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Article *in* Journal of Cataract and Refractive Surgery · December 2017

DOI: 10.1016/j.jcrs.2017.07.039

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ARTICLE

Clinical outcomes of laser in situ keratomileusis with an aberration-neutral profile centered on the corneal vertex comparing vector planning with manifest refraction planning for the treatment of myopic astigmatism

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Purpose: To evaluate clinical outcomes of laser in situ keratomileusis (LASIK) with an aberration-neutral profile centered on the estimated visual axis (considering 70% of the pupil offset toward the corneal vertex) comparing vector planning with manifest refraction planning for the treatment of myopic astigmatism.

Setting: Muscat Eye Laser Center, Muscat, Sultanate of Oman, Muscat, Oman.

Design: Retrospective case series.

Methods: The outcomes were evaluated at a 6-month follow-up in eyes showing ocular residual astigmatism (ORA) over 0.75 diopters (D) preoperatively.

Results: Eighty-five treatments were based on manifest astigmatism (preoperative sphere −2.11 D ± 1.3 [SD], cylinder −0.90 ± 1.0 D), and 79 treatments were based on vector planning (preoperative sphere −2.46 ± 1.5 D, cylinder −0.78 ± 0.79 D). At a 6-month follow-up, 128 patients (164 eyes) were evaluated and no significant differences were observed between the 2 groups in terms of difference between corrected distance visual acuity and uncorrected distance visual acuity (UDVA) ($P = .1$, t test and Fisher exact test Snellen lines 1 or better, $P = .4$) and postoperative UDVA ($P = .05$, t test and Fisher exact test for UDVA 20/16 or better, $P = .3$). Significant differences were observed between the 2 groups in terms of achieved spherical equivalent ($P = .04$), corneal toricity, and ORA ($P < .001$, t test and Fisher exact test for ORA $\leq$0.75 D, $P < .001$).

Conclusion: Performing LASIK for myopic astigmatism with the vector planning approach resulted in comparable visual outcomes to manifest refraction planning.

J Cataract Refract Surg 2017; 43:1504–1514 © 2017 ASCRS and ESCRS

Treatment of astigmatism in laser-based vision correction procedures is commonly done using 2 different planning strategies, 1 based on the ocular refraction of the eye and the other based on the shape of the cornea. The 2 treatment planning strategies originated because the refractive and topographic astigmatism do not always coincide precisely. Their differences can be precisely described by ocular residual astigmatism (ORA), defined as the vectorial difference between corneal astigmatism and the refractive cylinder at the corneal plane expressed in diopters (D) and degrees.[1,2] In normal eyes treated for myopic astigmatism, the ORA typically ranges from 0.73 to 0.81 D.[1,2] In 1 study,[1] the ORA exceeded 1.00 D in 34% of eyes. In addition, 7% of eyes treated with manifest refraction alone exceeded the preoperative magnitude of topographic astigmatism. The ORA can be even higher in more irregular corneas such as in cases of keratoconus (1.34 D).[3–5]

Submitted: March 24, 2017 | Final revision submitted: June 8, 2017 | Accepted: July 26, 2017

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Presented in part at the XXXIV Congress of the European Society of Cataract and Refractive Surgeons, Copenhagen, Denmark, September 2016, and the ASCRS Symposium on Cataract, IOL and Refractive Surgery, Los Angeles, California, USA, May 2017.

James K.Y. Ong, BOptom, PhD, NewVision Clinics, Melbourne, Australia, organized Figure 3.

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0886-3350/$ - see frontmatter
https://doi.org/10.1016/j.jcrs.2017.07.039

The influence of ORA on the postoperative status also depends on the goals of the refractive procedure. If the goal is only to eliminate the requirement for spectacles, laser ablations based only on manifest refraction can suffice. However, ignoring the ORA and sculpting the cornea based only on the manifest refraction has the disadvantage that the entire ORA remains as the postoperative surgical residual astigmatism, also resulting in induction of spherical aberrations in some cases.[1] This conflict between the 2 treatment planning strategies for astigmatism correction can be resolved in a balanced manner by following the vector planning method, which incorporates the measured corneal and refractive astigmatism data across the entire ablation profile.[1,6,7]

The aim of the present study was to compare the outcomes of laser in situ keratomileusis (LASIK) for correction of myopic astigmatism planned by considering only the manifest refraction of the patients (manifest refraction group, n = 85) with the treatments planned according to the vector planning method[1] by incorporating both the manifest refraction and the corneal topographic shape (vector planning group, n = 79). Furthermore, in each group, only eyes showing high preoperative ORA (strictly above 0.75 D) were included. The inclusion criteria of ORA greater than 0.75 D was selected to match the typical ORA ranges seen in normal eyes (0.73 to 0.81 D[1,2]). To our knowledge, the results of such a direct large-scale comparison of these 2 treatment planning strategies have not been published. We present this comparison based on the safety, efficacy, and accuracy of LASIK at 6-month follow-ups in each group.

PATIENTS AND METHODS

Patients

This cohort study was based on a consecutive case series of patients treated by the same surgeon (M.C.A.) with the Aberration-Free treatments (Schwind eye-tech-solutions GmbH & Co. KG) to correct myopic astigmatism at the Muscat Eye Laser Center, Muscat, Sultanate of Oman. Proper informed consent was obtained from each patient for the treatment and for the use of their de-identified clinical data for publication.

The outcomes of performing LASIK for correction of myopic astigmatism in consecutive eyes were retrospectively analyzed. Eyes meeting the inclusion criteria and treated with manifest astigmatism planning (manifest refraction group) were retrospectively compared with eyes meeting the inclusion criteria and treated with vector planning (vector planning group).

Inclusion criteria were patients older than 18 years, medically suitable for LASIK, ORA greater than 0.75 D, having myopic astigmatism with corrected distance visual acuity (CDVA) no worse than 20/25 in either eye, stable refraction (<0.5 D change in mean spherical equivalent [SE]) for 6 months before the study and discontinued use of contact lenses for at least 2 to 4 weeks (depending on contact lens type) before the preoperative evaluation. Patients were required to have a normal keratometry (K) reading and topography (visually no suspect or forme fruste keratoconus). The inclusion criteria of ORA greater than 0.75 D was considered only for this retrospective chart review and not for performing the treatments.

Patients who had systemic illnesses, a calculated corneal bed thickness less than 300 μm after ablation, preoperative central corneal thickness of less than 470 μm, previous ocular surgery, or had abnormal corneal topography were excluded from the study. Additional exclusion criteria were clinically relevant lens opacity, a pupil offset of 0.7 mm or more, and signs of binocular vision anomalies at distance and near.

Preoperative Assessment

Preoperatively, all the patients had a full ophthalmologic examination that included manifest refraction, cycloplegic refraction, slitlamp microscopy of the anterior segment, and corneal wavefront analyses (Keratron Scout, Optikon SpA). The CDVA and uncorrected distance visual acuity (UDVA) were assessed with the Early Treatment Diabetic Retinopathy Study charts. All the tests were performed monocularly.

The CDVA was always assessed with trial frames and not contact lenses. Corneal wavefront analysis was performed over a 6.0 mm diameter. The root-mean-square (RMS) higher-order aberrations (HOAs) were extracted.

Surgical Procedure

All the treatments were prepared using the Schwind CAM software in the aberration-free treatment mode (Schwind eye-tech-solutions GmbH and Co. KG). The devices used in this study bear the standards of European conformity (Conformité Européene) marking, but are not approved by the U.S. Food and Drug Administration.

The treatments were planned based on either the manifest refraction (manifest refraction group) or the refraction following the vector planning strategy[1] (vector planning group). The treatments were performed chronologically. Manifest refraction-based treatments were planned for all the patients being treated for myopic astigmatism until July 2, 2015; afterward, all the patients were treated with vector planning-based treatments. The change in treatment paradigm was a clinical measure to improve astigmatic outcomes. All treatments were analyzed at the 6-month postoperative follow-up, and the last eyes treated with manifest astigmatism planning and meeting the inclusion criteria were compared with the first eyes treated with vector planning and meeting the inclusion criteria.

The treatment parameters in the vector planning group were calculated using the Assort program (version 5.50, Assort Pty Ltd.). Vector planning is a treatment paradigm that combines refractive cylinder parameters with cornea astigmatism measures. This can include manifest, cycloplegic, or wavefront refractions and simulated K, manual K, autokeratometry, or corneal topographic astigmatism (anterior or total). The aim is to reduce the amount of corneal astigmatism remaining postoperatively compared with that remaining using treatment based on refractive cylinder parameters alone. It involves calculating the ORA and then using a user-determined emphasis (60% in the case series) by refractive parameters of the ORA to target remaining corneal astigmatism and refractive cylinder. The targeted sphere is such that an SE of zero (or any other target set by the use without consideration of vector planning method) is the goal. The target-induced astigmatism (TIA) vector or the astigmatism treatment is then calculated based on these targets. The emphasis placed on the ORA can be customized for each case from anywhere between 0% emphasis and 100% emphasis by refraction on the ORA.

In this study, the treatments in the vector planning group were designed with a 60% emphasis placed on the correction of refractive astigmatism and a 40% emphasis placed on the correction of corneal astigmatism. Previous studies using vector planning have also shown that placing an emphasis between 50% to 65% on refractive parameters (and 35% to 50% on corneal parameters) to be the ideal location for achieving an optimum visual outcome that incudes reducing aberrant symptoms related to corneal shape.[3,5] For the calculation of ORA as the vectorial difference between corneal and manifest refractive astigmatism, the manifest refraction was first evaluated at the corneal plane. The best-fit K readings of the Maloney index[8] were measured only for the anterior corneal surface; however, while retaining the use of 1.3375 as the refractive index in calculations, to also account for the typical posterior corneal surface.

For each treatment, the CAM planning software was used to calculate the size of the optimum transition zone, depending on the preoperative refraction and optical treatment zone. Drops of topical anesthetic were instilled in the upper and lower fornices. Flaps were made using the Femto LDV Crystal Line (Ziemer Ophthalmic Systems AG) with a 110 μm nominal flap thickness.

Additional drops of topical anesthetics were instilled; the lid margins and periocular region were disinfected using chlorhexidine gluconate 4%. A sterile drape covering the eyelashes and face was used to isolate the surgical field. A lid speculum was inserted to allow maximum exposure of the globe.

Proper alignment of the eye with the laser was achieved with a 1050 Hz infrared eye tracker with simultaneous limbus, pupil, and torsion tracking integrated into the laser system and centered on the corneal vertex. The eye tracker had a typical response time of 1.7 milliseconds with a system total latency time of 2.9 milliseconds. The flap was lifted and the excimer laser ablation was delivered to the stroma. Aspheric non-wavefront-guided treatments were performed in all cases.[9] The ablation profile was centered on an estimated visual axis determined by the topographer (taking 70% of the pupil toward the corneal vertex [offset value]), which closely approximates the visual axis. In addition, the topographic K readings at 3.0 mm diameter were used for the compensation of the loss of efficiency when ablating the cornea at non-normal incidences. Patients were requested to focus on a pulsing green fixation light throughout the ablation.

The flap was repositioned and the interface was irrigated with a balanced salt solution, removing any debris. Patients received topical antibiotic drops 4 times a day for 1 week, corticosteroid drops 4 times a day tapering off in 1 week, and ocular lubricants as needed.

Postoperative Evaluation

Patients were reviewed 6 months postoperatively. The postoperative evaluation included measurement of monocular UDVA, manifest refraction, monocular CDVA, topography, and corneal-wavefront analyses.

Statistical Analysis

To assess the level of significance of the findings, the minimum level of detection was calculated for this sample size and compared with the absolute mean differences, for a standard statistical power (? = 80%, ? = 5%) of all the analyzed metrics. Analysis of variance and *t* tests were performed between preoperative and postoperative status and between the 2 groups. The 2-tailed Fisher exact test was performed to examine the significance of the association (contingency) between the patient classifications into 2 groups. The statistical tests were performed based on the number of patients rather than number of treatments to prevent the bias of including both eyes of the same patient in the analyses. A *P* value less than 0.05 was used for all statistical tests as the level of significance.

Visual acuity was evaluated in decimal scale but converted to logarithm of the minimum angle of resolution (logMAR) for reporting comparability. The UDVA and CDVA, SE refraction, refractive astigmatism, cardinal and oblique astigmatism, surgically induced astigmatism (SIA), angle of error, ORA, and corneal toricity were individually analyzed for the manifest refraction group and the vector planning group. The correction index and difference vector were calculated for the vector planning group and the manifest refraction group using the refractive power as well as the corneal K readings.[1,2,10] The results are based on the standard for reporting astigmatism outcomes of refractive surgery.[11,12]

RESULTS

The study comprised 164 consecutive eyes (of 128 patients) of which there were 85 eyes in the manifest refraction group and 79 eyes in the vector planning group.

The mean optical treatment zone diameter was 6.9 mm $\pm$ 0.3 (SD) (range 6.3 to 7.5 mm, median 7.0 mm) in the manifest refraction group and 6.9 $\pm$ 0.2 mm (range 6.3 to 7.5 mm, median 7.0 mm) in the vector planning group; the differences between groups were not statistically significant (P = .24). The mean total ablation zone was 7.6 $\pm$ 0.5 mm (range 6.5 to 8.7 mm, median 7.6 mm) in the manifest refraction group and 7.6 $\pm$ 0.3 mm (range 6.7 to 8.3 mm, median 7.6 mm) in the vector planning group; the differences between groups were not statistically significant (P = .33). At the time of the surgery, the mean age of the patients was 27.8 $\pm$ 5.7 years and 26.2 $\pm$ 4.9 years in the manifest refraction group and vector planning group, respectively (P = .02). The sex distribution was 50% men and 50% women in both groups. In the manifest refraction group, 59 of 85 eyes completed the 6-month follow-up, whereas in the vector planning group, 65 of 79 eyes completed the 6-month follow-up. For the remaining eyes in each group, 3-month follow-up data were analyzed. Preoperatively, the mean SE refraction was −2.56 $\pm$ 1.15 D in the manifest refraction group and −2.85 $\pm$ 1.34 D in the vector planning group, respectively; there were no statistically significant differences between the 2 groups in terms of manifest refraction (sphere P = .053, cylinder P = .098, SE P = .092), keratometry (P = .15), ORA (P = .076), and individual and RMS HOAs (P > .05).

Efficacy

Figure 1 (*top row, left,* and *bottom row, left, respectively*) shows the differences between preoperative CDVA and postoperative UDVA and the distribution of monocular UDVA and CDVA. At the 6-month follow-up, 23 eyes in the vector planning group and 18 eyes in the manifest refraction group achieved 1 or more Snellen lines of UDVA compared with the preoperative CDVA, with significant improvements seen in the manifest (P < .005) and the vector planning group (P < .005). No significant differences were observed between the manifest and vector planning groups (P = .1, *t* test and Fisher exact test for the difference between UDVA and CDVA [Snellen lines] 1 or better, P = .4).

At the 6-month follow-up, 76 eyes in the vector planning group and 79 eyes in the manifest refraction group achieved 20/20 or better monocular UDVA (Figure 1, *bottom row, left*). No significant differences were observed between the 2 groups (P = .05, *t* test and Fisher exact test for UDVA 20/16 or better, P = .3) in terms of postoperative UDVA. The efficacy index based on the logMAR visual acuities was 1.05 and 1.07 in the manifest refraction group and the vector planning group, respectively.

Safety

Figure 1 (*top row, right*) shows the changes in monocular CDVA. At the 6-month follow-up, 23 eyes in the vector

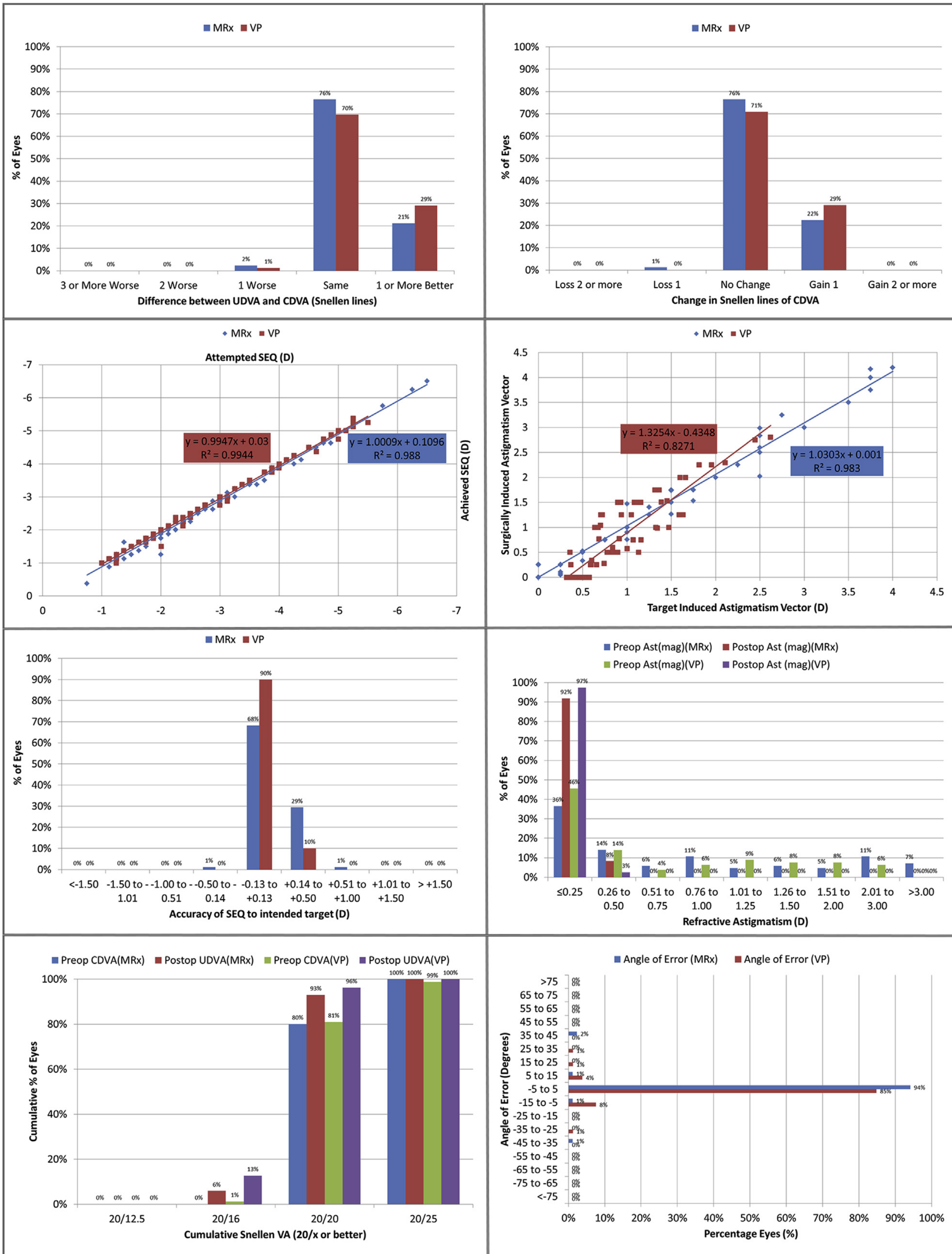

Figure 1. Clinical outcomes at 6-month follow-up after LASIK with an aberration-neutral profile centered on the corneal vertex (taking 70% of the pupil offset value) comparing vector planning (n = 79) to manifest refraction planning (n = 85) for the treatment of myopic astigmatism, based on the standard for reporting astigmatism outcomes of refractive surgery (Ast = astigmatism; CDVA = corrected distance visual acuity; mag = magnitude; MRx = manifest refraction group; SEQ = spherical equivalent; UDVA = uncorrected distance visual acuity; VA = visual acuity; VP = vector planning group).

planning group and 19 eyes in the manifest refraction group gained 1 Snellen line of CDVA, with no statistically significant differences between the 2 groups ($P = .06$, t test and Fisher exact test for gain in 1 Snellen line of CDVA, $P = .4$). The safety index based on the logMAR visual acuities was 1.05 and 1.07 in the manifest refraction group and vector planning group, respectively.

Accuracy

Figure 1 (*second row, left*) shows the relationship between the attempted and achieved SE. A nearly linear relationship was observed in both groups (coefficient of determination $r^2 = 0.99$, $P < .0005$ in the manifest refraction group and $r^2 = 0.99$, $P < .0005$ in the vector planning group). There was a significant difference observed between the 2 groups in terms of achieved SE ($P = .04$); however, the minimum level of detection was observed to be greater than the absolute differences between the mean achieved SE, suggesting a small sample size to confirm this finding with sufficient statistical power.

Figure 1 (*third row, left*) shows the accuracy of SE to the intended target (D). At the 6-month follow-up, 71 eyes in the vector planning group and 58 eyes in the manifest refraction group achieved an SE between −0.13 D and +0.13 D, respectively. Significant differences were observed between the 2 groups with an overall higher accuracy observed in the vector planning group ($P = .04$, t test, and Fisher exact test for accuracy of SE −0.13 to +0.13 D, $P = .003$).

Figure 1 (*second row, right*) shows the relationship between the attempted TIA and achieved SIA. Higher linearity was observed in the manifest refraction group ($r^2 = 0.98$) compared with the vector planning group ($r^2 = 0.83$), achieving statistical significance ($P = .01$). However, the level of detection was observed to be greater than the absolute differences between the mean achieved SIA, suggesting a small sample size to confirm this finding with sufficient statistical power.

In terms of refractive astigmatism (Figure 1, *third row, right*), 73 eyes in vector planning group and 78 eyes in the manifest refraction group achieved a postoperative refractive astigmatism of 0.25 D or less. No significant differences were observed between the groups ($P = .05$, t test and Fisher exact test for refractive astigmatism ≤0.25 D, $P = .4$).

Figure 1 (*bottom row, right*) shows the angle of error achieved in each group. At the 6-month follow-up, 67 eyes in the vector planning group and 80 eyes in the manifest refraction group showed an angle of error between −5 degrees and +5 degrees (manifest refraction group $P = .35$, vector planning group $P = .49$; $P = .40$ between groups).

Corneal Toricity and Ocular Residual Astigmatism

Figure 2 (*top left and top right, respectively*) shows the distribution of ORA and corneal toricity. At the 6-month follow-up, 59 eyes (75%) in the vector planning group and 29 eyes (34%) in the manifest refraction group achieved a corneal toricity less than 0.75 D. The differences between the 2 groups were statistically significant and favored the vector planning group ($P < .001$, t test and Fisher exact test for ORA ≤0.75 D, $P < .001$). Furthermore, the level of detection was observed to be smaller than the absolute differences between the 2 groups, suggesting a good sample size for this statistical power. The Figure 3 (*right and left*, respectively) polar graphs show the comparison of corneal toricity and refractive cylinder between the manifest refraction group and the vector planning group. The arithmetic mean corneal toricity reduced from 1.46 D preoperatively to 1.13 D postoperatively in the manifest refraction group and from 1.03 D to 0.69 D in the vector planning group, respectively. The summated vector mean increased in the manifest refraction group (preoperative 0.66 @ 93 to postoperative 1.00 @ 92), while remained stable in the vector planning group (preoperative 0.48 @ 92 to postoperative 0.50 @ 91) (Figure 3, *right*). The arithmetic mean refractive astigmatism reduced from 1.14 D preoperatively to 0.10 D postoperatively in the manifest refraction group and from 0.77 D to 0.07 D in the vector planning group, respectively. The summated vector mean changed significantly in the manifest refraction group (preoperative 0.33 @ 176 to postoperative 0.06 @ 96) and in the vector planning group (preoperative 0.34 @ 173 to postoperative 0.03 @ 167) (Figure 3, *left*).

At the 6-month follow-up, 34 eyes (43%) in the vector planning group and 18 eyes (21%) in the manifest refraction group achieved an ORA less than 0.75 D. The differences between the 2 groups were statistically significant and favored the vector planning group ($P = .001$, t test and Fisher exact test for ORA ≤0.75 D, $P = .013$). Furthermore, the level of detection was observed to be smaller than the absolute differences between the 2 groups, suggesting a good sample size for this statistical power.

The target-induced cardinal and oblique astigmatism correlated well with the surgically induced cardinal and oblique corneal toricity, respectively, for both groups (cardinal astigmatism, $r^2 = 0.86$ for the manifest refraction group and $r^2 = 0.80$ for the vector planning group; oblique astigmatism $r^2 = 0.43$ for the manifest refraction group and $r^2 = 0.54$ for the vector planning group). No significant differences were observed between the 2 groups.

Correction Index and Difference Vector

Figure 4 shows the correction index and difference vectors; the metrics calculated using the refractive power are shown on the left and the metrics calculated using the corneal K readings are shown on the right. Based on the refractive power, the vector planning group was more distributed with the majority (46 eyes) in the vector planning group, showing a difference vector between 0.26 D and 0.50 D compared with the manifest refraction group in which 78 eyes showed a difference vector of 0.25 D or less (Figure 4, *top left*). These differences decreased when analyzed based on the corneal K readings, whereas the 2 groups had a similar distribution of the difference vector.

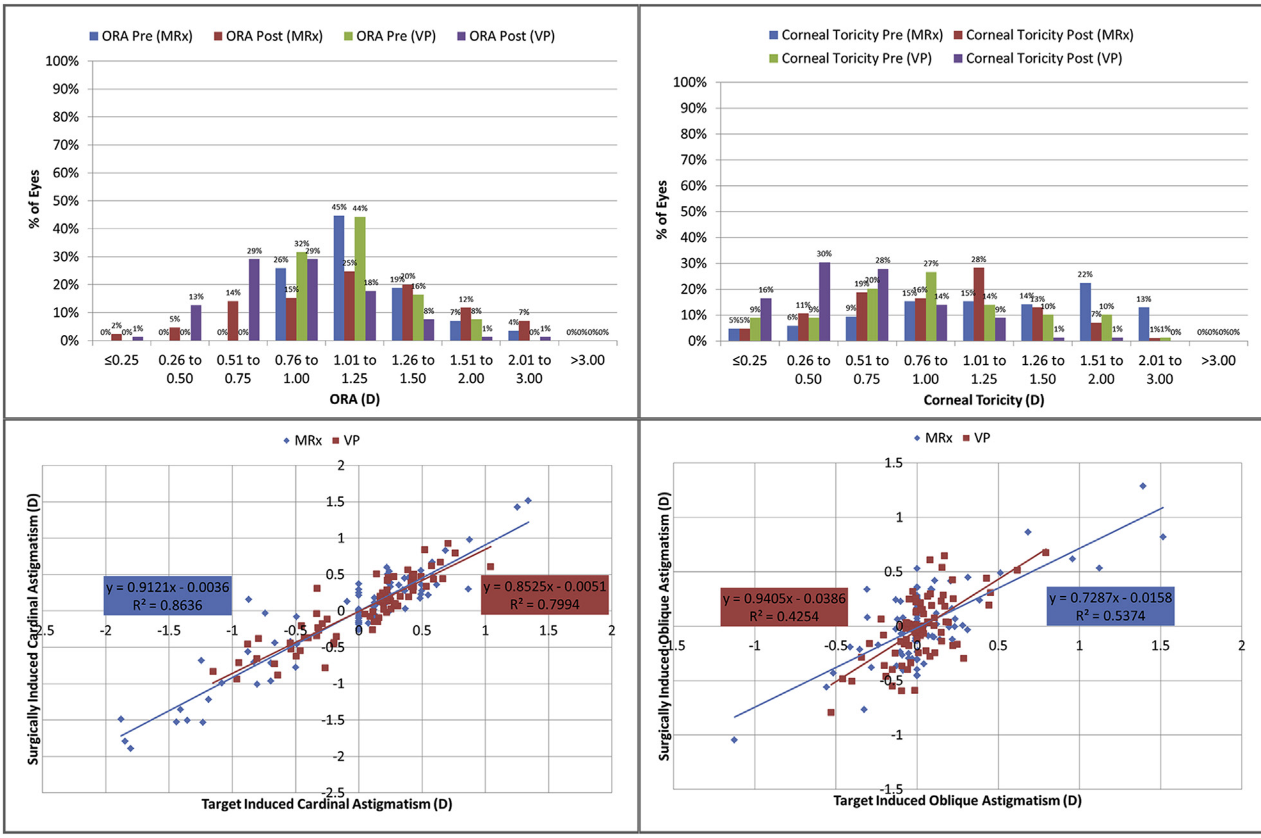

Figure 2. Distribution of ORA and corneal toricity at 6-month follow-up after LASIK with an aberration-neutral profile centered on the corneal vertex (taking 70% of the pupil offset value) comparing vector planning (n = 79) to manifest refraction planning (n = 85) for the treatment of myopic astigmatism. The bottom row shows the relationship between the target-induced cardinal and oblique astigmatism with the surgically induced cardinal and oblique astigmatism, respectively, for each group (MRx = manifest refraction group; ORA = ocular residual astigmatism; VP = vector planning group).

Based on the refractive power, the majority (73 eyes) in the manifest refraction group had a correction index between 90% and 120% (Figure 4, *middle left*), whereas the vector planning was more distributed throughout the spectrum. Similar to the difference vector, the contrast between the 2 groups decreased when analyzed based on the corneal K readings, whereas the 2 groups had a similar distribution. Based on the refractive power, the correction

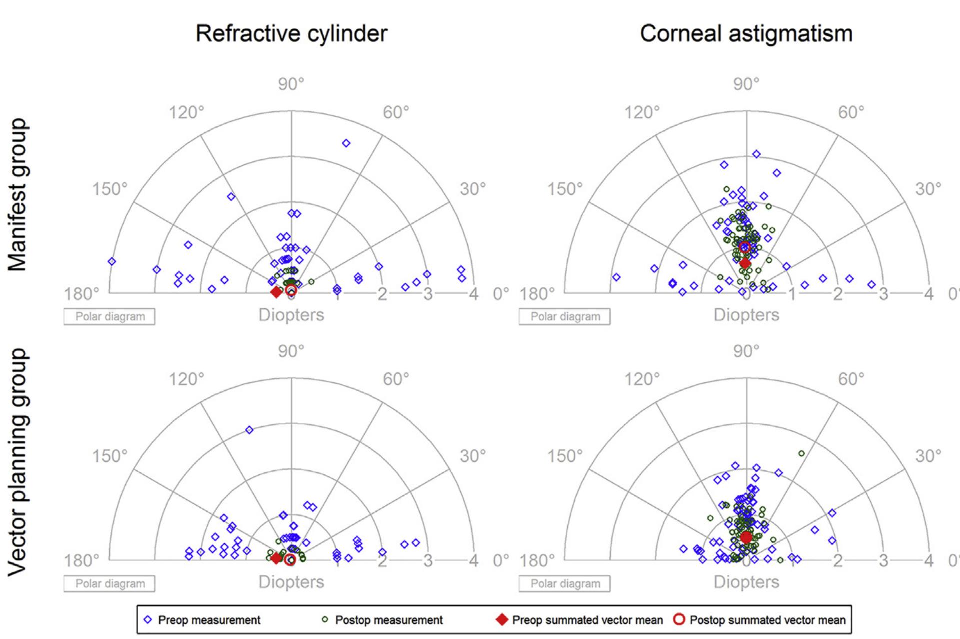

Figure 3. Polar diagrams showing the refractive cylinder (*left*) and corneal toricity (*right*) preoperatively and at the 6-month follow-up after LASIK with an aberration-neutral profile centered on the corneal vertex (taking 70% of the pupil offset value) for the treatment of myopic astigmatism. The manifest refraction group (n = 79, *top*) and vector planning group (n = 85, *bottom*) are compared based on the arithmetic mean measurements and summative vector mean measurements.

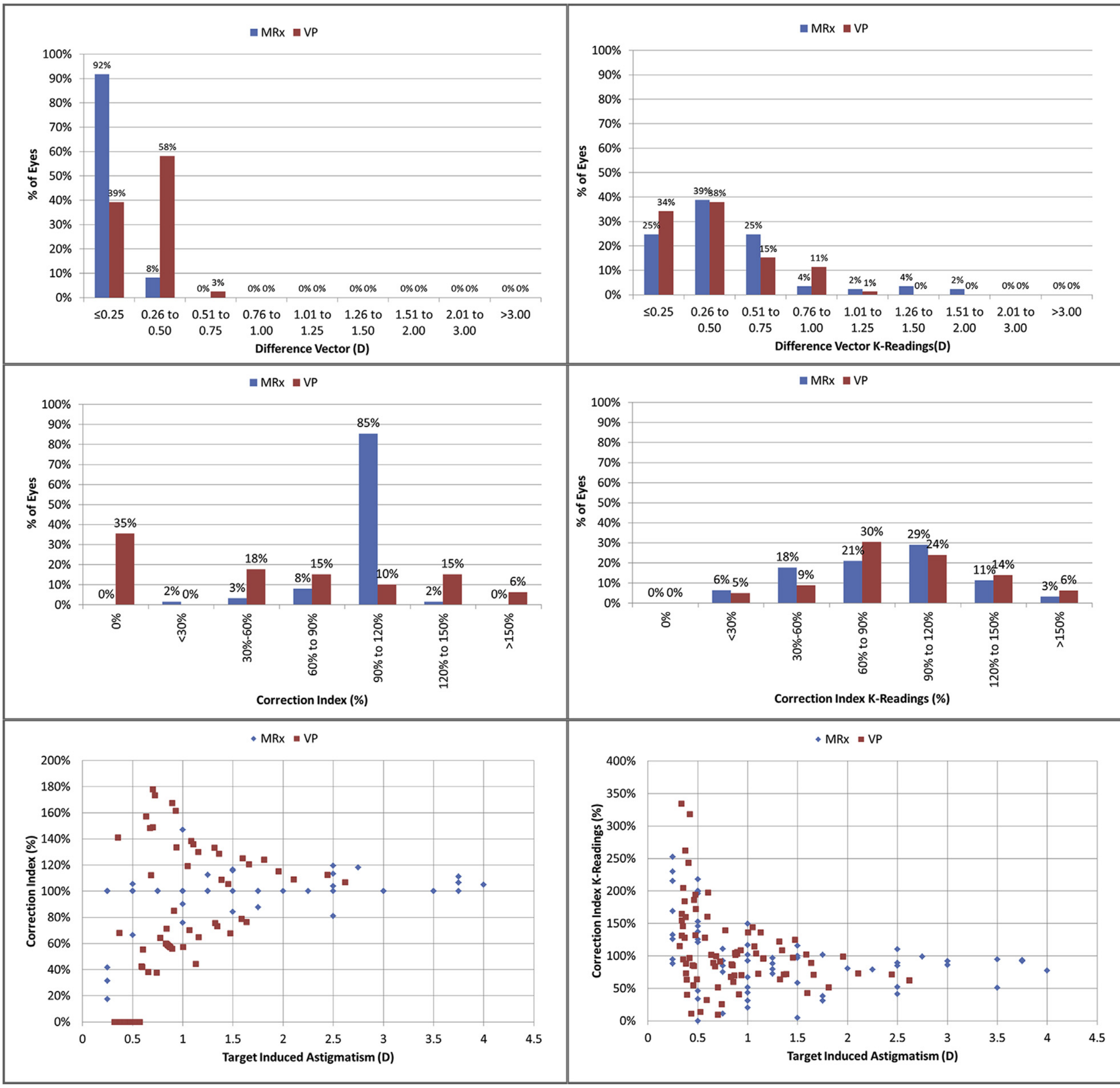

Figure 4. Correction index and difference vector at 6-month follow-up after LASIK with an aberration-neutral profile centered on the corneal vertex (taking 70% of the pupil offset value) comparing vector planning (n = 79) to manifest refraction planning (n = 85) for the treatment of myopic astigmatism. The metrics calculated using the refractive power are shown on the left and the metrics calculated using the corneal K readings are shown on the right. The bottom row shows the relationship between the correction index (refractive power readings on the *left*, and corneal K readings on the *right*) and the refractive TIA (K = keratometry; MRx = manifest refraction group; VP = vector planning group).

index in the manifest refraction group remained stable and close to 100% throughout the range of refractive TIA, whereas an envelope was seen in the vector planning group that decreased asymptotically close to 100% as the TIA increased (Figure 4, *bottom left*). Both groups showed a comparable distribution when analyzed based on corneal K readings (Figure 4, *bottom right*).

Higher-Order Aberrations

There were no statistically significant differences between the 2 groups in terms of individual and RMS HOAs ($P > .05$).

No retreatments were performed in the cohort.

DISCUSSION

Several approaches have been proposed to tackle the conflict between the treatment planning strategies for astigmatism correction, incorporating the manifest and corneal astigmatism in a balanced manner. The conventional approach of only targeting the manifest (no contribution of corneal topography) or the corneal astigmatism (all contribution from the corneal topography) has been customized with different combinations. These approaches include correcting a combination of one half of the manifest and corneal astigmatism minimizing the residual global astigmatism magnitude, correcting a combination of as much as possible manifest and corneal astigmatism without overcorrecting any of them, or correcting a combination of manifest and corneal astigmatism prioritizing with-the-rule corneal astigmatism. In this noninferiority comparative study, the treatments were designed in the vector planning group with a 60% emphasis placed on the reduction of refractive astigmatism and a 40% emphasis placed on the reduction of corneal astigmatism. We retrospectively compared the last 85 eyes meeting the inclusion criteria and treated with manifest astigmatism planning to the first 79 eyes meeting the inclusion criteria and treated with vector planning. Although we have not made a priori calculations of the sample size, we calculated the level of detection as a post hoc test to determine whether the detected significant differences had sufficient statistical power. Considering the typical standard deviation of postoperative astigmatism in the manifest refraction group (0.31 D) and using standard statistical power calculations of 80% and 5%, we obtained a level of detection better than 0.12 D, suggesting a good sample size for a comparative analysis.

Kugler et al.,[13] and Qian et al.[14] reported the importance of calculating the ORA preoperatively to prevent distressing visual symptoms postoperatively. They concluded that it was less efficacious to treat astigmatism in eyes with significant preoperative ORA. Another study by Archer et al.[15] found that eyes with high ORA and high corneal astigmatism resulted in less predictable manifest refractive cylinder postoperatively. A study by Alpins and Stamatelatos,[7] which compared the outcomes of wavefront-guided LASIK to LASIK based on wavefront combined with topography values using vector planning, found a greater reduction in corneal astigmatism (44% versus 39% reduction) and better visual outcomes under mesopic conditions for the group having LASIK based on wavefront combined with the topography. Because of the small number of eyes in this study (21 eyes of 14 patients), caused by the inability of the Visx Star excimer laser to allow the surgeon to rotate the astigmatic treatment independent of the HOAs, the statistical significance between the 2 groups was not anticipated. In another study to examine the outcomes of photoastigmatic refractive keratectomy using corneal and refractive parameters for myopia and astigmatism using vector planning in eyes with forme fruste and mild keratoconus,[3] the authors presented long-term outcomes (up to 10 years) in 45 eyes. At a 12-month follow-up, the UDVA was 20/20 or better in 56% of eyes and 20/40 or better in all eyes. The CDVA was 20/20 or better in 89% of eyes and 20/30 or better in all eyes; furthermore, no cases of keratoconus progression were reported. They concluded that incorporation of corneal astigmatism data into the treatment plan resulted in improvements in visual (refractive) and total (refractive plus corneal) astigmatism.

In a study to evaluate the influence of the origin of astigmatism on the correction of myopia or myopic astigmatism by femtosecond laser small-incision lenticule extraction, Qian et al.[16] showed that small-incision lenticule extraction was effective in correcting astigmatism but less effective in correcting ORA. In a similar study involving laser-assisted subepithelial keratectomy (LASEK) to correct myopia or myopic astigmatism, patients were divided into 2 groups according to their ORA and the efficacy of LASEK was compared between those with and those without a significant amount of intraocular astigmatism. That study found that LASEK was less effective in correcting myopic astigmatism when astigmatism was mainly located at the internal optics with horizontal coma increasing more after LASEK in patients with higher ORA.[17] Piñero et al.[18] evaluated the influence of ORA on outcomes obtained after LASIK surgery for correction of myopic astigmatism using solid-state laser technology. In their cohort, the mean overall efficacy and safety indices were not correlated with preoperative ORA ($r = -0.15$, $P = .15$). However, a significant correlation was found between ORA ($r = 0.81$, $P < .01$) and posterior corneal astigmatism postoperatively, but not preoperatively ($r = 0.12$, $P = .25$). Likewise, a significant correlation of ORA with manifest refraction was only found postoperatively ($r = -0.38$, $P < .01$). Studies suggest that the preoperative assessment of refractive surgery candidates should consider the interaction between topographic, refractive, and ORA for better outcomes.[19,20]

In our cohort, comparable visual outcomes were seen in manifest and vector planning groups (changes in preoperative CDVA to postoperative UDVA, postoperative UDVA and postoperative CDVA). Overall, a higher accuracy was observed in the vector planning group in terms of the achieved SE to the intended target. This could be because of the theoretical benefits of vector planning such as objective measurement of corneal toricity versus the measurement uncertainty involved in subjective manifest refraction, corneal toricity being the main driver of manifest astigmatism, and the optimum balance of manifest and corneal components (60% and 40%, respectively) in vector planning for a minimum residual risk. Furthermore, it can be speculated that the ablations in the vector planning group approached a morphologically natural cornea, retaining the corneal shape in the individual treated eyes for a more accurate postoperative SE. Although the naturally existent corneal toricity seen in healthy ametropic eyes was induced in postoperative eyes in the vector planning group, this corneal astigmatism did not manifest to increase the postoperative refractive astigmatism, with both groups showing differences that were not statistically significant in postoperative refractive cylinder; however, the corneal toricity was significantly smaller in the vector planning group. In this regard, it could be also argued that the claimed superiority of topography-guided or corneal wavefront-guided treatments in normal eyes[21,22] is not significantly related to the HOAs (because they are low in normal eyes and patients already have an excellent CDVA preoperatively), but instead related to the fact that the topography-guided treatments automatically capture the topographic toricity, which is indirectly incorporated into the treatment profile.

The differences between the 2 groups were also evident in terms of ORA, showing significant reduction in the vector planning group postoperatively. The horizontal bias (intercept) seen in the vector planning group in the TIA versus

SIA curve could mislead to show inferior outcomes in the vector planning group at the first glance. However, the observed bias can be because we also used the vector planning approach in patients with no refractive cylinder. The refractive astigmatism is not a direct indicator of risk for high ORA and patients with no refractive cylinder might also have large ORA. Although, we planned a small amount of cylinder ($\sim$0.5 D) in these patients based on the vector planning method, the ORA was well tolerated and did not present as manifest refraction (Figure 3). This was confirmed by the average TIA of approximately 0.5 D and a resulting SIA of approximately 0.0 D in the vector planning group. Frings et al.[23] performed a cross-sectional data analysis to determine the amount of topographic astigmatism in refractive plano eyes that results in reduced efficacy after myopic LASIK. Their findings suggested that a preoperative corneal astigmatism of up to 0.9 D could partially be considered in the LASIK design, even if the subjective refractive astigmatism is neutral. Theoretically, even though the vector planning group would have a higher TIA, this should lead to a smaller manifestation in the SIA because of the benefits of vector planning. This was confirmed by a larger difference vector found in the vector planning group than in the manifest refraction group.

The type of refraction and the measurement method used to estimate the refraction also play important roles in the findings. The different available manifest refraction strategies might indirectly incorporate a lower or larger amount of ORA into the refraction and treatment plan; for example, depending on the regional norms to estimate the manifest refraction, measurements could completely ignore the corneal component or could be based on a combination of SE with corneal toricity. Although in the first case ORA is completely ignored, the second case incorporates the complete ORA into the treatment plan. Several factors define the complicated relationships of visual acuity to refractive state or ametropia in a multivariate manner.[24,25] The standard model for describing the relationship between visual acuity and blur by Raasch,[26] has been used to propose simpler models that describe the quantitative relationship between unaided visual acuity and blur attributed to refractive errors, and also give a valid description for low-level refractive errors. However, the extent of refractive correction that shows a visual benefit is also limited by ocular resolution and its perception. Villegas et al.[27] evaluated how small amounts of astigmatism affect visual acuity and the minimum astigmatism values that should be corrected to achieve maximum visual performance. They used a wavefront sensor to measure astigmatism and HOAs in normal young eyes with astigmatism ranging from 0.0 to 0.5 D. Astigmatism was corrected for natural pupil diameters using a purpose-designed cross-cylinder device and visual acuity was evaluated. Their results suggested that under clinical conditions, the visual benefit of precise correction of astigmatism less than 0.5 D would be limited.

Astigmatic patients are adapted to their astigmatism and perceptually recalibrate after its correction. Moreover, the effect of possible positive interactions of aberrations (astigmatism and coma) might also alter after recalibration to correction of astigmatism. Vinas et al.[28] assessed the extent to which a previous adaptation to astigmatism affects visual performance, whether this effect is axis dependent, and the timescale of potential changes in visual performance after astigmatism correction. They measured visual acuity in 25 patients (astigmatic and nonastigmatic, corrected and uncorrected) under induction of astigmatism and combinations of astigmatism and coma while controlling for the patients' own aberrations through an adaptive optics setup. Their findings suggested that the effect of astigmatism on visual acuity is greatly dependent on the orientation of the induced astigmatism, even in nonastigmatic subjects. Previous experience to astigmatism also plays a significant role in visual acuity, with a strong bias toward the natural axis. In contrast to perceived isotropy, the correction of astigmatism does not shift the bias in visual acuity from the natural axis of astigmatism.

We have presented clinical outcomes with corneal vertex ablation centration, estimated while considering 70% of the pupil offset toward the corneal vertex. Chang et al.[29] explored the aspect of ablation centration in reference to astigmatism correction. They compared the refractive and visual outcomes between 2 ablation centration points, 80% and 100% from the pupil center toward the coaxially sighted corneal light reflex in eyes having myopic LASIK. In their cohort, more eyes achieved zero astigmatism in the 80% group than in the 100% group (43.9% versus 34.2%), and fewer eyes had astigmatism greater than 0.75 D in the 80% group (0.9% versus 6.1%) (P = .039).

There are some avenues for improving our methods. In our approach, we used the Maloney indices[8] and the standard value of keratometric refractive index (n = 1.3375), implying the assumption that both preoperative and postoperative cornea follows the Gullstrand ratio. This approximation might hold for the preoperative condition but might not be representative for the postoperative eye. Following other vector planning approaches that use different refractive index values, or considering both anterior and posterior cornea (tomographically),[30,31] might lead to different ORA values and correspondingly different preoperative to postoperative changes. Furthermore, we used the differences in the Maloney indices to estimate the corneal toricity to be used in the vector planning method. Other more sophisticated methods of calculating corneal toricity might influence the outcomes positively.[23,24] The 60% emphasis placed on the refractive astigmatism and 40% emphasis placed on the corneal astigmatism resulted in a condition in which positive outcomes were observed in terms of the corneal shape postoperatively without reducing the visual acuity. Using the complete corneal toricity (100% emphasis) should theoretically result in retaining the most natural corneal shape, magnifying the differences between the manifest and vector planning groups even further; however, there would be a risk for increasing residual refractive astigmatism affecting the visual performance. This relationship makes finding an optimum balance that minimizes the risks in visual performance and maximizes the benefits in retaining the natural corneal shape even more challenging.

The topographies used for the study incorporated only the anterior corneal surface. Incorporating a corneal astigmatism parameter, which includes the posterior cornea, could potentially reduce the magnitude of the ORA because it would better match the refractive cylinder. There would, however, still exist a difference in magnitude and or direction between the refractive cylinder and the corneal astigmatism of varying magnitudes that would be addressed by vector planning. In our experience, if the ORA for total corneal power were calculated, the mean would likely be less than the mean ORA for the anterior corneal power used in this study. The principle of vector planning is still valuable depending on each individual case; however, the proportion of 60/40, which was used in this study, might be different for an ORA calculated with total corneal power. The corneal topographic astigmatism (CorT)[31] total might be more advantageous than the total power calculated by the tomographer.

Compared with previous studies that used the vector planning approach,[1,3,5] our methods introduce an innovation in the following aspects: Unlike previous studies in which ocular wavefront objective refraction was used as the basis for the treatment planning, our methods used the manifest refraction (with or without corneal toricity) for both groups. Rather than using the pupil center as the ablation reference, we centered the ablation profile on the visual axis (estimated as 70% of the pupil offset toward the corneal vertex). Furthermore, we based the ablations on aspheric aberration neutral profiles.

In conclusion, performing LASIK for myopic astigmatism with the vector planning approach resulted in comparable visual outcomes to manifest refraction planning. However, the vector planning method showed significant improvements over manifest refraction planning in terms of accuracy, corneal toricity, and ORA postoperatively. Vector planning helps in retaining the natural corneal shape after refractive surgery without inducing manifest refractive astigmatism. This can be an added advantage for improving visual outcomes in LASIK patients increasing the satisfaction rate by beyond 95.4%[32] and for future cataract patients to better tolerate intraocular lenses.

Vector planning can be used for all cases because there are differences between refractive cylinder and corneal astigmatism. The ORA should be calculated routinely for all patients considering laser vision correction to ascertain whether all or most of the preoperative refractive and corneal astigmatism can be corrected. If the ORA is high (>0.75 D, as in this series), the vector planning method should be used to optimize the amount of astigmatism treated and corrected. By using the vector planning method for all eyes, benefit would be gained for patients with high ORA (the higher the ORA, the larger the potential benefit of using the vector planning method), whereas no risks arise for patients with low ORA (if ORA is zero, then manifest refraction planning and vector planning result in the same treatment plan and the lower the ORA, the lesser the difference between manifest refraction planning and vector planning treatment plans). Hence, by using vector planning, one gains corneal regularization and a reduction in corneal toricity in the patients at risk (high ORA) for no noticeable changes in refraction (because residual refraction remains largely below noticeable threshold), with no disadvantage for patients with low ORA (for whom the vector planning method results in a treatment plan very similar to manifest refraction planning).

WHAT WAS KNOWN

- A high ORA and high corneal astigmatism result in a less predictable manifest refractive cylinder after LASIK.
- Vector planning has been shown to prevent distressing visual symptoms postoperatively better than manifest refraction planning; however, this has not been analyzed in a large-scale comparative study of patients with high ORA.

WHAT THIS PAPER ADDS

- Performing LASIK for myopic astigmatism with the vector planning approach resulted in visual outcomes that were comparable to those with manifest refraction planning in patients with high ORA.
- The naturally existing corneal toricity in healthy ametropic eyes decreased more postoperatively in eyes that had vector planning than in eyes treated using manifest refraction parameters alone; however, this corneal astigmatism did not increase the postoperative refractive astigmatism.

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Disclosures: *Drs. Alpins and Stamatelatos have financial interests in the Assort program (Assort Pty Ltd.). Drs. Verma and Arba-Mosquera are employees of Schwind eye-tech-solutions GmbH & Co. KG. None of the other authors has a financial or proprietary interest in any material or method mentioned.*

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