Vector Analysis of Cross Cylinder LASIK With the NIDEK EC-5000 Excimer Laser for High Astigmatism

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ABSTRACT

PURPOSE: To evaluate visual outcomes of LASIK in eyes with high astigmatic refractive errors with low spherical component.

METHODS: We prospectively evaluated cross cylinder LASIK in patients with high astigmatic eyes with low spherical component over a 2-year period. All laser surgeries were performed with the NIDEK EC-5000 excimer laser. We used power vectors (M [spherical equivalent] and J0 and J95 [cylinder]) to analyze the astigmatic results. Main outcome measures were uncorrected visual acuity (UCVA), best spectacle-corrected visual acuity (BSCVA), manifest refraction, and complications.

RESULTS: Thirty-four eyes of 22 patients were included. Patients were followed for 21.8 ± 3.7 months. At the last examination, UCVA of 20/40 or better was observed in 33 (97.1%) eyes. Best spectacle-corrected visual acuity after LASIK improved significantly in comparison to BSCVA before surgery (P < .005). Mean preoperative cylinder was −4.73 ± 0.89 diopters (D) (range: −4.00 to −7.00 D), which decreased to −0.29 ± 0.47 D (range: 0.00 to −1.50 D) at last follow-up (P < .001). Reduction in the magnitude of power vectors was 92.4% for M, 103.2% for J0, and 76.4% for J95. No cases of postoperative astigmatic regression or corneal haze were observed.


The goal of the surgical treatment of astigmatism is to even up the axes, collapse the differing focal lines in the eye, and bring the focus to the retina. The excimer laser has provided an effective surgical technique to correct astigmatism.1-3 Three approaches exist for the correction of astigmatism: negative-cylinder, positive-cylinder, and bitoric. Astigmatic correction with monotoric techniques results in a wider optical zone and sharp transition along the steepest topographic meridian, which may lead to regression, corneal haze, and functional symptoms.4 Bitoric LASIK flattens the steepest meridian with central cylindrical ablation and steepens the flattest meridian with paracentral ablation.5-8

Because central ablation induces a spherical hyperopic shift, cross cylinder ablation was designed to treat simple myopic astigmatism, prevent significant hyperopic shifts, and reduce ablation depth and postoperative regression. The first clinical results of such treatments were reported by Alió et al.9 Other authors reported the same results for correction of simple myopic, mixed, simple hyperopic, and compound myopic astigmatism.9-12

Despite numerous studies, establishing the efficacy, safety, and predictability of photorefractive keratectomy (PRK) and LASIK for the treatment of low to moderate mixed astigmatism, to the best of our knowledge, no study reports treatment of high astigmatism with low spherical component, analyzing astigmatism using power vectors. In our study, we evaluate...
the efficacy, predictability, and safety of bitoric LASIK in high astigmatism.

**PATIENTS AND METHODS**

The present study comprised patients with cylinder $-4.00$ diopters (D) or greater and sphere between $-0.75$ and $+0.75$ D, older than 18 years of age, with a stable refractive history for 1 or more years. Exclusion criteria were best spectacle-corrected visual acuity (BSCVA) worse than 20/60, scotopic pupil diameter wider than 6.0 mm measured by Orbscan IIz (Bausch & Lomb, Rochester, NY), history of uveitis or presence of posterior synechiae, history of eye trauma or surgery, corneal dystrophy, intraocular pressure $\geq 21$ mmHg, central corneal thickness $<500$ μm detected by ultrasonic pachymetry (NIDEK UP 1000; NIDEK Co Ltd, Gamagori, Japan), keratoconus suspect by videokeratography, active ocular or systemic disease likely to affect corneal wound healing, any evidence of developing cataract, presence of any significant retinal or optic disc pathology, tear film abnormality, and inability to comply with the follow-up schedule given to patients prior to surgery.

Each patient had a complete preoperative ocular examination including uncorrected visual acuity (UCVA), BSCVA, refraction, slit-lamp microscopy, applanation tonometry, fundus examination, keratometry, ultrasonic pachymetry, computerized corneal topography (EyeSys Vista; EyeSys Vision Inc, Houston, Tex), and elevation topography (Orbscan IIz, Bausch & Lomb), which was performed by one of the authors (A.A.).

All surgical procedures were performed by one surgeon (A.A.) at the Basir Eye Center, Tehran, Iran. All patients were informed about the details, risks, and benefits of the LASIK procedure, and written consent was obtained.

The NIDEK EC-5000 CXIII excimer laser (NIDEK Co Ltd) was used with the following parameters: wavelength 193 nm, fluence 85 μJ/cm², pulse repetition rate 40 Hz, mean ablation depth per pulse 0.3 μm. Lamellar keratotomy was performed using the M2 microkeratome (Moria, Antony, France) to create a 160-μm flap with a superior hinge. The ablation zone was 5.0 or 5.5 mm and the transition zone was 8.0 to 8.5 mm based on corneal thickness and curvature.

If both eyes of the same patient were included in the study, they were considered separately. Retreatment was based on patient dissatisfaction with at least 1.00 D of residual astigmatism and was postponed for at least 6 months after the initial surgery. Retreatment data were analyzed separately.

**SURGICAL TECHNIQUE**

The operating room was maintained within the temperature and humidity ranges stated in the laser manual. All surgeries were performed under topical anesthesia. Immediately before surgery, one drop of povidone-iodine 5% solution was applied over the conjunctiva.

The cross-cylinder technique was used to correct astigmatism. After adding $-0.50$ D to the total cylinder to compensate for some regression (eg, $-4.00$ D of cylinder was entered as $-4.50$ D), the refractive error data were entered in the machine with the mode of cross cylinder by an expert technician. The machine divided total cylinder equally into minus and plus cylindrical components. Positive cylinder correction in the flat meridian was followed by negative cylinder correction in the steep meridian. Finally, spherical correction equal to spherical equivalent of the refractive error was performed. The software of the machine automatically compensates for the amount of hyperopic shift (0.30 D for 1.00 D of negative cylinder ablation).

Topical chloramphenicol 0.5% and betamethasone 0.1% were administered every 4 hours for 1 week after surgery. Patients were followed 1, 3, 7, and 28 days after surgery and 3, 6, 12, 18, and 24 months after surgery. At each follow-up, UCVA, BSCVA, refraction, slit-lamp examination, applanation tonometry, and retinal examination were performed.

**SAFETY, EFFICACY, AND PREDICTABILITY**

The safety of a refractive procedure is measured by evaluating the number of lines of BSCVA gained or lost by each eye at the end of follow-up. The safety index \(^{11,13}\) is the ratio between the mean postoperative BSCVA and the mean preoperative BSCVA. A direct proportional relationship exists, ie, the higher the safety index, the safer the procedure. The efficacy \(^{11,13}\) of a refractive procedure is evaluated by calculating the percentage and/or the number of eyes having a postoperative UCVA ranging from 20/40 to 20/20 (0.3 to 0.0 logMAR) at the end of the follow-up. The efficacy index is the ratio between the mean postoperative UCVA at the end of follow-up and the mean preoperative BSCVA. A higher efficacy index indicates a more efficient procedure. Predictability \(^{11,13}\) is evaluated by calculating the number of eyes having a postoperative spherical equivalent refraction or vector analysis indices within $\pm 0.50$ D and $\pm 1.00$ D of the desired preoperative correction. This is determined by comparing the desired correction (determined by the preoperative spherical equivalent refraction or vector analysis indices) and the achieved correction at the end of follow-up (determined by the postoperative spherical equivalent refraction or vector analysis indices).
**Vector Analysis**

Astigmatic data can be analyzed several ways.\textsuperscript{13,22} We chose the vectorial method proposed by Thibos et al.\textsuperscript{20,22} They introduced power vector, which is a geometrical representation of spherocylindrical refractive errors in three fundamental dioptic components. The first component is a spherical lens with power $M$ equal to the spherical equivalent of the given refractive error. If this spherical power is removed from the prescription, the result is a Jackson cross cylinder equivalent to a conventional cylinder of positive power $J$ at $\alpha + 90^\circ$ crossed with a cylinder of negative power $J$ at $\alpha$. By convention, this astigmatic component can be described as a Jackson cross cylinder of power $J$ at $\alpha$ (the meridian of maximum positive power). This Jackson cross cylinder can be further resolved into the sum of two other Jackson cross cylinder lenses, one with power $J_o$ at $\alpha = 0^\circ = 180^\circ$ and the other with power $J_{45}$ at $\alpha = 45^\circ$. With this decomposition method, we are able to express any spherocylindrical refractive error by the three dioptic powers ($M$, $J_o$, and $J_{45}$). It is convenient to interpret these three numbers geometrically as (x, y, z), representing a point in a three-dimensional dioptic power space. The length of this vector is a measure of the overall blurring strength $B$ of a spherocylindrical lens or refractive error.\textsuperscript{20,21}

Using the notation of Thibos et al.,\textsuperscript{20,21} any spherocylindrical refractive error ($S$ [sphere], $C$ [cylinder] × $\alpha$ [axis]) can be converted into a set of three components of a dioptic power: $M$, $J_o$, and $J_{45}$, by the following formulas, whether the conventional notation is made in negative or positive cylinder forms (Fig 1)\textsuperscript{21}:

$$M = S + C/2$$

$$J_0 = (-C/2) \cos (2\alpha)$$

$$J_{45} = (-C/2) \sin (2\alpha)$$

$$B = (M^2 + J_o^2 + J_{45}^2)^{1/2}$$

Visual acuity measurements were performed using Snellen acuities and analyzed using logMAR equivalents. For showing results, all logMAR units were converted to decimal notation. The results are expressed as logMAR means (decimal equivalent) ± standard deviation.\textsuperscript{24}

Statistical analysis was performed using SPSS version 13.0 statistic software package (SPSS Inc, Chicago, Ill). The normal probability plots confirmed normality of the data in each group. Monovariate t test and Hotelling $T^2$ test of multivariate statistics were used for astigmatism analysis. $P$ values <.05 were considered significant.

**RESULTS**

Thirty-four eyes of 22 patients were included (Table 1). Mean patient age at surgery was 28.2 ± 7.1 years (range: 20 to 40 years). Mean follow-up was 21.8 ± 3.7 months (range: 18 to 30 months).

**Visual Acuity**

Before surgery, mean BSCVA was 0.082 logMAR (0.83) ± 1.23 (range: 0.3 to 1.0) and at last follow-up, it was 0.060 logMAR (0.87) ± 1.13 (range: 0.3 to 1.0; $P$<.001). Best spectacle-corrected visual acuity was 20/40 or better in 33 (97.1%) eyes. Three eyes (8.8%)
lost 1 Snellen line of BSCVA, 10 (29.4%) eyes gained 1 line, 2 (5.9%) eyes gained 2 lines, and 1 (2.9%) eye gained 3 lines (Fig 2). The safety index was 1.05.

Mean UCVA was 1.094 logMAR (0.08) ± 0.67 (range: 0.01 to 0.5) before and 0.079 logMAR (0.83) ± 1.12 (range: 0.3 to 1.0) after LASIK (P<.001). Uncorrected visual acuities of 20/40 or better and 20/20 or better were observed in 33 (97.1%) eyes and 8 (23.5%) eyes, respectively. The efficacy index was 0.97. Figure 2 shows a cumulative decimal visual acuity bar chart comparing BSCVA before LASIK and at final postoperative follow-up.

**Refractive Data**

A summary of refractive data after vectorial conversion before and after bitoric LASIK is shown in Table 2. Mean preoperative cylinder was −4.73±0.89 D (range: −4.00 to −7.00 D), which reduced to −0.29±0.47 D (range: 0.00 to −1.50 D) at final follow-up (P<.001). The mean astigmatism (\(\sqrt{C_0^2 + C_4^2}\)) was 1.34 D before surgery, which reduced to 0.06 D after surgery. Mean sphere was −0.125±0.50 D (range: −0.75 to +0.75 D), which reduced to −0.04±0.52 (range: −1.25 to +1.00 D) at last follow-up (P>.05). Mean preoperative spherical equivalent refraction (M) was −2.49±0.56 D (range: −1.25 to −4.00 D), which was reduced to −0.19±0.60 D (range: −1.75 to 1.00 D) at final follow-up (P<.001).

To get an overall sense of surgical effects on manifest refractive errors, we collected the values of blur strength B into the frequency histograms (Fig 3). The results demonstrate that the procedure has compressed a wide range of preoperative refractive errors into a narrow distribution near emmetropia. These visual impressions are quantitatively weighted by numerical data in Table 2. The absolute value of power vector magnitudes reduced for M, I\(_0\), I\(_{45}\), and B after surgery, and a compression of the overall refractive error data was observed by reduction in standard deviations (from 1.88 D to 0.23 D for I\(_0\) and from 0.79 D to 0.14 D for I\(_{45}\)). There is a reduction of 92.4% in the magnitude of M, 103.2% in the magnitude of I\(_0\), 76.4% in the magnitude of I\(_{45}\), and 95.5% in the magnitude of the mean astigmatism (given by \(\sqrt{C_0^2 + C_4^2}\), which is distance of a point in Figure 4 from the origin). Figure 4, which shows astigmatic components of the power vector by a two-dimensional vector (U\(_0\), I\(_{45}\)), depicts this astigmatic change more precisely. The origin of this graph (0, 0)

**Table 2**

**Refraction After Vectorial Conversion Before and After Bitoric LASIK Using the NIDEK EC-5000 Excimer Laser in 34 High Astigmatic Eyes**

<table>
<thead>
<tr>
<th>Refraction (D)</th>
<th>Before LASIK (D)</th>
<th>After LASIK* (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>−2.49±0.563</td>
<td>−0.19±0.602</td>
</tr>
<tr>
<td>I(_0)</td>
<td>1.324±1.872</td>
<td>−0.04±0.234</td>
</tr>
<tr>
<td>I(_{45})</td>
<td>0.188±0.792</td>
<td>0.045±0.137</td>
</tr>
<tr>
<td>B</td>
<td>3.456±0.621</td>
<td>0.512±0.455</td>
</tr>
</tbody>
</table>

\(M = \text{spherical equivalent refraction, } I_0 = \text{cylinder at 0°, } I_{45} = \text{cylinder at 45°, } B = \text{blur strength}\)

*At last follow-up.
represents an eye free of astigmatism. Wide distribution of the preoperative data is compressed into a concentrated distribution around the graph origin after LASIK.

A series of three monovariate $t$ tests were performed to test whether three components of the power vector analysis could have a mean, which is statistically different from zero. The results revealed no difference from zero ($P=.073$ for $M; P=.31$ for $J_0; P=.068$ for $J_{45}$), which demonstrates adequate correction of refractive error by LASIK. A three-dimensional multivariate Hotelling $T^2$ test confirmed that the mean power vector after surgery was not significantly different from a zero length vector ($P=0.1$), which shows that LASIK achieved its objectives for correcting astigmatism.

Figure 5 shows the attempted versus achieved plot for spherical equivalent refraction ($M$) and for both components of astigmatism, $J_0$ and $J_{45}$. Regarding spherical equivalent refraction ($M$), 94.1% of cases were within $\pm1.00$ D, 70.6% were within $\pm0.50$ D, and 41.2% were within $\pm0.25$ D. For $J_0$, 100% of cases were within $\pm1.00$ D, 97.1% were within $\pm0.50$ D, and 79.4% were within $\pm0.25$ D. For $J_{45}$, 100% of cases were within $\pm1.00$ D, 100% were within $\pm0.50$ D, and 91.2% were within $\pm0.25$ D. These results indicate good predictability with the bitoric technique.

**RETREATMENT**

Retreatment for a residual refractive error and patient dissatisfaction after surgery was needed in only one eye. Uncorrected visual acuity after retreatment reached to 0.05 logMAR (0.9) and at last follow-up, residual refractive error was $-0.50 \times 30^\circ$. No complications related to the lamellar cut were noted. Decentered ablation or epithelial ingrowth was not observed in any eye. No case of postoperative astigmatic regression or corneal haze was observed.

**DISCUSSION**

Our results show that bitoric LASIK for the correction of high astigmatism is a safe, effective, and predictable refractive procedure. We achieved satisfactory results with good UCVA at final follow-up. Our results also demonstrate excellent reduction in magnitude of power vectors. Retreatment was needed in only one eye, and there were no noticeable complications such as postoperative regression and corneal haze.

Among the various methods used in surgical treat-
ment of astigmatism (eg, PRK, LASIK, and arcuate or transverse keratotomy), LASIK has shown excellent outcomes in mixed and compound myopic astigmatism.\textsuperscript{5,7,8,12,25,26} There are three LASIK-assisted methods for the correction of astigmatism: positive cylinder ablation, negative cylinder ablation, and bitoric ablation. Azar and Primack\textsuperscript{6} performed theoretical analysis of ablation depths and profiles in the treatment of compound hyperopic and mixed astigmatism using four approaches for each: 1) combined hyperopic spherical and myopic cylindrical treatments, 2) combined spherical (plus or minus) and hyperopic cylindrical treatments, 3) combined cylindrical treatments, and 4) combined cross cylinder and spherical equivalent treatments. They concluded that the second and third approaches are more tissue sparing. However, they noted that it is not known whether the hyperopic shift induced by the myopic cylindrical correction may allow the third approach to best preserve corneal thickness in mixed astigmatism. On the other hand, they depicted the fourth approach, which is the method we used, has less central and peripheral tissue loss than the first but more than that predicted in the second and third approaches.

In the literature, bitoric ablation is performed using two main methods.\textsuperscript{7,10,25,27} The first method is to perform a pure bitoric ablation, dividing the refraction into two cross cylinders without a spherical correction (third approach in Azar and Primack’s study\textsuperscript{6}). This modality has the advantage of removing less corneal tissue, which is preferred for correcting mixed astigmatism.\textsuperscript{7,10,25,26} The second option\textsuperscript{8,27,24} divides the total amount of cylinder into two equal parts of positive and negative cylinders, plus an additional spherical component to compensate for the rest of the refractive deficit (the fourth approach in Azar and Primack’s study\textsuperscript{6}). Such corneal resection has the following advantages: better preservation of the physiologically prolate and symmetrical shape of the cornea; relatively lower rate of myopic regression;\textsuperscript{4} and probable reduction of postoperative aberrations.\textsuperscript{28} Although the second method removes more corneal tissue than the first, due to the high amount of astigmatism and based on aforementioned reasons, we chose the second method, which seems to distort corneal shape minimally and might reduce the amount of root-mean-square for tetrafoil and trefoil after surgery.\textsuperscript{8}

In our study, final UCVA 20/40 or better was observed in 33 (97.1\%) eyes, whereas in other reports it was between 60\% and 93\% of eyes.\textsuperscript{5,7,10,11,25,26} More than 38\% of our cases gained 1 or more lines of BSCVA; other studies have reported values between 25\% and 68\%.\textsuperscript{5,7,10,11,25,26} In different studies, the safety index was between 1 and 1.16 and efficacy index was between 0.96 and 0.98.\textsuperscript{5,7,10,11,25,26} In our study, the safety and efficacy indices were 1.05 and 0.97, respectively, which show that our procedure is as safe and efficient as previous studies. In our study, 94.1\% of eyes had spherical equivalent refraction (M) within ±1.00 D and 70.6\% within ±0.50 D. Different studies have reported ranges from 57.5\% to 92\% for ±0.50 D and from 82.5\% to 100\% for ±1.00 D in different studies.\textsuperscript{5,7,10,11,25,26}

When LASIK is performed for the correction of high astigmatism, it is common to observe an increase in BSCVA after surgery.\textsuperscript{7,10,26} This might be explained by the fact that the optical compensation for high astigmatism produces a larger distortion of the image than that caused by a lens, which compensates for smaller degrees of astigmatism.\textsuperscript{10} As noted by Albarrán-Diego et al\textsuperscript{10}, meridional differences in retinal image size can reduce visual acuity in astigmatic individuals and this effect is more remarkable in astigmatism >3.00 D. Thus, a reduction in the amount of astigmatism such as that obtained in our study (from −4.73 to −0.29 D) would improve visual acuity by the reduction of the image distortion. By measuring the retinal image quality using the double-pass technique, Pujol et al\textsuperscript{29} demonstrated that higher amounts of astigmatism can cause reduction in retinal image quality and ultimately reduce visual acuity. Therefore, bitoric LASIK could be considered not only as a technique for avoiding the need for optical compensation, but also as a method for improving visual acuity in a significant percentage of patients with high astigmatism.

The mathematical representation and statistical manipulation of spherocylindrical refractive errors is a recurring topic in the ophthalmic literature.\textsuperscript{13-24,30-34} Much of this debate has revolved around the difficulties that arise when astigmatism is represented in the traditional polar form of magnitude and axis rather than the more mathematically tractable Cartesian form. In general, statistical analysis of angular data (eg, astigmatism axes, compass bearings, angle of disappearance of migratory birds over the horizon) is fundamentally different from the analysis of nondirectional data.\textsuperscript{17} Consequently, the inappropriate application of conventional statistical methods to directional data can give misleading results.

Among some reputable, thorough, and mathematically correct methods,\textsuperscript{13,15-17,21,30} we chose power vectors for representing and analyzing astigmatism.\textsuperscript{20,21} The primary advantage of this method is that each of the three fundamental power vector components of astigmatism is mathematically independent from one another. In other words, spherical lens cannot be produced by any combination of Jackson cross cylinder lenses. This notion of independence, which is formalized in the mathematical concept of orthogonality, simplifies
practical problems involving the combination, comparison, and statistical analysis of spherocylindrical lenses or refractive errors. Another advantage of this mathematical approach is that astigmatism is represented in rectangular vectors. Hence, conventional scalar methods can be applied to each vectorial component, and this notation allows application of standard multivariate statistics to population means and variances computation, confidence intervals definition, and hypotheses development. As proposed by Thibos et al., we analyzed both components of astigmatism ($I_{45}$, $I_{45}$) separately. The reduction in the magnitude of power vector was 92.4% for $I$, 103.2% for $I_{45}$, and 76.4% for $I_{45}$. The results of the monovariate $t$ tests revealed no statistical difference from zero in the three components of power vector ($P>.05$ for $I$, $I_{45}$, and $I_{45}$), ie, the refractive error was adequately corrected by LASIK. The preoperative mean cylinder was $-4.72 \pm 0.89$ D, which was reduced to $-0.29 \pm 0.47$ D at last follow-up, implying a reduction of 93.6%. Albarrán-Diego et al. using the same method, showed a reduction in vectorial astigmatism of 103% and 98% for $I_0$ and $I_{45}$, respectively. There was an 83.4% reduction in the mean cylinder ($-4.04 \pm 1.13$ D before surgery decreased to $-0.67 \pm 0.79$ D after surgery). Chayet et al. showed that 91.3% decrease in mean cylinder from $-4.02 \pm 1.22$ D before surgery to $-0.35 \pm 0.42$ D after surgery.

Our study shows that the cross cylinder method is clinically safe, effective, and predictable for the correction of high astigmatism. Furthermore, it has distinct advantages over other studies; we evaluated high astigmatic eyes with low spherical component and also used power vectors for analysis of astigmatic results. However, the number of patients is limited. Further studies are needed to assess the long-term efficacy of the cross cylinder method by taking factors such as postoperative astigmatic regression, contrast sensitivity, and corneal haze into consideration, which may affect the long-term postoperative outcome.

**AUTHOR CONTRIBUTIONS**

Study concept and design (A.A., A.S., A.R.); data collection (A.A., F.N.); analysis and interpretation of data (M.E., B.E., F.N.); drafting of the manuscript (A.A., M.E., B.E., F.N.); critical revision of the manuscript (A.A., A.S., A.R., M.E., B.E., F.N.); statistical expertise (M.E., B.E., F.N.); administrative, technical, or material support (A.S.); supervision (A.S.)

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