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Han Wang
The First Affiliated Hospital of Chongqing Medical University, Chongqing Eye Institute
Yi Chen
Chongqing Medical University
Zhikun Chen
Chongqing Medical University
Yan Ji
j_ycw@163.com

The First Affiliated Hospital of Chongqing Medical University, Chongqing Eye Institute

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Residual Astigmatic Error After SMILE for Myopic Astigmatism: Vector, Corneal Aberration, and Topographic Disparity Analyses

Han Wang[1] ,Yi Chen[2], Zhikun Chen[2],Yan Ji*[1]

1. The First Affiliated Hospital of Chongqing Medical University, Chongqing Key Laboratory for the Prevention and Treatment of Major Blinding Eye Diseases, Chongqing Eye Institute, Chongqing Branch of National Clinical Research Center for Ocular Diseases, Chongqing, P. R. China

2. Chongqing Medical University, Chongqing, P. R. China

Correspondence

Yan Ji*, MD, PHD, The First Affiliated Hospital of Chongqing Medical University, Chongqing Key Laboratory for the Prevention and Treatment of Major Blinding Eye Diseases, Chongqing Eye Institute, Chongqing Branch of National Clinical Research Center for Ocular Diseases, Chongqing, P. R. China

Email: j_ycw@163.com

Telephone: 86-13983369161

Purpose:

To evaluate the short-term outcomes of small incision lenticule extraction (SMILE) in eyes with higher myopic astigmatism and to characterize residual astigmatic error using Alpins vector analysis, corneal higher-order aberrations, and superior–inferior topographic disparity (TD).

Methods:

This retrospective study included 232 eyes of 192 patients undergoing SMILE. Eyes were divided according to preoperative cylinder into a lower-astigmatism group (<1.50 D; 116 eyes) and a higher-astigmatism group (≥1.50 D; 116 eyes), with spherical equivalent matched between groups. Visual acuity, manifest refraction, and corneal topography were evaluated preoperatively and at 1 week, 1 month, and 3 months postoperatively. Astigmatic correction was assessed using target-induced astigmatism (TIA), surgically induced astigmatism (SIA), difference vector (DV), correction index (CI), and angle of error (AE). Corneal higher-order aberrations within 4-mm and 6-mm zones and TD magnitude and angle were also analyzed.

Results:

Both groups achieved favorable and comparable postoperative visual and refractive outcomes (all $P>0.05$). The higher-astigmatism group had significantly greater TIA and SIA at all postoperative visits (all $P<0.0001$). From 1 week to 3 months, DV was significantly greater and CI significantly lower in the higher-astigmatism group (all $P<0.05$), with CI remaining below 1.0, indicating mild undercorrection. AE did not differ significantly between groups at 1 or 3 months (both $P>0.05$). Neither TD magnitude nor TD angle differed between groups ($P=0.7737$ and $P=0.4543$, respectively). Spherical aberration ($Z4^0$) within both 4-mm and 6-mm zones was greater in the higher-astigmatism group throughout follow-up (all $P<0.01$), whereas 4-mm vertical coma ($Z3^{-1}$) was greater only at 1 week and 1 month ($P=0.0011$ and $P=0.0065$, respectively).

Conclusions:

SMILE provided favorable short-term visual and refractive outcomes in eyes with higher myopic astigmatism. The greater residual vector error in these eyes was characterized predominantly by mild magnitude-related undercorrection rather than increased axis-related error or superior–inferior topographic disparity. Postoperative aberration differences were limited, consisting mainly of greater spherical aberration and transient early vertical coma. Integrating vector, topographic, and optical analyses provides a more comprehensive characterization of residual astigmatic error after SMILE and may inform future optimization of astigmatic correction strategies.

Keywords: SMILE; myopic astigmatism; vector analysis; residual astigmatism; correction index; topographic disparity; corneal aberrations

1.Introduction

Small-incision lenticule extraction (SMILE) has become an established corneal refractive procedure for the correction of myopia and myopic astigmatism. By creating an intrastromal refractive lenticule with a femtosecond laser and extracting it through a small peripheral incision, SMILE avoids the creation of a corneal flap and provides favorable efficacy, safety, predictability, and refractive stability. Recent clinical studies and meta-analyses have demonstrated that SMILE achieves visual and refractive outcomes broadly comparable to those of femtosecond laser-assisted laser in situ keratomileusis (FS-LASIK), while potentially inducing less postoperative spherical aberration and causing fewer flap-related and ocular-surface complications [1-4]. Nevertheless, the accuracy of astigmatic correction remains a clinically relevant concern, particularly in eyes with moderate-to-high astigmatism.

Unlike spherical refractive error, astigmatism is defined by both magnitude and axis. Consequently, postoperative cylindrical refraction alone cannot fully characterize the accuracy of surgical correction. The Alpins vector method provides a standardized framework for quantifying intended and achieved astigmatic changes through the target-induced astigmatism vector (TIA), surgically induced astigmatism vector (SIA), difference vector (DV), correction index (CI), and angle of error (AE)[2, 5]. Previous studies using vector analysis have confirmed that SMILE is effective for the correction of myopic astigmatism; however, increasing preoperative cylinder has frequently been associated with greater residual astigmatism and a tendency toward undercorrection[2, 5-8]. A systematic review comparing SMILE with LASIK for severe astigmatism similarly found that both procedures were effective and predictable, but that SMILE showed a more evident tendency toward astigmatic undercorrection[7]. In eyes with high astigmatism, Zhou et al. reported that SMILE achieved substantial astigmatic correction, although FS-LASIK with cyclotorsion compensation provided more favorable vector outcomes at 12 months[6].

Several mechanisms may contribute to residual astigmatic error after SMILE. Because conventional SMILE platforms lack active iris registration and automated cyclotorsion compensation, static cyclotorsion, intraoperative centration, and head positioning have been considered potential sources of axis-related error. More recent evidence, however, suggests that cyclotorsion may explain only part of the residual astigmatism. A 2024 systematic review and meta-analysis showed that cyclotorsion compensation could reduce residual astigmatism and coma, whereas a prospective randomized study found no significant improvement in refractive or vector outcomes when manual cyclotorsion-compensation techniques were used under well-controlled surgical positioning[9, 10]. These findings indicate that residual astigmatism after SMILE may also be related to insufficient correction magnitude, treatment nomograms, lenticule geometry, epithelial remodeling, or postoperative corneal biomechanical changes rather than axis misalignment alone.

Postoperative visual quality is another important consideration, because satisfactory uncorrected visual acuity does not necessarily indicate optimal retinal image quality. Corneal

refractive surgery may induce higher-order aberrations (HOAs), including spherical aberration and coma, which can contribute to glare, halos, ghosting, and reduced contrast sensitivity. A recent meta-analysis involving 1,503 eyes demonstrated significant increases in total HOAs, spherical aberration, and coma after SMILE, although the induction of total HOAs was lower than that observed after FS-LASIK[11]. The magnitude of postoperative HOAs may be influenced by preoperative refractive error, astigmatism, lenticule thickness, corneal thickness, optical-zone characteristics, centration, and follow-up duration[11]. Corneal epithelial remodeling after SMILE may further alter both lower-order refractive components and higher-order wavefront aberrations during the early postoperative period[12]. Evaluation of aberrations over different corneal diameters may therefore provide additional information regarding central visual quality and mesopic or scotopic visual performance.

Despite growing evidence regarding SMILE for myopic astigmatism, several questions remain insufficiently addressed. First, relatively few studies have directly compared high- and low-astigmatism eyes with matched spherical equivalent, an approach that may reduce confounding from the magnitude of myopic correction. Second, most studies have focused either on conventional refractive outcomes or on vector analysis, without simultaneously assessing corneal spherical aberration, total HOAs, horizontal and vertical coma over different analysis zones. Third, whether superior–inferior differences in corneal astigmatism contribute to residual vector error after SMILE remains unclear. Evaluating this regional corneal asymmetry may help distinguish whether reduced astigmatic accuracy in highly astigmatic eyes is associated with pre-existing corneal asymmetry, axis-related error, or insufficient correction magnitude.

Therefore, the present study compared short-term visual, refractive, and corneal optical outcomes after SMILE between eyes with high and low myopic astigmatism matched for preoperative spherical equivalent. Alpins vector analysis was used to evaluate TIA, SIA, DV, CI, and AE, while corneal spherical aberration, total HOAs, horizontal coma, and vertical coma were assessed within the central 4-mm and 6-mm zones. Superior–inferior corneal astigmatic differences were also analyzed using the TD magnitude and TD angle. We hypothesized that SMILE would provide comparable short-term visual and refractive outcomes in the two groups, but that eyes with high astigmatism might exhibit greater residual vector error, mild magnitude-related undercorrection, and distinct early postoperative corneal aberration changes.

2. Patients and methods

2.1 Study design and participants

This retrospective comparative case-series study included consecutive patients with myopic astigmatism who underwent small-incision lenticule extraction (SMILE) at the Refractive Surgery Center of the First Affiliated Hospital of Chongqing Medical University between February and December 2021. The study adhered to the tenets of the Declaration of Helsinki and was approved by

the Ethics Committee of the First Affiliated Hospital of Chongqing Medical University (GCP number: [KX2026-KYC668-01]; approval number: [2026-0694-01]). The requirement for informed consent for the use of anonymized retrospective clinical data was waived by the ethics committee, and all patients provided written informed consent before SMILE surgery. A total of 232 eyes from 192 patients were included and categorized according to preoperative manifest refractive cylinder: the low-astigmatism group (<1.50 D) and the high-astigmatism group (≥1.50 D), with 116 eyes in each group. Groups were matched for preoperative spherical equivalent to minimize potential confounding related to the magnitude of myopic correction.

2.2 Surgical technique

All SMILE procedures were performed by a single experienced surgeon under topical anesthesia using the VisuMax femtosecond laser system (Carl Zeiss Meditec AG, Jena, Germany). Patients received levofloxacin and sodium hyaluronate eye drops four times daily for 3 days before surgery. Oxybuprocaine hydrochloride eye drops were administered twice preoperatively for topical anesthesia.Laser parameters included a 500-kHz repetition rate, 135-nJ pulse energy, 4.3-μm spot size, 6.0–6.5-mm optical zone, 6.8–7.5-mm cap diameter, 105–120-μm cap thickness, and a 2.8-mm superior incision at 90° with a 90° side-cut angle. After laser photodisruption, the anterior and posterior lenticule interfaces were sequentially dissected, and the lenticule was extracted through the incision using microforceps. Complete lenticule removal was confirmed at the end of surgery.

2.3 Ophthalmic examination protocol

All patients underwent comprehensive ophthalmic examinations before and after SMILE, including uncorrected and corrected distance visual acuity (UDVA and CDVA), manifest refraction, slit-lamp and dilated fundus examinations, and corneal tomography. Corneal tomography and wavefront aberrations were measured using a Pentacam AXL panoramic biometer (Oculus GmbH, Wetzlar, Germany). Three automatic scans were obtained per eye, and only measurements with an “OK” quality specification were included.

Corneal wavefront aberrations were analyzed over 4.0- and 6.0-mm pupil diameters using Zernike decomposition, including total higher-order aberrations (HOAs), spherical aberration (Z40), horizontal coma (Z31), and vertical coma (Z3−1). Follow-up was performed at 1 day, 1 week, 1 month, and 3 months postoperatively. UDVA, CDVA, manifest refraction, spherical equivalent (SE), and complications were recorded at each visit; corneal tomography and wavefront aberrations were assessed preoperatively and at 1 week, 1 month, and 3 months after surgery.

2.4 Vector analysis of astigmatism

Astigmatic correction outcomes were evaluated using the Alpins vector analysis method13, in which astigmatism is represented as a vector incorporating both magnitude and axis information. Manifest refractive astigmatism was used for vector analysis, and astigmatic parameters, including

TIA, SIA, DV, ,DV Axis, CI and AE, were calculated using iASSORT software (ASSORT Pty. Ltd., Cheltenham, Victoria, Australia)3.Because astigmatic axes exhibit 180° periodicity, vector calculations were performed using double-angle analysis to appropriately account for the equivalence of axes separated by 180°.

2.5 Calculation of topographic disparity (TD)

Anterior corneal topographic data obtained from the Pentacam system were exported and imported into iASSORT software for calculation of topographic disparity (TD) according to the method described by Piñero et al[13].TD was defined as the vectorial difference between the regular astigmatism components derived from the superior and inferior corneal hemidivisions, representing the magnitude and orientation of anterior corneal topographic disparity[14]. All Pentacam measurements were processed using the same acquisition protocol, map type, analysis settings, and iASSORT software version. TD magnitude was expressed in diopters, and TD axis was treated as an axial variable with 180° periodicity.

2.6 Statistical analysis

Statistical analyses were performed using SPSS version 23 (IBM Corp., Armonk, NY, USA). Data distribution was assessed with the Shapiro–Wilk test. Normally distributed variables are presented as mean ± standard deviation (SD), and non-normally distributed variables as median (interquartile range [IQR]). Preoperative and postoperative measurements were compared using paired t-tests or Wilcoxon signed-rank tests, as appropriate. Generalized estimating equations (GEE) were used to compare groups and longitudinal changes while accounting for correlations between fellow eyes and repeated measurements. Because the TD axis has 180° periodicity, angular data were analyzed using circular statistics. A two-sided P value < 0.05 was considered statistically significant.

Results

3.1 Basic information of patients

A total of 232 eyes from 192 patients were included, with 116 eyes in each group (Table 1). The groups were comparable in sex distribution, optical zone diameter, preoperative spherical equivalent (SE), corrected distance visual acuity (CDVA), K2, and astigmatic axis (all $P > 0.05$). Compared with the low-astigmatism group, the high-astigmatism group was younger and had longer axial length, thicker caps, flatter K1, greater central corneal thickness, lower nomogram values, and higher preoperative refractive cylinder (DC) and target-induced astigmatism (TIA) (all $P < 0.05$).

Although TIA magnitude differed between groups, the TIA axis was comparable ($P = 0.0649$), indicating that baseline differences were primarily attributable to astigmatism magnitude rather than orientation. Comparable preoperative SE provided a balanced refractive baseline for subsequent analyses of astigmatic correction, wavefront aberrations, and topographic disparity.

Table 1 Baseline demographic and preoperative characteristics of the study population. (mean ± SD or Q2 ± IQR).

Parameter	Mean ± SD or Q2 ± IQR		P value
	High astigmatism (n=116 eyes)	Low astigmatism (n=116 eyes)	
Age (years)	20 ± 6	27 ± 10.75	<0.0001
Sex (Male/Female)	67/49	36/80	-
Eye (OD/OS)	59/57	66/50	-
Sphere (DS, D)	−6.75 ± 1.25	−7.50 ±0.468	0.65
Cylinder (DC, D)	−2.25 ± 0.50	−1.00 ±0.75	<0.0001
Cylinder axis (°)	170 ±165.8	127.5 ±157	<0.0001
SE (D)	−7.903 ± 1.188	−8.125 ±0.375	0.0649
BCDVA (logMAR)	0.00 ±0.00	0.00 ±0.00	0.2019
CCT (μm)	548.46±31.70	549.97 ±32.26	0.71
Cap thickness (μm)	115 ±10	110 ± 5	<0.0001

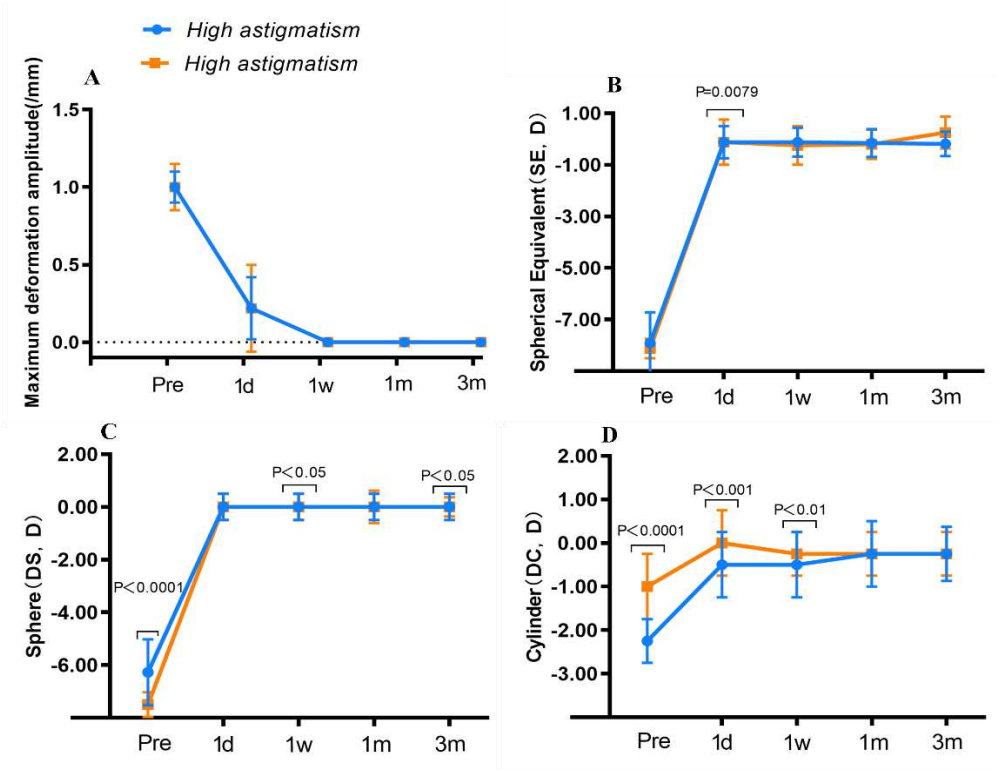
SE, Spherical equivalent ;logMAR, logarithm of the minimum angle of resolution; BCDVA, best corrected distance visual acuity; CCT, central corneal thickness;

3.2 Visual and refractive outcomes

Both groups achieved excellent visual and refractive outcomes following SMILE surgery, with rapid visual recovery and stable refractive correction throughout the follow-up period (Figure 1).Postoperative UDVA improved markedly in both groups. At postoperative day 1, the mean UDVA was comparable between the high- and low-astigmatism groups (0.22 ± 0.20 vs. 0.22 ± 0.28 logMAR, P = 0.4941). From postoperative week 1 onward, all eyes achieved a UDVA of approximately 0.00 logMAR, and no significant intergroup differences were observed at any follow-up visit (all P > 0.05； Fig 1A), indicating rapid visual rehabilitation regardless of the magnitude of preoperative astigmatism.Both groups showed excellent refractive predictability after surgery. Although the spherical equivalent (SE) differed slightly on postoperative day 1 (P = 0.0079), the difference was no longer significant from postoperative week 1 to month 3 (all P > 0.05； Fig 1B). Similarly, postoperative sphere (DS) remained close to plano in both groups during follow-up （Fig 1C）.Residual refractive cylinder (DC) was significantly reduced after surgery in both groups. Compared with the low-astigmatism group, the high-astigmatism group showed slightly greater residual cylinder at postoperative day 1 and week 1 (P = 0.0004 and P = 0.0087,

respectively). However, the difference gradually diminished and became statistically insignificant at 1 and 3 months (both P > 0.05； Fig 1D). These findings indicate that SMILE provided stable visual recovery and refractive correction in both groups, although eyes with higher preoperative astigmatism exhibited slightly slower early postoperative astigmatic recovery.

Figure 1. Visual and refractive outcomes following SMILE surgery during follow-up.



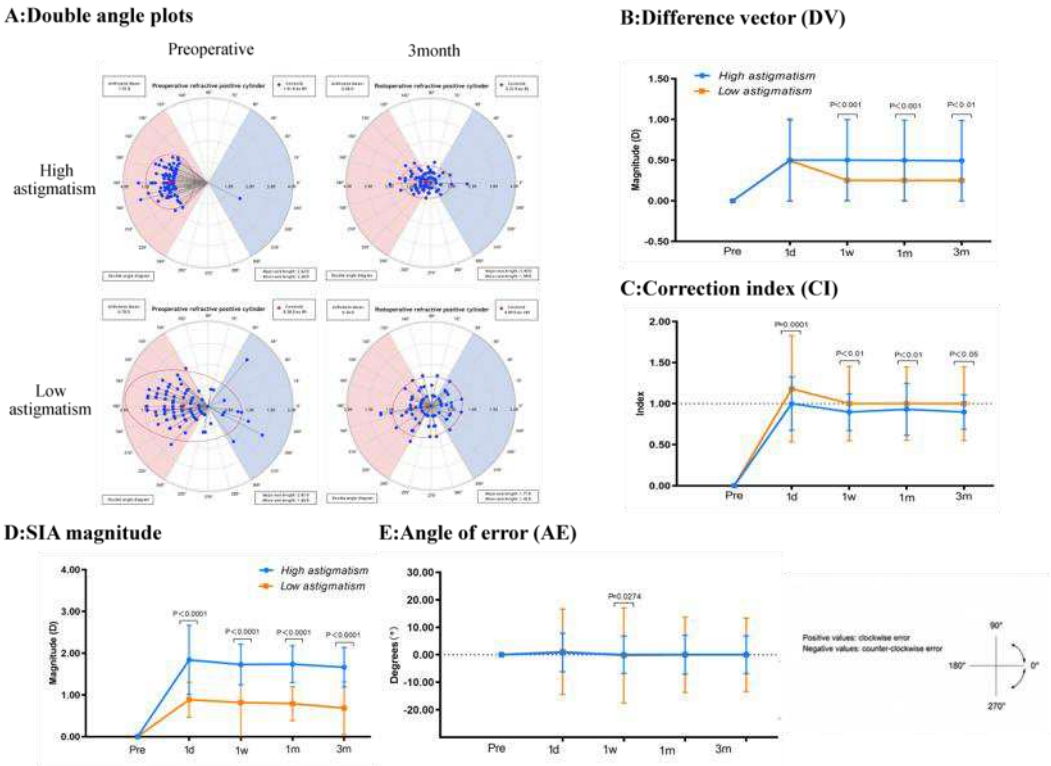
3.3 Alpins vector analysis

Alpins vector analysis was performed to evaluate the accuracy of astigmatic correction after SMILE (Figure 2).The magnitude of target-induced astigmatism (TIA) was significantly greater in the high-astigmatism group than in the low-astigmatism group (P < 0.0001), whereas the TIA axis showed no significant difference (P = 0.1573), indicating comparable astigmatic orientation between groups.The surgically induced astigmatism (SIA) magnitude remained significantly higher in the high-astigmatism group throughout follow-up, reaching 1.665 ± 0.475 D versus 0.684 ± 0.629 D at 3 months (P < 0.0001). The was also significantly greater in the high-astigmatism group at postoperative 1 week, 1 month, and 3 months (all P < 0.01), suggesting increased residual astigmatic error in eyes with higher preoperative astigmatism.The correction index (CI) was lower in the high-astigmatism group during follow-up (0.898–0.932), indicating a tendency toward relative undercorrection compared with the intended correction. In contrast, the

angle of error (AE) showed no significant intergroup differences at most postoperative time points, suggesting comparable axis accuracy between groups. The double-angle plots demonstrated good agreement between TIA and SIA vectors, with slightly greater dispersion in the high-astigmatism group.

Overall, SMILE provided effective astigmatic correction in both groups; however, eyes with higher preoperative astigmatism exhibited greater residual vector errors and a mild tendency toward undercorrection.

Figure 2. Alpins vector analysis of astigmatic correction after SMILE.



3.4 Corneal structural and optical quality outcomes

Corneal structural changes and optical quality after SMILE were evaluated using corneal tomography and wavefront aberration analysis (Figure 3).

Postoperative corneal tomography remained stable in both groups. The changes in keratometric parameters, including K1 and K2, were comparable between the high- and low-astigmatism groups during follow-up (all $P > 0.05$). Central corneal thickness (CCT) decreased after surgery in both groups and remained stable thereafter.Wavefront aberration analysis showed increased higher-order aberrations (HOA), spherical aberration (SA), horizontal coma, and vertical coma after SMILE at both 4-mm and 6-mm pupil diameters. The high-astigmatism group generally demonstrated greater increases in postoperative aberrations,

particularly for HOA and coma-related parameters, with more evident differences at the 6-mm pupil diameter.

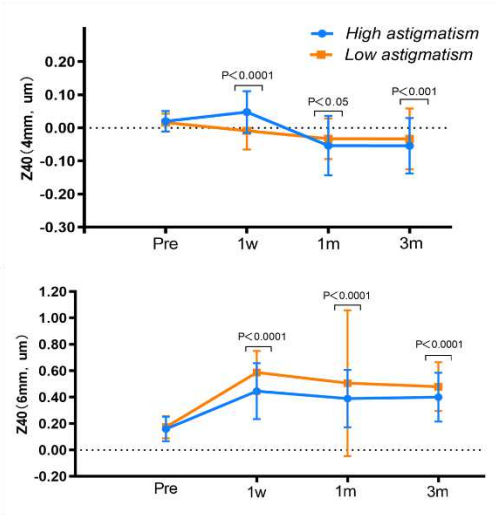
Overall, SMILE induced predictable corneal structural changes and maintained acceptable optical quality in both groups. However, eyes with higher preoperative astigmatism showed a tendency toward greater postoperative wavefront aberration changes.

Figure 3. Corneal structural and optical quality changes after SMILE(mean ± SD or Q2 ± IQR).

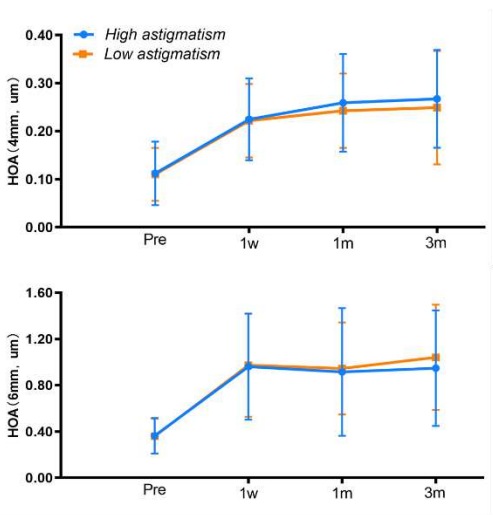
Corneal structural changes after SMILE(mean ± SD or Q2 ± IQR).

Variable	Time	Mean ± SD or Q2 ± IQR		P value
		High astigmatism (n=116 eyes)	Low astigmatism (n=116 eyes)	
K1 (D)	Pre	42.05±2	43.1±1.87	<0.0001
	1w	36.67±1.598	36.89±1.492	0.2878
	1m	36.86±1.528	37.12±1.419	0.2023
	3m	36.84±1.519	37.32±1.436	0.0144
K2 (D)	Pre	44.55±2.55	44.34±1.404	0.2494
	1w	37.35±2.8	37.58±1.596	0.6704
	1m	37.72±1.695	37.89±1.529	0.4208
	3m	37.4±2.8	38.07±1.612	0.0688
CCT (um)	Pre	547±20	535±16.8	<0.0001
	1w	424±23	419±14	0.0121
	1m	424±25	418±14	0.002
	3m	424±22	423±12	0.39

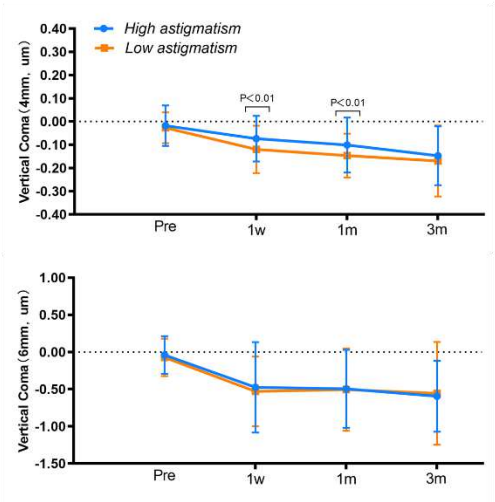
A:Z40(4mm and 6mm)



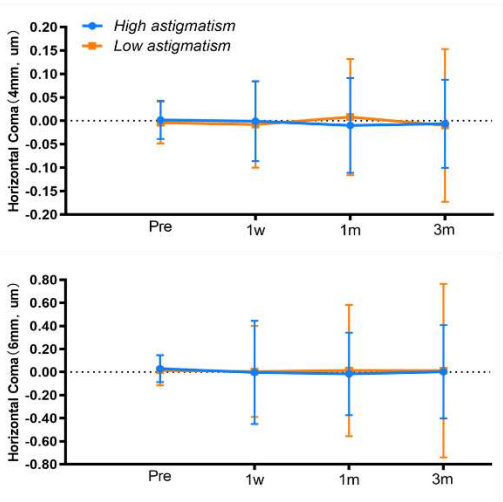
B:HOA(4mm and 6mm)



C:Vertical Coma(4mm and 6mm)



D:Horizontal Coma(4mm and 6mm)



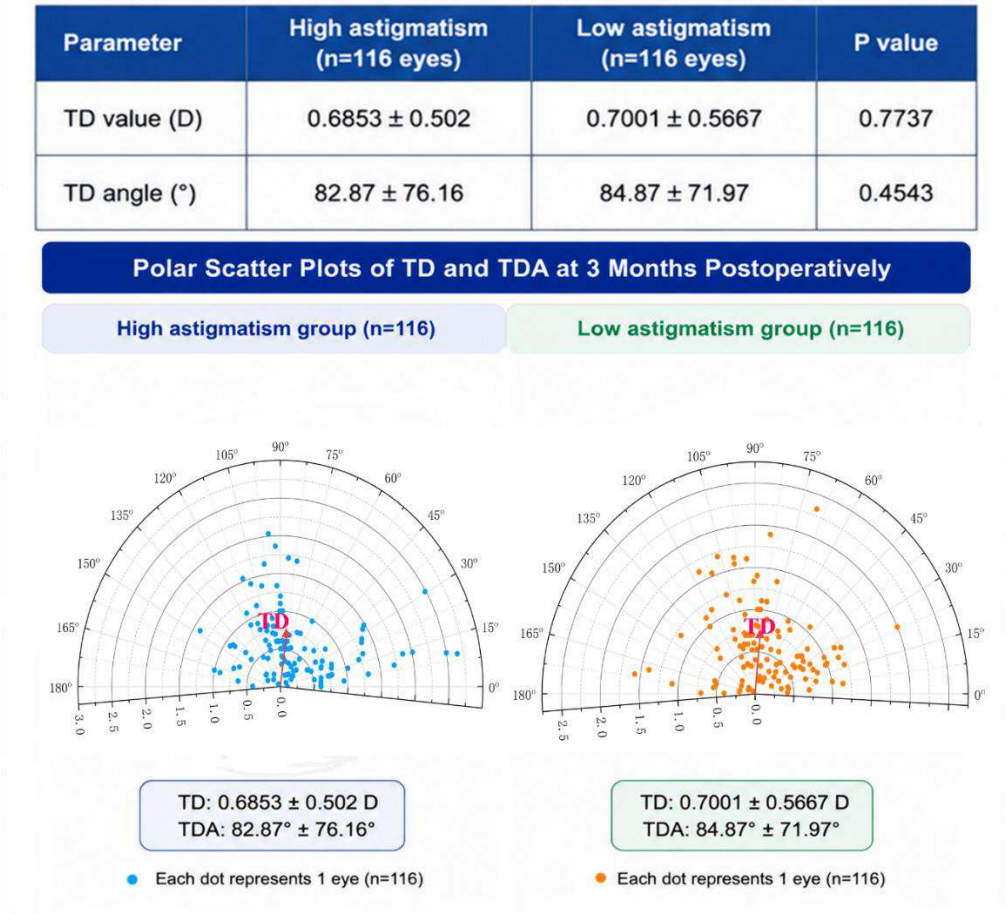
K1, flat keratometry; K2, steep keratometry; CCT, central corneal thickness; SD, standard deviation；Z40: The Z40 value, expressed as the Zernike coefficient C^0_4, was used to quantify corneal spherical aberration;HOA: higher-order aberrations

3.5 Topographic disparity

Topographic disparity (TD) and topographic disparity angle (TDA) were analyzed to evaluate the agreement between anterior and posterior corneal surfaces after SMILE (Figure 4). No significant intergroup differences were observed in superior-inferior astigmatic difference parameters at 3 months after SMILE. The TD value was 0.6853 ± 0.502 D in the high-astigmatism group and 0.7001 ± 0.5667 D in the low-astigmatism group (P = 0.7737), while the TD angle showed no significant difference between groups (82.87 ± 76.16° vs. 84.87 ± 71.97°, P = 0.4543). These results suggested that high preoperative astigmatism was not associated with increased superior-inferior corneal astigmatic asymmetry after SMILE. Therefore, the greater residual vector error observed in the high-astigmatism group was unlikely to be attributed to superior-inferior differences in corneal astigmatism.

Figure 4. Changes in topographic disparity (TD) and topographic disparity angle (TDA) after SMILE.

Parameter	High astigmatism (n=116 eyes)	Low astigmatism (n=116 eyes)	P value
TD value (D)	0.6853 ± 0.502	0.7001 ± 0.5667	0.7737
TD angle (°)	82.87 ± 76.16	84.87 ± 71.97	0.4543



Discussion

Small-incision lenticule extraction (SMILE) has become an important corneal refractive procedure for the correction of myopia and myopic astigmatism, and its safety, efficacy, and refractive stability have been widely demonstrated in previous studies[15-17]. However, the predictability of astigmatic correction after SMILE remains controversial, particularly in eyes with high astigmatism. Although favorable visual and refractive outcomes have been reported after SMILE, postoperative residual astigmatism may be influenced by multiple factors, including undercorrection of the intended cylindrical power, cyclotorsional or axial alignment errors, corneal biomechanical responses, epithelial remodeling, and postoperative changes in corneal morphology [18, 19]. Notably, most previous studies have primarily relied on conventional refractive indices to evaluate surgical outcomes[20], which may not fully capture subtle differences in the accuracy of astigmatic correction. Therefore, the sources of residual astigmatic error after SMILE in eyes with high astigmatism warrant further investigation.

In the present study, we compared the postoperative visual, refractive, and optical outcomes of SMILE between eyes with low and high astigmatism after matching for spherical equivalent. This study design minimized the potential confounding effects of myopic severity on stromal tissue removal, postoperative aberrations, and refractive outcomes, thereby allowing the observed differences to be more directly attributed to astigmatic correction itself. Although both groups achieved favorable uncorrected distance visual acuity and stable spherical equivalent refraction, Alpins vector analysis revealed differences in the precision of astigmatic correction between the two groups. In the high-astigmatism group, the difference vector remained consistently higher at 1 week, 1 month, and 3 months postoperatively, while the correction index was lower than 1.0. These findings indicate a larger residual astigmatic vector error and a clear tendency toward undercorrection in eyes with high astigmatism. These findings are consistent with previous studies reporting that SMILE is effective for myopic astigmatism but may show reduced predictability and greater undercorrection as the attempted cylindrical correction increases[4, 7, 21, 22].

Importantly, the increased residual error in the high-astigmatism group appeared to be primarily related to insufficient correction magnitude rather than axis misalignment. Although DV was significantly greater in the high-astigmatism group, no significant intergroup differences in the angle of error were observed at 1 and 3 months. This suggests that treatment-axis positioning and rotational stability were relatively well preserved, whereas the intended cylindrical correction was not fully achieved. Previous vector analyses have similarly shown that the accuracy of astigmatic correction after SMILE may decrease with increasing preoperative cylinder, although the relative contributions of magnitude and axis errors have varied among studies[4, 6, 21]. The mechanisms underlying undercorrection in eyes with high astigmatism are likely multifactorial. Larger cylindrical corrections require greater lenticule thickness variation and more extensive stromal reshaping, which may increase susceptibility to nonlinear biomechanical responses, epithelial compensation, and limitations of current nomograms. Previous studies have

demonstrated that epithelial remodeling after SMILE occurs predominantly during the first postoperative weeks to months and may partially offset the intended stromal correction, particularly in eyes undergoing larger cylindrical corrections [23-26]. In addition, biomechanical alterations after lenticule extraction may contribute to postoperative corneal stabilization and refractive predictability[27]. Corneal epithelial thickening and spatial redistribution have been documented after SMILE and may partially compensate for stromal curvature changes, thereby modifying the final refractive effect [19, 25, 26]. Changes in corneal biomechanical properties after lenticule extraction may also influence postoperative curvature stabilization and refractive predictability [27, 28]. The temporal pattern observed in this study provides further insight into these mechanisms. No significant difference in DV was detected on postoperative day 1, whereas the difference became evident at 1 week and persisted through 3 months. This suggests that residual astigmatic error may not be determined solely by the immediate surgical correction but may progressively emerge during early postoperative remodeling. Changes in epithelial thickness, stromal hydration, wound healing, and biomechanical redistribution during the first weeks after surgery may therefore contribute to the final astigmatic outcome [19, 25-28].

Another strength of this study was the incorporation of topographic disparity analysis to investigate whether anterior–posterior corneal asymmetry contributed to the greater residual vector error in highly astigmatic eyes. Although topographic disparity parameters changed after surgery, no significant differences were observed between the two groups. This negative finding is clinically meaningful because it indicates that the greater residual astigmatism in high-astigmatism eyes was unlikely to be primarily caused by increased superior–inferior or anterior–posterior corneal asymmetry. Instead, the results further support the interpretation that correction magnitude-related factors are the predominant contributors.

From a clinical perspective, our findings suggest that preoperative evaluation of high-astigmatism eyes undergoing SMILE should extend beyond conventional cylinder magnitude and axis assessment. Although satisfactory UDVA and spherical equivalent stability were achieved, Alpins vector analysis demonstrated a persistent tendency toward mild undercorrection and increased residual vector error with larger astigmatic corrections. These residual errors appeared to be mainly associated with insufficient correction magnitude rather than axis deviation or increased anterior–posterior corneal asymmetry, as indicated by comparable angle of error and topographic disparity parameters between groups. Therefore, individualized consideration of intended correction magnitude, potential vector error, and postoperative optical quality changes may improve surgical planning and patient counseling. A comprehensive evaluation combining Alpins vector analysis, corneal wavefront aberration assessment, and topographic evaluation may provide a more complete understanding of refractive accuracy and visual quality after SMILE, particularly in eyes requiring high cylindrical correction.In conclusion, SMILE demonstrated favorable short-term efficacy, safety, and refractive stability for correcting myopia with high astigmatism. However, eyes with greater preoperative astigmatism may exhibit persistent mild undercorrection and increased residual vector error during the early postoperative period, reflecting the challenges

associated with larger cylindrical corrections. Several limitations should be acknowledged. First, the retrospective design and relatively short follow-up period limit assessment of long-term refractive stability. Second, although topographic disparity and wavefront aberration analyses provided indirect information regarding postoperative corneal remodeling, direct evaluation of epithelial remodeling and corneal biomechanics was unavailable. Third, subjective visual quality parameters, including contrast sensitivity and dysphotopsia symptoms, were not assessed. Future prospective studies incorporating longer follow-up, epithelial thickness mapping, biomechanical measurements, patient-reported outcomes, and individualized nomogram optimization are warranted to further improve the predictability of high astigmatic correction after SMILE.

Conclusion

SMILE is an effective and safe procedure for correcting myopia with high astigmatism, providing satisfactory visual outcomes and short-term refractive stability. However, eyes with higher preoperative astigmatism showed reduced astigmatic correction predictability, characterized by greater residual vector error and a tendency toward mild undercorrection. Alpins vector analysis indicated that these errors were mainly related to insufficient correction magnitude rather than axis misalignment, while topographic disparity analysis did not support corneal asymmetry as a major contributing factor. Although postoperative higher-order aberrations increased slightly, these changes remained limited and stable over time. Comprehensive assessment incorporating vector analysis, optical quality evaluation, and corneal topography may further improve the predictability of SMILE for high astigmatic correction.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

1. Dishler JG, Slade S, Seifert S, Schallhorn SC. Small-Incision Lenticule Extraction (SMILE) for the Correction of Myopia with Astigmatism: Outcomes of the United States Food and Drug Administration Premarket Approval Clinical Trial. *Ophthalmology* 2020; **127**(8)**:** 1020-1034.

2. Chow SSW, Chow LLW, Lee CZ, Chan TCY. Astigmatism Correction Using SMILE. *Asia Pac J Ophthalmol (Phila)* 2019; **8**(5)**:** 391-396.

3. Moshirfar M, Thomson AC, West WB, Jr., Hall MN, McCabe SE, Thomson RJ *et al.* Initial Single-Site Experience Using SMILE for the Treatment of Astigmatism in Myopic Eyes and Comparison of Astigmatic Outcomes with Existing Literature. *Clin Ophthalmol* 2020; **14:** 3551-3562.

4. Cui G, Di Y, Yang S, Chen D, Li Y. Efficacy of small-incision lenticule extraction surgery in high astigmatism: A meta-analysis. *Front Med (Lausanne)* 2022; **9:** 1100241.

5. Hashemi H, Asgari S, Khabazkhoob M, Heidari Z. Vector analysis of astigmatism correction after PRK, FS-LASIK, and SMILE for myopic astigmatism. *Int Ophthalmol* 2023; **43**(11)**:** 3999-4009.

6. Zhou J, Gu W, Gao Y, He G, Zhang F. Vector analysis of high astigmatism (≥ 2.0 diopters) correction after small-incision lenticule extraction with stringent head positioning and femtosecond laser-assisted laser in situ keratomileusis with compensation of cyclotorsion. *BMC Ophthalmol* 2022; **22**(1)**:** 157.

7. Song J, Cao H, Chen X, Zhao X, Zhang J, Wu G *et al.* Small Incision Lenticule Extraction (SMILE) Versus Laser Assisted Stromal In Situ Keratomileusis (LASIK) for Astigmatism Corrections: A Systematic Review and Meta-analysis. *Am J Ophthalmol* 2023; **247:** 181-199.

8. Reinstein DZ, Archer TJ, Potter JG, Gupta R, Wiltfang R. Refractive and Visual Outcomes of SMILE for Compound Myopic Astigmatism With the VISUMAX 800. *J Refract Surg* 2023; **39**(5)**:** 294-301.

9. Yang X, Liu Y, Xiao K, Song Q, Xu Y, Li J *et al.* Effect of Cyclotorsion Compensation in Small Incision Lenticule Extraction Surgery for the Correction of Myopic Astigmatism: A Systematic Review and Meta-Analysis. *Ophthalmol Ther* 2024; **13**(5)**:** 1271-1288.

10. Xu J, Liu M, Liu Q. Outcomes of astigmatic correction with and without two different cyclotorsion compensation methods in small incision lenticule extraction surgery. *Photodiagnosis Photodyn Ther* 2024; **49:** 104272.

11. Du Y, Di Y, Yang S, Mo F, Cui G, Chen D *et al.* Differences in ocular high order aberrations before and after small incision lenticule extraction for correction of myopia: a systematic

review and meta-analysis. *Front Med (Lausanne)* 2024; **11:** 1274101.

12. Brunner BS, Feldhaus L, Mayer WJ, Siedlecki J, Dirisamer M, Priglinger SG *et al.* Epithelial Remodeling and Epithelial Wavefront Aberrometry after Spherical vs. Cylindrical Myopic Small Incision Lenticule Extraction (SMILE). *J Clin Med* 2024; **13**(13).

13. Piñero DP, Ruiz-Fortes P, Pérez-Cambrodí RJ, Mateo V, Artola A. Ocular residual astigmatism and topographic disparity vector indexes in normal healthy eyes. *Cont Lens Anterior Eye* 2014; **37**(1)**:** 49-54.

14. Lin J. The contribution of ocular residual astigmatism to anterior corneal astigmatism in refractive astigmatism eyes. *Sci Rep* 2021; **11**(1)**:** 1018.

15. Ang M, Gatinel D, Reinstein DZ, Mertens E, Alió Del Barrio JL, Alió JL. Refractive surgery beyond 2020. *Eye (Lond)* 2021; **35**(2)**:** 362-382.

16. Shen Z, Shi K, Yu Y, Yu X, Lin Y, Yao K. Small Incision Lenticule Extraction (SMILE) versus Femtosecond Laser-Assisted In Situ Keratomileusis (FS-LASIK) for Myopia: A Systematic Review and Meta-Analysis. *PLoS One* 2016; **11**(7)**:** e0158176.

17. Yan H, Gong LY, Huang W, Peng YL. Clinical outcomes of small incision lenticule extraction versus femtosecond laser-assisted LASIK for myopia: a Meta-analysis. *Int J Ophthalmol* 2017; **10**(9)**:** 1436-1445.

18. Chan TC, Ng AL, Cheng GP, Wang Z, Ye C, Woo VC *et al.* Vector analysis of astigmatic correction after small-incision lenticule extraction and femtosecond-assisted LASIK for low to moderate myopic astigmatism. *Br J Ophthalmol* 2016; **100**(4)**:** 553-559.

19. Luft N, Ring MH, Dirisamer M, Mursch-Edlmayr AS, Kreutzer TC, Pretzl J *et al.* Corneal Epithelial Remodeling Induced by Small Incision Lenticule Extraction (SMILE). *Invest Ophthalmol Vis Sci* 2016; **57**(9)**:** OCT176-183.

20. Liu YC, Rosman M, Mehta JS. Enhancement after Small-Incision Lenticule Extraction: Incidence, Risk Factors, and Outcomes. *Ophthalmology* 2017; **124**(6)**:** 813-821.

21. Jabbarvand M, Khodaparast M, Moravvej Z, Shahraki K, Ahmadi H, Shahraki K *et al.* Vector analysis of moderate to high myopic astigmatism after small-incision lenticule extraction (SMILE): 12-month follow-up. *Eur J Ophthalmol* 2022; **32**(6)**:** 3312-3320.

22. Zhong Y, Li M, Han T, Fu D, Zhou X. Four-year outcomes of small incision lenticule extraction (SMILE) to correct high myopic astigmatism. *Br J Ophthalmol* 2021; **105**(1)**:** 27-31.

23. Chen P, Hou X, Yu N, Ye Y, Wei H, Zhuang J *et al.* Corneal Epithelial Remodeling Following Cylinder Correction With SMILE or FS-LASIK: A Contralateral Comparative Study. *J Refract*

Surg 2024; **40**(10)**:** e728-e741.

24. Yu N, Ye Y, Chen P, Yang Y, Zhuang J, Yu K. Corneal Epithelial Thickness Changes Following SMILE for Myopia With High Astigmatism. *J Refract Surg* 2021; **37**(4)**:** 224-230.

25. Liu M, Jin C, Lu L, Yuan Y, Chen C, Zhao T *et al.* The Impact of Corneal Epithelial Thickening and Inhomogeneity on Corneal Aberrations After Small Incision Lenticule Extraction. *J Refract Surg* 2023; **39**(1)**:** 23-32.

26. Ye Y, Chen P, Yu N, Wan L, Lan M, Zheng H *et al.* Evaluation of Wide Corneal Epithelial Remodeling after Small Incision Lenticule Extraction (SMILE) with Wide-Field Optical Coherence Tomography. *J Ophthalmol* 2022; **2022:** 8764103.

27. Guo H, Hosseini-Moghaddam SM, Hodge W. Corneal biomechanical properties after SMILE versus FLEX, LASIK, LASEK, or PRK: a systematic review and meta-analysis. *BMC Ophthalmol* 2019; **19**(1)**:** 167.

28. Hou X, Chen P, Yu N, Luo Y, Wei H, Zhuang J *et al.* A Comparative and Prospective Study of Corneal Consumption and Corneal Biomechanics After SMILE and FS-LASIK Performed on the Contralateral Eyes With High Myopic Astigmatism. *Transl Vis Sci Technol* 2024; **13**(11)**:** 29.

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