with the orientation of cyclotorsion. In the current study, incyclotorsion was more common than excyclotorsion and no demographic or clinical features were found to be related to cyclotorsion orientation. Although the relationship between preoperative characteristics and cyclotorsion orientation has been stud-

ied previously, the effect of cyclotorsion orientation on postoperative refractive outcomes after excimer laser surgery remains unknown. From the results of the current study, it was concluded that cyclotorsion magnitude is not dependent on cyclotorsion orientation. Postoperative refractive outcomes, including spherical and cylindrical refractive errors, cylinder axis, and spherical equivalent, were independent of cyclotorsion orientation. In light of these results, it could be argued that cyclotorsion orientation does not affect the compensation capacity of the WaveLight EX500 PRK platform, and incyclotorsion and excyclotorsion can be equally compensable.

Previous studies have reported conflicting results about the relationship between preoperative characteristics and the magnitude of cyclotorsion. Alipour et al. [13] found several diverse factors including sex, magnitude of refractive error diopters, hyperopia, and high astigmatism to be related to a higher magnitude of cyclotorsion. Adib-Moghaddam et al. [14] reported that age, visual acuity, and keratometry are significantly associated with dynamic cyclotorsion. In contrast, Zhao et al. [9] stated that there was no association between preoperative characteristics (axial length, visual acuity, astigmatism degree, cylinder axis, age, and sex) and the magnitude of cyclotorsion. Risk analysis of cyclotorsion was beyond the aim of the current study and no regression analysis was performed. Nevertheless, when patients were grouped according to the magnitude of cyclotorsion, preoperative demographics (age and sex) and clinical characteristics (spherical and cylindrical refractive errors, cylinder axis, spherical equivalent, flat and steep keratomeries, and central and residual corneal thicknesses) were found to be similar, as in the Zhao et al. [9] study.

Static cyclotorsion magnitude has been reported to range from 0 to 16 degrees [15]. In one study, cyclotorsion of <2 degrees magnitude was reported at the rate of 84.1% in the incyclotorsion group and at 86.5% in the excyclotorsion group, and only 3.3% and 0.4% of patients had ≥ 4 degrees cyclotorsion in the incyclotorsion and excyclotorsion groups, respectively [16]. Tomita et al. [17] reported the mean magnitude of cyclotorsion as 2.29 degrees, with 28.7% of the subjects >3 degrees cyclotorsion and only 13% >4 degrees. According to their reports, these ratios can differ due to ethnic factors or a different workflow. Previous studies have stated that astigmatism correction can be altered and significant aberrations can be induced

by the excimer laser treatment when >2 degrees cyclotorsional movements are not corrected [16,17]. The current study included only subjects with a magnitude of cyclotorsion in the range of 0 to 10 degrees because the primary aim was to investigate the clinical effects of different orientation and magnitude of cyclotorsion on the compensation capacity of the WaveLight EX500 PRK platform. Therefore, subjects with ≥ 10 degrees cyclotorsion magnitude despite repositioning were excluded, as those values highly deviate from normal distribution. The mean magnitude of cyclotorsion was 3.44 degrees in this series. In 55% of the patients, cyclotorsion was ≤ 2.50 degrees and only 19% were determined to have ≥ 5.50 degrees cyclotorsion magnitude. These results are comparable with the findings of previous studies, although the results of each series are known to be highly dependent on the demographic and ethnic characteristics of the study groups and on technical differences in the methodology [18].

Aslanides et al. [15] reported better postoperative spherical and cylindrical refractive errors in subjects with compensated static cyclotorsion compared to subjects with non-compensated static cyclotorsion. Similarly, Fahd et al. [19] reported that post-laser *in situ* keratomileusis ≥ 1 D astigmatism was more prevalent in eyes without static cyclotorsion compensation compared to eyes with static cyclotorsion compensation. Many excimer laser devices only measure static cyclotorsion with static iris registration, and compensate for cyclotorsion according to the axis misalignment difference between seated and supine positions. Chang [16] stated that a part of the cyclotorsional movements can be detected by static eye trackers and effectiveness of topographic treatments is reduced because measured static cyclotorsion before surgery does not remain in the same position during surgery in most eyes. Therefore, the desired results cannot be achieved after all standard excimer laser procedures. Tomita et al. [17] compared two groups of subjects: those with static and dynamic cyclotorsion compensation and those with only dynamic cyclotorsion compensation. Better results in terms of postoperative refractive status including spherical and cylindrical refractive errors, and spherical equivalent, were reported in the subjects with both static and dynamic cyclotorsion compensation because either can be higher than the other. Thus, it is clear that to reach the best refractive outcomes, both static and dynamic cyclotorsion should be compensated because to compensate only one is not sufficient. The

WaveLight EX500 excimer laser platform provides an “artificial horizon,” which the patient sees in the supine position and the system allows compensation of both static and dynamic cyclotorsion with full automation, based on the iris registration technique. Even so, the compensation capacity of the system is not limitless. According to the results of the current study, each group with a lower magnitude of cyclotorsion had better postoperative cylindrical refractive error values than another group with a higher magnitude of cyclotorsion. Additionally, postoperative cylindrical refractive error after PRK using the WaveLight EX500 excimer laser device shows a significant correlation with magnitude of cyclotorsion. Therefore, the compensation capacity of the WaveLight EX500 device is directly affected by the magnitude of cyclotorsion.

Ivarsen et al. [20] reported 13% per diopter under-correction in low astigmatism and 16% per diopter in high astigmatism, due to non-compensation of cyclotorsion during small incision lenticule extraction. Ganesh et al. [10] reported far better results after small incision lenticule extraction with manual compensation of cyclotorsion, as 3% and 7% per diopter under-correction in low and high astigmatism, respectively. An important reason for the better results in low astigmatism in both non-compensated and manually compensated cyclotorsion is lower cyclotorsion compared to high astigmatism during surgery. Similarly, a positive correlation between preoperative cylindrical refractive error and the magnitude of cyclotorsion was found in this study. Lower postoperative cylindrical refractive error occurs after PRK using the WaveLight EX500 excimer laser device due to lower magnitude of cyclotorsion in subjects with lower preoperative cylindrical refractive error. Ganesh et al. [10] also reported that ≥ 5 degrees cyclotorsion causes significant under-correction in astigmatism. The results of the current study confirm these results because the magnitude of cyclotorsion was found to be positively correlated with postoperative cylindrical refractive error.

To investigate the clinical effects of different orientation and magnitude of cyclotorsion on the compensation capacity of the WaveLight EX500 PRK platform, only subjects with 0-10 degrees magnitude of cyclotorsion were included this study. The most important limitation of the current study is that there was no control group without cyclotorsion. Nevertheless, when the aim and method of the study are considered, the results provide a valuable contribution

to the literature. The subjects in the study had only compound myopic astigmatism. Although the study group was highly homogeneous, this design can be said to be a limitation in respect to generalization of the results to subjects without astigmatism. The 3-month postoperative clinical outcomes were obtained from the medical records of all patients as standard, but the retrospective nature and relatively short follow-up time may also be viewed as limitations of the study. Further prospective studies with longer follow-up, including control and study groups of different refractive status, would strengthen the findings of this study.

In conclusion, the current study showed that incyclotorsion and excyclotorsion can be equally compensable for compound myopic astigmatic subjects who underwent PRK with WaveLight EX500 platform. Eyes with ≤ 2.50 degrees cyclotorsion magnitude were seen to be more compensable than those with higher degrees of cyclotorsion magnitude. Preoperative high astigmatism was associated with high cyclotorsion magnitude, and a similar relationship was determined between cyclotorsion magnitude and postoperative astigmatic degree.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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