Topography-Guided Transepithelial Surface Ablation in the Treatment of Moderate to High Astigmatism

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ABSTRACT

PURPOSE: To analyze the outcomes of treatment of astigmatism of 2.00 diopters (D) or greater with topography-guided transepithelial surface ablation.

METHODS: Retrospective analysis of a series of 206 eyes divided into two groups: myopic astigmatism (153 eyes) and mixed astigmatism (53 eyes). All cases were treated with topography-guided transepithelial surface ablation. Efficacy, safety, and predictability were evaluated, and vector analysis of cylindrical correction was performed.

RESULTS: The median preoperative spherical equivalent was -2.63 and -0.63 D for the myopic and mixed astigmatism groups, respectively, with median cylinder of -2.50 D. Postoperative uncorrected distance visual acuity was 20/20 or better in 92% and 83% of eyes in the myopic and mixed astigmatism groups, respectively; the corresponding efficacy indices were 1.00 and 0.96 and residual astigmatism of 0.50 D or less was present in 82.4% and 56.7% of eyes in the myopic and mixed astigmatism groups, respectively. The arithmetic mean magnitude of the difference vector was 0.38 (myopic) and 0.65 (mixed) D. Difference vector magnitude was positively correlated with the magnitude of target induced astigmatism in both groups. The geometric mean coefficient of adjustment index was 1.04 and 1.19, representing undercorrection of 4% and 19% in the myopic and mixed astigmatism groups, respectively.

CONCLUSIONS: Topography-guided transepithelial ablation is a safe, effective, and predictable treatment for moderate to high astigmatism.

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Despite generally successful use of laser refractive surgery for vision correction, a comprehensive review concluded that approximately 4.6% of patients are dissatisfied with the outcome, most often due to residual refractive error.[1] Surgical correction of astigmatism with laser refractive surgery is technically more difficult and less effective than treatment of plain spherical refraction. Randleman et al.[2] showed that eyes with astigmatism of 1.00 D or greater were more likely to undergo re-treatment. Alió and Alpins[3] suggested that treating astigmatism with the most up-to-date treatment paradigms would substantially reduce the proportion of less satisfied patients. Recent advances have led to better refractive outcomes and reduced the incidence of higher order aberrations (HOAs). These advances include the development of fast repetition rate excimer lasers, use of aspheric ablation profiles, incorporation of wavefront and/or topographic measurements into customized and optimized ablation designs, and employment of cyclotorsional eye trackers.[4-7] A review of recent studies of laser refractive surgery for moderate to high astigmatism noted that the reported percentage of eyes achieving postoperative uncorrected distance visual acuity (UDVA) of 20/20 or better varied from 12% to 84%.[4-6,8-16]

Topography-guided transepithelial surface ablation has been demonstrated to be a safe, effective, and predictable treatment for myopia.[17] It has also been reported to be effec-

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tive as a treatment for irregular astigmatism.[18,19] To our knowledge, this is the first investigation of its safety, efficacy, and predictability as a treatment for moderate to high astigmatism.

PATIENTS AND METHODS

This retrospective study was based on analysis of charts for a series of eyes treated with topography-guided transepithelial ablation for astigmatism of 2.00 D or greater at SynsLaser Clinic, Oslo, Norway. The inclusion criteria for treatment were: age 18 years or older at the time of surgery; no soft contact lens wear for 1 week before baseline examination; no hard contact lens wear for 4 weeks before baseline examination; stable refraction for at least 24 months; and corrected distance visual acuity (CDVA) of at least 20/25. Exclusion criteria were: ocular pathology, including keratoconus or suspected keratoconus and glaucoma; previous corneal surgery; and systemic disease that might affect corneal wound healing. All patients provided informed consent to the anonymous use of their data in scientific analyses and publications.

Preoperative and postoperative examinations included slit-lamp biomicroscopy, Scheimpflug-based corneal topography/tomography (Precisio; iVIS Technology, Taranto, Italy), Placido-based corneal topography and wavefront aberrometry (Nidek OPD II; Nidek Co. Ltd, Aichi, Japan), eye tonometry (Icare tonometer; Revenio Group Corporation, Helsinki, Finland), assessment of UDVA and CDVA, and subjective spectacle refractometry.

Between July 2009 and December 2014 surgery was performed on 267 eyes with astigmatism of 2.00 D or greater. Only cases available for evaluation at least 3 months after surgery were included in this analysis, yielding a final sample of 206 eyes in 135 patients. The eyes were classified according to preoperative refraction, resulting in a myopic (compound and simple) astigmatism group and a mixed astigmatism group. The variables assessed were preoperative and postoperative visual acuity, refractive outcome, and corneal HOAs at a 5-mm zone. In the case of the 7 eyes that underwent a second treatment, only the outcomes of the original treatment were analyzed.

Topography-Guided Transepithelial Custom Ablation

The Corneal Interactive Programmed Topographic Ablation software (CIPTA) (iVIS Technology) was used to generate transepithelial custom ablation plans for each eye based on subjective refraction and corneal topography measured with the Precisio topographer/tomographer. The optical zone size of the ablation was suggested by the pMetrics (iVIS Technology) dynamic pupillometry. Preoperative topography was also used to customize transition zone size to provide a smooth transition between the ablated and non-ablated areas of the cornea. For myopic astigmatism surgeries, the mean optical and total ablation zone size was 6.24 ± 0.47 mm (range: 4.1 to 7.5 mm) and 8.36 ± 0.43 mm (range: 7.1 to 9.2 mm), respectively; the corresponding values for mixed astigmatic surgeries were 6.33 ± 0.47 mm (range: 5.2 to 7.3 mm) and 8.51 ± 0.51 mm (range: 7.5 to 9.5 mm). The CIPTA-planned transepithelial ablation consisted of refractive and lamellar components; the function of the latter was removal of the epithelium. The refractive component was derived by the intercept between a desired postoperative regular aconic surface and the preoperative corneal topography, with the tissue above the intersection to be ablated. The desired postoperative regular aconic surface represented a resolution of the vectors of the manifest and the preoperative corneal astigmatism. The maximum ablation depth of the refractive component was 71.1 ± 21.1 µm (range: 28 to 116 µm) and 47.2 ± 14.4 µm (range: 30 to 93 µm) for myopic and mixed astigmatism surgeries, respectively. The default value for the lamellar component was 52 µm, which could be adjusted based on preoperative measurements of epithelial thickness and/or clinical judgment. The refractive and lamellar components of the procedure were combined and executed as a single, uninterrupted ablation. The aim of all surgeries was emmetropia, and ablations were centered on the corneal vertex.

The surgeries were performed by two surgeons using a previously described protocol.[17] The 0.6-mm dual-flying-spot 1 KHz (2 × 500 Hz) excimer laser system (iRES; iVIS Technology) employs automatic intraoperative illumination adjustment, so the light intensity is automatically modulated to achieve the pupil size registered during the acquisition of topography. This contributes to precise registration along with the iris/scleral vessel-based dynamic cyclotorsional, in addition to synchronous x, y-pupil tracking.

Data Analysis

Visual acuity measured using a Snellen chart with a decimal scale was converted to logMAR for analysis. The safety and efficacy index and the predictability at last postoperative visit were calculated.

The Alpins method of vector analysis was used to assess astigmatism correction.[20,21] Preoperative and postoperative cylinder power and axis were used to calculate target induced astigmatism (TIA), surgically induced astigmatism (SIA), and difference vector (DV). To avoid right and left eye mirror symmetric effect, left eye data were transformed by mirroring the vectors on the y-axis (ie, changing the angle from α to $180°-\alpha$ for both preoperative and postoperative cylinder vectors). Finally, the magnitude of error, angle of error, correction

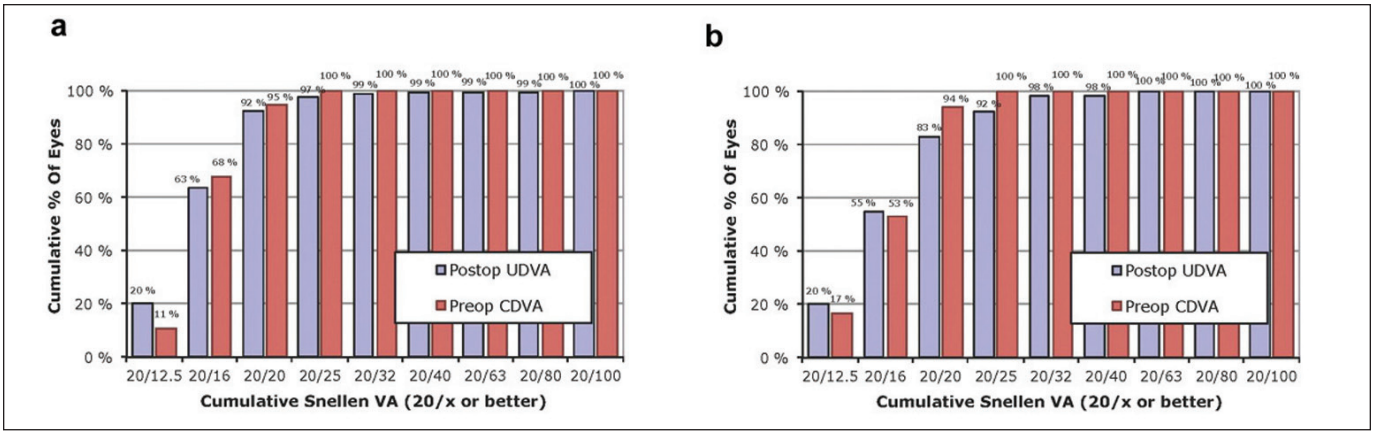

Figure 1. Comparison of preoperative corrected distance visual acuity (CDVA) and uncorrected distance visual acuity (UDVA) at the final postoperative assessment in the (A) myopic astigmatism and (B) mixed astigmatism groups.

index, index of success, and coefficient of adjustment were analyzed. Details of these parameters are given in **Table A** (available in the online version of this article). The geometric means for correction index and coefficient of adjustment were derived by taking the mean of the individual logarithmic values, followed by the antilog of this calculated mean value. Ocular residual astigmatism was calculated as the vector difference between refractive astigmatism at the corneal plane and the anterior corneal topographic astigmatism.

Statistical analysis was performed using SPSS for Windows software (version 21.0; SPSS, Inc., Chicago, IL) and Excel 2011 (Microsoft Corporation, Redmond, WA) software. Data not normally distributed are presented as medians and quartiles. Group differences were assessed using the non-parametric Mann–Whitney test. Within-group effects of surgery were evaluated with the Wilcoxon rank test. The Spearman coefficient test was used to assess associations between variables. The significance level was set at a *P* value of less than .05 for all tests.

RESULTS

The myopic astigmatism group included 153 eyes (70.6% male and 29.4% female). The mixed astigmatism group included 53 eyes (71.7% male and 28.3% female). The mean age was 38 years (range: 32 to 42 years) in the myopic astigmatism group and 39 years (range: 32 to 43 years) in the mixed astigmatism group.

Refractive data are summarized in **Table B** (available in the online version of this article). No intraoperative or postoperative sight-threatening complications or delays in epithelial healing were recorded. The mean preoperative intraocular pressure was 15.7 ± 3.6 mm Hg (range: 7 to 24 mm Hg). The mean time of the final follow-up assessment was 10.4 ± 5.9 months (range: 3 to 36 months) postoperatively for the myopic astigmatism group and 13.9 ± 10.9 months (range: 3 to 43 months) postoperatively for the mixed astigmatism group. At the final assessment, the mean intraocular pressure was 13.2 ± 3.6 mm Hg (range: 7 to 19 mm Hg). Grade 1 corneal haze was observed in 2.6% (n = 4) and 7.5% (n = 4) of eyes in the myopic and mixed astigmatism groups, respectively. There were no cases with haze above grade 1. None of the patients complained of decreased quality of vision under low light conditions. Four eyes in the myopic astigmatism group and three eyes in the mixed astigmatism group were re-treated after 9 months or later. No restrictions regarding the amount of residual refractive error to be treated were set.

EFFICACY, SAFETY, AND PREDICTABILITY

Postoperative data on visual acuity, refractometry, and aberrometry are presented in **Table B** and **Table C** (available in the online version of this article). At the final assessment, the efficacy index was 1.00 and 0.96 in the myopic astigmatism and mixed astigmatism groups, respectively. Postoperative UDVA was better than 20/40 in 99% (myopic astigmatism) and 98% (mixed astigmatism) of eyes, and better than 20/20 in 92% (myopic astigmatism) and 83% (mixed astigmatism) of eyes (**Figure 1**).

The safety index was 1.10 in the myopic astigmatism group and 1.12 in the mixed astigmatism group. The percentage of eyes showing no change or gaining up to two lines of CDVA was 97% and 96% in the myopic and mixed astigmatism groups, respectively. None of the eyes lost more than one line of CDVA (**Figure 2**).

Figure 3 compares achieved and attempted spherical equivalent correction. In the myopic astigmatism group, the outcome was within 0.50 D of target in 83.7% of eyes and within 1.00 D of target in 99.3% of eyes. In the mixed astigmatism group, the corresponding figures were 79.2% and 94.3%, respectively.

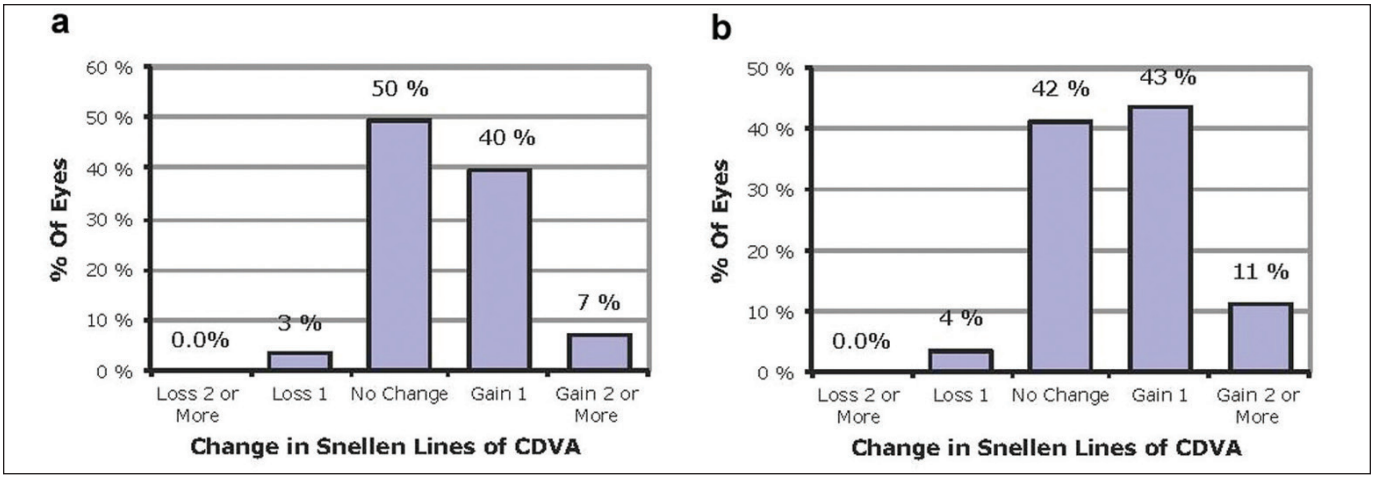

Figure 2. Change in corrected distance visual acuity (CDVA) in the (A) myopic astigmatism and (B) mixed astigmatism groups.

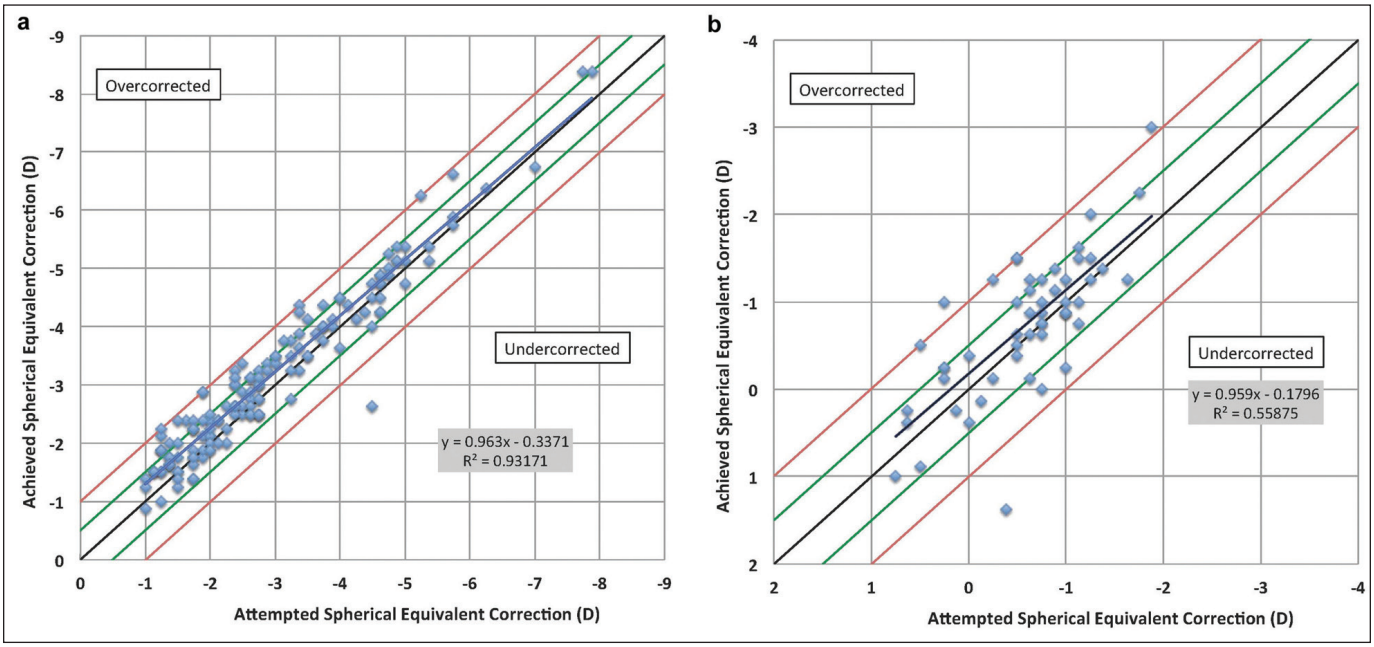

Figure 3. Attempted vs achieved spherical equivalent refraction in the (A) myopic astigmatism and (B) mixed astigmatism groups. D = diopters

Astigmatic Correction Outcome and Vector Analysis

In the myopic astigmatism group, residual refractive astigmatism of 0.50 D or less was achieved in 82.4% of eyes and residual refractive astigmatism of 1.00 D or less in 97.4%. The corresponding figures for the mixed astigmatism group were 56.7% and 84.9%, respectively (**Figure 4**).

The surgical variables calculated using vector analysis are shown in **Table D** (available in the online version of this article) and **Figures 5-6**. The summated vector mean TIA values were 0.83 × 172 and 0.89 × 173 for the myopic and mixed astigmatism groups, respectively, indicating an overall trend of treatment to induce a net steepening of the cornea at the horizontal meridian and hence an against-the-rule change. The summed vector means for DV (myopic astigmatism: 0.06 × 119 D; mixed astigmatism: 0.05 × 179 D) were close to zero, suggesting random variability.

Absolute mean values for angle of error were 2.2° and 3.7° in the myopic and mixed astigmatism groups, respectively; angle of error was zero in 33.3% (myopic astigmatism) and 18.9% (mixed astigmatism) of eyes. Geometric mean values for correction index and coefficient of adjustment were 0.96 and 1.04, respectively (myopic astigmatism) and 0.84 and 1.19, respectively (mixed astigmatism), demonstrating undercorrection of astigmatism by 4% (myopic astigmatism) and 19% (mixed astigmatism).

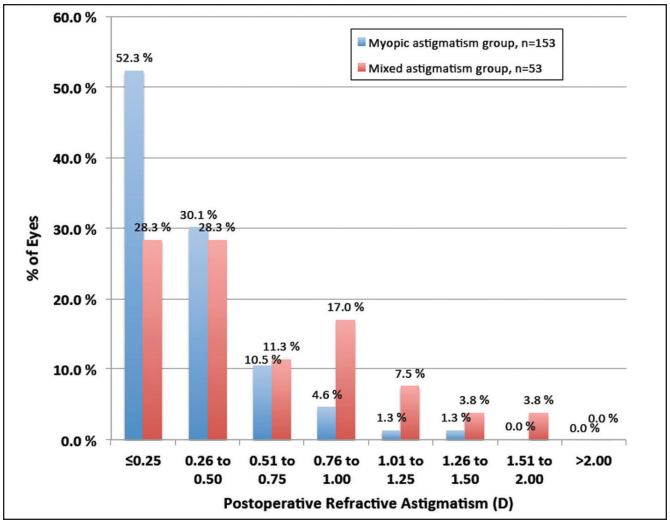

Figure 4. Postoperative refractive astigmatism distribution. D = diopters

When the sample was split into high ocular residual astigmatism (1.00 D or greater) and low ocular residual astigmatism (less than 1.00 D) groups there were no group differences in DV, correction index, coefficient of adjustment, and index of success. DV magnitude was correlated with TIA magnitude (myopic astigmatism: r = 0.166, mixed astigmatism: r = 0.439; both $P < .05$). In the mixed astigmatism group, optical zone size was correlated with DV magnitude (r = -0.336, $P < .05$) and index of success (r = -0.277, $P < .05$).

CORNEAL HOAS

Apart from a slight increase in corneal root mean square HOA in the mixed astigmatism group, surgery produced no changes in coma-type (S3+5+7) or spherical-type aberrations (S4+6+8) in either group (**Table B**).

DISCUSSION

A postoperative UDVA of at least 20/20 was achieved in 92% and 83% of eyes treated for myopic and mixed astigmatism, respectively. No change or a gain of up to two lines of CDVA was observed in 97% (myopic astigmatism) and 96% (mixed astigmatism) of eyes; no eye lost more than one line of CDVA, indicating that the procedures were highly effective and safe.

Data from a review of recent studies of corneal laser refractive surgery for moderate to high astigmatism are given in **Table E** (available in the online version of this article).[4-6,8-16] Across these studies, the percentage of eyes achieving postoperative residual cylinder of 1.00 D or less after treatment for myopic astigmatism ranged from 39.6% to 95.7%, compared with 97.4% in our series. The percentage of eyes achieving a postopera-

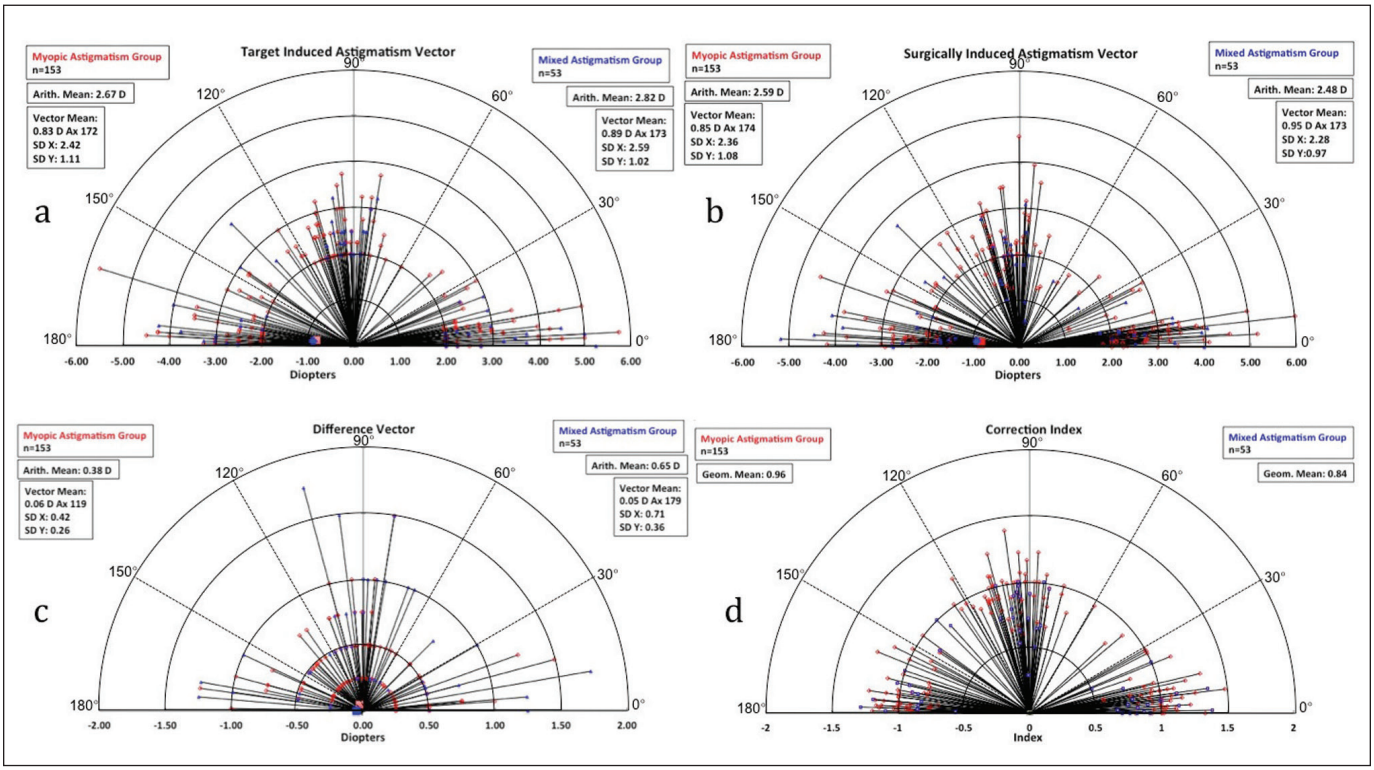

Figure 5. Single-angle polar plots for (A) the target induced astigmatism vector, (B) surgically induced astigmatism vector, (C) difference vector, and (D) correction index. The correction index for each individual treatment is displayed on the axis of target induced astigmatism.

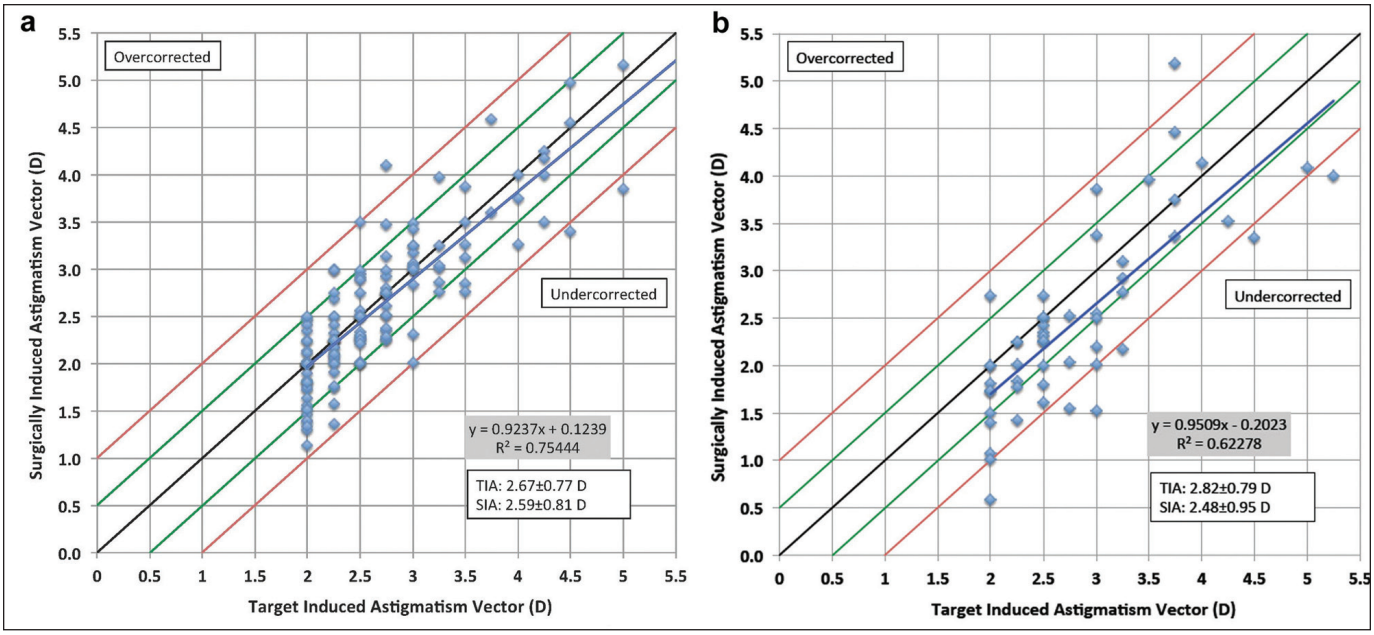

Figure 6. Comparison of target induced astigmatism and surgically induced astigmatism in the (A) myopic astigmatism and (B) mixed astigmatism groups. D = diopters

tive spherical equivalent within 1.00 D of the intended correction ranged from 86% to 99.2% compared with 99.3% in this study. Although reported preoperative cylindrical error varied between studies, our outcomes seem to compare favorably with other published results. This may be attributed to the use of topography-guided ablation, a smooth transition customized to the topography outside the treatment area, precise registration and tracking, and the integrated transepithelial ablation approach.

The ablation profile can have a significant impact on postoperative outcome. Alpins[22] recommended use of vector planning to link preoperative topographic measurements into the treatment plan with the refractive values. The topography-guided custom ablation pattern used in this study was based on a resolution of the vectors of the manifest and the corneal astigmatism as measured by topography and is consistent with Alpins' recommendations. Vinciguerra et al.[23] argued that creating a smooth transition (low dioptric gradient) between the treated and untreated cornea might improve the outcomes of surgery for astigmatism. We sought to achieve this by creating a customized transition that results in a continuously low dioptric gradient toward the untreated cornea. A smooth transition zone may be the key to low regression because it may prevent the counterproductive epithelial remodeling, which is induced by non-smooth transitions.

It is reported that conventional excimer laser keratorefractive procedures induce an increase in spherical-like and coma-like HOAs, mainly due to modification of corneal asphericity/inadequate optical zone size and optical decentration, respectively.[24-26] Good control of spherical aberration and a physiological postoperative corneal shape may be achieved with aspheric laser ablation profile design.[14] The ablation procedure used in this series minimizes the induction of spherical aberration by adjusting the target value for asphericity according to the preoperative anterior corneal curvature and the planned curvature change, as well as by compensating for the reduction in radial efficiency of the laser toward the corneal periphery. We did not observe an increase in coma-like HOAs in our study and this may also be attributed to the ablation design, which is based on the existing centering and symmetry of the corneal optics measured by topography. Some studies have demonstrated that visual outcomes are worse in eyes with high ocular residual astigmatism,[27-29] but in this study the predictability of astigmatic correction was similar for eyes with high and low ocular residual astigmatism. Further investigation is warranted to determine whether the topography-guided design is advantageous in this respect.

To circumvent the problem of mismatch between the morphology of the preoperative epithelial surface as measured by topography and the morphology of the treatment stromal surface after removal of the epithelium, we used a transepithelial approach in which manual epithelial removal is replaced by adding a lamellar component to the refractive ablation. With this approach, the epithelium and anterior stroma protruding into the lamellar ablation depth are uniformly ab-

lated across the treatment diameter. Based on similar reasoning, Reinstein et al.[30] used transepithelial phototherapeutic keratectomy to regularize the irregular corneal stromal surface. To apply transepithelial concept to treat refractive errors with high precision, the compatibility of ablation rates between the epithelium and the stroma must be achieved. Because the laser used in the cases reported here was specially designed for transepithelial ablation, it optimized the fluence, shot pattern, and frequency to minimize the difference in ablation rate between the epithelium and the stroma. This approach is different from that used in another laser platform (Schwind Amaris; Schwind eye-tech-solutions GmbH, Kleinostheim, Germany), which attempts to compensate for the ablation rate difference by employing a non-modifiable nomogram of ablating approximately 55 µm of epithelium at the center and 65 µm at the periphery (4 mm radially from the center), presumably based on population measurements of epithelial thickness.[31]

In integrated transepithelial treatment, total ablation volume far exceeds stromal ablation volume, typically by a factor of 3 to 6; it is therefore necessary to use a high-frequency excimer laser to achieve short ablation times to prevent stromal dehydration effects.[32] The laser used in this study maintains a local frequency of 4 Hz (ie, the laser beam will always hit the same spot in the treated area four times per second).[17] Because it produces a low, constant, and even delivery of energy across the ablation area, the unwanted thermal effects due to the high frequency are avoided. This is essential to achieving a smooth ablation surface, which is important for the prevention of postoperative haze.[33]

Misalignment of the axis in astigmatic treatment results in undercorrection.[34] It is well known that the pupil centroid varies with pupil size, resulting in registration error that may significantly affect the quality of laser surgery outcomes.[35,36] It follows that accurate centration and control of the cyclotorsional movements of the eye are necessary to optimize visual and refractive outcomes and reduce the induction of optical aberrations.[36] The system used in this study deals with centroid shift by using an intraoperative laser illumination adjustment to control pupil size and using x, y pupillary tracking for accurate centration during the ablation procedure. The use of iris registration and dynamic cyclotorsional eye tracking have also been shown to improve the accuracy of astigmatism treatment.[34] We observed small absolute mean angles of error (2.2° and 3.7° for the myopic and mixed astigmatism groups, respectively), which is consistent with the closeness of the aggregate vector mean TIA (0.83 × 172 and 0.89 × 173 D) and SIA (0.85 × 174 and 0.95 × 173 D) axes. Therefore, no significant systematic error due to misaligned treatment was evident. However, at individual patient level, angle of error ranged from -14° to 13° in myopic astigmatic correction and from -22° to 13° in mixed astigmatic correction, which may suggest variable factors at work, such as healing response.

Hyperopic and mixed astigmatism are technically demanding and difficult to correct.[13,14] We observed a slight undercorrection of astigmatism in both of our groups, but this was more evident in the mixed astigmatism group. Data indicating undercorrection of 4% (myopic astigmatism) and 19% (mixed astigmatism) are corroborated by negative mean magnitudes of error of -0.08 and -0.34 D, and arithmetic mean DVs of 0.38 and 0.65 D for the myopic and mixed astigmatism groups, respectively. The DV is a useful vector measure of uncorrected astigmatism. In our sample, DV magnitude was positively correlated with TIA and the DV was larger in the mixed astigmatism group.

Outcomes could be further improved by a better understanding of postoperative wound healing, postoperative irregular epithelial thickening, and corneal biomechanical changes.[26,37,38] The main drawbacks of this study are its retrospective design and high dropout rate (22.8%) and the lack of data on visual quality, such as contrast sensitivity data. Further research should be carried out using a prospective, randomized design in a larger cohort, including the analysis of the quality of vision and following up cases for a longer period of time.

Topography-guided transepithelial ablation performed with the iVIS platform is a safe, effective, and predictable treatment for moderate to high astigmatism.

AUTHOR CONTRIBUTIONS

Study concept and design (XC, AS, DS); data collection (XC, XW, YL); analysis and interpretation of data (XC, AS, TPU); writing the manuscript (XC, AS, XW, YL); critical revision of the manuscript (XC, AS, DS, TPU); statistical expertise (XC); supervision (AS, TPU)

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TABLE A

Definition of Different Variables

Variables	Definition
Target-induced astigmatism (TIA)	The vectorial difference between the target postoperative cylinder vector and preoperative cylinder vector, representing the intended astigmatic change.
Surgically induced astigmatism (SIA)	The vectorial difference between the achieved postoperative cylinder vector and preoperative cylinder vector. It is preferably equal to TIA.
Difference vector (DV)	The vectorial difference between TIA and SIA, representing the remaining uncorrected vector. It is preferably 0.
Magnitude of error (ME)	The arithmetic difference between the magnitude of the SIA and TIA. It is preferably 0.
Angle of error (AE)	The angle difference between the SIA and TIA (positive if the SIA is counterclockwise to the TIA and negative if the SIA is clockwise to the TIA). It is preferably 0.
Correction index	The ratio of magnitude of SIA and TIA. It is preferably 1. Values larger and smaller than 1 mean overcorrection and undercorrection, respectively.
Index of success (IOS)	The ratio of DV to the TIA. It is preferably 0.
Coefficient of adjustment (CA)	Calculated by dividing TIA by SIA, it is the coefficient required to adjust future astigmatism treatment magnitudes. It is preferably 1.
Flattening effect (FE)	The amount of astigmatism reduction achieved by the effective proportion of the SIA at the intended meridian. It is preferably 1.
Flattening index (FI)	Calculated by dividing the FE by the TIA. It is preferably 1.
Efficacy index	The ratio between the mean postoperative uncorrected distance visual acuity and preoperative corrected distance visual acuity.
Safety index	The ratio between the mean postoperative and preoperative corrected distance visual acuity.

TABLE B

Preoperative and Postoperative Refraction[a]

	Myopic Astigmatism				Mixed Astigmatism			
	Preoperative		Postoperative		Preoperative		Postoperative	
Parameter	Median	Q1-Q3	Median	Q1-Q3	Median	Q1-Q3	Median	Q1-Q3
Sphere (D)	-1.25*	-2.75, -0.50	0.25*	0.25, 0.75	0.50*	0.50, 1.25	0.50*	0.00, 0.75
Cylinder (D)	-2.50*	-3.00, -2.00	-0.25*	-0.50, -0.25	-2.50*	-3.25, -2.25	-0.50*	-1.00, -0.25
SE (D)	-2.63*	-3.75, -1.75	0.25*	0.00, 0.50	-0.63*	-1.00, -0.25	0.13*	-0.13, 0.50
CDVA (logMAR)	-0.08*	-0.08, -0.04	-0.11*	-0.15, -0.08	-0.08*	-0.11, 0.00	-0.11*	-0.18, -0.08
HOA RMS (μm)	0.26	021, 0.32	0.27	0.22, 0.32	0.25*	0.21, 0.31	0.27*	0.23, 0.34
S3+5+7 (μm)	0.21	0.14, 0.27	0.21	0.16, 0.25	0.18	0.14, 0.25	0.20	0.17, 0.26
S4+6+8 (μm)	0.16	0.12, 0.19	0.16	0.13, 0.21	0.15	0.12, 0.22	0.15	0.12, 0.22

Q1 = 1st quartile; Q3 = 3rd quartile; D = diopters; SE = spherical equivalent; CDVA = corrected distance visual acuity; HOA = higher order aberration; RMS = root mean square

*[a]The postoperative values were obtained at the last postoperative visit. Values marked with * represent difference between preoperative and postoperative, tested with the Wilcoxon rank test.*

TABLE C

Residual Refractive Error at Different Postoperative Time Points[a]

	Postoperative Time Points			
Parameter	**1 Month**	**3 Months**	**6 Months**	**12 Months**
Myopic astigmatism (eyes)	135	126	75	98
SE (D)	0.00 (-0.25, 0.25)	0.25 (-0.13, 0.38)	0.25 (0.00, 0.50)	0.25 (-0.13, 0.38)
Cylinder (D)	-0.50 (-0.75, -0.25)	-0.50 (-0.50, -0.25)	-0.50 (-0.75, -0.25)	-0.25 (-0.50, -0.25)
Mixed astigmatism (eyes)	44	43	25	34
SE (D)	0.00 (-0.50, 0.25)	0.00 (-0.25, 0.38)	0.13 (-0.25, 0.38)	0.25 (0.00, 0.50)
Cylinder (D)	-0.50 (-0.75, -0.25)	-0.50 (-1.00, -0.25)	-1.00 (-1.25, -0.75)	-0.50 (-1.00, -0.50)

SE = spherical equivalent; D = diopters
[a]*Data are presented as median and 1st and 3rd quartiles.*

TABLE D

Vector Analysis of Astigmatic Treatment

	Myopic Astigmatism		Mixed Astigmatism		
Parameter	**Median**	**Q1-Q3**	**Median**	**Q1-Q3**	***P***
TIA magnitude (D)	2.50	2.00, 3.00	2.50	2.25, 3.25	.159
TIA angle (degree)	96	11, 158	92	8, 135	.261
SIA magnitude (D)	2.40	2.01, 3.00	2.26	1.82, 2.92	.246
SIA angle (degree)	97	9, 156	98	23, 169	.407
DV magnitude (D)	0.25	0.25, 0.50	0.50	0.25, 1.00	.000
DV angle (degree)	85	4, 115	84	20, 107	.428
Magnitude of error (D)	0.00	-0.25, 0.07	-0.28	-0.73, 0.00	.000
Angle of error	0	-1, 2	0.00	-2, 3	.730
Correction index	1.00	0.89, 1.03	0.89	0.75, 1.00	.000
Index of success	0.13	0.07, 0.22	0.20	0.11, 0.33	.001
Flattening effect	2.36	2.00, 3.00	2.26	1.81, 2.78	.231
Flattening index	1.00	0.88, 1.03	0.86	0.74, 1.00	.000
Coefficient of adjustment	1.00	0.97, 1.12	1.12	1.00, 1.34	.000

Q1= 1st quartile; Q3= 3rd quartile; TIA= target induced astigmatism; D = diopters; SIA = surgically induced astigmatism; DV = difference vector

TABLE E

Literature Review of Studies Presenting Results of Laser Corneal Refractive Surgery for Moderate to High Astigmatism Correction

				Preoperative			Postoperative					
Author	**Surgery (Platform)**	**Follow-up (Mo)**	**Eyes**	**Sphere (D)**	**Cylinder (D)**	**Cylinder (D)**	**UDVA ≥ 20/40**	**UDVA ≥ 20/20**	**Cylinder ≤ 0.50 D**	**Cylinder ≤ 1.00 D**	**SE Within ±0.50 D**	**SE Within ±1.00 D**
Arbelaez et al.,[4] 2009	LASIK (Amaris)	6	50	–	-3.54 ± 0.85 (-4.75, -2.00)	-0.50 ± 0.26 (-1.25, 0.00)	100%	84%	76%	94%	78%	–
Abolhassani et al.,[8] 2009	LASIK (NIDEK EC-5000)	30	34	-0.125 ± 0.50 (-0.75, +0.75)	-4.73 ± 0.89 (-7.00, -4.00)	-0.29 ± 0.47 (-1.50, 0.00)	97.1%	23.5%	–	–	70.6%	94.1%
Igarashi et al.,[9] 2012	LASIK (Technolas 217z)	12	48	-5.10 ± 2.11 (-10.75, -1.50)	-2.74 ± 0.99 (-6.00, -2.00)	-0.63 ± 0.63 (-2.50, 0.00)	–	–	–	–	–	–
Hasegawa et al.,[10] 2012	LASIK (MEL-80)	12	30	-2.26 ± 2.39	-3.66 ± 0.44	-0.68 ± 0.52	–	–	53.3%	83.3%	–	–
Katz et al.,[11] 2013	LASIK (Allegretto 200/400)	2 to 6	57	-1.89 ± 1.72 (-6.75, 0.00)	-3.86 ± 0.57 (-5.75, -3.25)	-1.23 ± 0.51 (-3.75, 0.00)	91.2%	12%	–	54%	67%	93%
Katz et al.,[11] 2013	PRK (Allegretto 200/400)	2 to 6	57	-2.82 ± 2.06 (-6.75, 0.00)	3.81 ± 0.63 (-5.75, -3.25)	-1.29 ± 0.67 (-2.50, -0.25)	77.2%	21%	–	39%	54%	86%
Alió et al.,[5] 2013	LASIK (Amaris)	6	37	-2.72 ± 1.93 (-8.00, -0.25)	-3.61 ± 0.58 (-5.25, -3.00)	-0.45 ± 0.38 (-1.25, 0.00)	94%	61%	67%	93%	87%	97%
Alió et al.,[12] 2013	LASIK (Amaris)	3	52	2.41 ± 1.26 (0.25, 5.00)	-3.89 ± 0.70 (-5.25, -3.00)	-1.11 ± 0.67 (-3.50, 0.00)	85%	–	–	–	26.9%	65.3%
Ivarsen et al.,[13] 2013	LASIK (MEL-80)	3	46	-3.10 ± 2.60 (-10.00, 0.00)	-3.92 ± 0.82 (-6.00, -2.75)	1.00 ± 0.50 (-2.25, -0.25)	94.4%	25%	–	–	87%	98%
Ivarsen et al.,[13] 2013	LASIK (MEL-80)	3	52	3.50 ± 2.30 (0.00, 8.75)	-4.42 ± 1.10 (-6.50, -2.00)	-1.40 ± 0.90 (-4.50, 0.00)	86.4%	13.6%	–	–	71%	90%
Bohac et al.,[14] 2014	LASIK (Allegretto 400)	12	127	-2.80 ± 2.01 (-8.50, 0.00)	-3.30 ± 1.00 (-7.50, -2.00)	-0.55 ± 0.46 (-2.25, 0.00)	–	–	–	–	48%	–
Bohac et al.,[14] 2014	LASIK (Allegretto 400)	12	61	2.72 ± 1.79 (0.25, 7.00)	-3.84 ± 1.21 (-6.50, -2.00)	-0.85 ± 0.41 (-2.00, 0.00)	–	–	–	–	28%	–
Bohac et al.,[14] 2014	LASIK (Amaris 750S)	12	119	-2.44 ± 2.17 (-7.50, 0.00)	-3.21 ± 0.87 (-6.50, -2.00)	-0.43 ± 0.36 (-1.50, 0.00)	–	–	–	–	54%	–
Bohac et al.,[14] 2014	LASIK (Amaris 750S)	12	111	3.11 ± 1.57 (0.50, 7.50)	-3.66 ± 1.16 (-7.00, -2.00)	-0.58 ± 0.38 (-1.50, 0.00)	–	–	–	–	42%	–
Ivarsen et al.,[15] 2014	SMILE (VisuMax)	3	106	-4.30 ± 2.66 (-9.50, -0.25)	-3.22 ± 0.67 (-5.75, -2.50)	-0.79 ± 0.58 (-2.75, 0.00)	89%	39.6%	–	–	77%	97%
Frings et al.,[16] 2014	LASEK (Mel 80)	6	82	-3.98 ± 2.28 (-10.00, 0.00)	-2.50 ± 0.82 (-5.00, 0.00)	-0.27 ± 0.41 (-1.50, 0.00)	–	–	–	–	76%	89%
Schallhorn et al.,[6] 2015	LASIK (Visx S4 IR)	3	611	-2.79 ± 2.32 (-9.75, 0.00)	-2.76 ± 0.81 (-6.00, -2.00)	-0.37 ± 0.38 (-2.00, 0.00)	–	83.8%	79.1%	95.7%	90.3%	99.2%
Current study	Trans PRK (iVIS)	≥ 6	153	-1.58 ± 1.42 (-6.50, 0.00)	-2.67 ± 0.77 (-5.75, -2.00)	-0.39 ± 0.32 (-1.50, 0.00)	99%	92%	82.4%	97.4%	83.7%	99.3%
Current study	Trans PRK (iVIS)	≥ 6	53	0.83 ± 0.54 (0.25, 2.25)	-2.82 ± 0.79 (-5.25, -2.00)	-0.65 ± 0.46 (-1.75, 0.00)	98%	83%	56.7%	84.9%	79.2%	94.3%

D = diopters; UDVA = uncorrected distance visual acuity; SE = spherical equivalent; PRK = photorefractive keratectomy