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ORIGINAL PAPER

Comparisons of visual outcomes between bilateral implantation and mix-and-match implantation of three types intraocular lenses

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Abstract

Purpose To compare binocular static visual acuity (SVA), stereopsis, contrast sensitivity (CS) and dynamic visual acuity (DVA) of 5 combinations of bifocal intraocular lenses (IOLs), trifocal IOLs and extended-depth-of-focus (EDOF) IOLs in age-related cataract patients.

Methods Two hundred and ninety-two eyes of 146 patients who underwent cataract surgery in the ophthalmology department of the First Affiliated Hospital of Chongqing Medical University were involved. Subgroups included group MM (33patients, bilaterally bifocal IOL, ZMB00), group TT (31patients, bilaterally trifocal IOL, AT LISA tri839MP), group XX (34patients, bilaterally EDOF IOL, ZXR00), group MX (25patients, bifocal IOL, ZMB00 + EDOF IOL, ZXR00) and group TX (23patients, trifocal IOL, AT LISA tri839MP + EDOF IOL, ZXR00). The uncorrected SVAs (UDVA, UIVA and UNVA), uncorrected DVAs (UDDVA, UIDVA and UNDVA), near and distance stereopsis, and CS were assessed 3 months postoperatively.

Results Subgroups of TT, XX, MX and TX showed better UIVA than MM (bP = 0.039, 0.021, 0.035 and 0.037, respectively). MX showed better UNVA than MM and TX (bP = 0.031 and 0.013, respectively). MX group had the optimal outcomes of both near and distance stereopsis. In the UDDVA, XX group and MX group showed better outcomes than TX group at 24 fps (frames per second) (bP = 0.019 and 0.023, respectively). XX group and MX group showed optimal outcomes at all speeds of UIDVA ($P = 0.001$, 0.005, 0.003 and 0.005, respectively). As the speed increased, the XX group and the MX group showed better UNDVA than the MM group and the TT group ($P = 0.019$, 0.002 and 0.003, respectively).

Conclusions Mix-and-match implantation of bifocal IOLs and EDOF IOLs provides excellent and stable binocular visual outcomes including SVA, stereopsis and DVA in distant and near distances.

Keywords Multifocal intraocular lens · Extended depth of focus intraocular lens · Dynamic visual acuity · Mix-and-match implantation · Stereopsis · Contrast sensitivity

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Introduction

Phacoemulsification is gradually becoming a refractive surgery because of patients' demand for

optimal visual quality. In recent years, several types of presbyopia-correcting intraocular lenses (IOLs) have been designed to provide distance and near visual acuity for spectacle independence choices. Bifocal IOLs perform suboptimal intermediate visual acuity compared with satisfactory results for near and far distances with different near addition options [1]. Trifocal IOLs provide a third focal point to enhance intermediate visual acuity in addition to bifocal IOLs, but it has been reported that trifocal IOLs may reduce contrast sensitivity and increase unwanted optical phenomena such as glare and halos [2, 3]. Extended-depth-of-focus (EDOF) IOLs were developed to provide a continuous range of focus for most distances and a distinctive diffractive pattern with an achromatic design to overcome the photic phenomena [4, 5]. However, EDOF IOLs perform worse results for near visual acuity in comparison with bifocal or trifocal IOLs [6–8]. A combination of different types of IOLs, the so-called mix-and-match implantation, is one of the ways to compensate for these limitations. Such a combination has previously been shown to accomplish improved visual outcomes [9–14].

As for postoperative evaluation, we should not only focus on providing a satisfactory static visual acuity (SVA) across all ranges of distances and contrast sensitivity (CS) but also an optimal binocular visual quality including stereopsis and dynamic visual acuity (DVA) [15, 16]. DVA refers to the ability of identification details of an object when it moves relative to the observer [17]. Compared with SVA, DVA can be more helpful in assessing the ability of patients to complete everyday life tasks including sports activities and driving after surgery [18]. A previous multi-center study showed that trifocal IOLs can provide better DVA than monofocal IOLs [16]

Most of previous researches on the assessment of the clinical outcomes of bilateral and mix-and-match implantation focused on static visual function [9–14]. However, the binocular stereopsis and DVA of different combinations of IOLs were not investigated or compared before. The purpose of this study was to compare the visual outcomes including stereopsis and DVA of 5 combinations of bifocal IOLs (ZMB00), trifocal IOLs (AT LISA tri839MP) and EDOF IOLs (ZXR00).

Materials and methods

Study design

This study was a single-center, prospective case series involving age-related cataract (ARC) patients who underwent cataract surgery at the Department of Ophthalmology, The First Affiliated Hospital of Chongqing Medical University (CQMU), Chongqing, China. Written informed consent was obtained from all patients. The study conducted in accordance with the ethical principles originating from the Declaration of Helsinki, was approved by the CQMU Review Board (2015-7). Patients with ARC aged 50–65 years, who had axial length of the eyes of 23–24 mm and corneal astigmatism ≤ 1.0 D were included. The patients with postoperative spectacle independence requirements were scheduled for binocular presbyopia-correcting IOL implantations. Exclusion criteria included other ocular diseases (corneal disease, glaucoma, macular degeneration, optic neuropathy, uveitis, retinal detachment, diabetic retinopathy, hypertensive retinopathy, etc.), diseases (cerebrovascular disease, mental illness, etc.) that can cause unresponsiveness, complicated systemic disease or were incapable of completing study related visits.

Two hundred and ninety-two eyes of 146 patients were enrolled in the study. The patients were divided into five groups based on the bilateral or blended approaches as follows: the bilateral implantation of bifocal IOLs (ZMB00)(group MM), the bilateral implantation of trifocal IOLs (AT LISA tri839MP) (group TT), the bilateral implantation of EDOF IOLs (ZXR00) (group XX), the blended implantation of bifocal IOLs (ZMB00) and EDOF IOLs (ZXR00) (group MX), and the blended implantation of trifocal IOLs (AT LISA tri839MP) and EDOF IOLs (ZXR00) (group TX). All patients underwent a comprehensive preoperative ophthalmological examination, comprising slit-lamp, ophthalmoscopy, Goldmann tonometry, Scheimpflug tomography (Pentacam HR, Oculus, Germany) and biometry (IOL Master 500, Carl Zeiss Meditec, Germany). The power for IOLs was calculated using the Barrett Universal II formula and Haigis formula. The aimed postoperative refraction was 0 ± 0.25 D for bifocal IOLs (ZMB00) and trifocal IOLs (AT LISA tri839MP), and -0.5 ± 0.25 D for EDOF IOLs (ZXR00). Reaction of all patients was

tested by Hand-grabbing-ruler Test to exclude unresponsive patients.

Hand-grabbing-ruler test The examiner is holding a steel ruler, and the examinee's hand is placed 20 cm below the lower end of the ruler. The examiner suddenly let go of the ruler, and at the same time, the examinee grasps the falling ruler as fast as he can. The distance (cm) (reaction distance, RD) the ruler slides down represents the examinee's reaction speed. Each patient was tested three times to obtain the average value.

Study IOLs

The bifocal IOL (ZMB00, Johnson and Johnson Vision, America), the trifocal IOL (AT LISA tri 839 MP, Carl Zeiss Meditec, Germany) and the EDOF IOL (ZXR00, Johnson and Johnson Vision, America) were used for this study. ZMB00 is a bifocal, foldable hydrophobic acrylic one-piece IOL, which has 6.0-mm optics diameter and a near power of +4.0 D in the IOL plane splitting the light into two focal points for distance and near vision. AT LISA tri 839MP is a diffractive trifocal IOL made of hydrophilic acrylic material, and it has a trifocal part in the central 4.3 mm, which provides a near addition of +3.33 D and an intermediate addition of +1.66 D in the IOL plane. The two are collectively referred to as multifocal IOLs, which using the principle of light diffraction, so the light entering the eye can form multiple focal points to achieve the purpose of near and far vision at the same time. ZXR00, the so-called EDOF IOL, is a one-piece, hydrophobic acrylic and pupil-independent diffractive IOL, which has anterior aspheric surface and a posterior achromatic surface with an echelette design for correction of chromatic aberrations, enhancement of contrast sensitivity, and the introduction of a novel pattern of light diffraction that creates a single elongated focal point for enlarging the depth of focus and thus offers a wide range of vision.

Surgical technique

All surgical procedures were completed by the same experienced ophthalmologist using a standardized sutureless phacoemulsification with a 2.8 mm corneoscleral limbus main incision at the 11 O'clock position. And the assisted incision was performed at the 2 O'clock position. The selected IOL was implanted into the capsule. Contralateral surgery was performed at an interval of one week. All patients used a combined eye-drop including antibiotic and steroid agents postoperatively. No complications occurred during or after surgery.

Outcome measures

Three months after the MIOL implantations, the spherical equivalent (SE) and the corrected distance visual acuity (CDVA) were measured. And the binocular uncorrected near, intermediate, distance VAs (UNVA, UIVA and UDVA, respectively) were measured at the distances of 0.4, 0.8 and 5 m. Likewise, the binocular uncorrected near, intermediate, distance DVAs (UNDVA, UIDVA and UDDVA, respectively) at the distances of 0.4, 0.8 and 5 m were obtained using a DVA test system. The VAs were converted to the logarithm of the minimum angle of resolution (logMAR) for analysis. The CS and the near and distance stereopsis at 0.4 and 5 m was measured using the Binoptometer 4P (OCULUS, Germany).

DVA test system The test procedure is carried out in a dedicated visual function test room. The monitor (17-inch LCD screen, screen resolution 1920×1080, screen refresh frequency 75 Hz) (Fig. 1) was placed directly in front of the examinee. 11 optotypes moving horizontally on the monitor were developed to be the same size as the logMAR visual acuity chart with an adjustable speed, including 4, 8, 12, and 24 frames per second (fps). The adjacent optotypes have different directions, and the moving direction is from right to left. Adjust the examinee's seat so that the horizontal position of the eyes is at the same height as the center of the E optotype. The test distances are 0.4,

Fig. 1 Dynamic visual acuity test system

0.8 and 5 m, respectively. During the test, neither the examinee's body nor the head can be shaken. Do a rehearsal of this test method and process to familiarize the examinee. During the formal test, the examinee needs to quickly identify the optotype direction. The examiner marks the first optotype value that was identified incorrectly, and records the previous optotype value as the DVA value. Examinees have to rest for 2 min when each test is completed. Perform 5 tests to obtain the average value as the final DVA of the corresponding speed and distance. The design principles comprehensively refer to the method of Patel and other research teams [16–20].

Statistical analyses

The study planned to enroll at least 190 patients, 38 in each subgroup, which would provide 90% power to assess the statistically significant differences of the subgroups. However, as some patients were lost to follow-up, a total of 146 patients (292 eyes) were enrolled (the smallest sample size of the subgroup was 23). This sample size would provide 80% power based on a two sided *t* test with a significance level of 5%.

All statistical analyses were done with SPSS 26.0 software (IBM, SPSS Inc). All data were cross-checked by 3 trained researchers. Chi-square test performed for the comparisons of the enumeration data. The measurement data is first detected by the Kolmogorov Smirnov method to check whether it is a normal distribution: the normal distribution measurement data is expressed as means ± standard deviations, and the data of the five groups are compared using the analysis of variance; the abnormal distribution measurement data is expressed as medians (interquartile range) (M (IQR)), and the data comparisons among the five groups were analyzed by the Kruskal–Wallis H test with the Bonferroni correction. *P* values less than 0.05 were considered statistically significant.

Results

A total of 146 patients (292 eyes) were enrolled. Groups MM, TT, XX, MX and TX were comprised of 33, 31, 34, 25 and 23 patients, respectively. There were no statistically significance in the age, gender and RD among the five groups ($P=0.573$, $P=0.396$ and $P=0.862$, analysis of variance and chi-square test, respectively) (Table 1).

NO statistically significance in SE and CDVA at 3 months postoperatively were seen among the groups ($P=0.481$ and $P=0.634$, analysis of variance and Kruskal–Wallis *H* test, respectively). There were no statistically significance among the five groups in the UDVA ($P=0.737$, Kruskal–Wallis *H* test) at 3 months postoperatively. Comparisons between groups revealed that there were statistically significant differences between some specific IOLs in the UIVA and UNVA ($P=0.006$ and $P=0.038$, respectively, Kruskal–Wallis *H* test). Subgroups of TT (0.000 (0.53)), XX (0.000 (0.10)), MX (0.000 (0.10)) and TX (0.000 (0.15)) showed better UIVA than MM (0.100 (0.15)) (bP = 0.039, bP = 0.021, bP = 0.035 and bP = 0.037, respectively). Likewise, MX (0.000 (0.11)) showed better UNVA than MM (0.100 (0.15)) and TX (0.175 (0.15)) (bP = 0.031 and bP = 0.013, respectively) (Table 2; Fig. 2).

Table 1 Comparison of age, gender, and RD among patients in 5 groups

Groups	MM	TT	XX	MX	TX	*P* value
Implanted IOL	ZMB00, ZMB00	Tri.839, Tri.839	ZXR00, ZXR00	ZMB00, ZXR00	Tri.839, ZXR00	
n	33	31	34	25	23	–
Age, year	66.31 ± 3.7	63.52 ± 4.5	63.94 ± 4.6	64.21 ± 7.5	62.14 ± 6.3	0.573
Male [*n* (%)]	15 (46)	16 (52)	16 (47)	14 (56)	10 (43)	0.396
Female [*n* (%)]	18 (54)	15 (48)	18 (53)	11 (44)	13 (57)	–
RD, cm	8.39 ± 0.51	8.40 ± 0.87	8.33 ± 0.49	8.51 ± 0.14	8.49 ± 0.11	0.862

MM, Tecnis ZMB00 IOLs; TT, AT Lisa tri.839MPIOLs; XX, Tecnis ZXR00 IOLs; MX, Tecnis ZMB00 IOL and Tecnis ZXR00 IOL; TX, AT Lisa tri.839MPIOL and Tecnis ZXR00 IOL; *n*, number of cases; RD, reaction distance

$P<0.05$, significantly different

Table 2 SE and SVA 3 months postoperatively

Groups	MM	TT	XX	MX	TX	*P* value
SE, D	−0.2 ± 0.4	−0.4 ± 0.3	−0.5 ± 0.1	−0.3 ± 0.5	−0.3 ± 0.7	0.481
CDVA	0.050 (0.31)	0.047 (0.23)	0.000 (0.17)	0.000 (0.17)	0.043 (0.20)	0.634
UDVA	0.100 (0.11)	0.050 (0.23)	0.050 (0.10)	0.000 (0.20)	0.100 (0.10)	0.737
UIVA	0.100 (0.15)	0.000 (0.53)	0.000 (0.10)	0.000 (0.10)	0.000 (0.15)	**0.006***
	bP MM–TT **0.039***; MM–XX **0.021***; MM–MX **0.035***; MM–TX **0.037***					
	TT–XX 0.798; TT–MX 0.532; TT–TX 0.675					
	XX–MX 1.000; XX–TX 1.000					
	MX–TX 1.000					
UNVA	0.100 (0.15)	0.100 (0.13)	0.050 (0.16)	0.000 (0.11)	0.175 (0.15)	**0.038***
	bP MM–TT 1.000; MM–XX 0.075; MM–MX **0.031***; MM–TX 0.891					
	TT–XX 0.074; TT–MX 0.108; TT–TX 1.000					
	XX–MX 1.000; XX–TX 0.089					
	MX–TX **0.013***					

bP Bonferroni P, *SE* spherical equivalent, *SVA* static visual acuity, *CDVA* corrected distance visual acuity (logMAR), *UDVA* uncorrected distance visual acuity (logMAR), *UIVA* uncorrected intermediate visual acuity (logMAR), *UNVA* uncorrected near visual acuity (logMAR)

$P < 0.05$, significantly different

Bold and single asterisk indicate statistically significant P-value

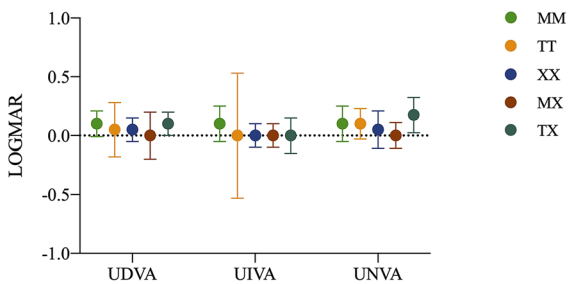

Fig. 2 Visual acuity 3 months postoperatively

The postoperative distance stereopsis were obtained in 10 (30%), 8 (26%), 22 (65%), 23 (92%) and 4 (17%) patients in the MM, TT, XX, MX and TX groups, respectively ($P = 0.005$, chi-square test). Likewise, the outcomes of the near stereopsis were 15 (45%), 13 (42%), 20 (59%), 24 (96%) and 10 (43%) patients in the MM, TT, XX, MX and TX groups, respectively ($P = 0.021$, chi-square test). The MX group had the highest rates in the normal range (72% and 68%) (stereopsis of 100 arcsec or better) and the normal adult range (28% and 40%) (stereopsis of 60 arcsec or better) (Table 3). Five groups had the equivalent outcomes in CS ($P = 0.709$, Kruskal–Wallis *H* test).

The results of DVA of the 5 groups 3 months postoperatively are summarized in Table 4 (Fig. 3). No statistically significance were found in the UDDVA at 4 fps, 8 fps and 12 fps ($P = 0.157$, $P = 0.089$ and $P = 0.102$, respectively, Kruskal–Wallis *H* test). The XX group (0.00 (0.00)) and the MX group

Table 3 Near and distance stereopsis 3 months postoperatively

Groups	*n*	Stereopsis					
		5 m			40 cm		
		YES (%)	100″ or better (%)	60″ or better (%)	YES (%)	100″ or better (%)	60″ or better (%)
MM	33	10 (30%)	6 (18%)	1 (3%)	15 (45%)	7 (21%)	1 (3%)
TT	31	8 (26%)	1 (3%)	0	13 (42%)	9 (29%)	2 (6%)
XX	34	22 (65%)	9 (26%)	4 (12%)	20 (59%)	15 (44%)	5 (15%)
MX	25	23 (92%)	18 (72%)	7 (28%)	24 (96%)	17 (68%)	10 (40%)
TX	23	4 (17%)	2 (8%)	0	10 (43%)	5 (22%)	2 (9%)
P value	–	**0.005***	**0.003***	**0.037***	**0.021***	**0.027***	**0.001***

YES, stereopsis can be obtained; 100″ or better, stereopsis of 100 arcsec or better; 60″ or better, stereopsis of 60 arcsec or better

$P < 0.05$, significantly different

Bold and single asterisk indicate statistically significant P-value

Table 4 DVA 3 months postoperatively

Groups	MM	TT	XX	MX	TX	*P* value
UDDVA						
4 fps	0.00 (0.10)	0.00 (0.10)	0.00 (0.10)	0.00 (0.00)	0.00 (0.20)	0.157
8 fps	0.00 (0.10)	0.00 (0.10)	0.00 (0.00)	0.00 (0.00)	0.10 (0.00)	0.089
12 fps	0.10 (0.00)	0.10 (0.00)	0.00 (0.00)	0.00 (0.00)	0.10 (0.00)	0.102
24 fps	0.10 (0.10)	0.10 (0.10)	0.00 (0.00)	0.00 (0.00)	0.25 (0.10)	**0.029***
bP MM–TT 1.000; MM–XX 0.857; MM–MX 0.753; MM–TX 0.076						
TT–XX 0.416; TT–MX 0.339; TT–TX 0.947						
XX–MX 0.951; XX–TX **0.019***						
MX–TX **0.023***						
UIDVA						
4 fps	0.25 (0.20)	0.20 (0.10)	0.10 (0.00)	0.00 (0.10)	0.20 (0.20)	**0.001***
bP MM–TT 1.000; MM–XX **0.021***; MM–MX **0.009*;** MM–TX 1.000						
TT–XX 0.072; TT–MX **0.017***; TT–TX 1.000						
XX–MX 1.000; XX–TX 0.052						
MX–TX **0.014***						
8 fps	0.30 (0.20)	0.20 (0.15)	0.10 (0.00)	0.10 (0.15)	0.20 (0.00)	**0.005***
bP MM–TT 0.175; MM–XX **0.005***; MM–MX **0.043***; MM–TX 0.875						
TT–XX **0.033***; TT–MX **0.041***; TT–TX 1.000						
XX–MX 1.000; XX–TX 0.816						
MX–TX 1.000						
12 fps	0.30 (0.15)	0.30 (0.10)	0.20 (0.00)	0.15 (0.10)	0.30 (0.10)	0.003*
bP MM–TT 1.000; MM–XX **0.039***; MM–MX **0.025***; MM–TX 1.000						
TT–XX **0.045***; TT–MX **0.008***; TT–TX 1.000						
XX–MX 1.000; XX–TX **0.046***						
MX–TX **0.041***						
24 fps	0.30 (0.15)	0.30 (0.10)	0.20 (0.10)	0.20 (0.00)	0.40 (0.00)	**0.005***
bP MM–TT 1.000; MM–XX **0.017***; MM–MX **0.022***; MM–TX 0.810						
TT–XX **0.029***; TT–MX **0.015***; TT–TX 0.795						
XX–MX 0.854; XX–TX **0.020***						
MX–TX **0.018***						
UNDVA						
4 fps	0.40 (0.00)	0.40 (0.10)	0.40 (0.00)	0.40 (0.00)	0.40 (0.10)	0.139
8 fps	0.45 (0.20)	0.50 (0.25)	0.40 (0.00)	0.40 (0.00)	0.45 (0.00)	**0.019***
bP MM–TT 1.000; MM–XX 0.297; MM–MX 0.458; MM–TX 1.000						
TT–XX **0.018***; TT–MX **0.021***; TT–TX 0.136						
XX–MX 1.000; XX–TX 0.674						
MX–TX 0.752						
12 fps	0.50 (0.15)	0.50 (0.00)	0.40 (0.10)	0.40 (0.15)	0.45 (0.03)	**0.002***
bP MM–TT 1.000; MM–XX **0.006***; MM–MX **0.005***; MM–TX 0.195						
TT–XX **0.017***; TT–MX **0.023***; TT–TX 0.258						
XX–MX 1.000; XX–TX 0.836						
MX-TX 0.742						
24 fps	0.60 (0.20)	0.60 (0.15)	0.50 (0.10)	0.45 (0.05)	0.60 (0.10)	**0.003***
bP MM–TT 1.000; MM–XX **0.011***; MM–MX **0.007***; MM–TX 1.000						
TT–XX **0.014***; TT–MX **0.002***; TT–TX 0.881						
XX–MX 0.972; XX–TX 0.089						
MX–TX **0.043***						

bP Bonferroni P, *DVA* dynamic visual acuity, *UDDVA* uncorrected distance dynamic visual acuity (logMAR), *UIDVA* uncorrected intermediate dynamic visual acuity (logMAR), *UNDVA* uncorrected near dynamic visual acuity (logMAR)

Bold and single asterisk indicate statistically significant P-value

$P < 0.05$, significantly different

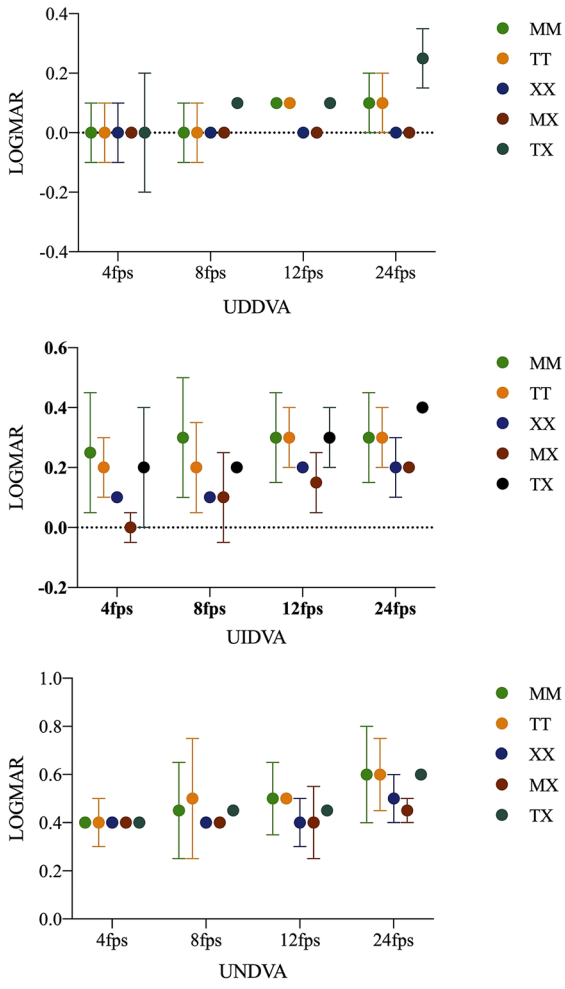

Fig. 3 Dynamic visual acuity 3 months postoperatively

(0.00(0.00)) showed better UDDVA at 24 fps than the TX group (0.25 (0.10)) (bP = 0.019 and bP = 0.023, respectively). UIDVA showed significant differences among the 5 groups at 4 fps, 8 fps, 12 fps and 24 fps ($P = 0.001$, $P = 0.005$, $P = 0.003$ and $P = 0.005$, respectively, Kruskal–Wallis H test). The significant differences in the UIDVA were found for the following comparisons: MM versus XX (bP = 0.021), MM versus MX (bP = 0.009), TT versus MX (bP = 0.017) and MX versus TX (bP = 0.014) at 4 fps; MM versus XX (bP = 0.005), MM versus MX (bP = 0.043), TT versus XX (bP = 0.033) and TT versus MX (bP = 0.041) at 8 fps; MM versus XX (bP = 0.039), MM versus MX (bP = 0.025), TT versus XX (bP = 0.045), TT versus MX (bP = 0.008), XX versus TX (bP = 0.046) and MX versus TX (bP = 0.041) at 12 fps; MM versus XX (bP = 0.017), MM versus MX (bP = 0.022), TT versus XX (bP = 0.029), TT versus MX (bP = 0.015), XX versus TX (bP = 0.020) and MX versus TX (bP = 0.018) at 24 fps. The XX group and the MX group showed the optimal outcomes at all speeds. Likewise, UNDVA showed significant differences at 8 fps, 12 fps and 24 fps ($P = 0.019$, $P = 0.002$ and $P = 0.003$, respectively, Kruskal–Wallis H test), which were found for the following comparisons: TT versus XX (bP = 0.018) and TT versus MX (bP = 0.021) at 8fps; MM versus XX (bP = 0.006), MM versus MX (bP = 0.005), TT versus XX (bP = 0.017) and TT versus MX (bP = 0.023) at 12 fps; MM versus XX (bP = 0.011), MM versus MX (bP = 0.007), TT versus XX (bP = 0.014), TT versus MX (bP = 0.002) and MX versus TX (bP = 0.043) at 24 fps. As the speed increased, the XX group (0.40 (0.00), 0.40 (0.10), 0.50 (0.10), at 8, 12 and 24 fps, respectively) and the MX group (0.40 (0.00), 0.40 (0.15), 0.45 (0.05), at 8, 12 and 24 fps, respectively) showed better UNDVA than the MM group (0.45 (0.20), 0.50 (0.15), 0.60 (0.20), at 8, 12 and 24 fps, respectively) and the TT group (0.50 (0.25), 0.50 (0.00), 0.60 (0.15), at 8, 12 and 24 fps, respectively).

Discussion

In recent years, the application of presbyopia-correcting IOLs such as multifocal IOLs and EDOF IOLs has gradually matured. The improvement of static vision function has been accurately verified [21, 22]. However, all of these IOLs have shortcomings and weaknesses [1, 8]. The approach, mix-and-match implantation, has previously been shown to be an effective way to improve visual outcomes [9–14].

In present prospective study, all bilateral and mix-and-match approaches have achieved equivalent and excellent binocular UDVA outcomes over the follow-up period of 3 months. However, bilateral implantation of ZMB00 performed suboptimal UIVA. Bilateral implantation of ZXR00 obtained similar results as bilateral ZMB00 and bilateral AT LISA tri839MP in terms of UNVA, which was different from previous studies [6–8]. In our study, the aimed postoperative refraction was 0 ± 0.25 D for ZMB00 and AT LISA tri839MP, and −0.5 ± 0.25 D for ZXR00. The optimal results of bilateral ZXR00 in UNVA may be related to the reserved diopter of myopia. Compared

with the other combinations, the combination of ZMB00 and ZXR00 showed a wide range of good postoperative vision across all distances.

Normal binocular interaction is a significant component of vision, in which the stereopsis correlated well with patient satisfaction and modulation transfer function (MTF) [15]. A value of 100 arcsec is the effective stereoacuity, and the normal stereoacuity of adults can reach 60 arcsec or better [23]. Previous studies have reported a worsening of stereoscopic threshold with age and in pseudophakic patients [24, 25]. Titiyal et al. speculated that the near stereoacuity after binocular EDOF IOLs was better compared with after bilateral multifocal or monofocal IOL implantation [15]. To our knowledge, binocular near and distance stereopsis of various mix-and-match implantation has not been compared previously, and this is the first study to evaluate both distance and near stereoacuity after bilateral or mix-and-match implantation of multifocal IOLs and EDOF IOLs. In our study, the combination of ZMB00 and ZXR00 showed optimal results for near and distance stereopsis: all patients had a near stereoacuity, and 80% patients had a distance stereoacuity, in both which 60% had an effective stereopsis of 100 arcsec or better.

The evaluation of dynamic visual function includes two categories: DVA and kinetic visual acuity (KVA). DVA refers to objects that move horizontally or vertically, and KVA refers to objects that move toward the observer [26]. Both are closely related to the postoperative quality of life. To our knowledge, currently, various DVA assessment systems have been developed notwithstanding, there is no standard detection method or detection instrument [16]. Two main methods include object movement and head movement; however, the latter is generally suitable for assessing vestibular function [10]. Our study utilized a self-developed test system, and its design principles comprehensively refer to the method of Patel and other research teams [16–20]: optotypes of different sizes consistent with the logMAR visual acuity chart move horizontally in front of the examinee at different speeds.

Ren et al. [16] demonstrated that trifocal IOLs provide superior DVA over monofocal IOLs at both low and high speeds in a multi-center study, and they proposed excellent SVA and continuous range of vision are related to better DVA which provides better predictive abilities of the position of dynamic objects and thus increases the accuracy of the catch-up saccade. In our previous study (Ke S, Li C, unpublished data, September 2021), we found that compared with bifocal IOLs and trifocal IOLs, EDOF IOLs showed stable optimal monocular DVA at all distances and all speeds, which we speculated is related to its own single elongated focal point for enlarging the depth of focus and excellent neuroadaptation. In the present study, bilateral ZXR00 and the combination of ZMB00 and ZXR00 showed stable and excellent DVA of all distances at both low and high speeds.

DVA is closely related to the vision-related quality of life of patients, especially driving and sports [18]. With the maturity and promotion of DVA test system, perhaps its application is not limited to the assessment of visual quality after intraocular lens implantation.

There are limitations exists in our study, which include the small sample size, the large difference in sample size between groups, the short duration of follow-up (3 months) and not distinguishing the dominant and non-dominant eyes. Relevant conclusions still need a larger sample size and longer follow-up time to confirm.

The present study demonstrated that mix-and-match implantation of bifocal IOLs and EDOF IOLs can provide excellent and stable stereopsis and DVA in all distances without reducing SVA and CS. Thus this combination seems to be a good option for patients with high demands for binocular visual quality.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Consent to participate Written informed consent was obtained from the parents.

Consent to publication The authors affirm that human research participants provided informed consent for publication.

Ethical approval This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of Chongqing Medical University (2015–2017).

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