Effect of the Vectorial Difference Between Manifest Refractive Astigmatism and Anterior Corneal Astigmatism on Topography-Guided LASIK Outcomes

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ABSTRACT

PURPOSE: To characterize the preoperative vectorial difference between manifest refractive astigmatism and anterior corneal astigmatism, termed ocular residual astigmatism (ORA), and to investigate its influence on topography-guided laser in situ keratomileusis (LASIK) outcomes.

METHODS: Comparative retrospective analysis of 21,581 consecutive eyes treated on the manifest refractive astigmatism. Standard outcomes of the 7,180 eyes with the lowest ORA (first tercile: 0.35 ± 0.13 diopters [D]) were compared to the 7,208 eyes with the highest ORA (last tercile: 1.13 ± 0.25 D).

RESULTS: The ORA followed a right-skewed normal distribution (R^2 = 0.99) with a mean ± standard deviation of 0.73 ± 0.36 D. The efficacy index of eyes with low versus high ORA was identical (0.98 ± 0.07 vs 0.98 ± 0.08; *P* = .99), with a similar percentage having a spherical equivalent within ±0.50 D of the intended target (94.7% vs 94.1%; *P* = .11). The safety index (1.00 ± 0.04 vs 1.00 ± 0.04; *P* = .99) and Alpins correction index (1.01 ± 0.37 vs 1.00 ± 0.43; *P* = .10) were identical. A greater number of eyes with high versus low ORA had postoperative residual astigmatism of 0.75 D or greater (6.1% vs 3.9%). Eyes with very high ORA (ORA ≥ 1.50 D; 2.5% of the population) marginally reduced the efficacy index from 0.98 to 0.97 (*P* < .001).

CONCLUSIONS: The contribution of ORA to topography-guided clinical outcomes in most virgin eyes is negligible, with excellent efficacy, accuracy, and safety in both low ORA and high ORA groups. Myopic eyes with high ORA treated on the manifest refraction should not be excluded from topography-guided LASIK.

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Ocular residual astigmatism (ORA) is the vectorial difference between manifest refractive astigmatism and anterior corneal astigmatism calculated at the corneal plane, accounting for both the astigmatism magnitude and axis.[1] The ORA represents the sum of all intraocular astigmatism sources, including the posterior cornea, the lens, the vitreous, retinal tilt, and non-optical cortical perception.[1,2] Several studies suggest that higher ORA affects laser in situ keratomileusis (LASIK), laser epithelial keratomileusis, and small incision lenticule extraction (SMILE) outcomes negatively.[3-6] Others failed to find ORA to be an influential factor.[7-9] The effect of ORA on topography-guided LASIK outcomes has not been studied in depth.

The primary topography-guided Contoura (termed T-CAT at that time) U.S. Food and Drug Administration (FDA) study only included eyes where the anterior corneal astigmatism and refractive astigmatism were similar with little disparity, which equated to eyes with very low ORA.[10,11] Subsequent to Contoura's approval based on the FDA study, many surgeons believe that eyes with high ORA and those that would undergo removal of higher amounts of anterior corneal higher order aberrations (HOAs) would result in poorer outcomes. Therefore, there is a reluctance to use Contoura LASIK on primary eyes with higher ORA. Surgeons exclude eyes if the discrepancy between anterior corneal and refractive astigmatism magnitude is greater than 0.75 D or the axis discrepancy is larger than 10 degrees, with variability in these exclusion criteria.[11-14] According to a recent unpublished retrospective review,[15] such criteria would exclude as many as 65% of all primary virgin eyes from

being treated, but without evidence-based outcomes to suggest doing so. Other surgeons perform topography-guided LASIK on all eyes irrespective of astigmatism magnitude and axis discrepancy or ORA, whereas others advocate modifying the manifest astigmatism protocol to instead target the anterior corneal astigmatism (TMR[16] or LYRA[17] protocols), in contrast to the FDA study.[10-13]

The impact of ORA remains to be elucidated when using topography-guided treatments. Our large sample study of 21,581 eyes undergoing myopic LASIK examined whether the amount of preoperative ORA affects refractive and visual outcomes when using primary topography-guided excimer ablation targeting the refractive astigmatism.

PATIENTS AND METHODS

SELECTION OF PATIENTS

A retrospective electronic medical record database review of 21,581 consecutive eyes that underwent a primary Contoura topography-guided procedure using the Wave-Light EX500 Excimer Laser (Alcon Laboratories, Inc) between July 2018 and July 2019 was conducted. Standard inclusion criteria for LASIK were required, including no evidence of keratoconus or subclinical keratoconus on corneal topography, adequate corneal tissue, no previous ocular surgery or disease including visually significant cataract or macular changes, no systemic diseases that affect corneal healing, and age older than 18 years. The differences between the clinically measured subjective refractive astigmatism and the Contoura-measured anterior corneal astigmatism magnitude and axis were not used as inclusion or exclusion criteria. Eyes with myopia and myopic astigmatism, naturally occurring irregular astigmatism, and asymmetrical topographies on keratometric maps were all included. There were no exclusions based on the amount of ORA. Eyes with intraoperative flap complication(s) were removed from analyses. This study was approved by the institutional Ethics Review Board, and all patients provided a written consent for surgery and use of anonymized data for research. All procedures performed fulfilled the principles of the Declaration of Helsinki.

LASIK SURGICAL TECHNIQUE

Surgeons followed the same previously described standardized technique,[2,18,19] using the same clinical settings, equipment, and identical surgical nomogram. Hansatome Microkeratome (Z15 or Z16 heads; Bausch & Lomb) in combination with an 8.5-, 9-, or 9.5-mm suction ring were used to create corneal flaps. The Wave-Light EX500 Excimer Laser with Contoura software was used for the excimer ablations. A standardized postoperative regimen[19] of antibiotics and steroids was followed.

CONTOURA SURGICAL PLANNING

Contoura image acquisition was performed using the WaveLight Topolyzer VARIO topographer as described previously.[2,18,20] Prior to treatment, the HOA ablation pattern was verified to be consistent with anterior elevation topography and to ensure that there were no artifacts affecting the ablation pattern. Topolyzer scans were viewed in the "compare examinations" display to assess the reproducibility of the data, including keratometry, Q-value, and axis of astigmatism. Eyes with poorly reproducible scans were excluded. Clinically measured manifest refraction sphere and cylinder averages from preoperative examination and surgery day were entered into the Contoura software as treatment parameters. When preoperative manifest refractions were greater than 0.25 D (magnitude) or 20 degrees (axis) from day of surgery values, a third refraction was performed. A custom nomogram using a large electronic medical record outcomes database was used. The target spherical refraction was plano with a small modifier for age. The nomogram did not factor or use the HOA ablation profile, the HOA ablation depth, the amount of discrepancy between refractive and Contoura-measured astigmatism, or any Zernike information.

STUDY OUTCOME VARIABLES

The preoperative ORA was used as the single independent variable and calculated as the vectorial difference between refractive astigmatism and anterior corneal astigmatism at a vertex distance of 0 mm (corneal plane). Outcomes of the first tercile of eyes with the lowest ORA (low ORA group) were compared to those of the last tercile of eyes with the highest ORA (high ORA group). The same surgeons (including AW and MC) performed the treatment in both groups.

DATA

Ophthalmic examinations were performed preoperatively and between 1 and 3 months postoperatively, with a median follow-up of 1 month and an average of 1.3 months. A short follow-up period was chosen to minimize the effect of secondary corneal biomechanical and epithelial changes and to minimize cerebral adaptation to astigmatism. The intention was to get an accurate gauge of the immediate and actual impact of treatment with less effect from secondary compensation. Accuracy, efficacy, and safety were assessed. Standard graphs, defined by the *Journal of Refractive Surgery*,[21] were produced. Astigmatism correction was assessed using the Alpins vector analysis method.[21-23] Standard Alpins vector graphs, calculated at the corneal plane, were produced with the AstigMATIC soft-

ware.[24] Postoperative data reported were before any subsequent excimer enhancement surgery.

STATISTICAL ANALYSIS

Statistical analyses were conducted in MATLAB R2019b software (The MathWorks). Unpaired samples *t* tests and non-parametric Mann–Whitney–Wilcoxon tests were used where applicable. The Pearson correlation coefficient was used to assess the relationship between selected variables. Statistical significance was set at a *P* value of less than .05 and all data were reported as mean ± standard deviation. Effect size, expressed as the Cohen's *d*, was also calculated to better quantify the differences between the groups.

RESULTS

A total of 21,581 Contoura-treated eyes were included in this study. The ORA followed a right-skewed normal distribution (R^2 = 0.99) with a mode of 0.65, a median of 0.69, and a mean of 0.73 ± 0.36 D. A total of 31.1%, 80.2%, 97.5%, 99.8%, 99.9%, and 100% of eyes had ORA of 0.50, 1.00, 1.50, 2.00, 2.50, and 3.00 D or less, respectively (**Figure 1A**). Of the 21,581 eyes, 7,180 (33.3%; first tercile) had ORA of 0.54 D or less (low ORA group; **Figure 1A**: purple bars in the histogram), whereas 7,208 eyes (33.4%; last tercile) had ORA of 0.85 D or greater (high ORA group; **Figure 1A**: orange bars of the histogram). Outcomes of the intermediate ORA group (second tercile; **Figure 1A**: gray bar of the histogram) were not statistically or clinically different from the first and last terciles and are therefore not reported in the current study.

PREOPERATIVE CHARACTERISTICS

The mean ORA was 0.35 ± 0.13 D in the low ORA group and 1.13 ± 0.25 D in the high ORA group (*P* < .0001, effect size: -4.08; **Table 1**). Although the distribution of ORA axis was largely against-the-rule (ATR)–oriented in both groups, the ATR prevalence was higher in eyes with high ORA (**Figures 1B-1C** and **Table 2**). As expected, the magnitude and axis discrepancy between refractive and anterior corneal astigmatism was higher in eyes with high ORA (**Table 1**). Some preoperative characteristics differed between groups. Namely, eyes with high ORA had significantly more Contoura-measured anterior corneal astigmatism (*P* < .0001; effect size: -0.73), but not refractive astigmatism (*P* = .57; effect size: -0.06). As a result, there was a moderate correlation between preoperative ORA and preoperative anterior corneal astigmatism (*R* = 0.44; *P* < .0001), but a weak correlation with preoperative refractive astigmatism (*R* = 0.07; *P* < .0001). Eyes with high ORA had a significantly higher prevalence of moderate to high anterior corneal astigmatism
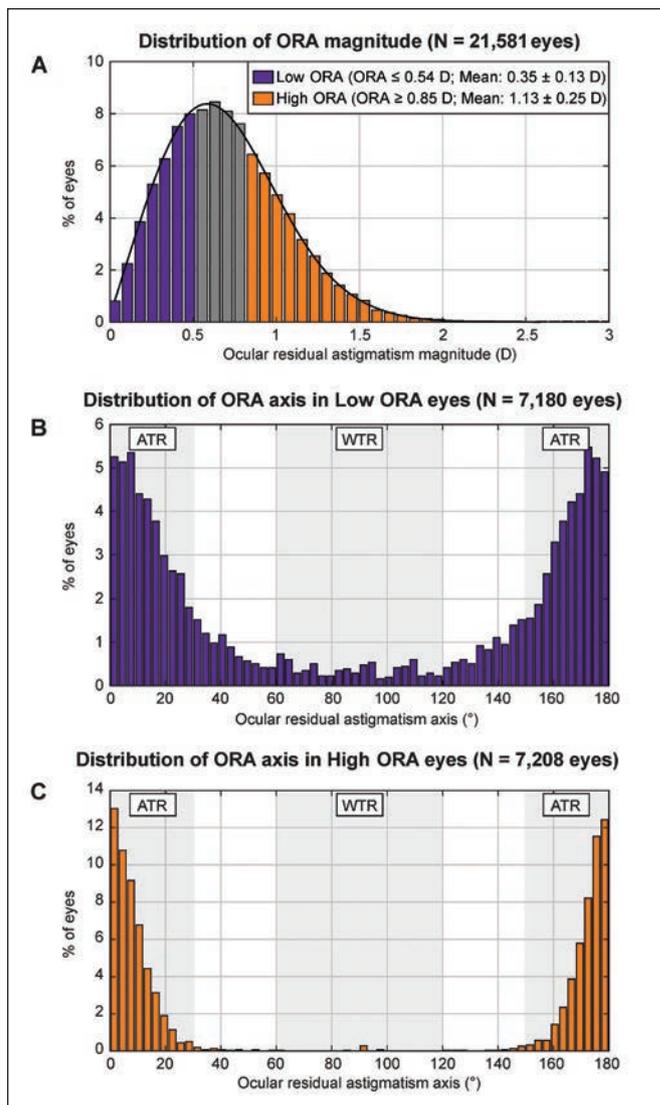

Figure 1. (A) Distribution of the ocular residual astigmatism (ORA) in 21,581 eyes. The thick black curve represents the fitting of the right-skewed normal distribution, having good coefficient of determination (R^2 = 0.99). The purple and orange bars represent the segregation of the low and high ORA groups, respectively. (B and C) Distribution of the ORA axis in eyes with low and high ORA, respectively. ATR = against-the-rule; WTR = with-the-rule; ORA = ocular residual astigmatism; D = diopters

of 2.00 D or greater (21.0% vs 8.3%; *P* < .0001). The elevated anterior corneal astigmatism explains the higher maximum keratometry values (*P* < .0001; effect size: -0.38) and slightly higher HOA ablation depth in the high ORA group (7.7 ± 2.5 vs 8.3 ± 2.7 µm; *P* < .0001; effect size: -0.22). Other preoperative characteristics such as total root mean square coma had statistical significance between groups due to the large number of eyes but were not clinically meaningful, as shown by a Cohens' *d* value of less than 0.2, which is considered a small effect size (**Table 1**). Analyses of refractive astigmatism, anterior corneal astigmatism,

and ORA orientation (**Table 2**) reveal that eyes with high ORA have a higher prevalence of with-the-rule (WTR)–oriented anterior corneal astigmatism (88% vs 79%, *P* < .0001), a higher prevalence of ATR-oriented ORA (98% vs 78%, *P* < .0001), and a much lower prevalence of oblique astigmatism (1.7% vs 15.8%; *P* < .0001). The prevalence of WTR-oriented refractive astigmatism was also slightly lower in eyes with high ORA (67% vs 75%, *P* < .0001). There was no statistically or clinically meaningful difference in coma orientations between groups (**Table 2**).

VISION EFFICACY

A slightly greater number of eyes with low ORA achieved a cumulative postoperative unilateral uncorrected distance visual acuity (UDVA) of 20/20 (91.9% vs 89.1%) and 20/25 (98.3% vs 97.2%), but the efficacy index of eyes with low and high ORA was identical (0.98 ± 0.07 vs 0.98 ± 0.08; *P* = .99; **Figure 2A**). A marginally greater number of eyes with low ORA had the same or better postoperative UDVA than preoperative corrected distance visual acuity (**Figure 2B**; 92.2% vs 89.6%). An identical number of eyes achieved a cumulative postoperative bilateral UDVA of 20/20 (98.4% vs 98.0%; *P* = .07; **Figure 2C**).

SPHERICAL EQUIVALENT AND DEFOCUS EQUIVALENT ACCURACY

The attempted versus achieved spherical equivalent scatterplot revealed a high predictability in both groups

TABLE 2
Astigmatism and Anterior Corneal Coma Orientation

Astigmatism	Low ORA	High ORA	P
Subjective refractive astigmatism			
Within-the-rule eyes (%)	74.8	66.6	< .0001
Oblique eyes (%)	9.8	11.7	.0043
Against-the-rule eyes (%)	15.3	21.7	< .0001
Anterior corneal astigmatism			
Within-the-rule eyes (%)	79.1	88.1	< .0001
Oblique eyes (%)	10.3	5.3	< .0001
Against-the-rule eyes (%)	10.6	6.6	< .0001
Anterior corneal coma			
Within-the-rule eyes (%)	40.1	38.0	.0084
Oblique eyes (%)	30.8	32.1	.3805
Against-the-rule eyes (%)	29.1	29.9	.7251
ORA			
Within-the-rule eyes (%)	6.2	0.3	< .0001
Oblique eyes (%)	15.8	1.7	< .0001
Against-the-rule eyes (%)	78.0	98.0	< .0001

ORA = ocular residual astigmatism

with R^2 values of 0.98 and 0.97, respectively (**Figure AA**, available in the online version of this article). A similar percentage of eyes with low and high ORA had a spherical equivalent within 0.25, 0.50, 0.75, and 1.00 D of the intended target (78.9% vs 77.4%, 94.7% vs 94.1%, 98.6% vs 98.5%, and 99.7 vs 99.8%; not clinically meaningful; **Figure 3A**). Cumulative defocus equivalent histograms revealed that the low ORA group had marginally more eyes achieving a defocus equivalent of 0.25, 0.50, and 0.75 D or less (70.1% vs 65.7%, 91.2% vs 88.4%, and 97.2% vs 96.2%; $P < .0001$; **Figure 3B**).

REFRACTIVE ASTIGMATISM ACCURACY

In the low ORA group, more eyes were within 0.25, 0.50, 0.75, and 1.00 D of the intended plano cylinder (82.5% vs 77.1%, 96.1% vs 93.9%, 99.4% vs 98.3%, and 99.8% vs 99.6%; $P < .0001$; **Figure 3C**) compared to eyes with high ORA. A greater number of eyes with high ORA had residual astigmatism of 0.75 D or greater, compared to eyes with low ORA (6.1% vs 3.9%; **Figure 3C**). Due to the large numbers (21,581 eyes), there was a statistically significant correlation between the preoperative ORA and the amount of postoperative refractive astigmatism, defocus equivalent, and spherical equivalent, although the correlations were weak ($R = 0.09, 0.04$, and 0.03; $P < .0001$).

CYLINDER VECTOR ANALYSIS

The target induced astigmatism (TIA) to surgically induced astigmatism (SIA) treatment predictability was not different between groups, with R^2 values of 0.90

(**Figure AB**). Eyes with low and high ORA had identical Alpins correction index values (1.01 ± 0.37 vs 1.00 ± 0.43; $P = .10$; effect size = 0.01; **Table 3**), with a similar index of success (0.20 ± 0.32 vs 0.24 ± 0.36; $P < .0001$; effect size: -0.10; **Table 3**). The Alpins difference vector was similar between eyes with low and high ORA (0.16 ± 0.22 vs 0.19 ± 0.25; $P < .0001$; effect size = -0.16; **Table 3**). The Alpins magnitude of error and angle of error were similar between groups (**Table 3**). Additional Alpins vectors and parameters are reported in **Table 3** and graphed as single-angle polar plots in **Figure B** (available in the online version of this article).

SAFETY

The safety index was identical between eyes with low and high ORA (1.00 ± 0.04 vs 1.00 ± 0.04; $P = .99$; **Figure 4**). In both groups, the percentage of eyes losing, gaining, or without change in lines of corrected distance visual acuity was identical (**Figure 4**).

RE-TREATMENTS

The laser re-treatment rate was 0.29% (21 eyes) in eyes with low ORA and 0.81% (56 eyes) in eyes with high ORA ($P < .0001$).

DISCUSSION
PREOPERATIVE ORA CHARACTERISTICS

This study is the first to characterize ORA in a large preoperative myopic study population of 21,581 eyes, showing an ORA magnitude having a right-skewed nor-
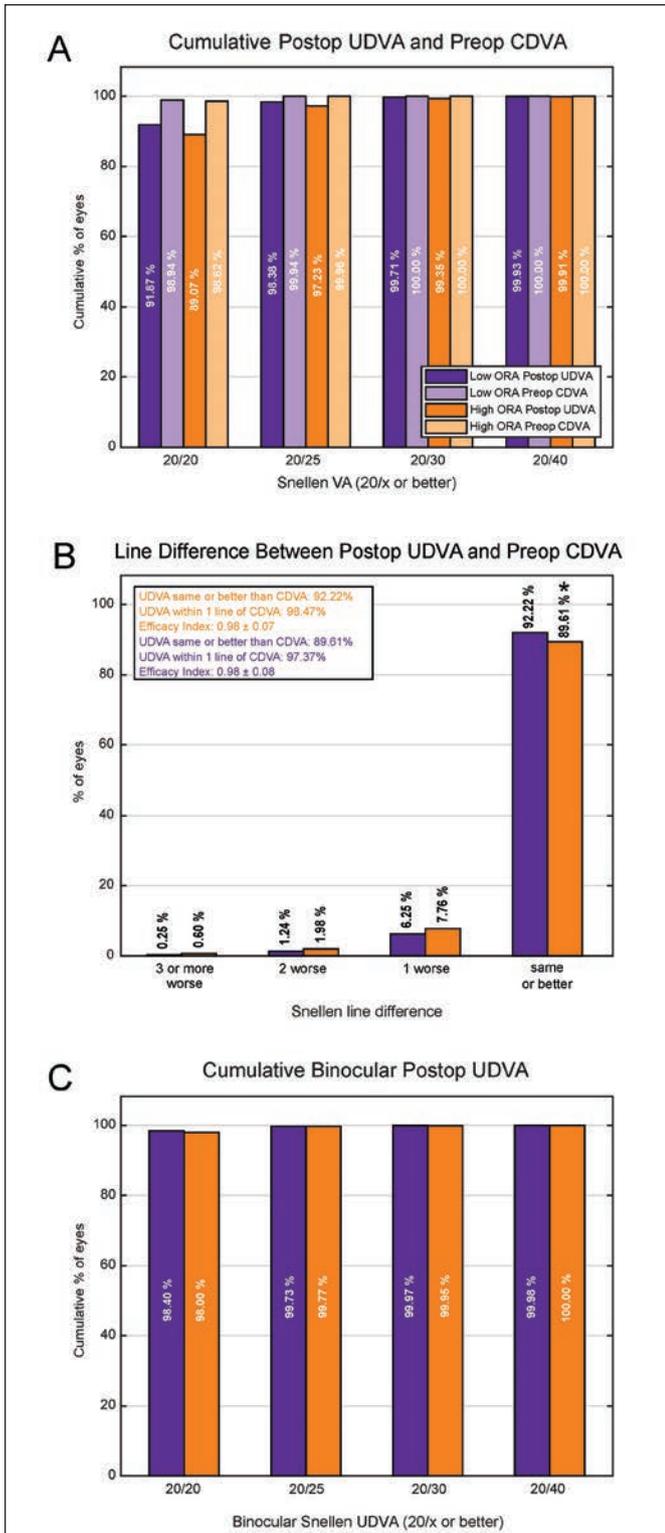
Figure 2. (A) Difference in cumulative postoperative monocular uncorrected distance visual acuity (UDVA) lines in eyes with low and high ocular residual astigmatism (ORA), compared to preoperative monocular corrected distance visual acuity (CDVA). (B) Difference in lines of postoperative monocular UDVA compared to monocular preoperative CDVA. (C) Cumulative postoperative binocular UDVA lines. LASIK = laser in situ keratomileusis
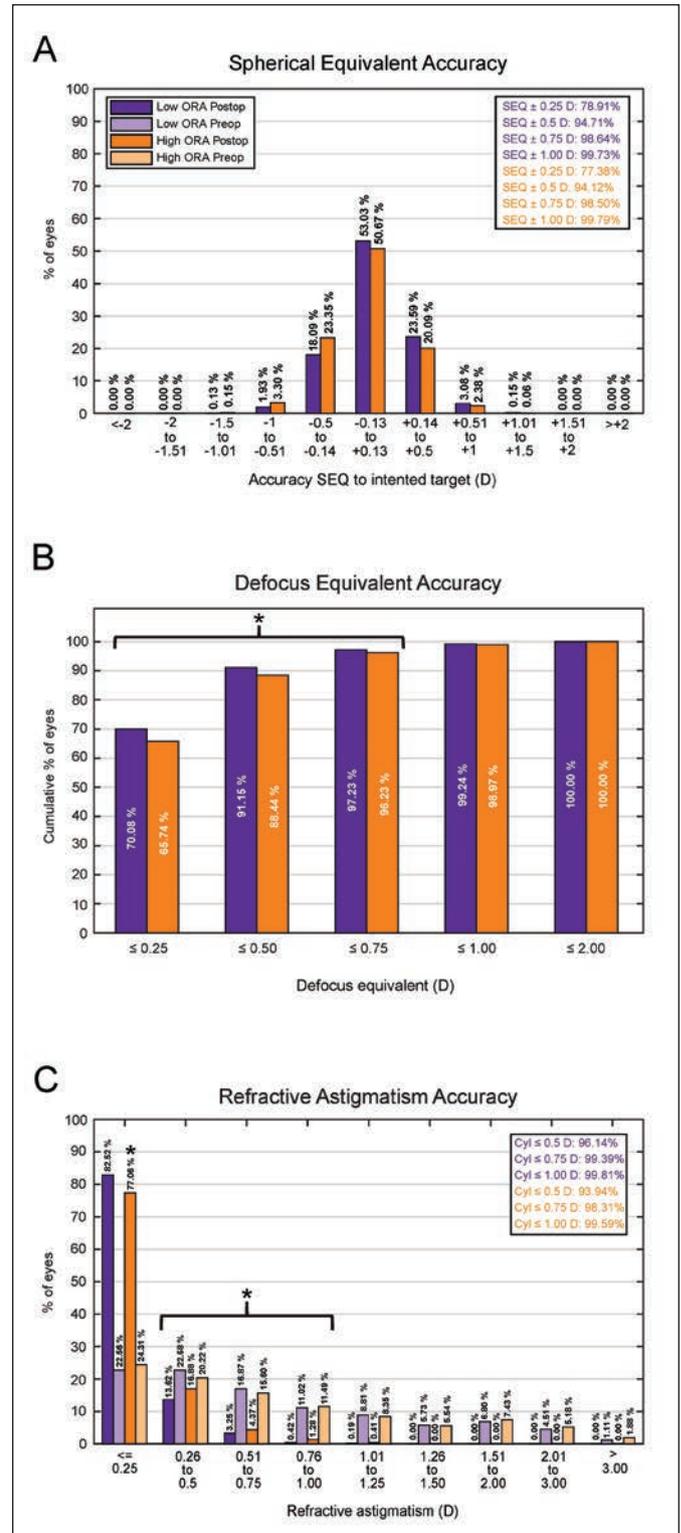
Figure 3. (A) Postoperative spherical equivalent (SEQ) histogram of eyes with low and high ocular residual astigmatism (ORA). (B) Cumulative postoperative defocus equivalent (DEQ) histogram. DEQ is defined as the summation of the absolute value of the SEQ and half the absolute value of the astigmatism. (C) Refractive astigmatism before and after surgery. Black asterisks indicate statistically significant differences. D = diopters; cyl = cylinder; LASIK = laser in situ keratomileusis

Comparison of Postoperative Astigmatism Vectors

Parameter	Low ORA (7,180 Eyes) Mean ± SD	High ORA (7,208 Eyes) Mean ± SD	P (ES)
TIA vector (D)	0.79 ± 0.62	0.82 ± 0.70	.5704 (-0.06)
SIA vector (D)	0.82 ± 0.61	0.86 ± 0.70	0.4880 (-0.06)
DV (D)	0.16 ± 0.22	0.19 ± 0.25	< .0001 (-0.16)
Correction index	1.01 ± 0.37	1.00 ± 0.43	.1035 (0.01)
Index of success	0.20 ± 0.32	0.24 ± 0.36	< .0001 (-0.10)
ME (D)	0.02 ± 0.20	0.01 ± 0.22	.0646 (0.02)
AE (°)	0.36 ± 9.4	0.15 ± 11.6	.3551 (0.02)
% ME within 0.50 D	97.3%	96.3%	.0137
% ME within 1.00 D	99.9%	99.8%	.2686
% with | AE | within 15°	92.7%	89.7%	< .0001
% with AE greater than	4.1%	5.4%	.0087
% with AE less than -15°	3.3%	4.9%	.0003

ORA = ocular residual astigmatism; SD = standard deviation; ES = effect size; TIA = target induced astigmatism; D = diopters; SIA = surgically induced astigmatism; DV = difference vector; ME = magnitude of error; AE = angle of error

mal distribution (R^2 = 0.99) with an average of 0.73 D. This compares to six previous small cohort studies of at least 100 eyes, where the average ORA ranged between 0.57 and 0.86 D,[6,25-27] although ORA was reported to be higher in young Chinese students.[28] More than 80% had ORA of 1.00 D or less, 2.5% had ORA of greater than 1.50 D, and only 0.2% had ORA greater than 2.00 D, showing how infrequent very high ORA is in virgin eyes. Similar to previous studies, eyes with high ORA had 50% more anterior corneal astigmatism than eyes with low ORA, but not more refractive astigmatism.[8] ORA was almost always (87%) ATR-oriented with a higher ATR prevalence in eyes with high ORA (98%).

The average preoperative total, horizontal, and vertical anterior corneal coma was nearly identical in the 7,180 and 7,208 eyes with the lowest and highest ORA, respectively (**Table 1**). These findings lend further evidence to previous findings showing that the amount of preoperative anterior corneal HOAs does not correlate with ORA,[29] unlike with highly aberrated irregular flap corneas or keratoconic eyes with high coma.[30]

THE EFFECT OF ORA ON OUTCOMES

The influence of preoperative ORA on topography-guided LASIK outcomes is reported here on a large scale. Weak, non-clinically meaningful correlations were found between the preoperative ORA and the amount of postoperative refractive astigmatism (*R* = 0.07), postoperative defocus equivalent (*R* = 0.04), and postoperative spherical equivalent (*R* = 0.03). Because ORA did not have a meaningful correlation on outcomes, this study provides further evidence that the amount of preopera-
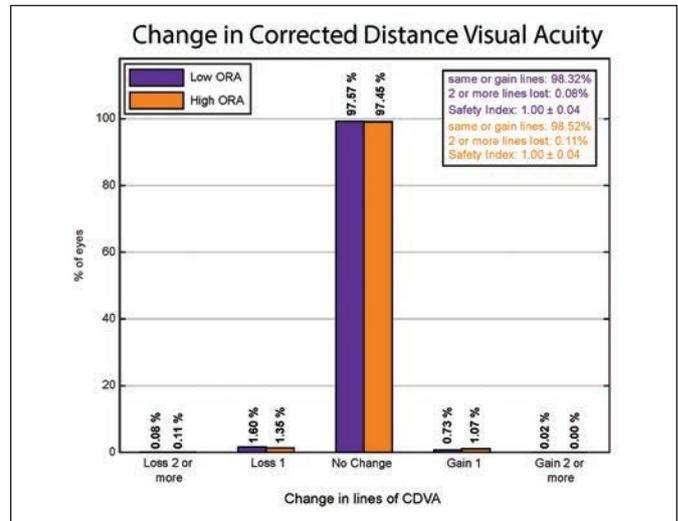
Figure 4. Change in postoperative Snellen lines of corrected distance visual acuity (CDVA) compared with preoperative CDVA in the low and high ocular residual astigmatism (ORA) groups. LASIK = laser in situ keratomileusis

tive ORA, in most virgin corneas, either does not or minimally influences outcomes, which is in agreement with previous non-topography–guided studies[7-9] and a recent topography-guided study.[18]

The standard refractive outcomes of the first (low ORA group; mean ORA of 0.35 D) and last (high ORA group; mean ORA of 1.13 D) terciles were compared after undergoing Contoura LASIK treated on subjective refractive astigmatism. Contoura LASIK in the low ORA group resulted in 92% achieving 20/20 at 1 month, which was better than the 88% of 249 eyes

in the FDA topography-guided study, where corneas were preselected to exclude both topographic irregular astigmatism and eyes with differences between subjective refractive astigmatism and anterior corneal astigmatism. The postoperative refractive astigmatism accuracy in this low ORA group was also superior to the FDA results, with 96% of eyes having postoperative residual astigmatism of 0.50 D or less.

The high ORA group showed identical efficacy and safety indexes to those of the low ORA group, with a mean postoperative refractive astigmatism difference between groups of only 0.03 D. Although the results are comparable, a greater number of eyes with high versus low ORA had postoperative residual astigmatism of 0.75 D or greater (6.1% vs 3.9%), which we defined as an outlier outcome. Considering that the Alpins correction indices were equal between groups, meaning the relative treatment accuracy was the same, this suggests that the main contributing cause to the outcome difference was not the treatment itself. Looking at differences between the groups, the preoperative prevalence of anterior corneal astigmatism greater than 2.00 D was 2.5-fold higher in the high ORA group (21.0% vs 8.3%). This explains the 2% higher rate of outlier eyes with residual cylinder of 0.75 D or greater postoperatively in the high ORA group and a 0.52% higher re-treatment rate (0.81% vs 0.29%). Eyes with high corneal cylinder have been shown to have greater refractive cylinder postoperatively with topography-guided or conventional treatments.[18]

Of interest is that the FDA study, which preselected eyes with minimal ORA,[10] had a higher rate of postoperative cylinder of 0.75 D or greater (10% vs 6.1% in the current high ORA group) and a greater loss of one line or more of CDVA (3.6% vs the 1.6% and 1.4% in the current high and low ORA groups, respectively).[10] The superior outcomes of this study are likely attributed to the newer generation excimer laser (WaveLight EX500 vs Allegretto Wave Eye-Q 400), faster repetition rate, cyclotorsional tracking, better image acquisition protocols, and custom electronic medical record large database nomogram used. The current 1-month study outcomes would be expected to further improve at 3 and 12 months in both groups, due to epithelial remodeling, cortical adaptation, and amelioration in ocular surface, as shown with progressive improvement in UDVA in recent reports.[10,31]

Because there was a suggestive trend of marginally lower accuracy and efficacy and greater cumulative defocus equivalent with higher ORA, we performed an ad hoc analysis on extreme eyes with high ORA of 1.50 D or greater, accounting for 2.5% of eyes (n = 531). Above this ORA level, 87% of eyes achieve 20/20 and 91% are within ±0.50 D of intended plano

cylinder. The TIA to SIA predictability ($R^2 = 0.90$) was identical to eyes with low ORA, with efficacy and safety being 0.97 and 1.00, respectively. This shows only a 1% efficacy reduction compared to the low ORA group (0.98). These outcomes are also better than the subset of eyes with cylinder of greater than 2.00 D in the FDA study, where only 80% of eyes achieved 20/20 UDVA and 90% of eyes were within 0.50 D of intended plano cylinder. To add context, a recently published Contoura study on eyes with 2.00 D or greater of cylinder showed an 18% postoperative rate of cylinder of 0.75 D or greater,[18] which is significantly higher than seen here in the eyes with high (6.1%) and very high (8.6%) ORA. In other words, performing surgery on eyes with very high ORA of 1.50 D or greater results in good outcomes, comparable to those achieved in moderate to high cylinder eyes.[18] Therefore, there should be no accuracy, efficacy, or safety reasons to exclude these eyes. We recommend that eyes with higher ORA not be excluded from Contoura topography-guided treatments because the outcomes using the refractive cylinder as input are as good as those reported in the low ORA FDA study.[10]

THE MEANING OF COMPARING ORA/TIA TO OUTCOMES

Previous non-topography studies investigating only the effect of ORA (as opposed to ORA/TIA) in eyes undergoing non-topography–guided laser treatments report no statistically significant differences in outcomes for low versus high ORA,[7-9] except in one SMILE study[4] that showed higher postoperative astigmatism and index of success in eyes with high ORA. Index of success is a relative measure of laser treatment performance defined by dividing the postoperative cylinder, termed difference vector, by the preoperative cylinder, termed TIA. Several studies[3-7] segregated groups based on an ORA/TIA ratio smaller or greater than 1. They found that eyes with an ORA/TIA ratio of greater than 1 had a higher index of success and concluded poorer refractive astigmatism outcomes. Although these studies describe these poorer outcomes as eyes with high ORA, ORA/TIA is not the same measure as only ORA. The conclusion that eyes with higher ORA have poorer outcomes based on the ORA/TIA metric is inaccurate, as evidenced in this study and explained below.

To replicate the ORA/TIA grouping methodology, we conducted ad hoc Alpins analyses using the ORA/TIA ratio (**Table A**, available in the online version of this article). We found similar results, with a higher index of success in the ORA/TIA greater than 1 groups. However, the most important clinically relevant outcome measure is the average amount of postoperative cylinder, and not index of success. A high index of success gives us an in-

dication of laser performance relative to the preoperative cylinder but is not necessarily indicative of a practical clinical outcome. As can be seen in **Table A**, ORA/TIA greater than 1 groups with a higher index of success also had lower postoperative cylinder compared to ORA/TIA less than 1, with a lower index of success. Therefore, despite a higher index of success, these eyes do better and achieve lower postoperative cylinder than eyes with ORA/TIA of less than 1.

ORA/TIA greater than 1 groups had clinically meaningful (effect size: 2.6) higher preoperative cylinder, with a much higher preoperative prevalence of moderate to high astigmatism of greater than 2.00 D. This explains why they have more residual postoperative cylinder. Studies that used the ORA/TIA ratio cannot be used to conclude that eyes with high ORA result in poorer outcomes.

TOPOGRAPHY-GUIDED TREATMENT TARGETING THE REFRACTIVE ASTIGMATISM

The current study used the subjective refractive astigmatism (as opposed to anterior corneal topographic astigmatism) as the treatment input for Contoura treatment in all eyes. The manifest refraction astigmatism was chosen because it takes into consideration all sources of ocular optical astigmatism, as well as the non-optical physiological interpretation by the brain. In other words, the treatment considers ORA.[2,32] Using this methodology yielded comparable outcomes in the low and high ORA groups, with identical refractive astigmatism predictability. Good outcomes were even achieved in eyes with very high ORA and those with large differences between refractive and anterior corneal astigmatism. Had the study ignored ORA by treating on the Contoura-measured anterior corneal astigmatism as some surgeons advocate,[16,17] that would have left untreated internal astigmatism, leading to eyes with high ORA having significantly poorer outcomes.[2,32,33]

Several other studies have also shown good outcomes using refractive astigmatism as the Contoura treatment input.[2,10,12,18,31,34-38] This study adds more than 21,000 eyes to the current literature using this methodology, validating that treating on the refractive astigmatism is a strategy that works exceptionally well.

ORA did not have a meaningful impact on topography-guided refractive and visual outcomes in most eyes using a technology that treats and reduces anterior corneal HOAs while concurrently treating the refractive astigmatism. Therefore, this study further validates previous work that shows preoperative anterior corneal HOAs, in virgin eyes without pathology, contribute little to ORA or to refractive astigmatism.[20,29,32] Several surgeons still believe that the main cause of

ORA is the presence of HOAs on the anterior surface of the cornea. This study further invalidates such claims.

CONCLUSIONS

Almost all eyes undergoing LASIK have some ORA preoperatively, but only a small percentage (2.5%) have very high ORA greater than 1.50 D. ORA does not correlate to preoperative anterior corneal HOAs. The contribution of ORA to clinical outcomes in most virgin eyes is negligible, with excellent efficacy, accuracy, and safety in both groups. Eyes with very high ORA of greater than 1.50 D trend to marginally poorer outcomes, but they are still comparable to or better than those for eyes with moderate to high cylinder. Eyes with greater ORA do well when treated on the clinically measured refractive astigmatism and should not be excluded from topography-guided surgery.

AUTHOR CONTRIBUTIONS

Study concept and design (AW, MG); data collection (MG, SRQ); analysis and interpretation of data (AW, MG, SRQ, MC); writing the manuscript (AW, MG, SRQ, MC); critical revision of the manuscript (AW, MG, SRQ, MC); statistical expertise (MG); supervision (AW, MC)

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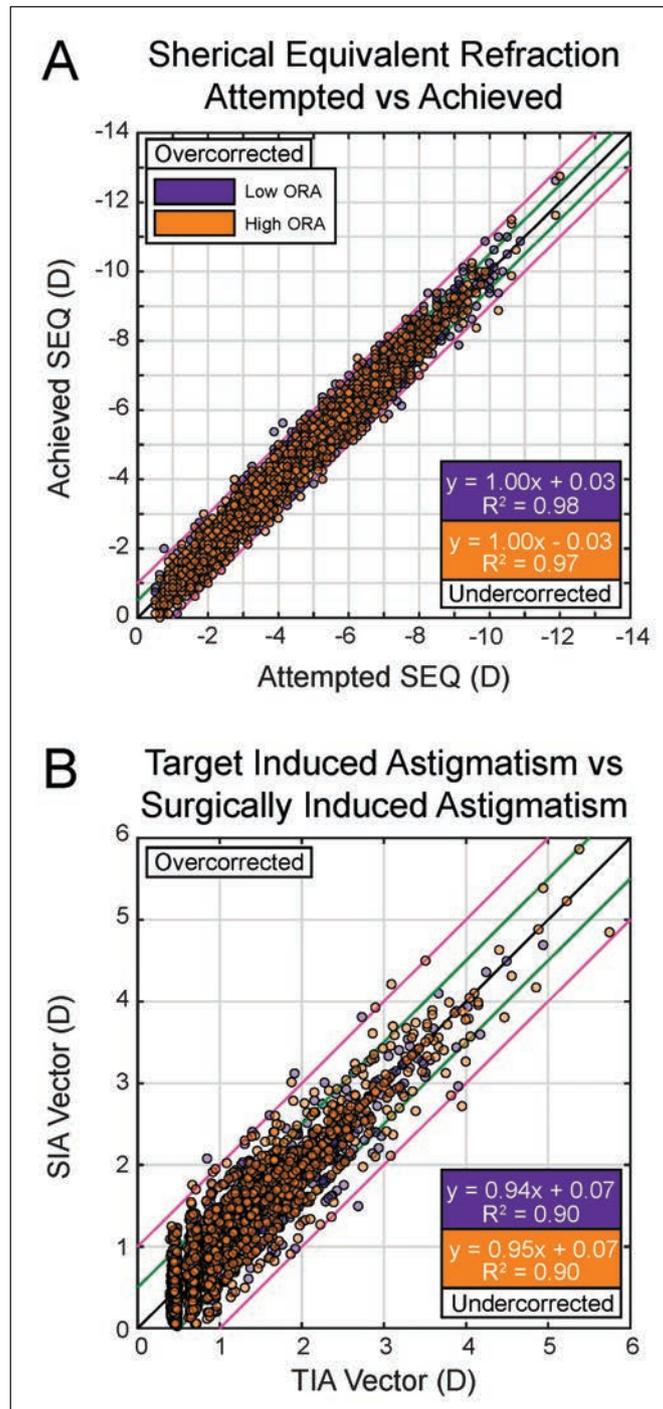
Figure A. (A) Attempted spherical equivalent (SEQ) before surgery vs achieved SEQ after surgery in the low and high ocular residual astigmatism (ORA) groups (purple and orange data-points, respectively). Black line indicates attempted = achieved, green lines indicate ±0.50 diopters (D), and pink lines indicate ±1.00 D. (B) Target induced astigmatism (TIA) vector versus surgically induced astigmatism (SIA) vector in the low and high ORA groups (purple and orange data-points, respectively). Black line indicates TIA = SIA, green lines indicate ±0.50 D, pink lines indicate ±1.00 D. LASIK = laser in situ keratomileusis
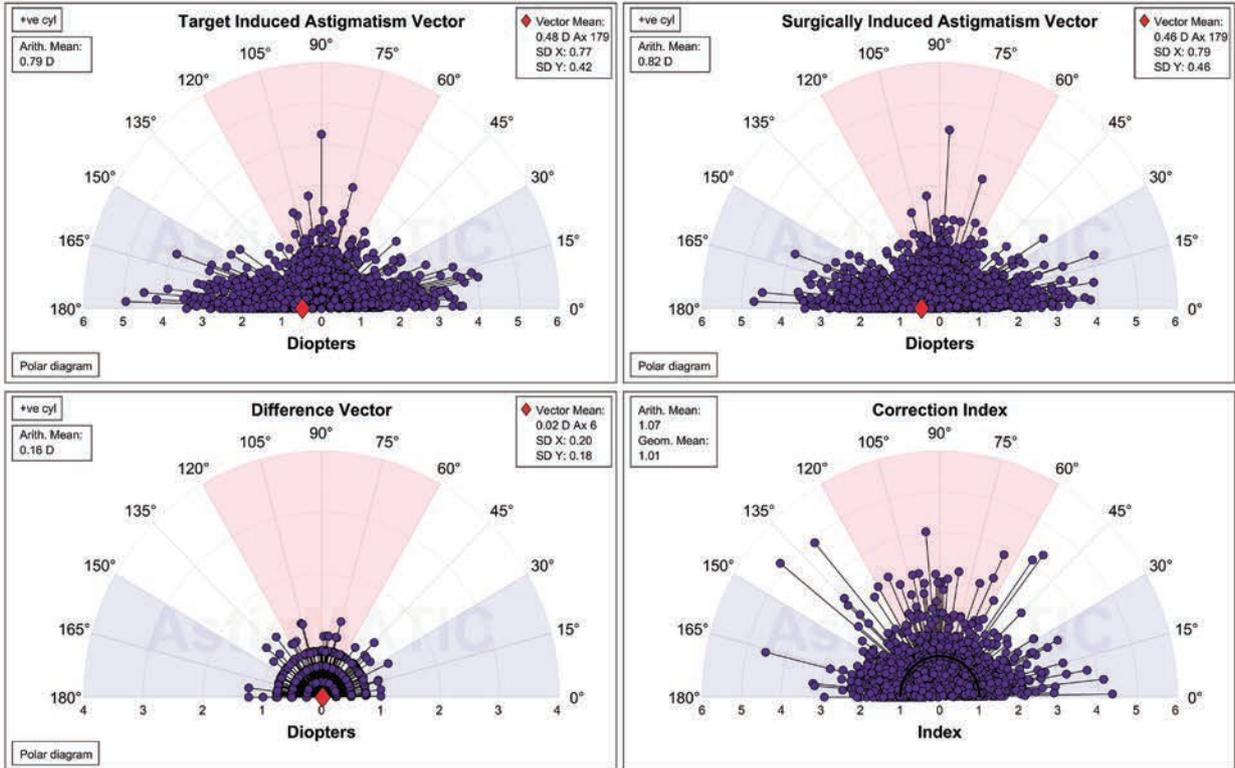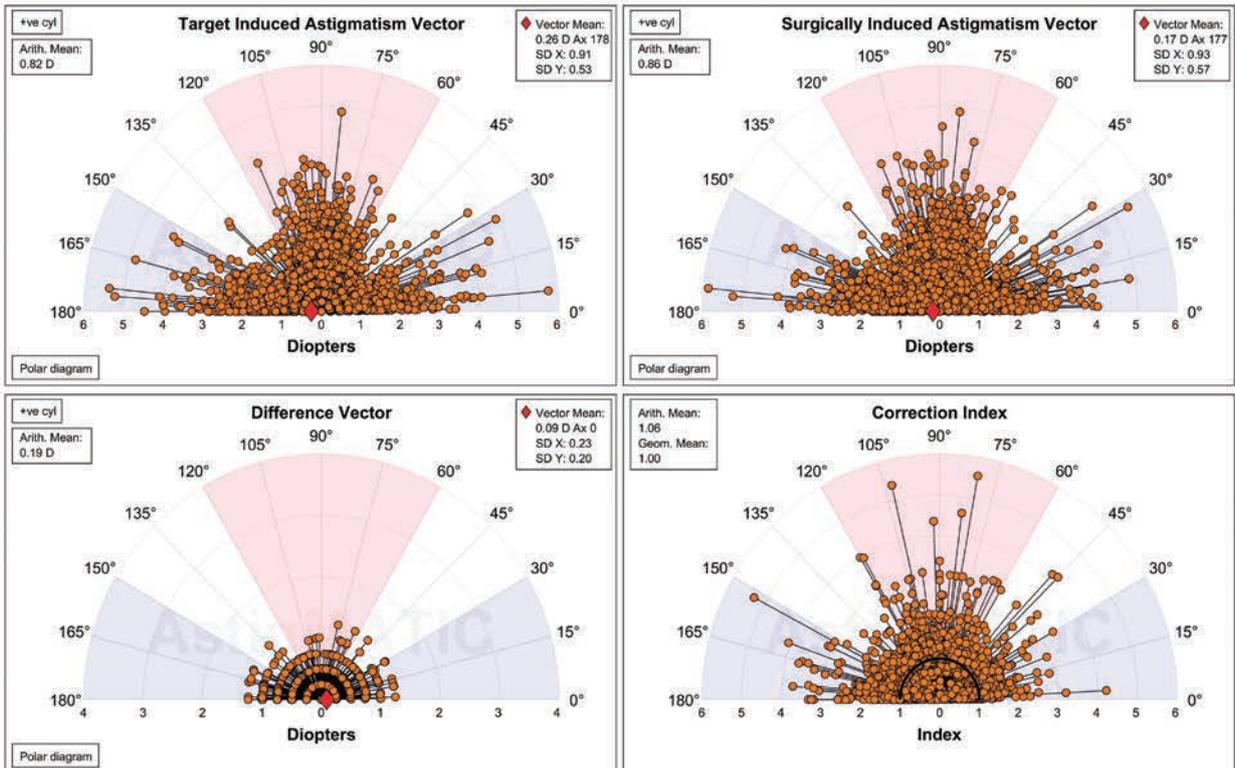
Figure B. (A) Single-angle polar plots generated using the AstigMATIC software[24] to illustrate the target induced astigmatism (TIA) vector, surgically induced astigmatism (SIA) vector, difference vector (DV), and correction index (CI) in the (A) low and (B) high ocular residual astigmatism (ORA) groups. All vectors were calculated at the corneal plane. The vector means are plotted as a red diamond. D = diopters; SD = standard deviation

TABLE A

Comparison of the Index of Success in Eyes With ORA/TIA Ratios < and > 1

Group	Index of Success	DV (D)	TIA Vector (D)	Eyes With TIA > 2.00 (%)
Low ORA				
ORA/TIA < 1 (5,805) eyes	0.22 ± 0.38	0.16 ± 0.28	0.97 ± 0.59	6.62
ORA/TIA > 1 (1,375 eyes)	0.52 ± 0.79	0.14 ± 0.20	0.30 ± 0.10	0.00
P (ES)	< .0001 (-0.63)	.0328 (0.10)	< .0001 (1.27)	< .0001 (N/A)
High ORA				
ORA/TIA < 1 (2,011 eyes)	0.15 ± 0.18	0.24 ± 0.28	1.74 ± 0.70	26.2
ORA/TIA > 1 (5,197 eyes)	0.40 ± 0.64	0.18 ± 0.24	0.58 ± 0.30	0.09
P (ES)	< .0001 (-0.47)	< .0001 (0.22)	< .0001 (2.60)	< .0001 (N/A)

ORA/TIA = ocular residual astigmatism/target induced astigmatism; DV = difference vector; D = diopters; SD = standard deviation; ES = effect size; N/A = not applicable