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Tel: 8629-82245172 8629-82210956 Email: ijopress@163.com

· Clinical Research ·

Corneal higher-order aberrations following small incision lenticule extraction for high myopic astigmatism correction

Yin Liu, Cheng Hu, Juan Yu, Nian Xiang, Bo Zeng, Wen-Shan Jiang

Department of Ophthalmology, General Hospital of Central Theater Command, Wuhan 430070, Hubei Province, China
Co-first Authors: Yin Liu and Cheng Hu
Correspondence to: Wen-Shan Jiang and Bo Zeng. Department of Ophthalmology, General Hospital of Central Theater Command, No. 627 Wuluo Road, Wuchang District, Wuhan 430070, Hubei Province, China. wenshanj@126.com; zbtjmu@163.com
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Abstract

● **AIM:** To compare the visual outcomes and corneal higher-order aberrations (HOAs) of patients with high or low myopic astigmatism after small incision lenticule extraction (SMILE).

● **METHODS:** A total of 157 eyes of 157 patients who underwent SMILE were included in this retrospective, nonrandomized, comparative study. All the eyes which were with the rule astigmatism were divided into high astigmatism group (HAG; astigmatism ≤-2.00 D, 73 eyes) and low astigmatism group (LAG; astigmatism ≥-1.00 D, 84 eyes). Visual and refractive examinations were performed, HOAs of the anterior surface, posterior surface, and total cornea of the eyes were evaluated preoperatively and 6mo postoperatively.

● **RESULTS:** At the postoperative 6-month follow-up, uncorrected distance visual acuity of 20/20 or better was achieved in 97% and 100% eyes in HAG and LAG respectively and 74% and 100% eyes were within -0.50 D. Vector analysis revealed no significant differences in the correction index (P=0.066), angle of error (P=0.091) or flattening index (P=0.987) between two groups. The magnitude of error was -0.37±0.31 D in HAG and -0.04±0.19 D in LAG (P<0.001). Index of success (IOS) was 0.22±0.09 in the HAG and 0.50±0.46 in the LAG (P<0.001). HOAs of most anterior, posterior and total cornea significantly increased after SMILE, especially the spherical aberration and coma. For HAG, the SMILE procedure induced significantly higher anterior, posterior and total cornea horizontal coma and total corneal total HOAs compared with LAG (P<0.001) and these surgically induced HOAs predominantly originated from the anterior surface of the cornea.

● **CONCLUSION:** SMILE surgery induces more HOAs and a mild under-correction of astigmatism in eyes with high astigmatism. The increment in HOAs after SMILE is related to preoperative astigmatism.

● **KEYWORDS:** small incision lenticule extraction; high astigmatism; higher-order aberrations; myopia
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INTRODUCTION

Currently, small-incision lenticule extraction (SMILE) is the mainstream surgery for the correction of myopia and myopic astigmatism. The safety, efficacy, and stability of SMILE have been confirmed in previous studies[1-7]. To achieve better refraction performance, nomograms, which are refraction adjustment values, are used in SMILE to design individual refraction parameters[8]. However, we discovered a little under-correction in some patients with high astigmatism (≤-2.00 D) during our clinical work. Higher-order aberrations (HOAs) play an important role in the evaluation of visual quality[9-10]. SMILE is excellent in correcting lower-order aberrations; however, SMILE induces HOAs, resulting in decreased night-vision and glare[11-12]. In previous studies, changes in HOAs after SMILE were noted mainly on the anterior surface and the total cornea. The shape of posterior surface of the cornea reflects its biomechanical properties[13]; therefore, the changes in HOAs of the posterior surface of the cornea also deserve special attention. To the best of our knowledge, no studies have evaluated the HOAs of the posterior corneal surface of SMILE in terms of the correction of high astigmatism. The posterior corneal HOAs could provide valuable information in determining the cause of poor visual quality after corneal refractive surgery[14]. Hence, we performed this retrospective study to investigate the visual outcomes and corneal HOAs of the anterior surface, posterior surface and total cornea of patients with high (≤-2.00 D) and low (>-1.00 D) astigmatism after SMILE to have a better understanding of postoperative visual qualities.

PARTICIPANTS AND METHODS

Ethical Approval This study adhered to the tenets of the Declaration of Helsinki (2008) and was approved by the Ethics Committee of General Hospital of Central Theater Command (approval number [2024]124-01).

Participants This was a retrospective, nonrandomized, comparative study. We analyzed the visual quality of subjects who underwent SMILE between January 2015 and November 2019 at the Department of Ophthalmology. A total of 157 eyes of 157 patients (79 females and 78 males) were included. The high astigmatism group (HAG) consisted of 73 eyes, and the low astigmatism group (LAG) consisted of 84 eyes. We explained the benefits and risks of SMILE to all patients and obtained signed informed consent forms. Moreover, all the patients independently selected the operation type.

Inclusion and Exclusion Criteria The inclusion criteria in this study were as follows: 1) age ≥18y; 2) stable refractive status for at least 2y (change ≤0.50 D annually); 3) corneal thickness≥480 μm; 4) sphere up to -10.00 D and cylinder up to -5.00 D. Patients with ocular pathology or abnormal corneal topography were excluded.

Methods To characterize the precision of SMILE in the correction of astigmatism, vector analysis was used to compare the effectiveness of astigmatism. Refractive data were converted into three fundamental vectors, which included target-induced astigmatism (TIA), surgically induced astigmatism (SIA), and difference vector (DV). Magnitude of error (ME), angle of error (AE), correction index (CI), flattening index (FI), and index of success (IOS) were analyzed as suggested by Alpins[15]. ME was the arithmetic difference between the SIA and TIA. AE was the angle described by the vector of SIA versus TIA. AE was positive if the achieved correction was on an axis counterclockwise (CCW) to where it was intended and negative if the achieved correction was clockwise (CW) to its intended axis. CI was defined as the SIA divided by the TIA. The value might be preferred, and astigmatism was considered under-corrected if the CI was lower than 1. IOS was the DV divided by the TIA. The correlation of the induced HOAs and astigmatism as well as sphere equivalent (SE) was analyzed using Pearson correlation analysis.

Senior optometrists performed baseline and follow-up examinations that included uncorrected distance visual acuity (UDVA), corrected distance visual acuity (CDVA), and intraocular pressure (IOP) using an auto-noncontact tonometer (NIDEK NT-2000, Japan). Corneal topography and 6.0 mm pupil corneal HOAs were analyzed using Pentacam (OCULUS Wetzlar, Germany). Refraction was examined with a phoropter (NIDEK ARK-1, Japan). Anterior segment and fundus examination were performed.

Surgery and Postoperative Management The surgery was performed by the same skilled surgeon (Jiang WS) using a VisuMax Femtosecond Laser (500 kHz, Carl Zeiss Meditec, AG, Jena, Germany). The spot energy was set to 145 nJ. The treatment was centered on the corneal vertex. The cap thickness was 110-120 μm, the cap diameter was 7.0-7.5 mm, and the lenticule diameter was set at 6.0-6.5 mm. At the end of the procedure, the lenticule was extracted from a 2-mm incision at the 11 o'clock.

The preoperative treatment consisted of gatifloxacin eye drops (0.3% Otsuka, China) and artificial tears four times daily for 3d. Topical anesthesia consisted of three drops of proparacaine hydrochloride (0.5%; Alcon, USA). Postoperatively, the patients received gatifloxacin eyedrops four times daily for 1wk, and fluorometholone (0.1% Santen, Japan) was tapered slowly from 6 times daily for 1mo. Patients were examined regularly at 1d, 1wk, 1, 3, and 6mo postoperatively.

Statistical Analysis Statistical analysis were performed using SPSS version 25.0 (IBM Corp., Armonk, NY, USA). Descriptive data are presented as the mean±standard deviation (SD). Kolmogorov-Smirnov test was performed to check for normality. Wilcoxon signed-rank test or paired samples *t*-test was used to assess the preoperative and postoperative results for non-normally distributed data, whereas the independent *t*-test or Mann-Whitney *U* test were used to compare continuous variables between groups. The correlation of the induced HOAs and astigmatism as well as SE was analyzed using Pearson correlation analysis. To minimize potential confounding effects, multivariate regression analysis was performed to adjust for age, preoperative corneal thickness, and other relevant baseline characteristics. Post-hoc power analysis (G*Power Version 3.1.9.2, Franz Faul, Universitat Kiel, Germany) was used to demonstrate the rationality of the sample size. $P<0.05$ was considered statistically significant.

RESULTS

The preoperative mean age were 22.58±5.49y (range: 18-43y) and 23.14±4.26y (range: 18-38y), the mean thinnest cornea thickness were 554.30±27.82 μm (range: 490-662 μm) and 547.44±30.76 μm (range: 481-630 μm), the mean SE were -5.78±1.53 D (range: -9.125 to -2.50 D) and -4.56±1.14 D (range: -7.125 to -1.75 D), astigmatism were -2.85±0.71D (range: -5.00 to -2.00 D) and -0.60±0.23 D (range: -1.00 to -0.25 D) in the HAG and LAG, respectively (Table 1).

Efficacy and Safety Six months postoperatively, all the eyes in the HAG and LAG achieved a postoperative UDVA of 20/25

Table 1 Patient demographic and preoperative parameters *n*=157, mean±SD

Characteristics	HAG	LAG	*P*
Eyes (*n*)	73	84	-
Gender (female, %)	50.7	50.0	-
Age (y)	22.58±5.49	23.14±4.26	0.55
Thinnest corneal thickness (μm)	554.30±27.82	547.44±30.76	0.381
Pre-CDVA (logMAR)	0.01±0.03	-0.02±0.04	<0.001[a]
Refractive errors (D)			
Sphere	-4.36±1.54	-4.26±1.14	0.718
Cylinder	-2.85±0.71	-0.60±0.23	<0.001[a]
SE	-5.78±1.53	-4.56±1.14	<0.001[a]

HAG: High astigmatism group; LAG: Low astigmatism group; SE: Spherical equivalent; D: Diopter; CDVA: Corrected distance visual acuity; SD: Standard deviation. [a]Significant difference between LAG and HAG.

or better. The cumulative Snellen visual acuity was shown in Figure 1A. The mean UDVA (logMAR) was 0.01±0.03 (range 0.1 to 0) and -0.02±0.04 (range 0 to -0.1) in HAG and LAG, respectively. At the last follow-up, 97% and 100% of the eyes in HAG and LAG achieved a UDVA of 20/20 after SMILE, respectively. Figure 1B showed the changes in the Snellen lines of the CDVA. No vision-threatening complications were observed during surgery or 6mo postoperatively in the two groups. At the last follow-up, no eyes lost one line or more in two groups, 29% showed no change in CDVA, 72% gained one line or more in the LAG. Meanwhile, 34% showed no change in CDVA, 66% gained one line or more in the HAG (Figure 1C).

Predictability and Stability At 6mo postoperatively, the SE in LAG was 0.07±0.32 D. However, the SE in HAG was 0.11±0.44 D. Figure 1D showed the scatterplot of attempted and achieved SE. The attempted and achieved SE corrections in LAG and HAG were highly correlated in LAG and HAG (r=0.966, 0.960, both P<0.001). Regarding astigmatism, the postoperative refractive astigmatism was -0.24±0.17 D (range -0.50 to 0) and -0.52±0.23 D (range -1.25 to 0) in LAG and HAG, respectively. The postoperative refractive astigmatism in 100% of the eyes in LAG and 74% of the eyes in HAG were within 0.50 D, and 100% and 93% of the eyes in LAG and HAG were within 0.75 D, respectively (Figure 1G). At 6mo postoperatively, SE of 96% and 100% of the eyes in LAG and 81% and 99% of the eyes in HAG were within ±0.5 and ±1.0 D, respectively (Figure 1E). No obvious regression was observed during the 6-month follow-up period (Figure 1F). The AE in 70% and 100% of the eyes in LAG and HAG was within ±15º, respectively (Figure 1I).

Vector Analysis Table 2 summarized the vector analysis results 6mo after SMILE. Figure 1H showed a scatterplot of the TIA and SIA for the LAG and HAG. Figure 1I showed the distribution of the AE for both groups. No significant differences were observed in AE (P=0.091), CI (P=0.066) or FI (P=0.987) between the LAG and HAG. The DV and ME were higher (both P<0.001), whereas IOS was lower (P<0.001) in the HAG than in the LAG.

Table 2 Vector analysis results of refractive astigmatism 6mo after SMILE mean±SD

Parameters	LAG	HAG	*P*
TIA (D)	0.54±0.21	2.49±0.62	<0.001[a]
SIA (D)	0.50±0.28	2.12±0.66	<0.001[a]
DV (D)	0.24±0.17	0.53±0.22	<0.001[a]
ME (D)	-0.04±0.19	-0.37±0.31	<0.001[a]
AE (degree)	-4.03±22.55	-0.55±3.92	0.091
CI	0.91±0.36	0.85±0.13	0.066
FI	0.76±0.49	0.84±0.13	0.987
IOS	0.50±0.46	0.22±0.09	<0.001[a]

SMILE: Small incision lenticule extraction; HAG: High astigmatism group; LAG: Low astigmatism group; TIA: Target induced astigmatism; SIA: Surgically induced astigmatism; DV: Difference vector; ME: Magnitude of error; AE: Angle of error; CI: Correction index; FI: Flattening index; IOS: Index of success; SD: Standard deviation. [a]Significant difference between LAG and HAG.

Higher-Order Aberrations HOAs of the anterior surface, posterior surface, and total cornea for a 6 mm pupil in the LAG and HAG after SMILE were presented in Tables 3, 4, and 5.

As seem in Table 3, on the anterior surface, there was a significant increase in spherical aberration and vertical coma in both groups (all P<0.001). The horizontal coma in the HAG and vertical trefoil in the LAG also increased significantly (both P<0.05). Other HOAs remained unchanged after SMILE. The increments in horizontal coma in the HAG were greater than those in the LAG (P<0.05). However, the increments in the vertical coma were less in the HAG than in the LAG (P<0.05). There was no significant difference in surgically induced spherical aberration (P=0.063), vertical trefoil (P=0.075) or oblique trefoil (P=0.864) between the two groups.

On the posterior surface (Table 4), there was a significant increase in spherical aberration and vertical coma in both groups (all P<0.05), as well as the horizontal coma and vertical trefoil in the HAG (both P<0.05). Other HOAs remained

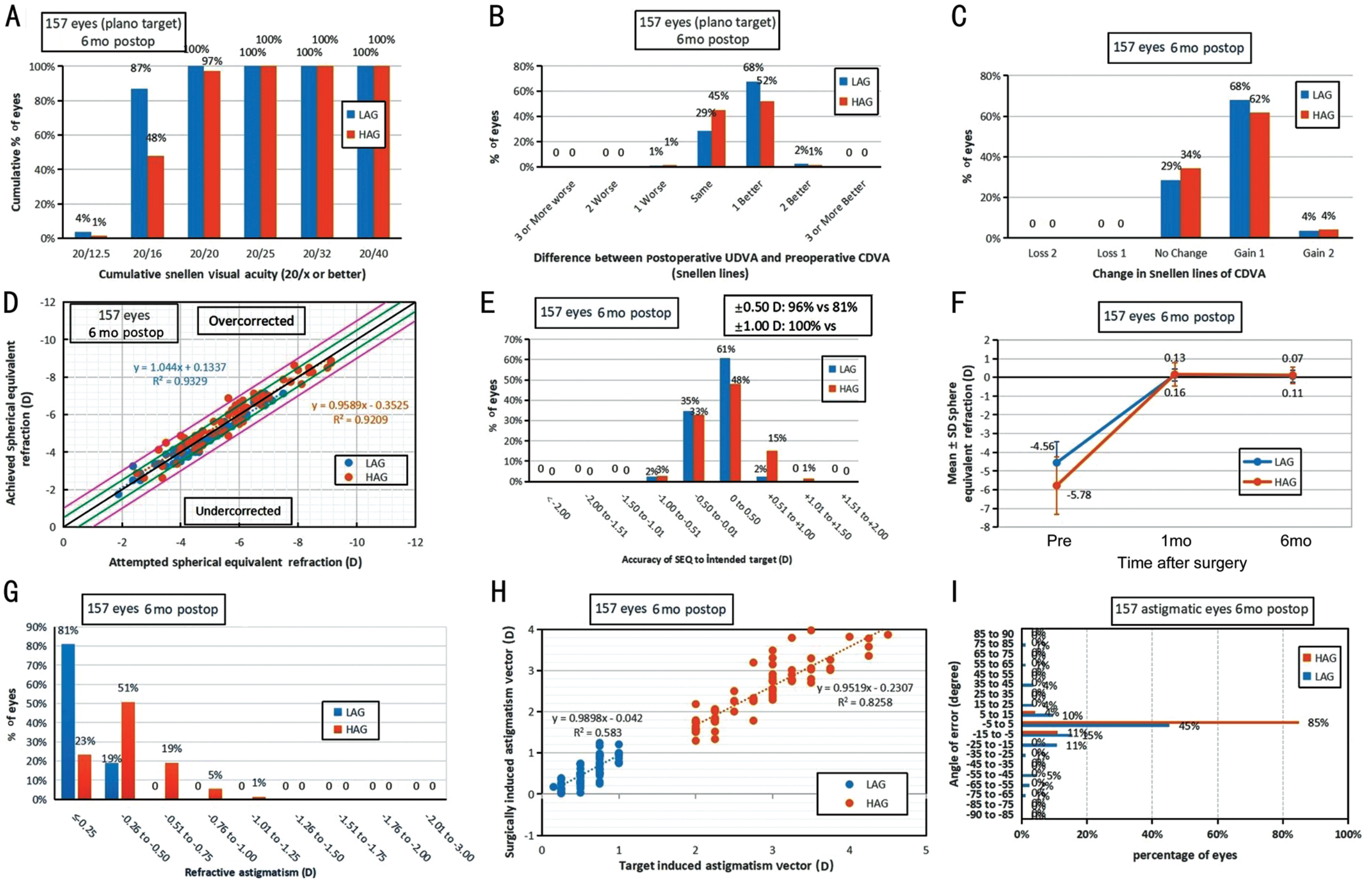

Figure 1 Visual outcomes at 6mo after SMILE for HAG and LAG A: Uncorrected distance visual acuity (UDVA); B: Postoperative UDVA and preoperative corrected distance visual acuity (CDVA); C: Change in CDVA; D: Distribution of achieved spherical equivalent outcomes; E: Spherical equivalent refractive accuracy; F: Stability of spherical equivalent refraction; G: Refractive astigmatism; H: Target induced versus surgically induced astigmatism vectors of keratometric astigmatism; I: Keratometric astigmatism angle of error distribution. HAG: High astigmatism group; LAG: Low astigmatism group; D: Diopters; SMILE: Small incision lenticule extraction.

Table 3 Preoperative, postoperative and increment in cornea higher-order aberrations of anterior surface for a 6 mm pupil diameter in eyes after SMILE

Parameters	HAG				LAG				*P* (HAG *vs* LAG)		
	Preop.	Postop.	Increment in HOA	[1]*P*	Preop.	Postop.	Increment in HOA	[1]*P*	Preop.	Postop.	Increment in HOA
Spherical aberration (μm)	0.21±0.09	0.29±0.16	0.08±0.16	<0.001[a]	0.23±0.08	0.34±0.11	0.11±0.11	<0.001[a]	0.344	0.048[a]	0.063
Vertical coma (μm)	0.03±0.19	-0.13±0.31	-0.16±0.24	<0.001[a]	-0.00±0.18	-0.23±0.24	-0.23±0.21	<0.001[a]	0.259	0.011[a]	0.044[a]
Horizontal coma (μm)	-0.00±0.14	0.08±0.27	0.08±0.18	0.001[a]	-0.03±0.12	-0.03±0.27	0.00±0.21	0.892	0.214	0.020[a]	0.029[a]
Vertical trefoil (μm)	0.01±0.13	0.01±0.18	-0.00±0.19	0.525	-0.01±0.12	0.02±0.14	0.03±0.13	0.027[a]	0.296	0.853	0.075
Oblique trefoil (μm)	-0.01±0.16	-0.03±0.24	-0.01±0.21	0.544	-0.01±0.10	-0.03±0.11	-0.02±0.10	0.217	0.983	0.434	0.864

SMILE: Small incision lenticule extraction; HAG: High astigmatism group; LAG: Low astigmatism group; HOAs: Higher-order aberrations. [a]Significant difference. [1]*P*: Preop. *vs* postop.

unchanged after SMILE. The increments in horizontal coma in the LAG were significantly greater than that in the HAG (P<0.05). There was no significant difference in surgically induced spherical aberration (P=0.061), vertical coma (P=0.104), vertical trefoil (P=0.097) or oblique trefoil (P=0.968) between the two groups.

In the total cornea (Table 5), total HOAs, spherical aberration, and vertical coma increased significantly in both groups (all P<0.05); the horizontal coma in the HAG and vertical trefoil in the LAG also increased significantly (both P<0.05). Other HOAs remained unchanged after SMILE. For a 6 mm pupil, the increment in vertical coma in the HAG were significantly lesser than that in the LAG; however, the increments in total HOAs and horizontal coma in the HAG were significantly greater than those in the LAG (all P<0.05). There was no significant difference in surgically induced spherical aberration (P=0.064), vertical trefoil (P=0.393) or oblique trefoil (P=0.591) between the two groups.

Table 4 Preoperative, postoperative and increment in cornea higher-order aberrations of posterior surface for a 6 mm pupil diameter in eyes after SMILE

Parameters	HAG				LAG				P (HAG *vs* LAG)		
	Preop.	Postop.	Increment in HOA	[1]*P*	Preop.	Postop.	Increment in HOA	[1]*P*	Preop.	Postop.	Increment in HOA
Spherical aberration (μm)	-0.14±0.04	-0.16±0.05	-0.01±0.04	<0.001[a]	-0.15±0.03	-0.16±0.03	-0.01±0.02	0.001[a]	0.677	0.154	0.061
Vertical coma (μm)	-0.00±0.04	0.00±0.06	0.01±0.04	0.009[a]	-0.01±0.04	0.00±0.04	0.01±0.03	<0.001[a]	0.208	0.683	0.104
Horizontal coma (μm)	0.01±0.03	0.00±0.03	-0.01±0.03	0.031[a]	0.01±0.03	0.02±0.03	0.00±0.03	0.079	0.965	0.028[a]	0.003[a]
Vertical trefoil (μm)	0.01±0.06	0.03±0.07	0.01±0.06	0.015[a]	0.03±0.05	0.02±0.06	-0.00±0.06	0.855	0.098	0.604	0.097
Oblique trefoil (μm)	-0.04±0.06	-0.04±0.08	0.00±0.08	0.556	-0.02±0.06	-0.02±0.07	0.00±0.08	0.553	0.028[a]	0.069	0.968

SMILE: Small incision lenticule extraction; HAG: High astigmatism group; LAG: Low astigmatism group; HOAs: Higher-order aberrations. [a]Significant difference. [1]*P*: Preop. *vs* postop.

Table 5 Preoperative, postoperative and increment in cornea higher-order aberrations of total cornea for a 6 mm pupil diameter in eyes after SMILE

Parameters	HAG				LAG				P (HAG *vs* LAG)		
	Preop.	Postop.	Increment in HOA	[1]*P*	Preop.	Postop.	Increment in HOA	[1]*P*	Preop.	Postop.	Increment in HOA
Total HOAs (μm)	0.47±0.13	0.82±0.25	0.35±0.22	<0.001[a]	0.42±0.09	0.68±0.21	0.26±0.24	<0.001[a]	0.030[a]	<0.001[a]	0.009[a]
Spherical aberration (μm)	0.17±0.10	0.22±0.18	0.06±0.17	0.005[a]	0.19±0.09	0.27±0.12	0.09±0.12	<0.001[a]	0.298	0.101	0.064
Vertical coma (μm)	0.04±0.20	-0.16±0.35	-0.18±0.27	<0.001[a]	-0.02±0.19	-0.26±0.26	-0.25±0.22	<0.001[a]	0.117	0.008[a]	0.045[a]
Horizontal coma (μm)	0.01±0.16	0.09±0.29	0.08±0.19	0.001[a]	-0.02±0.13	-0.07±0.27	-0.05±0.20	0.084	0.162	0.001[a]	<0.001[a]
Vertical trefoil (μm)	0.02±0.15	0.04±0.22	0.02±0.23	0.610	0.01±0.13	0.03±0.13	0.02±0.13	0.037[a]	0.556	0.887	0.393
Oblique trefoil (μm)	-0.05±0.18	-0.05±0.22	0.00±0.19	0.913	-0.03±0.13	-0.05±0.14	-0.02±0.13	0.404	0.275	0.979	0.591

SMILE: Small incision lenticule extraction; HAG: High astigmatism group; LAG: Low astigmatism group; HOAs: Higher-order aberrations. [a]Significant difference. [1]*P*: Preop. *vs* postop.

Correlation Between Surgically Induced HOAs and Preoperative Astigmatism and SE In both groups, a statistically significant correlation was observed between the total HOAs of the total cornea and the preoperative astigmatism and SE (both $P<0.001$; Table 6).

There was a notable correlation between the preoperative astigmatism and the surgically induced spherical aberration in the corneal anterior surface, posterior surface, as well as the total cornea (all $P<0.05$). Furthermore, a significant correlation was also found between the preoperative astigmatism and the induced horizontal coma in both the corneal anterior surface and the total cornea ($P<0.05$).

There was a significant correlation between the preoperative SE and the surgically induced spherical aberration in the corneal anterior surface, posterior surface, as well as the total cornea (all $P<0.05$). Furthermore, a significant correlation was also found between the preoperative SE and the surgically induced horizontal coma in both the corneal anterior surface and the total cornea ($P<0.05$).

Table 6 Correlation between surgically induced HOAs and preoperative astigmatism

Surgically induced HOAs	Astigmatism		SE	
	r	*P*	*r*	*P*
Anterior cornea				
Spherical aberration	0.183	0.022[a]	-0.265	0.001[a]
Vertical coma	-0.141	0.079	0.108	0.177
Horizontal coma	-0.187	0.019[a]	-0.173	0.030[a]
Posterior coenea				
Spherical aberration	0.172	0.031[a]	0.164	0.040[a]
Vertical coma	0.054	0.504	0.057	0.477
Horizontal coma	0.148	0.063	0.105	0.192
Total cornea				
Total HOAs	-0.228	<0.001[a]	-0.316	<0.001[a]
Spherical aberration	0.175	0.028[a]	-0.311	<0.001[a]
Vertical coma	-0.135	0.092	0.124	0.122
Horizontal coma	-0.306	<0.001[a]	-0.286	<0.001[a]

HOAs: Higher-order aberrations; SE: Sphere equivalent. [a]Significant difference.

DISCUSSION

This study demonstrated that SMILE was safe, effective, predictable, and stable for correcting high astigmatism. The induced total HOAs and horizontal coma increase with the increase of preoperative astigmatism in SMILE surgery. The induced HOAs mainly originate from the anterior surface of the cornea rather than the posterior surface.

During long-term follow-up for myopia and myopic astigmatism correction, SMILE produced satisfactory refractive outcomes in terms of efficacy, safety, predictability, and stability[1-7]. With the increasing popularity of this surgery, there is an increasing need for improved visual quality and precision. Studies have shown that uncorrected astigmatism has an obvious effect on the visual quality and the quality of life[16]. HOAs play an important role in the evaluation of visual quality[9-10]. In previous studies, changes in HOAs after SMILE were noted mainly on the anterior surface and the total cornea; therefore, the changes in HOAs of the posterior surface of the cornea also deserve special attention. To the best of our knowledge, few studies have compared the visual quality of SMILE in correcting high and low astigmatism using vector analysis and HOAs in posterior cornea.

In this study, 97% of the eyes in the HAG achieved a UDVA of 20/20 after SMILE. No vision-threatening complications were observed during surgery or 6mo postoperatively. No eyes lost one line or more, 34% showed no change in CDVA, 66% gained one line or more in the HAG. Hou *et al*[17] showed 87.27% eyes with 20/20 or better UDVA in 55 eyes of high myopic astigmatism (<-2.00 D) at 3mo after SMILE surgery. The discrepancy of UDVA results may due to the different study subjects. The mean preoperative SE of their study was -6.48 D, while in this study, the mean preoperative SE was -5.78 D，and our follow-up time was longer. Considering predictability and stability, SE of 87.27% and cylinder of 89.09% of eyes were within ±0.50 D in the study by Hou *et al*[17], SE of 87.4% and cylinder of 88% of eyes were within ±0.50 D in the study by Taneri *et al*[5], and these values were 81% and 74% in our study. No obvious regression was observed during the 6-month follow-up period. The angle of error in all of the eyes in the HAG of our study was within ±15º. But in Taneri *et al*'s[5] results, angle error in 94% of the eyes was within ±15º. Considering of difference in the degree of astigmatism, the mean preoperative cylinder in Taneri *et al*'s[5] was about -1.52 D, in our study, the cylinder in HAG was about -2.85 D. Moreover, our 6-month follow-up time was longer. For astigmatism correction according to previous studies, there is a tendency for under-correction of astigmatism after SMILE[18-20]. In the present study, the magnitude of error during the 6-month follow-up after SMILE was -0.37±0.31 D in the HAG, which indicated that for myopic astigmatism greater than -2.00 D, there is a -0.37 D under-correction after SMILE surgery. This was in accordance with the studies of Taneri *et al*[5], Jabbarvand *et al*[21], and Moshirfar *et al*[22], in which the postoperative under-correction of astigmatism was -0.38, -0.33 and -0.31 D with high astigmatism. Igras *et al*[23] observed that, for high astigmatism (>1.5 D), with the rule astigmatism was more prone to under-correction. Similar findings were observed in this study, the 6-month postoperative magnitude error of HAG was -0.37 D, while for LAG, the value was -0.04 D. Similarly, Yan *et al*[24], Ivarsen *et al*[25], Allen *et al*[26] and Dishler *et al*[1] also found a cylinder under-correction in various myopic surgeries. Correction of index in the HAG after SMILE was 0.85, which was similar to the results (0.83) 12mo postoperatively of Moshirfar *et al*[22]. Mean angle of error in the HAG was -0.55°, Moshirfar *et al*[22] showed -2.99° of angel error after SMILE with a preoperative astigmatism of over -2.00 D. We found that the achieved and attempted SE were highly correlated in both groups, and results of regression equation showed that the goodness of fit in LAG (R^2=0.9329) was slightly better than that in HAG (R^2=0.9209). The treatment accuracy did not seem poorer in the HAG. Contrarily, in terms of postoperative astigmatism, 54 eyes (74%) were within -0.50 D, and 72 eyes (99%) were within -1.00 D in HAG, whereas 84 eyes (100%) were within -0.50 D in the LAG. The distribution of postoperative astigmatism was more satisfactory in the LAG. The results from Taneri *et al*[5] were more satisfactory with postoperative astigmatism in 83.1% of the eyes were within -0.50 D on the basis that the preoperative decimal CDVA of the patients selected was 1.0 or better, and the range of astigmatism was from -1.50 to -3.00 D. The differences were due to the fact that preoperative corrected distance visual acuity (CDVA) of some of the patients we enrolled in HAG could not reach 1.0, and there was a clear trend toward suboptimal preoperative CDVA and postoperative UDVA in patients with long-term under-correction of myopia and myopic astigmatism in their glasses.

HOAs play a crucial role in visual quality. Similar to previous studies[7,27-28], total HOAs, spherical aberrations, coma of the total cornea significantly increased in SMILE surgery. In our study, a significant increase was found in the total HOAs and spherical aberration in the anterior surface, posterior surface, and total cornea after SMILE in the 6-month follow-up period. Our results are similar to the results of Wu and Wang[11] and Jin *et al*[14]. In their studies, anterior and total corneal HOAs, especially coma and spherical aberration, significantly increased, which were consistent with our study. The increments were 0.08, -0.01, and 0.06 μm in spherical aberration, -0.16, 0.01, and -0.18 μm in vertical coma, 0.08, -0.01, and 0.08 μm in horizontal coma of the anterior surface, posterior surface and total corneal. From these results, it can be concluded that the increase in sphere aberration and coma of the anterior corneal surface mainly contributed to the increase in total corneal HOAs. These results may be due to the ablation being performed on the anterior surface of the cornea. However, most posterior HOAs remained unchanged three months after SMILE in their results. The 6-month postoperative spherical aberration, vertical coma, horizontal coma, vertical trefoil in our study was about -0.16, <0.01, <0.01, and 0.03 μm, corresponding values in Jin *et al*'s[14] study were -0.16, -0.01, <0.01, and -0.04 μm，the results are almost exactly the same. For high astigmatism in our results, coma, spherical aberration and vertical trefoil increased significantly, but from a practical numerical perspective, the increase in HOAs on the posterior surface was slight, only negligible changes may occur in the posterior corneal HOAs 6mo after

SMILE surgery. Zhong *et al*[29] reported no difference in the increments in HOA, spherical aberration, or coma between the HAG and LAG in a 4-year study. The reasons for this difference may be our larger sample size and the degree of corneal wound healing response owing to the shorter follow-up period.

Our study not only discovered that the coma and spherical aberration of the anterior and total cornea, increased significantly after SMILE but also found that the increments in these HOAs were significantly correlated with the preoperative astigmatism. To our knowledge, this is the first research that reported the correlation between induced HOAs and astigmatism. From the results of Chen *et al*[30], the greater the degree of ablation, the greater the refractive difference between the unablated and ablated areas, which also causes HOA induction; Wu and Wang[11] analyzed the HOAs after SMILE and found that the changes of anterior and total corneal coma are significantly correlated with SE, Jin *et al*[14] analyzed the HOAs in high myopia and mild to moderate myopia and found that changes in anterior surface and total corneal HOAs, especially vertical coma and spherical aberrations, are related to the SE, which were partly in acordance with our study. In our study, induced total HOAs, spherical aberration and horizontal coma in total cornea positively correlated with the severity of myopia after SMILE. The changes mainly derived from the anterior surface of cornea. Regarding the impact of preoperative astigmatism on HOAs, we found that induced total HOAs and horizontal coma in total cornea positively correlated with the severity of astigmatism after SMILE. This change also mainly originates from the anterior surface of the cornea. Du *et al*[27] analyzed the association of myopia and astigmatism with postoperative ocular high order aberration after SMILE, and found that HOA positively correlated with the severity of myopia and astigmatism after SMILE, but the increase in HOA was not linearly correlated with the increase in myopia.

This study has several limitations. First, its retrospective and non-randomized design may introduce selection bias, despite our efforts to adjust for confounders. Second, the sample size, though statistically adequate, was limited to a single center, which may affect generalizability. Future prospective randomized trials with larger cohorts are warranted to validate our findings. Finally, since the degree of astigmatism affects the increase in HOA caused by SMILE, different astigmatism axis that would affect postoperative visual quality were not explored.

In conclusion, SMILE surgery induces more HOAs and a mild under-correction of astigmatism in eyes with high astigmatism. The increment in HOAs after SMILE is related to preoperative astigmatism.

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