scientific reports

Check for updates

OPEN

Peripheral refraction and aberrations in myopic eyes after small-incision lenticule extraction (SMILE) surgery

Lin Zhang[1,2], Yan Wang[1,2,3,4]✉, Xinheng Zhao[1,2] & Tong Cui[5]

To investigate peripheral refraction and aberrations in myopic eyes after small-incision lenticule extraction (SMILE) surgery and to understand the relationship between visual symptoms and wide-field wavefront aberrations. A total of 28 patients with myopia and myopic astigmatism underwent SMILE surgery. Peripheral refraction and aberrations were measured both before and six months after surgery using a modified wide-field Shack–Hartmann wavefront (SHWS) sensor-based aberrometer. The peripheral refraction and aberrations from the axis (0°) to (15°) in both the horizontal and vertical directions were measured. A visual questionnaire was administered to assess visual quality before and six months after surgery. Post-surgery, peripheral relative refraction exhibited reduced hyperopia. The spherical aberration Z_4^0 changed from 0.12 ± 0.11 µm before surgery to 0.24 ± 0.14 µm (t = 20.047, P = 0.000) after surgery on the optical axis(0°). Post-surgery, the spatial pattern of spherical aberration remained constant. Greater variability of peripheral aberrations was observed in the direction of the horizontal retina than in the vertical axis after surgery. Horizontal coma significantly increased after surgery and appeared to be more variable in the direction of the surperior region. Z_3^{-1} shifted from -0.03 ± 0.16 µm preoperatively to -0.12 ± 0.18 µm postoperatively (t = 0.580, P = 0.573), Z_3^1 changed from 0.03 ± 0.22µm preoperatively to 0.37 ± 0.35 µm postoperatively (t = −3.780, P = 0.003) on the central axis. The majority of patients were satisfied with the postoperative daytime vision; there was no significant deterioration in nighttime visual symptoms compared to preoperative levels. Our study demonstrated that SMILE significantly reduced peripheral refraction in myopic eyes, however with increased asymmetry along the vertical axis. Notably, the relationship between nighttime visual symptoms and large-field aberrations was not found to be significant.

Keywords Small-incision lenticule extraction (SMILE), Myopia, Peripheral refraction, Aberrations, Refractive surgery

The investigations on visual quality have focused significantly on refractive surgeries and their clinical outcomes. However, there is still a lack of understanding regarding the mechanism by which wide-field optical quality affects the entire retinal image. High-quality peripheral retinal images are essential for many everyday activities, including driving, mobility, and search tasks[1,2]. Furthermore, night vision complications following refractive surgery, such as glare and halo, tend to manifest predominantly in a relatively dark mesopic vision state, where the pupil dilates, and peripheral optical quality may have more significant implications[3,4]. The rise in high-order aberrations caused by corneal refractive surgery, especially the increase in spherical aberrations, has been regarded as having a causal impact, although some mechanisms remain unclear. Previous studies on postoperative aberrations primarily focused on the central axial region, with limited attention given to off-axis optical quality.

As peripheral optical quality plays a crucial role in myopic control, an increasing number of physicists have shifted their focus to studying the effects of optical correction on peripheral vision. Consequently, methods have been developed to measure peripheral optical quality accurately[5]. The Shack–Hartmann wavefront sensor

[1]Tianjin Eye Hospital, Tianjin, China. [2]Tianjin Key Lab of Ophthalmology and Visual Science, Tianjin, China. [3]Nankai University Eye Institute, Nankai University, Tianjin, China. [4]Clinical College of Ophthalmology, Tianjin Medical University, Tianjin, China. [5]Shanxi Eye Hospital, Taiyuan 030002, Shanxi Province, China. ✉email: wangyan7143@vip.sina.com

(SHWS) has been widely used to measure the axial wavefront aberrations of human eyes objectively. More recently, it has been adapted for measuring off-axis aberrations[6,7].

In this study, we designed an optical measurement system for measuring peripheral retinal aberrations based on the SHWS. The objective measurement of the aberration in the off-axis field was based on the eyeball rotation of the subjects. To assess the influence of refractive surgery on wide-field aberrations, we measured and evaluated wide-field aberrations using the above design to further explore imagery in the peripheral fields of eyes that underwent small-incision lenticule extraction (SMILE). Notably, SMILE is considered a less invasive laser eye surgery with improved visual quality.

In myopic eyes, the peripheral refraction is often less hyperopic compared to the central refraction[8]. This suggests that the peripheral retina is more flattened than the central retina. Consequently, this difference can result in a decrease in visual acuity and alterations in the shape of the retinal image[9]. Following SMILE surgery, there may be changes in peripheral refraction due to the manipulation of the corneal tissue[10]. Additionally, aberrations in myopic eyes may also change after surgery due to altered corneal structures. These changes in peripheral refraction and aberrations have the potential to impact vision quality and visual performance after surgery.

It is important to note that the changes in peripheral refraction and aberrations after SMILE surgery may vary based on factors such as the preoperative refractive state, surgical technique, and individual patient factors. Therefore, it is essential to closely evaluate and monitor these changes postoperatively to ensure optimal visual outcomes for patients.

Our study aims to investigate peripheral refractions and aberrations after SMILE surgery and to understand the relationship between visual symptoms and wide-field wavefront aberrations.

Methods

Instrument design

Figure 1 illustrates a schematic of the apparatus used in the study. A commercial Shack–Hartmann wavefront (SHWS) sensor-based aberrometer (WaveScan WaveFront System, AMO Wavefront Sciences, Albuquerque, NM, USA) was modified to measure monochromatic aberrations both on and off axes. To achieve this, a beam splitter was installed between the aberrometer and the human eye to reflect the light from the light-emitting diode (LED) targets on the wall. Virtual images of the LED targets served as fixation points in different visual fields. When the eye fixates on a target in a specific visual field, such as 15°, light from the aberrometer illuminates the peripheral retinal area. Consequently, the aberrations obtained from the aberrometer correspond to off-axis wavefront aberrations. Each line-of-sight (LoS) was measured an average of three times. Collecting a series of measurements along multiple LoS to access a wide visual field is essential. However, the image quality may not be optimal due to the influence of peripheral curvature and increased astigmatism. Unlike in axial aberrometry, the Purkinje reflection point should be clearly visible. Autofocus is typically suboptimal and may require manual adjustment.

Calibration

We set the distance between the external target and SHWS to 2 m, that is, m = 2, and used the following formula: Fig. 2

$$\alpha = \operatorname{atan}(\mathrm{d}/\mathrm{m})$$

The spacings, d, at 5°, 10°, and 15° were 0.175 m, 0.3526 m, and 0.5358 m, respectively.

A photometric illuminometer (PR-650) was used to measure the environmental illumination. With each LoS measurement on the eye, four independent direction measurements were performed under low illumination (~2.0 lx).

When measuring peripheral aberrations, the pupil becomes elliptical. Despite this geometrical significance, a previous study found no significant difference in the measured ocular aberrations between the elliptical pupil and raw data for eccentricities below 20°[11]. Therefore, following the findings of previous research, we selected a wavefront with a pupil diameter of 5 mm for all measurements.

Clinical data

A total of 28 patients with myopia and myopic astigmatism, aged 20–40 years old, with an average of (24.37 ± 4.83) years, were considered candidates for corneal refractive surgery at Tianjin Eye Hospital.

Inclusion criteria: aged between 18 and 45 years; myopic spherical scope ≤ −10.00 D, astigmatism ≤ −0.50 D, the best corrected visual acuity ≥ 20/30; stable refraction for at least 2 years (± 0.50 D); residual corneal stroma bed thickness after surgery ≥ 280 µm; no abnormality in preoperative or postoperative corneal topography; no severe dry eyes detected on the tear function test; smooth corneal epithelium, transparent cornea without macular corneal; no eye active disease, glaucoma, cataract, or fundus lesions; no history of eye trauma; discontinuation of soft contact lens wear for more than 2 weeks, hard contact lens for more than 1 month, and orthokeratology lens wear for more than 3 months prior to surgery.

The exclusion criteria were as follows: age < 18 years; corneal scar and irregular astigmatism, amblyopia; keratoconus, or asymmetrical keratoconus with suspicious topography; rough corneal epithelium; severe dry eye disease; pupil diameter > 7 mm in a dark environment; active ocular inflammation or any ocular disease; history of previous eye surgery and trauma; uncontrolled systemic connective tissue diseases and severe autoimmune diseases; uncontrolled diabetes; high or abnormal psychological expectations; and presence of mental illness.

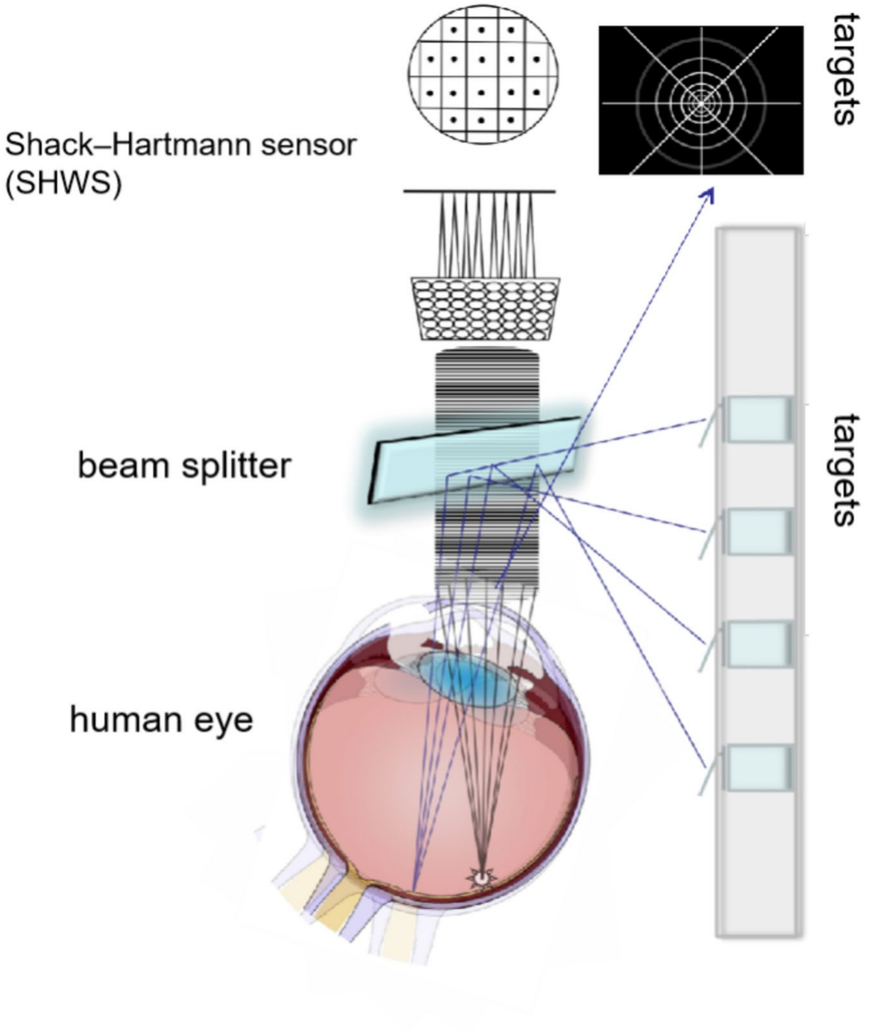

Fig. 1. A modified Shack–Hartmann wavefront (SHWS) sensor-based aberrometer was used to measure monochromatic aberrations on-axis and off-axis. A beam splitter was installed between the aberrometer and the human eye, reflecting the light from LED targets on the wall. Virtual images of the LED targets served as fixation points in different visual fields. Measurement process of the off-axis aberration is based on the eye rotation of the subjects. Measurement is conducted at an interval of 5° from the temporal field (nasal retina) to the nasal field (temporal retina) and from the superior (inferior retina) to the inferior field (superior retina). When the eye is fixating on a target at a specific visual field, such as 15°, the light from the aberrometer illuminates the peripheral retinal area.

Ophthalmic examination

Each patient underwent a comprehensive ophthalmic examination, which included the measurement of uncorrected visual acuity, best-corrected visual acuity, determination of the dominant eye, manifest refraction, intraocular pressure examination, slit-lamp examination, and corneal topography examination (Pentacam, Oculus, Germany). Pre- and post-surgical wide-field aberrations were evaluated using the aforementioned wide-field wavefront sensor. To ensure that the pupil size was sufficient for off-axis measurements, 5 g/L tropicamide eye drops were administered to dilate the pupil.

SMILE procedure

Surgeon YW performed SMILE surgery using the VisuMax system from Carl Zeiss Meditec AG. The parameters were carefully established as follows: energy level of 130 nanojoules (nJ), lenticule diameter of 6.5 mm with a transition zone of 0.1 mm, cap thickness of 120 μm, incision length of 3 mm, and an incision position at 12 o'clock. Additionally, a basement of 10 μm was added above the lenticule.

Visual quality questionnaire

The questionnaire used in this study was adapted from a multicenter visual quality assessment of patients undergoing refractive surgery in the United States[12].

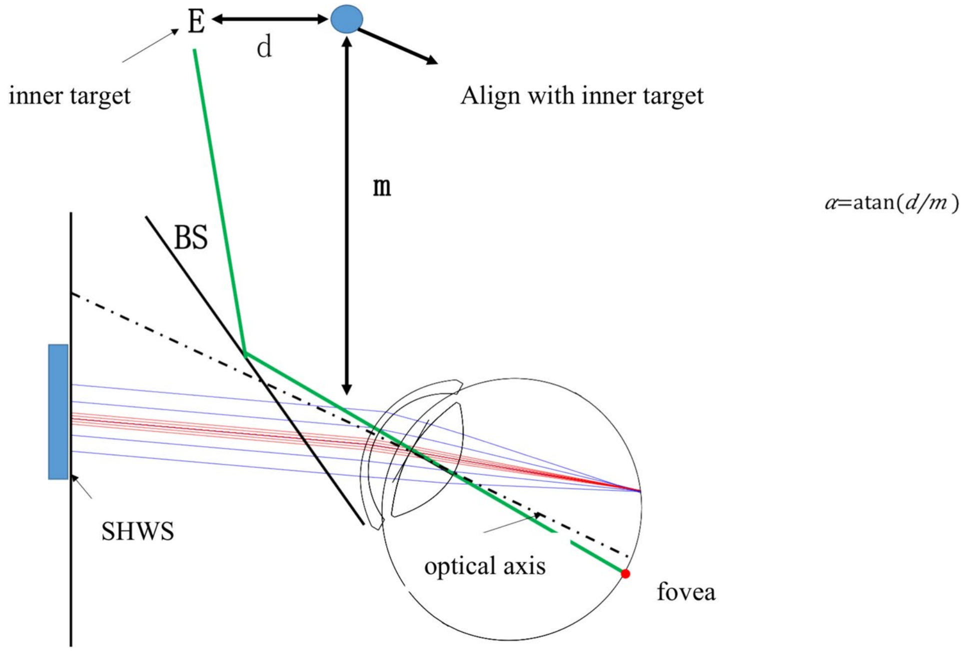

Fig. 2. Schematic diagram of the peripheral aberration measurement. Shack Hartmann wavefront sensor (SHWS); BS (beam splitter).

The preoperative baseline evaluation queried patients regarding their visual satisfaction and symptoms. At postoperative follow-up appointments, the patients were asked additional questions about their visual performance.

Vision satisfaction was assessed on a scale of 0–4, where a score of 5 indicated "very satisfied" and a score of one indicated "very dissatisfied." Patients also rated the frequency of various visual symptoms before surgery and after surgery. Frequency ratings ranged from 0–4, with a score of 5 indicating "never had symptoms" and a score of 1 indicating "always experiencing symptoms."

Data and statistical analysis

Statistical analyses were conducted using Statistical Package for the Social Sciences (SPSS) software (version 22; IBM Corporation). The Shapiro–Wilk test was used to assess normal distribution. Continuous variables with a normal distribution were expressed as mean ± standard deviation. Paired t-tests were performed to compare the changes in the LoSs before and after surgery. Pearson's linear correlation analysis was conducted to analyze the correlation between wide-field aberration characteristics, equivalent spherical values, ablation depth, and subjective visual symptoms. For all analyses, a P value of less than 0.05 was considered statistically significant.

Results

Distribution of relative peripheral refraction (RPR) after surgery

Twenty-eight left eyes from 28 patients with myopia and myopic astigmatism, aged from 20 to 40 years, with an average age of 24.37 ± 4.83 years, were included in this study. The spherical equivalent refraction (SEQ) was −5.08 ± 1.38 diopter. All the refraction and aberration data collected both before and after surgery adhere to a normal distribution pattern.

Refraction components across the visual field were displayed before and after surgery in (Fig. 3). Prior to surgery, myopic subjects presented with almost symmetrically distributed relative hyperopia in the horizontal direction (+ 0.10 D to + 0.20 D at 10 to 15°) between the temporal and nasal retina and almost flat refraction across the central 10°. The distribution trends and characteristics remained largely unchanged after surgery. (t = −2.081, P = 0.083).

In the vertical direction, the peripheral refraction pattern became more asymmetrically distributed, with more relative hyperopia in the superior retina (approximately + 0.10 D to + 0.35 D) in the superior 10° to 15° than in the inferior retina, and there was a clear difference in vertical meridians in the 15° superior retina (t = 0.338, P = 0.036) compared to the preoperative and postoperative relative peripheral refraction.

Distribution of high-order aberrations over wide field retina after surgery

Spherical aberration

The spherical aberration Z_4^0 increased from 0.12 ± 0.11 μm before surgery to 0.24 ± 0.14μm after surgery on the axis. The Zernike coefficients of Z_4^0 increased significantly after surgery across the entire retina (t = 20.047, P = 0.000). However, the trend in the different directions of Z_4^0 was in accordance with the preoperative trend.

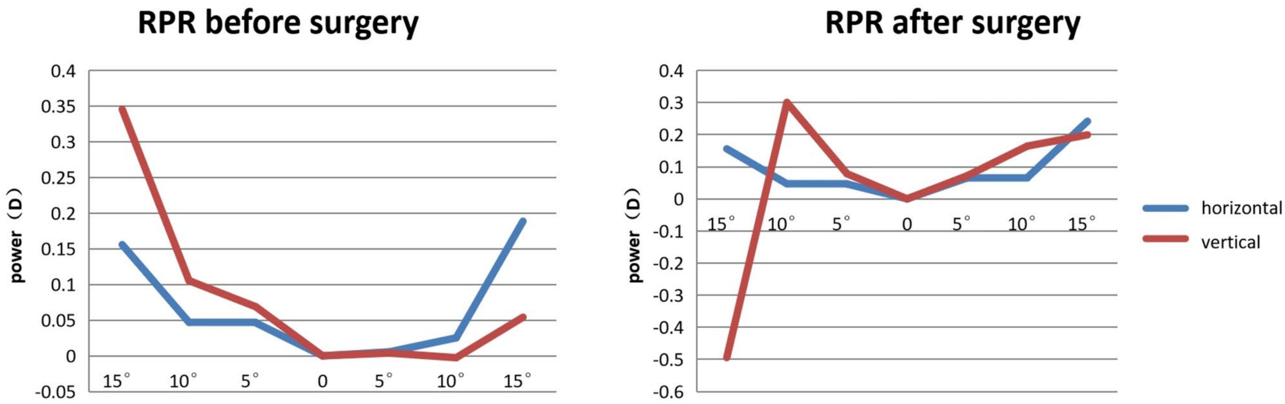

Fig. 3. Refraction components across the visual field were displayed before and after surgery. RPR, relative peripheral refraction.

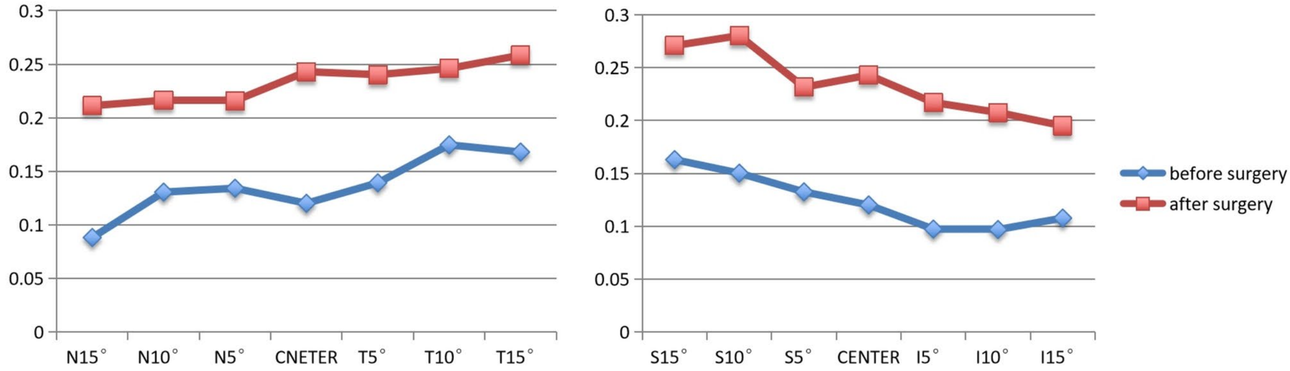

Fig. 4. Comparison of spherical aberration (Z_4^0) before and after surgery, vertical (left) and horizontal (right) direction. *N* nasal, *T* temporal, *S* superior, *I* inferior.

The spatial variation in spherical aberration remained constant and independent of the LoS, both before and after surgery. Figure 4

Coma

The vertical coma Z_3^{-1} shifted from -0.03 ± 0.16 µm preoperatively to −0.12 ± 0.18 µm postoperatively on the visual axis (t = 0.580, P = 0.573). Horizontal coma Z_3^1 changed from 0.03 ± 0.22µm preoperatively to 0.37 ± 0.35 µm postoperatively on the central axis (t = −3.780, P = 0.003). There seemed to be greater variability in the direction of the horizontal retina compared to the vertical axis. Figure 5

To compare the data before and after surgery, a linear fit was conducted over a 30° field, and the slope of the fit was calculated. A positive slope coefficient indicated a positive measurement in the nasal and superior fields and a negative measurement in the temporal and inferior visual fields for the horizontal and vertical meridians, respectively. Figure 6

Assessment of Visual Symptoms Following SurgeryAll the subjects completed the visual questionnaire before and 6 months after surgery. The questionnaire employed a scale ranging from 0 to 45 (very poor, poor, fair, good, and very good). The content of the questionnaires involved the assessment of vision and visual symptoms, such as glares, halos, ghosting, and difficulty driving at night (Table 1).

Before surgery, 25% (7/28) of the patients complained of poor night vision. Additionally, 14.3% (4/28 cases) experienced mid-glare symptoms, while 28.6% (8/28 cases) reported mostly mild halo symptoms. Furthermore, 7.1% (2/28 cases) experienced moderate ghosting, and none of the patients complained of difficulty driving at night.

Six months post-surgery, the majority of patients were satisfied with their postoperative daytime vision. However, 35.7% (10/28 cases) still reported poor night vision, 14.3% (4/28 cases) had symptoms of mild glare, 14.3% (4/28 cases) had symptoms of halo, only one patient complained of severe halo, and no patient complained of ghosting or difficulty in driving at night.

Discussion

Refractive surgery is sought after for its promise of improved visual quality. Despite guaranteed safety and effectiveness, there remain challenges to overcome in achieving the best visual quality. SMILE has emerged as

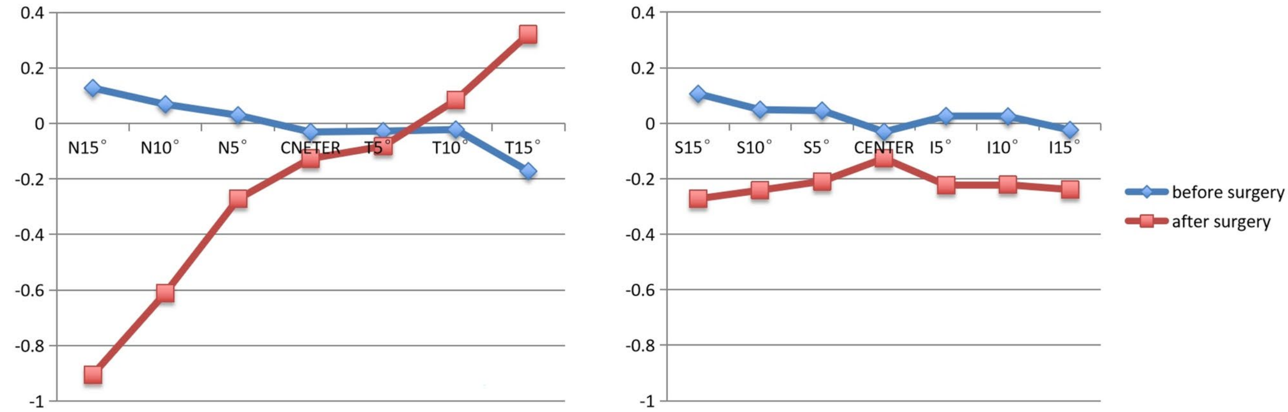

Fig. 5. Comparison of coma (Z_3^{-1}) before and after surgery, vertical (left) and horizontal (right) direction. *N* nasal, *T* temporal, *S* superior, *I* inferior.

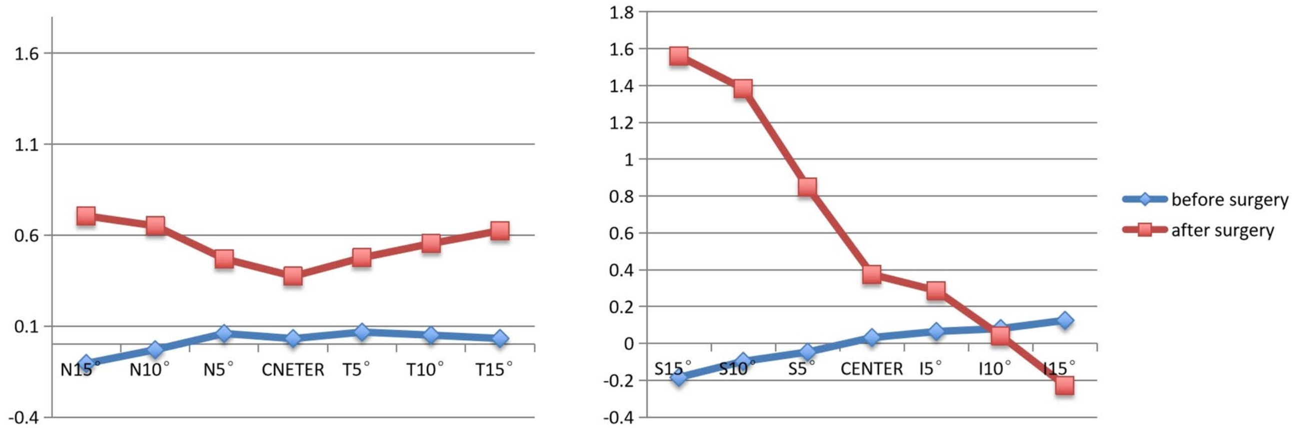

Fig. 6. Comparison of coma (Z_3^{1}) before and after surgery, vertical (left) and horizontal (right) direction. *N* nasal, *T* temporal, *S* superior, *I* inferior.

	Photopic vision	Mesopic vision	Scotopic vision	Driving vision at night	Glare	Halo	Ghost	Driving difficulties at night
Before surgery	0.467	1.400	0.9333	0.5333	0.267	0.6000	0.2	0
After surgery	0.727	1.409	1.454	1.091	0.273	0.364	0	0.045
t	−0.938	−0.035	−1.618	−1.701	−0.035	−0.840	1.685	−0.822
P	0.355	0.972	0.115	0.098	0.972	0.406	0.101	0.417

Table 1. Comparison of subjective visual quality questionnaire results before and after surgery.

the new trend in corneal refractive surgery. Shah et al. found that higher-order aberrations, such as coma and spherical aberrations, increased approximately 6 months after SMILE surgeries[13]. However, Kamiya found that the increase in high-order aberrations, particularly spherical aberrations, was lower compared to FS-LASIK surgery, suggesting that SMILE still had the advantage of better postoperative visual quality[14].

Our study revealed that 35.7% (10/28 cases) of patients reported subjective changes in vision perception in mesopic vision and glare 6 months after SMILE surgery. This underscores the importance of measuring and assessing the optical quality of the entire eye in a broader field after refractive surgery.

Tuan et al. showed that residual refractive error is a major predictor of patient satisfaction after surgery, challenging the traditional understanding of the effect of mesopic pupil diameter on patient satisfaction[15]. However, further research is necessary to fully understand the impact of residual refractive errors on postoperative patient satisfaction. It is important to note that the traditional understanding of the effect of the mesopic pupil diameter may not be as significant as previously believed. Therefore, it is necessary to reevaluate the factors that affect patient satisfaction and explore new ways to improve the outcomes of refractive surgery. Finally, it is important to note that patient satisfaction is a complex metric influenced by many factors beyond residual refractive error and mesopic pupil diameter. Surgical technique, surgeon expertise, pre-and postoperative counseling, and patient expectations, as well as satisfaction with the overall surgical experience, all play vital roles in evaluating the outcomes of refractive surgery.

Queirós et al. conducted a study measuring axial and off-axis refractions after LASIK surgery, revealing changes in peripheral refraction post-surgery[16]. Unlike orthokeratology, which decreases relative peripheral hyperopia, LASIK reduces myopia across the horizontal meridians of the visual field[17]. Previous studies have shown that when orthokeratology lenses correct myopia, peripheral refraction changes from relative hyperopia (+0.90 ± 0.14 D) to relative myopia (−1.84 ± 0.61 D)[18]. Du Y[19] observed the variations in retinal refraction difference values (RDV) and aberrations following SMILE, and discovered a reduction in retinal peripheral hyperopic defocus. Our study found that corneal refractive surgery had minimal effect on the overall peripheral refraction profile. However, significant refractive changes were observed in the superior region, likely due to the incisions made during the SMILE surgery and subsequent wound healing. These changes in refraction in the superior region may impact the visual field and the visual experience after surgery. Therefore, it is crucial to consider the impact of corneal refractive surgery on peripheral refractive profiles, particularly in the superior region. Additionally, regular follow-up examinations are necessary for patients who have undergone corneal refractive surgery to ensure the safety and effectiveness of the surgery.

There have been several studies investigating wide-field order aberrations after refractive surgery, with most focusing on calculations on simulated eyes. Montés-Micó analyzed the possible effects of photorefractive keratectomy (PRK) in the peripheral visual field[20]. However, unlike emmetropia, the peripheral optical quality is significantly different, with major effects typically occurring beyond 40°. In this study, we used objective measurement data in vivo to validate this conclusion. Although the refraction at the fovea of postoperative SMILE eyes may be comparable to that of an emmetropic eye, the refractive components and aberrations generally exhibited quadratic changes along the vertical meridian in the postoperative SMILE eyes. For 5 mm pupils, horizontal and vertical comas were the dominant higher-order aberrations after SMILE across the visual field. The spherical aberration became more positive in the overall field compared to preoperative results. This has been corroborated by other research groups indicating that changes in refractive components and higher-order aberrations after surgery are not only limited to the central visual field but also extend to the peripheral visual field[21]. Therefore, it is imperative to evaluate the entire visual field after surgery to obtain a more accurate understanding of changes in ocular optical quality.

Furthermore, while postoperative refraction is often used as a measure of surgical success, our study demonstrated that changes in refraction alone may not fully reflect changes in higher-order aberrations after surgery. Therefore, it is necessary to consider both refraction and higher-order aberrations when evaluating surgical outcomes. We employed high-order aberrometry to measure and analyze the distribution of high-order aberrations across the wide-field retina after surgery. We found that the postoperative changes in high-order aberrations were consistent with those in previous studies. Our method also allowed us to analyze the distribution of these changes across the entire retina. Our results suggest that the postoperative changes in high-order aberrations are not randomly distributed but instead follow a pattern associated with specific retinal areas and meridians. Changes in spherical aberration and coma post-surgery may be attributed to alterations in corneal biomechanical properties and the surgical procedure itself. Increased coma after surgery may be related to the imperfect alignment of the corneal tissue during surgery or postoperative changes in corneal thickness and curvature. Similarly, increased spherical aberration may result from changes in corneal asphericity post-surgery.

Six months post-surgery, the subjects completed the same visual questionnaire again. Comparing pre- and post-surgery questionnaire results allowed us to evaluate improvements in night vision and quality of life. People report that their night driving vision has improved following the surgery., and most patients no longer had symptoms of glare, halo, and ghosting. This underscores the significant improvement in the quality of life of patients following refractive surgery. The distribution of high-order aberrations across a wide-field retina provides important information for understanding the optical quality of the cornea after refractive surgery. Our method can be used to evaluate the impact of different surgical techniques on corneal optical quality and optimize surgical outcomes by reducing high-order aberrations.

Limitations

Firstly, the sample size was relatively small, comprising only 28 patients. This limited sample size may restrict the generalizability of the results to a broader population. Additionally, the follow-up period after SMILE surgery was relatively short, spanning only six months. A longer follow-up duration would provide more comprehensive insights into the stability of the observed changes in peripheral refraction and aberrations over time. The study also relied on subjective visual assessments through a questionnaire, introducing potential biases in the reported outcomes. Supplementing subjective assessments with objective measures of visual function, such as contrast sensitivity testing, could offer a more comprehensive evaluation of visual outcomes. Finally, the study did not investigate changes in corneal biomechanics following SMILE surgery, which could also impact peripheral refraction and aberrations.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Received: 25 September 2024; Accepted: 11 February 2025
Published online: 23 February 2025

References

1. Wood, J. M. & Troutbeck, R. Effect of restriction of the binocular visual field on driving performance. *Ophthal. Physiol. Opt.* **12**, 291–298. https://doi.org/10.1111/j.1475-1313.1992.tb00400.x (1992).
2. Patino, C. M. et al. Central and peripheral visual impairment and the risk of falls and falls with injury. *Ophthalmol.* **117**, 199-206. e1. https://doi.org/10.1016/j.ophtha.2009.06.063 (2010).
3. Wang, Y., Zhao, K., Jin, Y., Niu, Y. & Zuo, T. Changes of higher-order aberration with various pupil sizes in the myopic eye. *J. Refract. Surg.* **19**, S270–S274. https://doi.org/10.3928/1081-597X-20030302-21 (2003).
4. Schallhorn, S., Brown, M., Venter, J., Hettinger, K. & Hannan, S. The role of the mesopic pupil on patient-reported outcomes in young patients with myopia 1 month after wavefront-guided LASIK. *J. Refract. Surg.* **30**, 159–165. https://doi.org/10.3928/1081597X-20140217-02 (2014).
5. Erdinest, N. et al. Peripheral defocus and myopia management: A mini-review. *Korean J. Ophthalmol.* **37**, 70–81. https://doi.org/10.3341/kjo.2022.0125 (2023).
6. Wei, X. & Thibos, L. Design and validation of a scanning shack-hartmann aberrometer for measurements of the eye over a wide field of view. *Opt. Express* **18**, 1134–1143. https://doi.org/10.1364/OE.18.001134 (2010).
7. Liu, Y. et al. Comparison of wavefront aberrations in the object and image spaces using wide-field individual eye models. *Biomed. Opt. Express* **13**, 4939–4953. https://doi.org/10.1364/BOE.464781 (2022).
8. Rosén, R., Lundström, L. & Unsbo, P. Influence of optical defocus on peripheral vision. *Invest. Ophthalmol. Vis. Sci.* **52**(1), 318–323. https://doi.org/10.1167/iovs.10-5623 (2011).
9. Lou, Q. et al. Investigation of aberration characteristics of eyes at a peripheral visual field by individual eye model. *Appl. Opt.* **54**, 5917–5923. https://doi.org/10.1364/AO.54.005917 (2015).
10. Lou, Q. et al. Statistical characteristics of aberrations of human eyes after small incision lenticule extraction surgery and analysis of visual performance with individual eye model. *Appl. Opt.* **54**, 7490–7493. https://doi.org/10.1364/AO.54.007490 (2015).
11. Hartwig, A., Murray, I. J. & Radhakrishnan, H. Peripheral aberration measurements: Elliptical pupil transformation and variations in horizontal coma across the visual field. *Clin. Exp. Optom.* **94**, 443–451. https://doi.org/10.1111/j.1444-0938.2011.00624.x (2011).
12. Tanzer, D. J. et al. Laser in situ keratomileusis in United States naval aviators. *J. Cataract Refract. Surg.* **39**, 1047–1058. https://doi.org/10.1016/j.jcrs.2013.01.046 (2013).
13. Shah, R., Shah, S. & Sengupta, S. Results of small incision lenticule extraction: All-in-one femtosecond laser refractive surgery. *J. Cataract Refract. Surg.* **37**, 127–137. https://doi.org/10.1016/j.jcrs.2010.07.033 (2011).
14. Kamiya, K., Shimizu, K., Igarashi, A., Kobashi, H. & Komatsu, M. Comparison of visual acuity, higher-order aberrations, and corneal asphericity after refractive lenticule extraction and wavefront-guided laser-assisted in situ keratomileusis for myopia. *Br. J. Ophthalmol.* **97**, 968–975. https://doi.org/10.1136/bjophthalmol-2012-302047 (2013).
15. Tuan, K. M. Visual experience and patient satisfaction with wavefront-guided laser in situ keratomileusis. *J. Cataract Refract. Surg.* **32**, 577–583. https://doi.org/10.1016/j.jcrs.2006.01.002 (2006).
16. Queirós, A. et al. Relative peripheral refraction across 4 meridians after orthokeratology and LASIK surgery. *Eye Vis. (Lond.)* **5**, 12. https://doi.org/10.1186/s40662-018-0106-1 (2018).
17. Queirós, A., Villa-Collar, C., Jorge, J., Gutiérrez, A. R. & González-Méijome, J. M. Peripheral refraction in myopic eyes after LASIK surgery. *Optom. Vis. Sci.* **89**, 977–983. https://doi.org/10.1097/OPX.0b013e31825ddf54 (2012).
18. Lin, Z. et al. Peripheral defocus with single-vision spectacle lenses in myopic children. *Optom. Vis. Sci.* **87**, 4–9. https://doi.org/10.1097/OPX.0b013e3181c078f1 (2010).
19. Du, Y., Zhou, Y., Ding, M., Zhang, M. & Guo, Y. Changes in relative peripheral refraction and optical quality in Chinese myopic patients after small incision lenticule extraction surgery. *PLoS One* **18**(10), e0291681. https://doi.org/10.1371/journal.pone.0291681 (2023).
20. Montés-Micó, R. & Charman, W. N. Image quality and visual performance in the peripheral visual field following photorefractive keratectomy. *J. Refract. Surg.* **18**, 14–22. https://doi.org/10.3928/1081-597X-20020101-02 (2002).
21. Lin, Z., Lu, Y., Artal, P., Yang, Z. & Lan, W. Two-Dimensional peripheral refraction and image quality for four types of refractive surgeries. *J. Refract. Surg.* **39**, 40–47. https://doi.org/10.3928/1081597X-20221115-01 (2023).

Acknowledgements

The optic design was guided by PhD. Tao Liu. The authors would like to express our appreciation for the reviewers' comments and suggestions to improve our manuscript.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Lin Zhang, Yan Wang, Xinheng Zhao,and Tong Cui. The first draft of the manuscript was written by Lin Zhang, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding

This work was supported by National Natural Science Foundation of China (82301255), and NanKai University Eye Institute (NKYKK202205), and Tianjin Key Medical Discipline(Specialty) Construction Project (No.TJYXZDXK-016A).

Declarations

Competing interests

The authors declare no competing interests.

Ethics approval

This study was performed in line with the principles of the Declaration of Helsinki and was approved by the local Research Ethics Committee.(The Medical Ethics Committees of Tianjin Eye Hospital , 2023/03/06, KY2023019).

Consent to participate

The subjects gave informed consent prior to participation.

Additional information

Correspondence and requests for materials should be addressed to Y.W.