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Neurosensory binocular vision after bilateral implantation of an extended depth of focus intraocular lens with micro-monovision: a prospective cohort study

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Abstract

Background The goal of this study was to evaluate the presbyopia-correcting performance, binocular visual quality and neurosensory binocular vision of bilateral implantation of an extended depth of focus (EDOF) intraocular lens (IOL) with micro-monovision and compare this IOL with two multifocal IOLs.

Methods This prospective cohort study enrolled patients with bilateral implantation of diffractive EDOF IOL (Tecnis Symfony ZXR00, Abbott Medical Optics, Inc.), diffractive trifocal IOL (AT LISA tri 839MP, Carl Zeiss Meditec AG) and refractive rotationally asymmetric bifocal IOL (SBL-3, Lenstec, Inc.). Monocular outcomes including visual acuity and refraction status, binocular outcomes including visual acuity at different distances, defocus curve and contrast sensitivity, neurosensory binocular vision outcomes including simultaneous perception, fusion and stereoscopic vision, and questionnaire results including spectacle independence, photic phenomena and satisfaction were assessed three months after surgery. One-way ANOVA and Kruskal–Wallis H test were used to compare the mean of three groups. Chi-square test and Fisher exact test were used to compare the proportions.

Results The efficacy, safety and accuracy of the EDOF group reached a similar level to the trifocal group. The bilateral EDOF IOL with micro-monovision performed better in intermediate visual acuity (versus the bifocal group, $P = 0.031$) and far stereoscopic vision (versus the other two groups, $P < 0.05$), but there were disadvantages in binocular visual acuity with the -3.0 ~ -4.0D addition (versus the other two groups, $P < 0.05$), binocular contrast sensitivity (versus the other two groups, $P < 0.05$), near spectacle independence (versus the trifocal group, $P = 0.030$) and photic phenomena (versus the bifocal group, $P < 0.05$). No significant difference was found in simultaneous perception, fusion and satisfaction at different distances (all $P > 0.05$).

Conclusion Bilateral EDOF IOL implantation with micro-monovision successfully treated cataract, provided reliable binocular far and intermediate visual acuity, good neurosensory binocular vision and patient satisfaction. It achieved better far stereoscopic vision than multifocal IOLs, but lagged behind in near visual acuity, near spectacle independence and binocular contrast sensitivity.

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Trial registration This study was retrospectively registered and posted on clinicaltrials.gov at 12/02/2020 (NCT04265846).

Keywords Cataract, Intraocular lens, Extended depth of focus, Multifocal, Binocular vision

Introduction

Cataract surgery and intraocular lens (IOL) implantation, once aimed at blindness prevention and treatment, are now designed to provide good vision across all distances. Multifocal intraocular lenses (MIOLs), with the aim of presbyopia-correcting, split the incident light into several focal points [1]. But they will reduce contrast sensitivity and increase disturbing photic phenomena [2–4]. The diffractive extended depth of focus (EDOF) IOL (Tecnis Symfony ZXR00, Abbott Medical Optics, Inc.) has achieved successful presbyopia-correcting performance with a minimal level of disturbing photic phenomena [5–8]. It was the first United States FDA-approved EDOF IOL in 2016. It has an extended focus of 1.50 D and compensates the chromatic and spherical aberrations through its diffractive design [9]. In clinical practice, there is a micro-monovision design of the target refraction, in which the nondominant eye is targeted for −0.50 D ~ −0.75 D to improve binocular near and intermediate visual acuity [5, 10, 11].

Binocular vision, including simultaneous perception, fusion and stereoscopic vision, played important roles in postoperative adaptability, especially for patients whose bilateral eyes were not completely balanced [12]. Esophoria tendency and overall decrease of fusional reserves and stereoscopic vision after monovision treatment have been reported [13]. Few studies reported findings on the binocular vision of patients after IOL implantation with micro-monovision. Binocular vision assessment methodologies diverge across studies: quantitative motor evaluations with alternate cover test, near point of convergence, fusional ranges and so on [14], contrast with evaluation of neurosensory part using synoptophore [15–17].

Therefore, the aim of this study was to evaluate the presbyopia-correcting performance, binocular visual quality and neurosensory binocular vision function of the EDOF IOL with micro-monovision, and compare this IOL with two different multifocal IOLs.

Methods

Patients

This prospective cohort study included consecutive patients scheduled for bilateral cataract surgery with implantation of three IOL models: Tecnis Symfony ZXR00 with EDOF design, AT LISA tri 839MP (Carl Zeiss Meditec AG) with diffractive trifocal design and SBL-3 (Lenstec, Inc.) with refractive rotationally asymmetric bifocal design. Surgery was performed between September 2019 to January 2022 at Department of Ophthalmology, Peking University Third Hospital. The study protocol adhered to the Declaration of Helsinki for the use of human participants in biomedical research and received the approval of the ethics committee of Peking University Third Hospital. Written informed consent was obtained from all participants prior to enrollment. In compliance with ICMJE guidelines for clinical trial registration, this study was retrospectively registered and posted on clinicaltrials.gov on February 12, 2020 (NCT04265846).

Inclusion criteria comprised: (1) age ≥40 years old; (2) anticipated postoperative corneal astigmatism ≤1.0 D; (3) 2.75 mm ≤photopic pupil diameter ≤5.75 mm; (4) angle kappa ≤0.5 mm; (5) corneal spherical aberration ≤0.5 μm at 6-mm optical zone. Exclusion criteria included preoperative anisometropia (> 1.0 D), amblyopia, strabismus (alternate cover test), dry eye, corneal scarring, glaucoma, uveitis, pseudoexfoliation syndrome, macular degeneration or other retinal impairment, posterior capsule rupture or other serious intraoperative complications, history of previous eye surgery and inability to complete the 3-month postoperative follow-up.

Intraocular lenses

The Tecnis Symfony ZXR00 is a hydrophobic acrylic UV-filtering IOL with 13.0 mm overall diameter and 6.0 mm optic. Featuring a biconvex wavefront-designed anterior aspheric surface and posterior achromatic diffractive surface, it extends depth-of-focus (+ 1.50 D) while compensating corneal chromatic aberration [9, 18, 19].

The AT LISA tri 839MP is a bi-aspheric trifocal IOL made of foldable hydrophilic acrylic material (25% water content) with a hydrophobic surface. This diffractive IOL has a 6.0 mm biconvex optic, a total diameter of 11.0 mm and a 4-haptic design, with a diffractive profile on its anterior surface. It has a near add of +3.33 D and an intermediate add of +1.66 D [20, 21].

The SBL-3 is a bi-aspheric hydrophilic acrylic bifocal IOL with a neutral aberration profile, a 5.75 mm optic and an 11.0 mm diameter. It has a near segment with a + 3.00 D addition in the inferior anterior optic. The distance segment occupies 50% of the optic, near segment occupies 42%, and two small wedge-shaped transition zones occupy the other 8% [22].

Preoperative examinations

Preoperative evaluation comprised visual acuity, tonometry, slitlamp evaluation, subjective refraction, and multimodal imaging including biometric evaluation (IOLMaster 700, Carl Zeiss Meditec AG), corneal topography (Pentacam HR, Oculus Optikgerate GmbH), fundoscopy and retinal optical coherence tomography examination (Cirrus 4000, Carl Zeiss Meditec AG) [23]. Visual acuity was recorded in the logarithm of the minimum angle of resolution (logMAR) form. Holladay 2 and Barrett Universal II formula were applied for IOL calculation. Target refraction was set at −0.25 D for both eyes in the trifocal/bifocal groups and the dominant eyes in the EDOF group, with micro-monovision adjustment (−0.75 D) applied to non-dominant eyes in the EDOF group.

Surgical technique

All surgeries were performed by an experienced surgeon under topical anesthesia. Corneal astigmatism determined incision placement: either a 135° primary incision or steep-axis incision. After a 5.0–5.5 mm anterior capsulorhexis and phacoemulsification (Centurion Vision System, Alcon Laboratories Inc), the IOL was implanted into the capsular bag. The incision and capsulorhexis were performed with Callisto Eye System (Carl Zeiss Meditec AG).

Postoperative examinations

Routine examinations at days 1, 7 and 30 included uncorrected and corrected distance visual acuity (UDVA and CDVA), tonometry and slitlamp evaluation. All patients followed the same postoperative regimen for 1 month, including 0.5% levofloxacin, 0.1% diclofenac sodium and 1% prednisolone acetate eye drops 4 times a day. The frequency decreased by 1 time a week.

At the 3-month postoperative evaluation, comprehensive ophthalmic assessments were systematically conducted. Visual acuity and refractive outcomes were determined through subjective refraction, UDVA and CDVA. Presbyopia-correcting performance assessments included binocular UDVA, CDVA, uncorrected and distance-corrected visual acuity at intermediate (80 cm) and near (40 cm) distances (UIVA, DCIVA, UNVA and DCNVA), and binocular uncorrected defocus curve (additional spherical diopters ranging from +2.0 D to −4.0 D with 0.5 D steps, corresponding to viewing distance from infinity to 25 cm) [24]. Visual quality was evaluated with binocular contrast sensitivity (OPTEC 6500 Vision Tester, Stereo Optical Co. Inc, USA) across five spatial frequencies (1.5, 3, 6, 12, and 18 cycles per degree [cpd]) and under four illumination scenarios (photopic condition [85 cd/m^2], mesopic condition [3 cd/m^2], photopic condition with glare and mesopic condition with glare) [23].

In the assessment of neurosensory binocular vision, subjective and objective squint angle were measured with synoptophore (TSJ-IV A synoptophore, Changchun Photoelectric Instrument Co., Ltd.) to assess the simultaneous perception. The fusion function was evaluated through fusion point, convergence, divergence and fusion range with synoptophore. The distance stereoscopic vision was also measured with synoptophore, while the near stereoscopic vision was measured with Titmus stereo test. All the neurosensory binocular vision outcomes were measured without correction.

This study employed a structured visual satisfaction questionnaire comprising three dimensions: spectacle independency, photic phenomena and subjective satisfaction quantification. Participants were instructed to: 1) report spectacle usage requirements across standardized visual task distances (yes/no); 2) identify occurrences of adverse photic phenomena, including glare, halo and starburst (present/absent); 3) assess their own satisfaction at different distances in the form of scores (1 = extremely dissatisfied, 2 = slightly dissatisfied, 3 = nertral; 4 = slightly satisfied, 5 = completely satisfied).

Statistical analysis

Statistical analysis was conducted using SPSS Statistics (version 22.0, IBM Corp, USA). Normality was verified through Kolmogorov–Smirnov testing. Continuous variables (mean ± SD) were compared through one-way ANOVA (parametric, with LSD test for multiple comparisons) or Kruskal–Wallis H test (non-parametric, with Bonferroni corrections for multiple comparisons). Categorical variables compare employed Chi-square test or Fisher exact test (expected frequencies < 5), with Bonferroni corrections for multiple comparisons. A P value less than 0.05 was considered statistically significant.

Results

Demographic and preoperative parameters

This study initially enrolled 95 patients. Affected by COVID-19 epidemic, 7 patients were excluded due to difficulties in completing the follow-up. There were eventually 176 eyes of 88 patients: 30 patients with bilateral EDOF IOL, 24 patients with bilateral trifocal IOL and 34 patients with bilateral bifocal IOL. Table 1 showed the demographics and preoperative characteristics of every group. There was no significant difference in sex ratio, age, CDVA, spherical equivalent (SEQ), corneal astigmatism and axial length among three groups (all $P > 0.05$). The IOL power of the EDOF group was significantly higher than the other two groups ($P = 0.002$).

Table 1 Demographics and preoperative characteristics

Parameter	EDOF group	Trifocal group	Bifocal group	*P* Value
Sex (male/female)	8/22	11/13	11/23	0.351
Age (years)	66.0 ± 11.7	66.3 ± 9.7	69.9 ± 9.0	0.233
CDVA (logMAR)	0.22 ± 0.22	0.18 ± 0.16	0.26 ± 0.17	0.102
SEQ (D)	−0.54 ± 2.54	−1.25 ± 2.21	−0.98 ± 2.21	0.083
Corneal astigmatism (D)	0.73 ± 0.29	0.60 ± 0.30	0.70 ± 0.38	0.132
AL (mm)	23.10 ± 0.99	23.32 ± 1.24	23.37 ± 0.96	0.361
IOL power (D)	22.12 ± 2.62[b,c] (22.68 ± 2.70)	20.52 ± 3.30[a]	19.94 ± 2.87[a]	0.002*

One-way ANOVA test or Kruskal–Wallis H test

The contents in brackets represent the data of the nondominant eyes in the EDOF group

AL Axial length, *CDVA* Corrected distance visual acuity, *D* Diopter, *EDOF* Extended depth of focus, *IOL* Intraocular lens, *logMAR* Logarithm of the minimum angle of resolution, *SEQ* Spherical equivalent

[a] $P < 0.05$ versus the EDOF group

[b] $P < 0.05$ versus the trifocal group

[c] $P < 0.05$ versus the bifocal group

[*] $P < 0.05$ among three groups

3.2 Efficacy, safety and accuracy

Table 2 showed the postoperative mean value of monocular UDVA, CDVA, cylinder and SEQ. For the dominant and nondominant eyes in the EDOF group, a result was recorded separately if it was influenced by the different target SEQ. For the efficacy of IOLs, no significant difference was obtained in the monocular UDVA among three groups, but the monocular CDVA in the bifocal group was relatively lower ($P = 0.001$). In Figure 1 A1 ~ 3, no significant difference was found in the proportions of eyes with UDVA reaching Snellen 20/20 among the three groups (43%, 44% and 41%, $P = 0.957$), but the bifocal group had a lower proportion with CDVA reaching Snellen 20/20 (77%, 83% and 62%, $P = 0.032$). In Figure 1 B1 ~ 3, no significant difference was found in the proportions of eyes with UDVA same or better than CDVA

Table 2 Refractive results and visual acuity three months after implantation

Parameter	EDOF group	Trifocal group	Bifocal group	*P* value
Monocular UDVA (logMAR)	0.11 ± 0.10 (0.16 ± 0.10)	0.12 ± 0.13	0.13 ± 0.13	0.850
Monocular CDVA (logMAR)	0.04 ± 0.07	0.02 ± 0.05[c]	0.08 ± 0.10[b]	0.001*
Postoperative cylinder (D)	−0.59 ± 0.42	−0.74 ± 0.47	−0.70 ± 0.49	0.226
Postoperative SEQ (D)	−0.51 ± 0.42 (−0.88 ± 0.53)	−0.27 ± 0.45[c]	−0.56 ± 0.56[b]	0.030*
Binocular UDVA (logMAR)	0.06 ± 0.08	0.05 ± 0.08	0.07 ± 0.12	0.709
Binocular UIVA (logMAR)	0.01 ± 0.07[c]	0.04 ± 0.08	0.07 ± 0.10[a]	0.031*
Binocular UNVA (logMAR)	0.12 ± 0.10	0.09 ± 0.11	0.08 ± 0.08	0.159
Binocular CDVA (logMAR)	0.03 ± 0.06	0.00 ± 0.05	0.05 ± 0.10	0.071
Binocular DCIVA (logMAR)	0.03 ± 0.07	0.07 ± 0.10	0.07 ± 0.08	0.147
Binocular DCNVA (logMAR)	0.20 ± 0.12[b]	0.08 ± 0.12[a]	0.12 ± 0.10	0.001*

One-way ANOVA test or Kruskal–Wallis H test

The contents in brackets represent the data of the nondominant eyes in the EDOF group

CDVA Corrected distance visual acuity, *D* Diopter, *EDOF* Extended depth of focus, *logMAR* logarithm of the minimum angle of resolution, *DCIVA* Distance-corrected intermediate visual acuity, *DCNVA* Distance-corrected near visual acuity, *SEQ* Spherical equivalent, *UDVA* Uncorrected distance visual acuity, *UIVA* Uncorrected intermediate visual acuity, *UNVA* Uncorrected near visual acuity

[a] $P < 0.05$ versus the EDOF group

[b] $P < 0.05$ versus the trifocal group

[c] $P < 0.05$ versus the bifocal group

[*] $P < 0.05$ among three groups

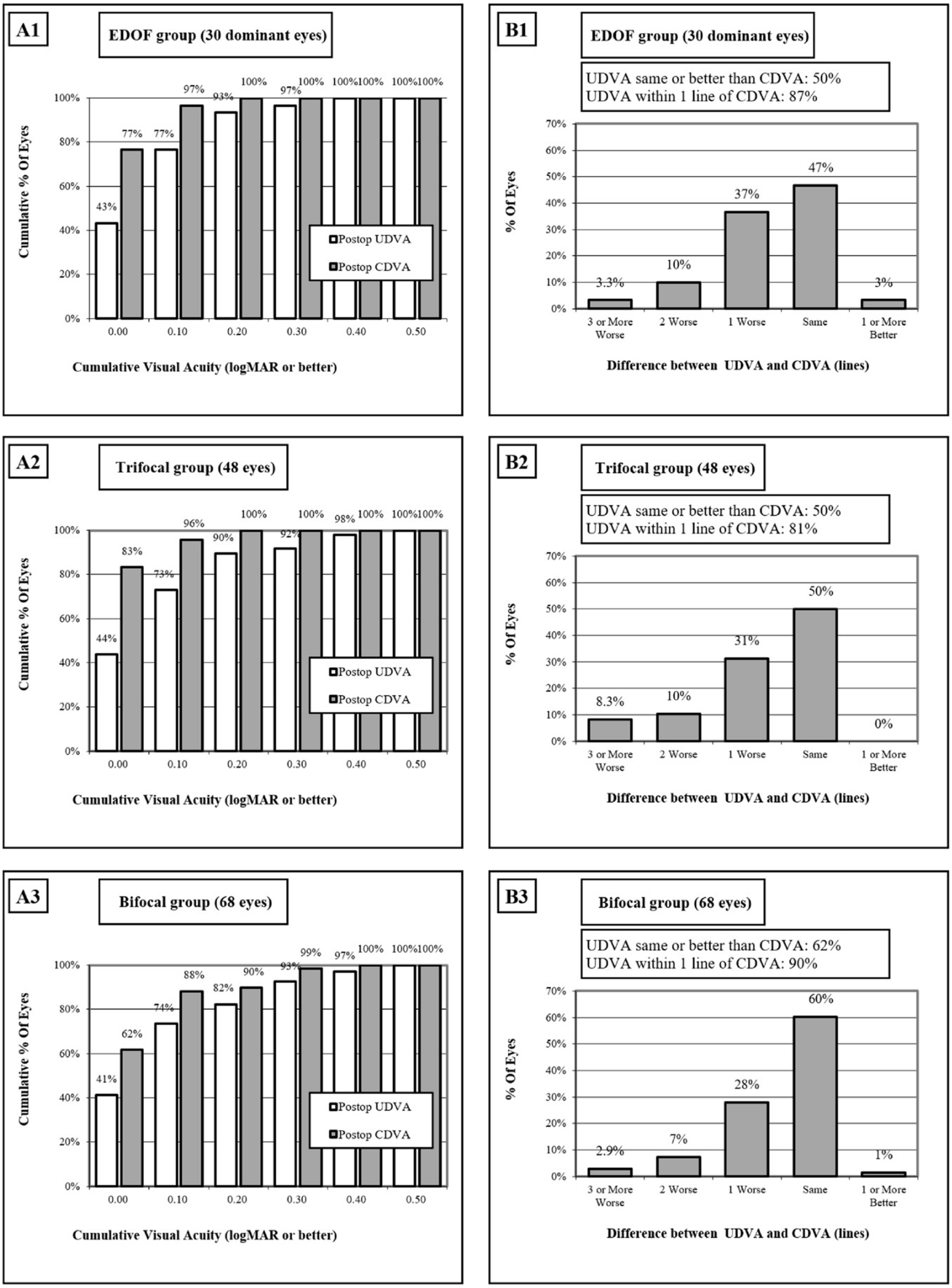

Fig. 1 Monocular visual outcomes of the EDOF group (dominant eyes), the trifocal group and the bifocal group three months after IOL implantation. (A1 ~ 3) Cumulative postoperative UDVA and CDVA of the three groups. (B1 ~ 3) Differences between postoperative UDVA and CDVA of the three groups. (CDVA = corrected distance visual acuity; D = diopter; EDOF = extended depth of focus; IOL = intraocular lens; UDVA = uncorrected distance visual acuity)

among the three groups (50%, 50% and 62%, $P = 0.361$). For the safety, none of the eyes in this study was found with worse CDVA postoperatively than before.

And for the accuracy, eyes in the bifocal group had a significantly higher degree of myopia than that of the trifocal group ($P = 0.030$). But Figure 2 A1 ~ 3 showed that the proportions of eyes with postoperative SEQ between −0.50 to +0.13 D were similar among the three groups (56%, 67% and 48%, $P = 0.152$). In addition, no significant difference was found in the postoperative cylinder among three groups ($P = 0.226$). And the proportions of eyes with cylinder no more than 0.50 D of the three groups were also similar (63%, 46% and 55%, $P = 0.313$) in Fig. 2 B1 ~ 3.

Binocular visual acuity at different distances

As is shown in Table 2, the binocular UIVA of the bifocal group was significantly lower than that of the EDOF group ($P = 0.031$), and the DCNVA of the EDOF group was significantly lower than that of the trifocal group ($P = 0.001$). No other significant difference was found.

Binocular defocus curve

Figure 3 showed the binocular uncorrected defocus curve of the three groups. The binocular visual acuity of the bifocal group was not as good as the other two groups at −1.0 D and −1.5 D ($P = 0.031$ and 0.009). The binocular visual acuity of the EDOF group was lower from −3.0 D to −4.0 D ($P = 0.040$, $P < 0.001$ and $P < 0.001$). No other significant difference was found.

Binocular contrast sensitivity

Figure 4 showed the binocular uncorrected contrast sensitivity of the three groups at different light conditions. The binocular contrast sensitivity of the EDOF group was lower at 6.0 and 12.0 cpd in the photopic condition ($P = 0.002$ and 0.006), at 1.5, 3.0, 6.0 and 12.0 cpd in the photopic condition with glare ($P = 0.001$, 0.009, 0.001 and 0.009), at 6.0 cpd in the mesopic condition ($P = 0.012$) and at 6.0 and 12.0 cpd in the mesopic condition with glare ($P = 0.047$ and 0.012). No other significant difference was found.

Neurosensory binocular vision

Table 3 showed three different aspects of neurosensory binocular vision. In the simultaneous perception, the subjective and objective squint angles of every patient were the same. No significant difference was found in the squint angle among three groups ($P = 0.176$). In the fusion outcomes, there was also no significant difference in fusion point, convergence, divergence and fusion range among three groups ($P = 0.110$, 0.546, 0.233 and 0.459). In the distance stereoscopic vision, the proportion of patients rated "good" (≤ 63″) of the EDOF group was the highest ($P = 0.020$), and the measured value of the EDOF group was significantly higher than that of the bifocal group ($P = 0.012$). In the near stereoscopic vision, the proportion of "good" and the measured value of the bifocal group were both lower than those of the trifocal group ($P = 0.077$ and 0.039).

Spectacle independence, photic phenomena and satisfaction

In Table 4, the near spectacle independence of the EDOF group was not as good as that of the trifocal group ($P = 0.030$). The incidence of starburst and halo at night of the EDOF group was significantly higher ($P = 0.037$ and 0.024). There was no significant difference in the satisfaction at different distances ($P = 0.370$, 0.524 and 0.209).

Discussion

As traditional monofocal IOLs lead to presbyopia symptoms, advanced IOLs with different optical design have been widely applied in recent years [2, 4]. SBL-3, a refractive bifocal IOL, has been proved to provide high light efficiency and good intermediate visual acuity even without a corresponding focal point [22, 25, 26]. AT LISA tri 839MP has been widely recognized as a trifocal IOL that provides good visual quality and high spectacle independence [2, 27, 28]. Multifocal IOLs typically target emmetropia with personalized adjustments to optimize visual outcomes while minimizing dysphotopsia risks. In our cohort, patients in the trifocal and bifocal groups exhibited preoperative mild myopia (around −1.00 D, Table 1). The −0.25D refractive target was strategically selected to enhance near vision performance and patient-reported satisfaction with presbyopia-correcting performance.

Tecnis Symfony ZXR00 is a relatively new IOL with EDOF design. With a 1.50 D depth-of-focus, it offers good intermediate vision without much compromise to the distance vision. However, compared to MIOLs, the suboptimal near vision of EDOF IOL has become the primary limitation in clinical adoption [18, 29–31]. Based on the EDOF IOL-based continuous vision range, the micro-monovision design has been proved to enhance the binocular near visual acuity to some extent [10]. And micro-monovision of around 0.75 D successfully provided good presbyopia-correcting performance with minimal photic phenomena and high levels of patient satisfaction [32].

This study comprehensively evaluated the efficacy, safety, accuracy, presbyopia-correcting performance, binocular visual quality, neurosensory binocular vision and satisfaction of the EDOF IOL, and compared them with two kinds of MIOLs. The demographics and biometric

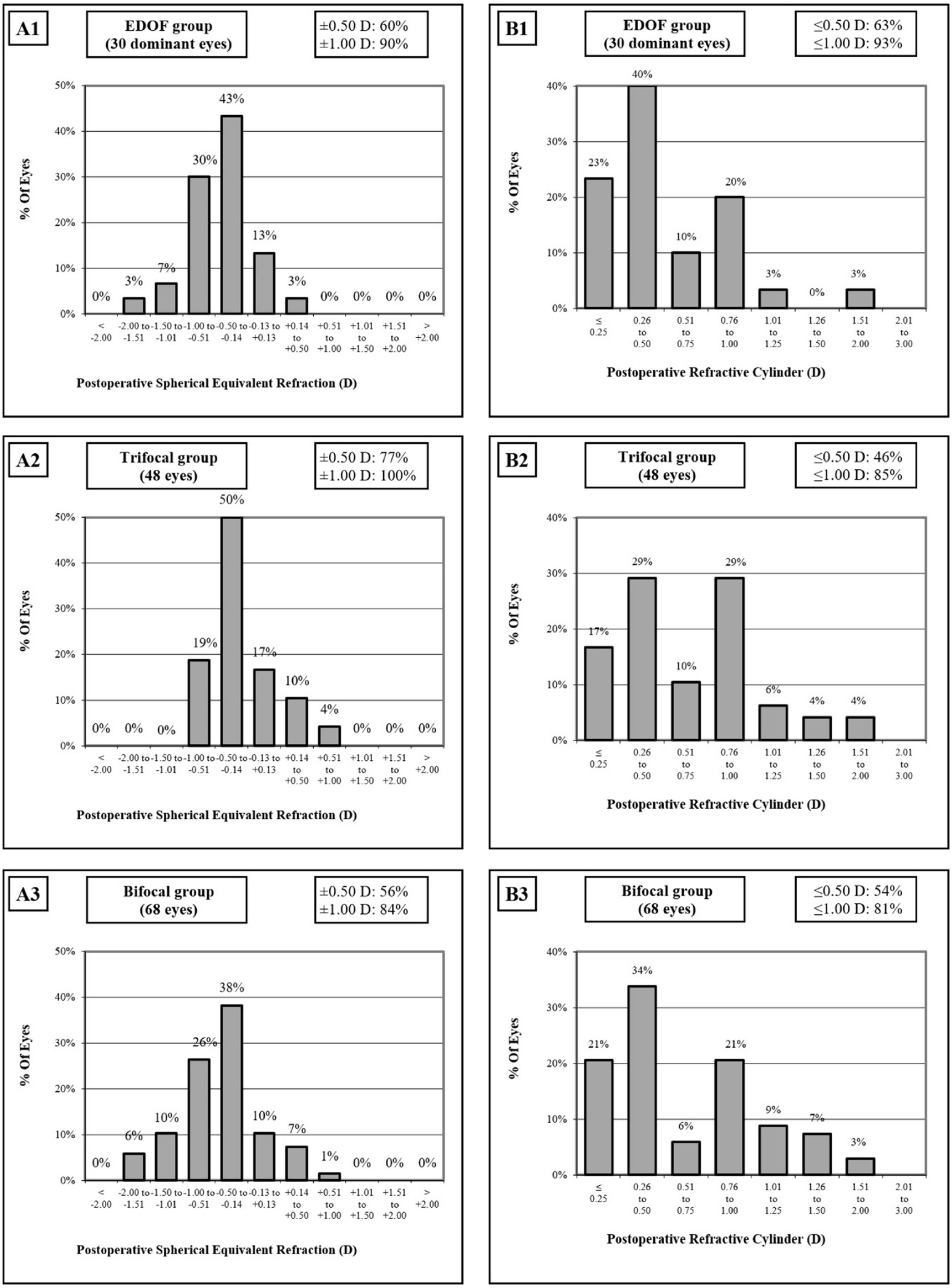

Fig. 2 Monocular refractive outcomes of the EDOF group (dominant eyes), the trifocal group and the bifocal group three months after IOL implantation. (A1 ~ 3) Postoperative spherical equivalent refraction of the three groups. (B1 ~ 3) Postoperative refractive cylinder of the three groups. (D = diopter; EDOF = extended depth of focus; IOL = intraocular lens)

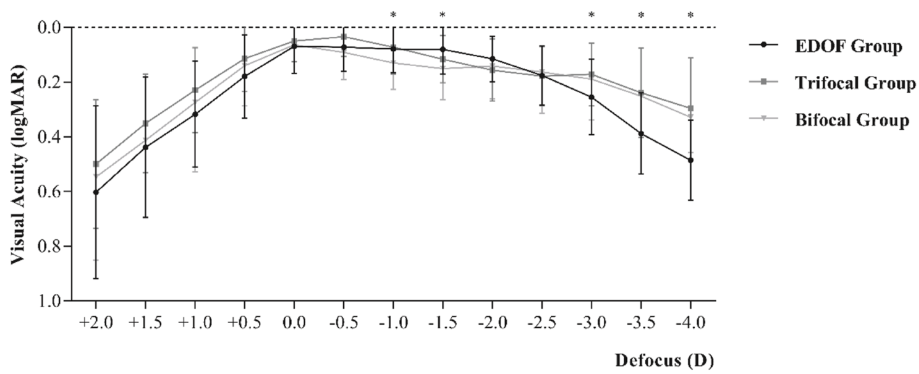

Fig. 3 Binocular defocus curves of the three groups. (D = diopter; EDOF = extended depth of focus; logMAR = logarithm of the minimum angle of resolution; *P < 0.05 among three groups)

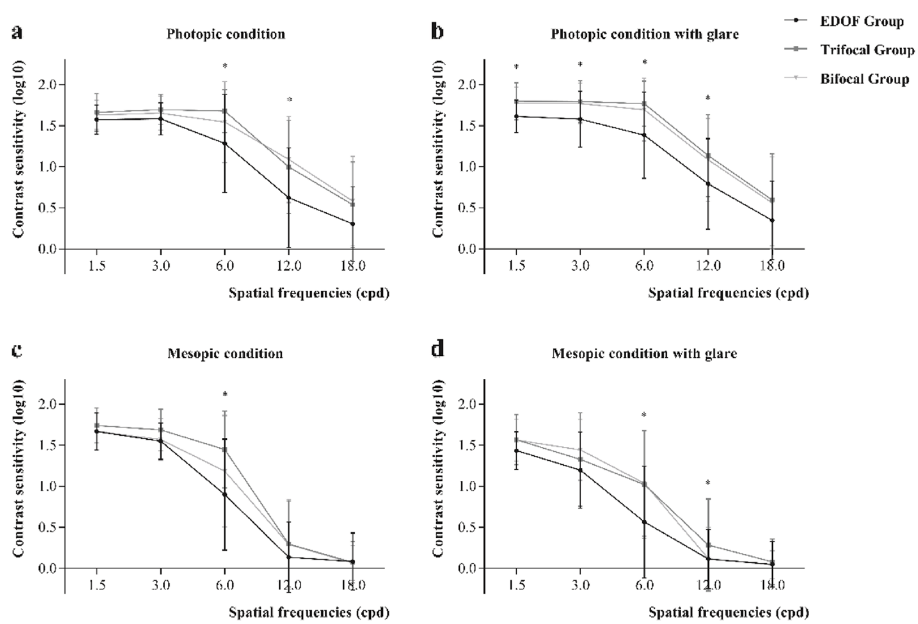

Fig. 4 Binocular contrast sensitivity of the three groups. (cpd = cycle per drgree; EDOF = extended depth of focus; *P < 0.05 among three groups)

parameters of the three groups were matched. The difference in IOL power might be mainly due to the different A-constant, a critical parameter in IOL power calculation varying across different IOL models [33].

Three months after implantation, the monocular visual results were satisfactory. The efficacy, safety and accuracy of the EDOF IOL achieved basically the same level as the trifocal IOL. The imperfection in the CDVA of the bifocal group might be caused by the larger higher-order aberration, coma aberration and trefoil aberration of SBL-3 [34]. In the IOL power calculation, the bifocal IOL showed a relatively lower accuracy. Even so, the UDVA of the three groups was similar, which had little effect on the evaluation of binocular uncorrected visual outcomes. Notably, Bellucci et al. demonstrated that infrared-based autorefraction overestimated myopia by approximately 0.50 D in eyes with EDOF or multifocal IOLs due to interference from refractive or diffractive near-add optical effects [35]. Subjective refraction based on autorefraction results might not fully avoid this effect, which could have potential implications for assessing IOL calculation accuracy postoperatively.

In terms of presbyopia-correcting performance, the EDOF group obtained better binocular UIVA (80 cm) than the bifocal group. It was consistent with the result at −1.0 D and −1.5 D in the binocular defocus curve. It proved that the elongated focus of 1.50 D of the EDOF IOL could provide great intermediate visual acuity, and

Table 3 Neurosensory binocular vision outcomes three months after implantation

Parameter		EDOF group	Trifocal group	Bifocal group	*P* value
Simultaneous perception	Subjective squint angle (°)	0.4 ± 3.6	2.1 ± 3.6	1.8 ± 3.6	0.176
	Objective squint angle (°)	0.4 ± 3.6	2.1 ± 3.6	1.8 ± 3.6	0.176
Fusion	Fusion point (°)	0.0 ± 3.7	2.0 ± 3.5	1.3 ± 3.3	0.110
	Convergence (°)	15.9 ± 8.3	13.5 ± 9.2	14.3 ± 7.6	0.546
	Divergence (°)	5.4 ± 1.2	4.8 ± 1.7	5.3 ± 1.2	0.233
	Fusion range (°)	21.3 ± 8.5	18.3 ± 10.3	19.6 ± 8.2	0.459
Stereoscopic vision (far)	Good (≤ 63″)	12 (40.0%)[b,c]	3 (12.5%)[a]	5 (14.7%)[a]	0.020*
	Moderate (≤ 200″)	11 (36.7%)	15 (62.5%)	14 (41.2%)	0.156
	Poor (> 200″)	7 (23.3%)	6 (25.0%)	15 (44.1%)	0.148
	Value (log arcsec)	2.12 ± 0.43[c]	2.23 ± 0.41	2.42 ± 0.45[a]	0.012*
Stereoscopic Vision (near)	Good (≤ 63″)	3 (10.0%)	7 (29.2%)[c]	3 (8.8%)[b]	0.077
	Moderate (≤ 200″)	20 (66.7%)	13 (54.2%)	19 (55.9%)	0.606
	Poor (> 200″)	7 (23.3%)	4 (16.7%)	12 (35.3%)	0.270
	Value (log arcsec)	2.28 ± 0.40	2.10 ± 0.39[c]	2.38 ± 0.51[b]	0.039*

One-way ANOVA test or Kruskal–Wallis H test to compare the mean; Chi-square test or Fisher exact test to compare the proportions

EDOF Extended depth of focus

[a] $P < 0.05$ versus the EDOF group

[b] $P < 0.05$ versus the trifocal group

[c] $P < 0.05$ versus the bifocal group

[*] $P < 0.05$ among three groups

Table 4 Spectacle independence, photic phenomena and satisfaction three months after implantation

Parameter			EDOF group	Trifocal group	Bifocal group	*P* value
Spectacle independence	Far		30 (100.0%)	24 (100.0%)	34 (100.0%)	> 0.999
	Intermediate		30 (100.0%)	23 (95.8%)	32 (94.1%)	0.489
	Near		23 (76.7%)[b]	24 (100.0%)[a]	30 (88.2%)	0.030*
Photic phenomena	Starburst	Day	2 (6.7%)	2 (8.3%)	2 (5.9%)	> 0.999
		Night	13 (43.3%)[c]	6 (25.0%)	5 (14.7%)[a]	0.037*
	Halo	Day	1 (3.3%)	4 (16.7%)	1 (2.9%)	0.120
		Night	11 (36.7%)[c]	7 (29.2%)[c]	3 (8.8%)[a,b]	0.024*
	Glare	Day	9 (30.0%)	6 (25.0%)	5 (14.7%)	0.367
		Night	3 (10.0%)	5 (20.8%)	3 (8.8%)	0.430
Satisfaction	Far		4.7 ± 0.6	4.6 ± 0.8	4.5 ± 0.8	0.370
	Intermediate		4.8 ± 0.5	5.0 ± 0.2	4.8 ± 0.6	0.524
	Near		4.6 ± 0.6	4.8 ± 0.4	4.8 ± 0.7	0.209

One-way ANOVA test or Kruskal–Wallis H test to compare the mean; Chi-square test or Fisher exact test to compare the proportions;

EDOF Extended depth of focus

[a] $P < 0.05$ versus the EDOF group

[b] $P < 0.05$ versus the trifocal group

[c] $P < 0.05$ versus the bifocal group

[*] $P < 0.05$ among three groups

the micro-monovision also played an important role [5, 30, 36]. The EDOF IOL successfully offered good and stable vision with additional spherical diopters from 0.0 D (far) ~ −2.0 D (corresponded to an approximate viewing distance of 50 cm), which was an unique advantage. Previous studies indicated that SBL-3 could provide satisfactory intermediate visual acuity, but without an intermediate focal point, it was still not as good as the EDOF IOL [22]. In addition, as the elongated focus of the EDOF IOL was only + 1.50D, the binocular DCNVA (40 cm) of the EDOF group was limited. But in the meanwhile, benefiting from the micro-monovision design, no significant difference was in binocular UNVA. As shown in the binocular defocus curve, the UNVA of the EDOF group would decline when looking at something closer [37, 38]. These indicated that EDOF IOLs are better suited for patients prioritizing stable distance and intermediate vision, while multifocal IOLs might perform better for those requiring frequent near tasks as well as spectacle independence.

Theoretically, the EDOF IOL performs better in monocular contrast sensitivity due to the combination of the compensation of the chromatic and spherical aberrations [9]. Previous studies about the characteristics of the EDOF IOL had also confirmed that [18, 39]. However, the binocular uncorrected contrast sensitivity was not as good as trifocal group when implanted with the micro-monovision design, especially in photic condition with glare. It might be owing to the binocular imbalance, caused by the mild anisometropia, and then limited the ability of the eyes to fuse and distinguish details.

To evaluate neurosensory binocular vision, synoptophore and Titmus stereo test were applied in this study. Binocular vision might be dynamically re-established following cataract surgery due to restoration of interocular refractive status. Previous studies indicated that some binocular vision problems found after cataract surgery were in fact already present prior to surgery [13]. In the exclusion criteria, patients with preoperative anisometropia (> 1.0 D), amblyopia and strabismus (alternate cover test) were excluded to minimize potential confounding effects of preexisting binocular visual dysfunction on postoperative outcomes. Preoperative assessment of binocular vision could further reduce residual confounding. However, as the visual acuity of these cataract patients were too low to obtain reliable synoptophore and Titmus stereo test outcomes preoperatively, reliable baseline data were not available for this part.

Existing studies have adopted divergent methodological approaches to binocular vision assessment: some investigations focused on quantifying motor aspects through alternate cover test, near point of convergence, and fusional convergence ranges [14], while others employed synoptophore to characterize sensory neural integration mechanisms [15–17]. The cover test is a key method for assessing the severity of strabismus, while the simultaneous perception test using a synoptophore focuses on evaluating the synchronized visual perception capability of both eyes, reflecting neural-level coordination mechanisms. Assessment of near point of convergence evaluates ocular motor function, while synoptophore-based fusional function testing measures the brain's capacity to integrate binocular disparity into a unified percept, reflecting neural integration mechanisms. Therefore, this study employed synoptophore-based assessment to evaluate the simultaneous perception and fusion function of patients.

Unlike the contrast sensitivity, the simultaneous perception, fusion and stereoscopic vision (far and near) of the EDOF group showed no significant decline. In the stereoscopic vision outcomes, the EDOF group had the highest proportion of patients rated "good" at far distance, while this proportion declined sharply at near distance. The continuous vision range of the EDOF IOL provided better stereoscopic vision, but it was strongly influenced by the decreased visual acuity at near distances. Weakley [12] concluded that spherical myopic anisometropia of more than 2 D or spherical hypermetropic anisometropia of more than 1 D significantly influenced binocular function. In this study, the micro-monovision of 0.50 ~ 0.75 D improved near visual acuity to some extent, without significant decrease in the neurosensory binocular vision.

Besides, the bifocal group obtained poor stereoscopic vision whether at far or near distance. Unlike the EDOF IOL with a continuous vision range, nor the trifocal IOL with three focal points, the bifocal IOL with a + 3.0 D near add seemed to provide too limited depth of field to produce better stereoscopic vision. There were few studies on the binocular vision after EDOF IOL and MIOLs implantation. In this study, neurosensory binocular vision served as an indirect biomarker reflecting the neuroadaptive processes following cataract surgery. We plan to conduct further investigations incorporating functional magnetic resonance imaging and other neuroimaging metrics to systematically explore the neural plasticity patterns during postoperative neuroadaptation.

Consistent with the near visual acuity results, the near spectacle independence of the EDOF group was lower. Previous studies had confirmed that the incidence of photic phenomena of the EDOF IOL was low [30, 36]. But compared with the refractive bifocal IOL, the incidences of starburst and halo at night were still significantly higher in the diffractive EDOF IOL (significant difference), and relatively higher in the diffractive trifocal IOL (difference did not reach statistical significance). These were because refractive multifocal IOLs could effectively avoid optical disturbance [40].

Detailed preoperative communication on the advantages and disadvantages of IOLs were provided for patients to set appropriate patient expectations, which might significantly improve subjective satisfaction. In addition, the relatively reasonable cost and good neurosensory binocular vision performance of the EDOF IOL enhanced patient satisfaction to some extent.

One of the limitations of this study was the non-randomized IOL implantation. The IOL selection was determined by individualized patient needs following detailed clinician-patient discussion. While this real-world approach introduces potential selection bias, it reflects clinical practice where patient preferences actively guide IOL selection, aligning with patient-centered decision-making. The second limitation was the follow-up of three months, which might be a relatively short period to assess neurosensory binocular vision and postoperative adaptation of different IOLs. Evaluation at different postoperative time points, especially a minimum 12-month or longer follow-up might better reflect the establishment process of the binocular vision. Besides, while the limited cohort size may affect generalizability, sufficient statistical power was ensured for the key outcome metrics. And in order to avoid too limited near visual acuity, there was not a control EDOF group with bilateral emmetropia design in this study. Future studies will involve multicenter trials with larger samples, incorporating functional magnetic resonance imaging to assess post-cataract neuroadaptive processes and explore links between binocular visual rehabilitation and neural adaptation.

Conclusions

Bilateral EDOF IOL implantation with micro-monovision successfully treated cataract, provided reliable binocular far and intermediate visual acuity, good neurosensory binocular vision and patient satisfaction. It achieved better far stereoscopic vision than multifocal IOLs, but lagged behind in near visual acuity, near spectacle independence and binocular contrast sensitivity.

Abbreviations

CDVA	Corrected distance visual acuity
cpd	Cycles per degree
DCIVA	Distance-corrected intermediate visual acuity
DCNVA	Distance-corrected near visual acuity
EDOF	Extended depth of focus
IOL	Intraocular lens
logMAR	Logarithm of the minimum angle of resolution
MIOL	Multifocal intraocular lens
SEQ	Spherical equivalent
UDVA	Uncorrected distance visual acuity
UIVA	Uncorrected intermediate visual acuity
UNVA	Uncorrected near visual acuity

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Authors' contributions
Study conception and design (HQ, TS); data collection (TS, QL, CT, RQ, LB, WL); data analysis and interpretation (TS, XZ); writing the manuscript (TS, XZ); critical revision of the manuscript (YL, QL, HQ); statistical expertise (XZ, YL, HQ); obtaining funding (HQ, TS, QL); administrative, technical, or material support (HQ); supervision (HQ).

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Data availability
The datasets generated and analyzed during the current study are not publicly available due to ethical restrictions but are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
This study adhered to the Declaration of Helsinki for the use of human participants in biomedical research and received the approval of the ethics committee of Peking University Third Hospital. Informed consent was obtained from all participants included in the study. Written informed consent was obtained from all subjects.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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References

1. Wolffsohn JS, Davies LN. Presbyopia: Effectiveness of correction strategies. Prog Retin Eye Res. 2019;68:124–43.
2. Alio JL, Plaza-Puche AB, Fernandez-Buenaga R, Pikkel J, Maldonado M. Multifocal intraocular lenses: An overview. Surv Ophthalmol. 2017;62(5):611–34.
3. Negishi K, Hayashi K, Kamiya K, Sato M, Bissen-Miyajima H, Survey Working Group of the Japanese Society of C, et al. Nationwide Prospective Cohort Study on Cataract Surgery With Multifocal Intraocular Lens Implantation in Japan. Am J Ophthalmol. 2019;208:133-144.
4. Rampat R, Gatinel D. Multifocal and Extended Depth-of-Focus Intraocular Lenses in 2020. Ophthalmology. 2020.
5. Cochener B, Concerto Study G. Clinical outcomes of a new extended range of vision intraocular lens: International Multicenter Concerto Study. J Cataract Refract Surg. 2016;42(9):1268–75.
6. Akella SS, Juthani VV. Extended depth of focus intraocular lenses for presbyopia. Curr Opin Ophthalmol. 2018;29(4):318–22.
7. Pilger D, Homburg D, Brockmann T, Torun N, Bertelmann E, von Sonnleithner C. Clinical outcome and higher order aberrations after bilateral implantation of an extended depth of focus intraocular lens. Eur J Ophthalmol. 2018;28(4):425–32.
8. Megiddo-Barnir E, Alió JL. Latest development in extended depth-of-focus intraocular lenses: an update. Asia Pac J Ophthalmol (Phila). 2023;12(1):58–79.
9. Weeber HA, Meijer ST, Piers PA. Extending the range of vision using diffractive intraocular lens technology. J Cataract Refract Surg. 2015;41(12):2746–54.

10. Sandoval HP, Lane S, Slade S, Potvin R, Donnenfeld ED, Solomon KD. Extended depth-of-focus toric intraocular lens targeted for binocular emmetropia or slight myopia in the nondominant eye: Visual and refractive clinical outcomes. J Cataract Refract Surg. 2019;45(10):1398–403.
11. Sandoval HP, Lane S, Slade SG, Donnenfeld ED, Potvin R, Solomon KD. Defocus curve and patient satisfaction with a new extended depth of focus toric intraocular lens targeted for binocular emmetropia or slight myopia in the non-dominant Eye. Clin Ophthalmol. 2020;14:1791–8.
12. Weakley DR. The association between nonstrabismic anisometropia, amblyopia, and subnormal binocularity. Ophthalmology. 2001;108(1):163–71.
13. Garcia-Montero M, Albarran Diego C, Garzon-Jimenez N, Perez-Cambrodi RJ, Lopez-Artero E, Ondategui-Parra JC. Binocular vision alterations after refractive and cataract surgery: a review. Acta Ophthalmol. 2019;97(2):e145–55.
14. Cacho-Martínez P, Cantó-Cerdán M, Carbonell-Bonete S, García-Muñoz Á. Characterization of Visual Symptomatology Associated with Refractive, Accommodative, and Binocular Anomalies. J Ophthalmol. 2015;2015:895803.
15. Veverka KK, Hatt SR, Leske DA, Brown WL, Iezzi R Jr, Holmes JM. Causes of Diplopia in Patients With Epiretinal Membranes. Am J Ophthalmol. 2017;179:39–45.
16. Dormegny L, Foch M, Messerlin A, Bourcier T, Sauer A, Gaucher D. Binocular visual function improvement after pars plana vitrectomy for epiretinal membrane. Acta Ophthalmol. 2023;101(7):807–14.
17. Tidbury LP, O'Connor AR, Wuerger SM. The effect of induced fusional demand on static and dynamic stereoacuity thresholds: the digital Synoptophore. BMC Ophthalmol. 2019;19(1):6.
18. Mencucci R, Favuzza E, Caporossi O, Savastano A, Rizzo S. Comparative analysis of visual outcomes, reading skills, contrast sensitivity, and patient satisfaction with two models of trifocal diffractive intraocular lenses and an extended range of vision intraocular lens. Graefes Arch Clin Exp Ophthalmol. 2018;256(10):1913–22.
19. Kohnen T, Suryakumar R. Extended depth-of-focus technology in intraocular lenses. J Cataract Refract Surg. 2020;46(2):298–304.
20. Ganesh S, Brar S, Pawar A. Long-term visual outcomes and patient satisfaction following bilateral implantation of trifocal intraocular lenses. Clin Ophthalmol. 2017;11:1453–9.
21. Sezgin AB. Visual and refractive outcomes, spectacle independence, and visual disturbances after cataract or refractive lens exchange surgery: Comparison of 2 trifocal intraocular lenses. J Cataract Refract Surg. 2019;45(11):1539–46.
22. Venter JA, Barclay D, Pelouskova M, Bull CE. Initial experience with a new refractive rotationally asymmetric multifocal intraocular lens. J Refract Surg. 2014;30(11):770–6.
23. Sun T, Liu Y, Gao Y, Tang C, Lan Q, Yang T, et al. Comparison of visual outcomes of a diffractive trifocal intraocular lens and a refractive bifocal intraocular lens in eyes with axial myopia: a prospective cohort study. BMC Ophthalmol. 2022;22(1):407.
24. Kohnen T, Lemp-Hull J, Suryakumar R. Defocus curves: focusing on factors influencing assessment. J Cataract Refract Surg. 2022;48(8):961–8.
25. Lian H, Ma W, Wei Q, Yuan X. A comparative study on early vision quality after implantation of refractive segmental and diffractive multifocal intraocular lens. Pak J Med Sci. 2020;36(7):1607–12.
26. Liu Y, Lan Q, Sun T, Tang C, Yang T, Duan H, et al. Binocular visual function after unilateral versus bilateral implantation of segmented refractive multifocal intraocular lenses: a pilot study. Graefes Arch Clin Exp Ophthalmol. 2022;260(4):1205–13.
27. Law EM, Aggarwal RK, Buckhurst H, Kasaby HE, Marsden J, Shum G, et al. One-year post-operative comparison of visual function and patient satisfaction with trifocal and extended depth of focus intraocular lenses. Eur J Ophthalmol. 2021:11206721211069737.
28. Chen L, Sun L, Tang Y, Sui W, Bian A, Zhang X, et al. Visual performance, safety, and patient satisfaction after binocular clear lens extraction and trifocal intraocular lens implantation in Chinese presbyopic patients. BMC Ophthalmol. 2024;24(1):305.
29. Xu J, Zheng T, Lu Y, Fernandes P. Comparative Analysis of Visual Performance and Astigmatism Tolerance with Monofocal, Bifocal, and Extended Depth-of-Focus Intraocular Lenses Targeting Slight Myopia. J Ophthalmol. 2020;2020:1–11.
30. Webers VSC, Bauer NJC, Saelens IEY, Creten OJM, Berendschot T, van den Biggelaar F, et al. Comparison of the intermediate distance of a trifocal IOL with an extended depth-of-focus IOL: results of a prospective randomized trial. J Cataract Refract Surg. 2020;46(2):193–203.
31. Tavassoli S, Ziaei H, Yadegarfar ME, Gokul A, Kernohan A, Evans JR, et al. Trifocal versus extended depth of focus (EDOF) intraocular lenses after cataract extraction. Cochrane Database Syst Rev. 2024;7(7):Cd014891s.
32. Cochener B. Influence of the level of monovision on visual outcome with an extended range of vision intraocular lens. Clin Ophthalmol. 2018;12:2305–12.
33. Langenbucher A, Szentmáry N, Cayless A, Wendelstein J, Hoffmann P. Evaluating intraocular lens power formula constant robustness using bootstrap algorithms. Acta Ophthalmol. 2023;101(3):e264–74.
34. Wang X, Tu H, Wang Y. Comparative Analysis of Visual Performance and Optical Quality with a Rotationally Asymmetric Multifocal Intraocular Lens and an Apodized Diffractive Multifocal Intraocular Lens. J Ophthalmol. 2020;2020:7923045.
35. Bellucci C, Mora P, Tedesco SA, Gandolfi S, Bellucci R. Automated and subjective refraction with monofocal, multifocal, and EDOF intraocular lenses: review. J Cataract Refract Surg. 2023;49(6):642–8.
36. Savini G, Schiano-Lomoriello D, Balducci N, Barboni P. Visual Performance of a New Extended Depth-of-Focus Intraocular Lens Compared to a Distance-Dominant Diffractive Multifocal Intraocular Lens. J Refract Surg. 2018;34(4):228–35.
37. Bohm M, Petermann K, Hemkeppler E, Kohnen T. Defocus curves of 4 presbyopia-correcting IOL designs: Diffractive panfocal, diffractive trifocal, segmental refractive, and extended-depth-of-focus. J Cataract Refract Surg. 2019;45(11):1625–36.
38. Cochener B, Boutillier G, Lamard M, Auberger-Zagnoli C. A Comparative Evaluation of a New Generation of Diffractive Trifocal and Extended Depth of Focus Intraocular Lenses. J Refract Surg. 2018;34(8):507–14.
39. Pedrotti E, Carones F, Aiello F, Mastropasqua R, Bruni E, Bonacci E, et al. Comparative analysis of visual outcomes with 4 intraocular lenses: Monofocal, multifocal, and extended range of vision. J Cataract Refract Surg. 2018;44(2):156–67.
40. Liu X, Wu X, Huang Y. Laboratory Evaluation of Halos and Through-Focus Performance of Three Different Multifocal Intraocular Lenses. J Refract Surg. 2022;38(9):552–8.

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