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RESEARCH

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Full range of vision and visual quality after mini-monovision FS-LASIK in high myopic patients with presbyopia

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Abstract

Background To evaluate clinical outcomes and visual quality 3 months after mini-monovision (spherical equivalent [SE] between −0.25 D and −0.50 D) femtosecond laser-assisted in situ keratomileusis (FS-LASIK) for correction of high myopia in patients with presbyopia.

Methods Patients who had mini-monovision FS-LASIK for high myopia (SE < -6.0 D) and aged between 40 and 50 years were included. At the 3-month postoperative visit, we evaluated full range of visual acuity; defocus curve; optical quality; accommodation function, contrast sensitivity and stereopsis. Binocular tests were done twice, once in mini-monovision condition and once with the residual myopia in the non-dominant eye corrected. Subjective visual quality was evaluated with questionnaire postoperatively with mini-monovision correction.

Results Clinical data of 31 cases were analyzed. The average patient age was 42.58 ± 3.06 years. At the 3-month follow-up, the mean uncorrected binocular visual acuity at distance, intermediate, and near was −0.11 ± 0.07, -0.06 ± 0.10, and 0.04 ± 0.11 logMAR separately. In comparison, patients with binocular full distance correction achieved better uncorrected distance visual acuity (UDVA), and they achieved superior uncorrected near visual acuity (UNVA, $P = 0.04$) with mini-monovision correction. FS-LASIK induced significant increases in higher-order aberrations (HOAs) ($P < 0.001$). For accommodative function, only the negative relative accommodation (NRA) improved significantly after surgery ($P < 0.001$). A slight decrease in contrast sensitivity was observed at low spatial frequency with mini-monovision correction ($P < 0.05$). Questionnaire demonstrated high satisfaction with near vision and visual quality.

Conclusion FS-LASIK with mini-monovision (SE between −0.25 D and −0.50 D) appeared to be safe and effective in treating high myopia combined with presbyopia to get satisfying visual quality at distant and at near.

Keywords Refractive surgery, Vision, Binocular, Myopia, Presbyopia

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Introduction

Age-related accommodative deficiency, also known as presbyopia, manifests as a gradual deterioration in the clarity of near vision with age, usually occurs in people aged 40 or older [1]. To properly manage presbyopia while correcting the existing refractive error, femtosecond laser-assisted in situ keratomileusis (FS-LASIK) with monovision/ optimized monocular vision protocol, an unbalanced correction between the two eyes in which the dominant eye is corrected to emmetropia mainly used for distance vision, whereas the non-dominant eye retains a certain degree of spherical diopter for intermediate or near vision, continues to be the regular and effective choice [2, 3]. Studies have demonstrated good clinical outcomes of this scheme in myopes with presbyopia, and most have focused only on the correction of low to moderate myopia [3–5], or analyze all included eyes without further grouping by degree of myopia [6, 7].

With the increasing prevalence of high myopia worldwide nowadays, more and more patients during the incipient phase of presbyopia with relatively clear lenses are prone to seek corneal refractive surgeries to correct high myopia as well as presbyopia [8]. Notably, higher degrees of myopic correction changes corneal morphology to a greater extent, introducing more higher-order aberrations (HOAs) and might thus take a toll on visual performance [9–11]. Besides, refractive surgery breaks the balanced state of binocular visual function suddenly while changing refractive status [12], for presbyopes with high myopia, the size and nature of ciliary body have changed to some extent, concerns have thus been raised whether this asymmetry correction would have an adverse effect on reorientation of visual system [13].

Hence, conclusions of the studies in low-to-moderate myopia cannot be directly generalized. The aim of this study is to evaluate the efficacy and safety of mini-monovision FS-LASIK in high myopia combined with presbyopia, and focusing on the postoperative visual quality and patient satisfaction comprehensively.

Patients and methods

This retrospective study included 31 consecutive patients undergoing Q-value-guided FS-LASIK with monovision at the Peking University Third Hospital (Beijing, China) between Jan. 2023 and Sep. 2023. The study was approved by the ethics committee of the Peking University Third Hospital (IRB00006761-M2023402) and adhered to the tenets of the Declaration of Helsinki. Informed consent for the use of clinical data for analysis and publication was obtained from all patients as a routine in our practice.

The inclusion criteria were as follows: age between 40 and 50 years, stable refractive error (≤0.5 D change per year in refractive error in the past 2 years), spherical equivalent (SE) of -6.0 D or higher, and astigmatism of up to -3.0 D. The exclusion criteria were as follows: patients with a history of refractive or corneal surgery, suspicion of keratectasia, visually significant cataracts or other pre-existing ocular diseases, any significant abnormality in binocular visual function.

Preoperative assessments

All patients underwent comprehensive ocular examinations, including uncorrected and corrected distance visual acuity (UDVA, CDVA) evaluated in the logarithm of the minimum angle of resolution (logMAR), subjective manifest and cycloplegic objective refraction (compound Tropicamide eye drops; Sinqi Pharmaceutical, China), noncontact intraocular pressure (NIDEK Co., Ltd), standard slit-lamp evaluation (IM 900, Köniz), dilated fundus examination, and corneal tomography (Pentacam, Oculus). Ocular dominance was determined using the pinhole test [14]. Corneal asphericity (Q factor), higher-order aberrations (HOAs) of anterior corneal surface within the central 6-mm region, and retinal image quality (the Strehl ratio, SR), were determined using the Sirius (Costruzione Strumenti Oftalmici, Florence, Italy) tomography instrument. Root mean square (RMS) values for the total amount of HOAs, astigmatism, spherical aberration, and coma were automatically calculated through Fourier transformation.

The necessary addition (NA) for reading Parinaud 2 at 40 cm distance was obtained using the "minimal addition" method [15]. The "minus lens method" measured accommodative amplitude (AA), and positive and negative relative accommodation (PRA and NRA), were evaluated by phoropter as the patients viewed a high-contrast target at 40 cm with full near correction [16]. The actual accommodation parameters were calculated by subtracting NA added before testing [16].

Surgical technique

FS-LASIK procedures were performed by a highly experienced surgeon (YG Chen) using the FS-200 femtosecond laser and WaveLight EX500 excimer laser (Alcon Laboratories, Inc.) under topical anesthesia. In all cases, an 8.5 to 9.0 mm diameter superior 50-degree hinged corneal flap with a 90-degree side-cut and 110 μm thickness was dissected. Following blunt dissection and flap lift, the stromal photoablation was performed with a 6.5-mm optical zone and 1.25-mm transition zone using Q-value-guided (F-CAT) treatment option. Preoperative Q Values were measured using the WaveLight Topolyzer Vario instrument (Alcon Laboratories, Inc), reflecting the distribution of characteristics of corneal curvature within 30° of the central cornea. For the dominant eye, the target refraction was set at emmetropia, and for the non-dominant eye, the refractive target was set to slight myopia between −0.25 D and −0.50 D, according to the age and requirements of patients [17]. No adjustment was made for Q value. Postoperatively, all the eyes received treatment with 0.1% fluorometholone (FML, Allergan, Inc., Irvine, CA, United States) in tapering dose for 4 weeks, 0.5% levofloxacin (Cravit, Santen, Inc., Japan) four times a day for 2 weeks and lubricating drops four times a day for 4 weeks.

Postoperative assessments

Follow-up visits included postoperative days 1 and 7, months 1 and 3. Results at the 3-month follow-up were included for data analysis in this study. The monocular and binocular UDVA, CDVA, refractive status, corneal asphericity, objective image quality, and accommodation function were measured in the same manner as preoperatively. The uncorrected intermediate and near visual acuity (UIVA, UNVA) were measured at 80 cm and 40 cm distances. Defocus curves from −3.0 D to +1.0 D in increments of 0.5 D were obtained by phoropter binocularly. Visual acuity was converted into logMAR scale from the decimal notation for data analysis.

Contrast sensitivity measured with CSV-1000E (Vector Vision) was evaluated binocularly under photopic (85 cd/m^2) and mesopic (3 cd/m^2) conditions at four spatial frequencies (3.0, 6.0, 12.0, and 18.0 cpd), and outcomes were recorded in log unit [3].

Stereopsis was measured using the Yan's stereoscopic test. Distance stereoacuity was determined using the synoptophore, and near stereoacuity was measured at a standard viewing distance of 40 cm [18]. Results were classified as follows: stereoacuity greater than or equal to 60 s of arc (central stereopsis); stereoacuity ranged between 80 and 200 s of arc (macular stereopsis); stereoacuity ranged between 300 and 800 s of arc (peripheral stereopsis); and stereoacuity above 800 s of arc (stereo blindness) [19].

In this study, patients with myopic diopter in the non-dominant eye postoperatively were asked to have all binocular tests performed twice, once in monovision condition without spectacles, and once with the residual myopia in the non-dominant eye corrected with spectacles (reverting monovision to full distance correction), serving as control group.

At last, all patients were asked to fill out a questionnaire including their perception of near-visual ability (satisfaction with near visual acuity and reading spectacle independence) and visual disturbance. The second part includes 8 common complaints after refractive surgery: glare, halos, starbursts, blurred vision, monocular diplopia, fluctuation in vision, focusing difficulty, and difficulty judging depth perception. The incidence and severity of respective symptoms were recorded.

Statistical analysis

All statistical analyses were performed using SPSS Statistics for Windows (version 22.0., IBM Corp.). The normality of data was assessed by histogram frequency analysis and the Shapiro-Wilks test. Data were expressed as mean ± standard deviation (SD). The paired samples *t*-test and the independent samples *t*-test were performed on normally distributed data, and the Wilcoxon rank-sum test and the Mann–Whitney U-test were performed on non-normally distributed data. The Fisher exact probability test was used for comparisons of categorical variables. *P* value less than 0.05 was considered statistically significant.

Results

The study comprised 31 patients (62 eyes). The mean age of the 19 women (61.29%) and 12 men (38.71%) was 42.58 ± 3.06 (SD) years (range 40 to 50 years), and the mean addition for binocular near vision was 0.34 ± 0.46 D. Supplemental Table 1 shows the preoperative characteristics in dominant eyes and nondominant eyes by group.

Efficacy, accuracy and safety

At the 3-month follow-up, the mean UDVA was −0.07 ± 0.08 in the dominant eye, with a mean residual spherical equivalent (SE) defect of 0.01 ± 0.33 D (range: -0.75 to 0.63 D). In the nondominant eye, the UDVA was −0.01 ± 0.09, with a mean residual SE defect of -0.38 ± 0.36 D (range: 0.13 to -1.00 D).

Figure 1 shows the standard graphs for reporting outcomes of refractive surgery in dominant eye. The accuracy of the achieved spherical equivalent compared to the intended target was within ±1.00 D in all (100%) dominant eye treated, whereas 90% of eyes were within ±0.50 D.

All surgeries were uneventful, with no infection, inflammation, or intraoperative complications noted in any of the patients enrolled in the study. No eyes lost lines of CDVA at 3 months post-surgery.

Binocular visual acuity and defocus curves

For all patients, the mean postoperative uncorrected binocular visual acuity at distance, intermediate, and near was −0.11 ± 0.07 logMAR, -0.06 ± 0.10 logMAR, and 0.04 ± 0.11 logMAR separately. The binocular defocus curve is shown in Fig. 2A. Regarding the defocus range from 0 D to – 2.50 D (from far to near distance of 40 cm), the mean uncorrected visual acuity was maintained above 20/25.

After surgery, 7 patients showed emmetropia status and 2 showed hyperopia status in the non-dominant eye, and there were 2 patients refused to repeat binocular tests with spectacles. Eventually, only 20 patients had

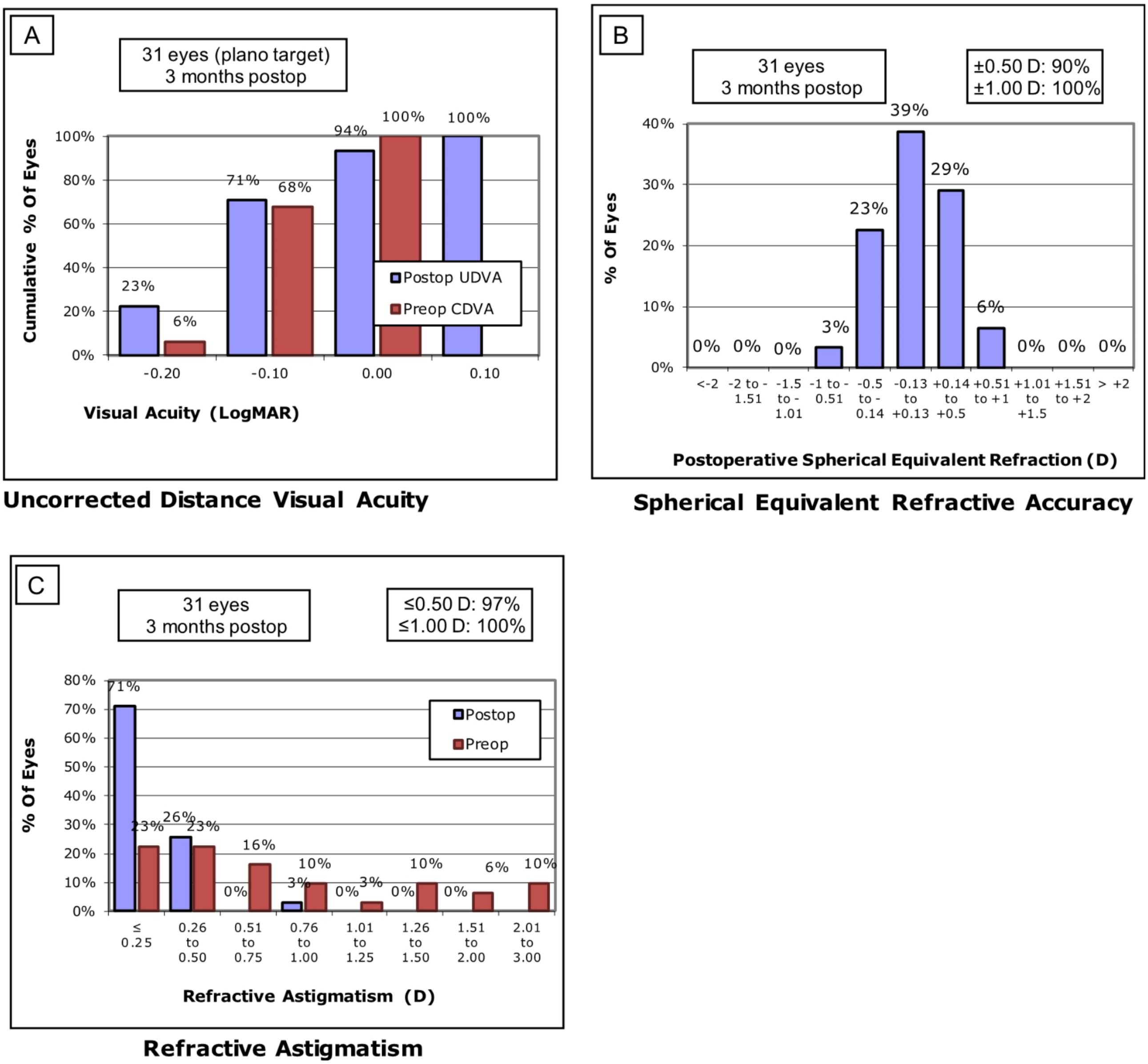

Fig. 1 Refractive outcomes at 3 months after monovision FS-LASIK for the dominant eye. (**A**) Cumulative histogram showing postoperative uncorrected distance visual acuity (UDVA) and preoperative corrected distance visual acuity (CDVA). (**B**) Histogram showing the accuracy of the intended spherical equivalent refraction. (**C**) Histogram showing refractive astigmatism before and after treatment

residual myopia in the non-dominant eye corrected with spectacles and serving as control group. Postoperative binocular visual outcome in monovision compared to full distance correction are shown in Table 1. The two groups had comparable mean binocular UINA. For the distant visual acuity, better outcome was achieved in the full distance correction group ($P=0.02$); for the near visual acuity at 40 cm, superior result was observed in the monovision group instead ($P=0.04$). Similarly, as shown in Fig. 2B, patients in the monovision group showed significant better results regarding the defocus range from − 2.00 D to − 3.00 D (corresponding to a distance range of 50–33 cm).

Corneal asphericity, aberrations, and image quality

Corneal asphericity and objective image quality before and after treatment are summarized in Table 2. Compared to preoperative measurements, postoperative examinations showed corneal asphericity was more positive in both dominant eyes and non-dominant eyes ($P<0.05$). The RMS of total HOAs, coma and SA significantly increased after the surgery ($P<0.05$) when measured over a 6 mm pupil. However, the SR value did not show statistically significant changes due to the surgery.

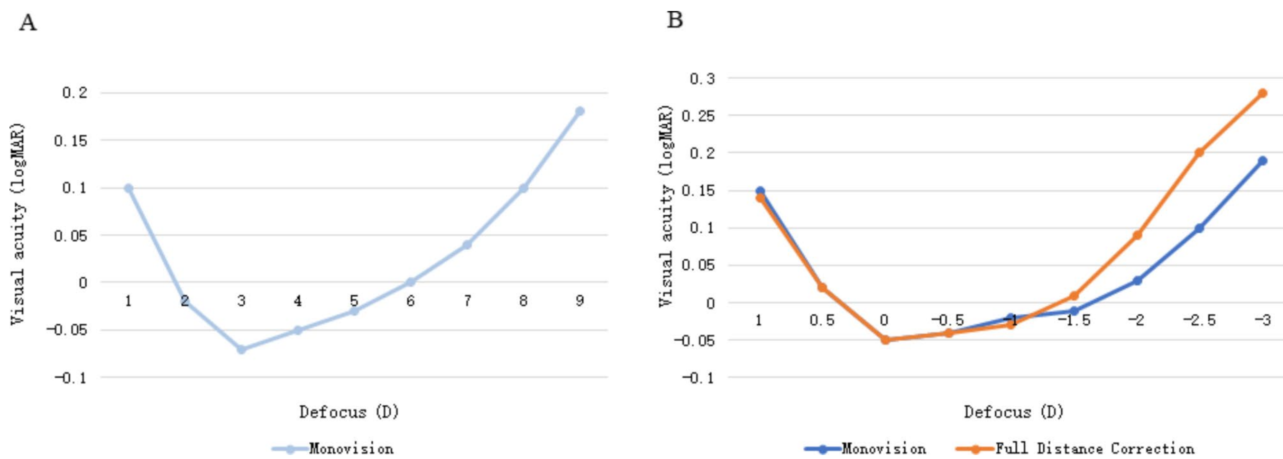

Fig. 2 Binocular defocus curves assessed at 3 months follow-up. (**A**) Binocular defocus curve for all patients (*n* = 31). (**B**) Comparision of binocular defocus curve between the monovision and the full distance correction groups (*n* = 20)

Table 1 Comparison of binocular visual acuity between monovision and full distance correction

	Monovision (*n* = 20)		Full Distance Correction (*n* = 20)		*P*
	Mean ± SD	Range	Mean ± SD	Range	
UDVA (LogMAR)	-0.07 ± 0.06	0, -0.18	-0.10 ± 0.04	-0.08, -0.20	0.02*
UIVA (LogMAR)	-0.03 ± 0.09	-0.20, 0.20	-0.04 ± 0.09	0.10, -0.20	0.68
UNVA (LogMAR)	0.07 ± 0.11	-0.10, 0.40	0.12 ± 0.19	-0.10, 0.70	0.04*

UDVA = uncorrected distance visual acuity; UIVA = uncorrected intermediate visual acuity; UNVA = uncorrected near visual acuity;

All values are presented as mean ± standard deviation; The Wilcoxon rank-sum test was used to compare differences between the two groups

* statistically significance

Table 2 Preoperative and postoperative corneal asphericity, aberrations, and objective image quality (6 mm)

Parameters	Dominant Eye (*n* = 31) (Mean ± SD)			Nondominant Eye (*n* = 31) (Mean ± SD)		
	Preop	Postop	*P*	Preop	Postop	*P*
Q value	-0.15 ± 0.12	0.46 ± 0.45	< 0.001*	-0.15 ± 0.11	0.63 ± 0.55	< 0.001*
Total HOAs (μm)	0.47 ± 0.14	0.94 ± 0.34	< 0.001*	0.46 ± 0.11	0.92 ± 0.34	< 0.001*
SA (μm)	0.25 ± 0.09	0.56 ± 0.22	< 0.001*	0.25 ± 0.07	0.59 ± 0.23	< 0.001*
Coma (μm)	0.23 ± 0.14	0.61 ± 0.33	< 0.001*	0.23 ± 0.12	0.55 ± 0.31	< 0.001*
SR	0.13 ± 0.05	0.15 ± 0.04	0.08	0.15 ± 0.04	0.14 ± 0.04	0.50

HOAs = higher-order aberrations; SA = spherical aberration; SR = strehl ratio; preop = preoperative; postop = postoperative

All values are presented as mean ± standard deviation; The Wilcoxon rank-sum test was used to compare differences before and after the operation

* statistically significance

Table 3 Preoperative and postoperative accommodation function

Parameters	Preop (*n* = 31)		Postop (*n* = 31)		*P*
	Mean ± SD	Range	Mean ± SD	Range	
AA (D)	3.91 ± 1.16	2.50, 6.50	3.58 ± 0.91	2.50, 5.50	0.08
NRA (D)	1.70 ± 0.52	0.50, 2.75	2.41 ± 0.49	1.50, 3.50	<0.001*
PRA (D)	-1.41 ± 1.16	0, -4.00	-1.08 ± 0.91	0, -3.00	0.08

AA = accommodative amplitude; NRA = negative relative accommodation; PRA = positive relative accommodation; preop = preoperative; postop = postoperative;

All values are presented as mean ± standard deviation; *P* values for comparations before and after the operation of NRA was calculated by paired samples t-test. The Wilcoxon rank-sum test was used to compare differences of AA and PRA before and after the operation

* statistically significance

Binocular accommodation function

Table 3 shows the results of the assessment of binocular accommodation function. The postoperative NRA was on average about 0.71 D higher than the preoperative value ($P<0.001$), but binocular minus-lens-stimulated AA and PRA did not show any statistically significant changes before and after surgery.

Binocular contrast sensitivity and stereoacuity

There were 17 patients showed myopia status in the non-dominant eye after surgery and were willing to have contrast sensitivity and stereoacuity test performed twice. Postoperative binocular contrast sensitivity measurements in the monovision and full distance correction groups at 3, 6, 12, and 18 cpd under photopic and mesopic conditions with and without glare stimuli are shown in Supplemental Fig. 1. Compared to the logarithmic scale, contrast sensitivity was generally reduced with monovision compared to binocular full distance correction in most test conditions. This reduction was only of statistically significant at low spatial frequency of 6.0 cpd under photopic and mesopic conditions ($P<0.05$ for all comparisons).

The binocular distance and near stereoacuity are shown in Supplemental Table 2. Stereoacuity decreased slightly with monovision compared to full distance correction, but the noted differences were not statistically significant ($P>0.05$).

Subjective visual quality and near visual ability

For the near visual ability, 6 patients (19.35%) were fully satisfied with their near visual acuity, 23 patients (74.19%) were moderately satisfied, and the remaining 2 patients (6.45%) were not very satisfied; 24 patients (70.97%) reported that they never required to wear reading glasses while reading or doing close work, 6 patients (19.35%) needed reading glasses in few cases, and only 1 patient (3.23%) needed reading glasses in most cases.

Supplemental Table 3 shows patients' perception of visual disturbance. The three most commonly reported visual symptoms after surgery were blurred vision, glare, and halos with the cumulative number of 20 patients (64.52%), 19 patients (61.29%), and 19 patients (61.29%), respectively, reporting these symptoms "occasionally," "often," or "usually". Besides, subjective problems with depth perception had been found in only 4 patients (12.90%), which was considered closely related to reduction in stereoacuity, and no one considered them severely bothering.

Discussion

Results of the study demonstrated that monovision procedure was safe and effective for the treatment of high myopia combined with presbyopia. Binocular vision, which is considered of great clinical significance and simulates better in daily tasks than monocular vision, as patients always function under binocular conditions [20], was satisfying at whole course 3 months postoperatively. All patients achieved 20/20 or better UDVA, 20/30 or better UIVA, and 20/50 or better UNVA. There were 27 (87.10%) patients achieving unaided far, intermediate, and near visual acuity of 20/25 or better simultaneously. Results of subjective questionnaire were also well related to the functional visual acuity, that the satisfaction rate of unaided near vision was found to be upwards of 94%, and full-distance spectacle independence has also been largely achieved.

In the current study, a significant mild reduction in the binocular near vision was observed with full distance correction (wearing spectacles in the non-dominant eye) compared to mini-monovision, and although there was a decrease in distance vision with mini-monovision condition, the difference may fail to achieve clinical significance. This further indicates that mini-monovision enables better results for near work while maintaining good uncorrected distance visual function for this subset of patients.

This study also focuses on binocular visual function. It has been theoretically proven that the abrupt emmetropization with myopic refractive surgery increases the accommodation and convergence demands for near suddenly [21]. The binocular function would be hence more altered in high myopia, which raises our concerns of binocular vision impairment or apparent asthenopia in this population with standard physiological function of eye tissue already degraded to some extent [21, 22]. Regarding accommodation function, the AA and PRA was unaltered, and we even observed a relatively small preoperative NRA that increased after surgery surprisingly. Possible reasons could include the following. Firstly, it has been found that the accommodation demand for myopes is generally lower than in emmetropes owing to the presence of the spectacle vertex distance (the distance between the lens's inner surface and the cornea's vertex) and prism effect of concave lens [23], which also interacted with convergence demand and leads to reduced accommodative convergence accordingly. Studies have shown that myopes with spectacles tended to have increased exophoria deviation when viewing a near target, especially in those with high myopia [23–25]. As a result, the myopic eye may end up using more of its fusional convergence to maintain binocular single vision. Postoperatively, the accommodation demands increased, inducing more convergence demands and thus less exophoria [24]. A previous study also reported that significant decline of exophoria was observed after FS-LASIK, when compared to preoperative exophoria with the corrected lens [23]. When adding positive lenses in front of both eyes to relax accommodation, the accommodative convergence decreased, and fusional convergence, which had been heavily used preoperatively, had to further increased to maintain binocular function, thus the preoperative NRA was significantly lower in comparison. Additionally, the increased needs for physiological binocular function might has a training effect on muscles control capability of the brain, thus making binocular function more efficient and coordinated. Moreover, in a state of myopia, people favored near-work activities and putting muscles under high tension for long periods. After the refractive error was corrected, the eye's far point was away from the corneal plane, which helps significantly in relaxing tensed muscles.

Regarding the optical visual quality, the corneal HOAs at 6 mm pupil increased significantly, which aligned with the principle of myopia correction. Besides, attenuation of contrast sensitivity and reduction of stereopsis were thought to be the major disadvantage associated with monovision [2]. In this study, we also found a slight reduction in binocular contrast sensitivity and stereopsis, compared to the full distance correction. However, the optical quality measured on retinal plane did not show significantly worse performance, and the subjective visual function in real-life scenarios did not worsen. These good results may be partly due to the mild myopic refraction targeted in our series compared to other related studies [26]. Moreover, it should be noted that postoperative visual quality also was strongly related to laser platform and ablation profiles used in this procedure, which cannot be generalized to others with different ablation protocol. In our study, a Q-value-guided profile with WaveLight EX500 excimer laser system was used for treatment, in which the Q factor was adjusted intending to better preserve the original prolate shape of cornea, resulting in fewer surgically induced HOAs within the suitable range and resulted in no severe adverse effects on visual quality, as well as better conservation of cornea thickness [27]. There are also other lasers available, such as the SCHWIND Amaris laser, with different ablation model and geometric modelling, thus postoperative visual quality cannot be predicted.

In this study, patients at the early stage of presbyopia were included [2], and the mean age was relatively younger compared with relevant studies. One reason was that, as the median age would reach 40 years by 2050 under the backdrop of an ageing global population [28], it is expected that the number of patients aged around 40 years seeking for refractive surgery will continue to grow. Besides, most patients at this age made the firm choice to choose monovision protocol after being fully informed, rather than full correction in our clinical experience.

Limitations of the study include its retrospective design, a small sample size and short duration of follow up. Besides, binocular measurements performed with the residual myopia in the non-dominant eye corrected were not available for all patients. Furthermore, the questionnaire used was indigenously devised and not validated.

In conclusion, FS-LASIK with mini-monovision (SE between −0.25 D and −0.50 D) appeared to be safe and effective in treating high myopia combined with presbyopia to get satisfying visual quality at distant and at near.

Abbreviations

AA	Accommodative amplitude
CDVA	Corrected distance visual acuity
FS-LASIK	Femtosecond laser-assisted in situ keratomileusis
HOAs	Higher-order aberrations
NRA	Negative relative accommodation
PRA	Positive relative accommodation
RMS	Root mean square
SE	Spherical equivalent
SR	Strehl ratio
UDVA	Uncorrected distance visual acuity
UIVA	Uncorrected intermediate visual acuity
UNVA	Uncorrected near visual acuity

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12886-024-03698-x.

Supplementary Material 1

Supplementary Material 2

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Not applicable.

Author contributions
Ruiyu Zhang, Yifei Yuan and Yu Zhang participated in the design of the study, Ruiyu Zhang performed the statistical analysis and revised the manuscripts. Yueguo Chen conceived of the study, and participated in its design and coordination and helped to draft the manuscript. All authors read and approved the final manuscript.

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Data availability
The data underlying this article cannot be shared publicly due to privacy reasons of the participants. The data will be shared on reasonable request to the corresponding author.

Declarations

Ethics approval and consent to participate
This study adhered to the tenets of the Declaration of Helsinki and received approval from the Ethics Committee of Peking University Third Hospital (IRB00006761-M2023402). Informed consent was obtained from each subject.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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