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ORIGINAL RESEARCH

Stereoacuity and Aniseikonia: Evaluation Before and After Bilateral Implantation of Three Types of Presbyopia-Correcting Intraocular Lenses in Uncomplicated Phacoemulsification with Due Consideration of Interocular Differences in Higher Order Aberrations, Axial Lengths, Refractive Errors, and Acuities

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Purpose: To determine if the changes in stereoacuity and aniseikonia, following bilateral implantation of presbyopia correcting intraocular lenses could be predicted from preoperative measurements of higher order aberrations (HOAs), axial lengths (AL), refractive errors (RE) and corrected visual acuities (CVAs).

Patients and Methods: Stereoacuity (Randot tests, @6m & 40cm, in steps of 20 arcsecs") vertical and horizontal aniseikonia (Awaya test @6m, in steps of 1%) with best correction and HOAs (Shack-Hartmann aberrometer) were measured before, 3 and 6 months after uncomplicated bilateral phacoemulsification. Twenty patients (I) underwent a mix-and-match procedure (Tecnis MF, ZKB00 in one eye and ZLB00 in the other), 17 (II) were implanted with a trifocal (AT LISA 839 triMP) and 18 (III) with a one-piece diffractive (Synergy OU) intraocular lens. The resultant aniseikonia (A_R) of vertical and horizontal pairs of aniseikonia measurements was calculated using the Pythagorean theorem. Twenty untreated age/gender matched cases were recruited as controls (IV).

Results: The key results ($p < 0.001$) were a) stereoacuity at distance (SAD) and near (SAN) improved, A_R reduced in groups I, II & III remaining unchanged in group IV; b) some significant intergroup differences in SAD, SAN & A_R were detected at postop; c) at 6 months postop, changes (Δ=pre- minus postoperative value) correlated with preoperative values (x). Linear regression revealed, I ΔSAD=0.66x-57.47 [0.832, ±66.4], ΔSAN=0.96x-34.59 [0.821, ±16.9], $\Delta A_R=0.93A_R-2.12$ [0.795, ±1.4] II ΔSAD=0.79x-62.91 [0.916, ±38.1], ΔSAN=0.96x-31.49 [0.892, ±8.0], $\Delta A_R=0.91A_R-0.91$ [0.839, ±1.3] III ΔSAD=0.67x-35.50 [0.991, ±23.7], ΔSAN=0.88x-38.51[0.988, ±10.6], $\Delta A_R=0.86A_R-0.96$ [0.900, ±1.3]. Figures in parentheses are the corresponding r_s and ±limits of agreement between actual and estimated values. Definitive overarching associations connecting interocular differences in HOAs, AL, RE, and CVAs with SAD, SAN and A_R were not found.

Conclusion: Changes in stereoacuity and aniseikonia can be predicted using preoperative values. ΔSAN can be predicted within ±1, and ΔA_R within ±2, scale divisions. In group III ΔSAD can be predicted within ±1, and in group I ±3, scale divisions.

Keywords: presbyopia-correcting intraocular lenses, aberrometry, stereoacuity, aniseikonia

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Introduction

Stereoacuity tends to improve after binocular implantation of multifocal intraocular lenses (MFIOLs).[1–9] Reducing interocular differences in visual acuities, anisometropia, and consequently aniseikonia are expected to improve stereoacuity. Yet, correlations between clinical measures of anisometropia and aniseikonia following routine cataract surgery are poor.[10–12] Aniseikonia <2% is tolerated with no discernible impact on stereoacuity[12] and >2% results mainly from interocular differences in the axial lengths.[13] However, changing interocular differences in corneal shape or higher order aberrations (HOAs) could affect the dissimilarity between the two retinal images and impact on binocular summation and stereoacuity.[14–20]

The optical design of the MFIOL will influence the HOAs of the eye, and there are conflicting reports on the effect of implant design on stereoacuity. For example, better stereoacuity was reported after implanting an aspheric MFIOL in comparison with a monofocal non-presbyopia correcting IOL.[3,21] Reduced stereoacuity was reported in cases implanted with diffractive MFIOLs compared with refractive MFIOLs.[6] Another study reported no difference in the near stereoacuity when unilateral cases implanted with MFIOLs were compared with unilateral cases implanted with monofocal IOLs.[5] MFIOLs are types of presbyopia correcting IOLs (PCIOLs), and the previous studies lead to the question: Is the stereoacuity and aniseikonia after bilateral PCIOL implantation related to clinical measurements of HOAs?

The mix-and-match procedure is an attempt to maximize the clinical benefits of two different MFIOL designs. This carries the risk of improving stereoacuity but to a lower level compared with implanting both eyes with the same design of IOL. Yet, mix-and-match cases demonstrate better stereoacuity compared with bilateral cases implanted with monofocal IOLs,[22] and there are insignificant differences in stereoacuity between mix-and-match cases and those bilaterally implanted with same design MFIOLs.[23]

The aim of this study was twofold. Firstly, to assess the effect of bilateral implantation of different designs of PCIOLs on stereoacuity, aniseikonia and HOAs over a period of 6 months. Secondly, to determine if preoperative measurements of stereoacuity, aniseikonia, inter-ocular differences in HOAs, corrected visual acuities and axial lengths are associated with the postoperative stereoacuity and aniseikonia values.

Materials and Methods

Study Design

This was a prospective, interventional, non-randomized, comparative clinical study, at the Svjetlost Eye Hospital in Zagreb between January 2016 and January 2023. The study was approved by the Ethics Committee of the Svjetlost Eye Clinic in Zagreb, and the tenets of the Helsinki agreement were followed throughout. Signed informed consent was obtained from all patients after fully explaining the procedures, risks, and benefits. All patients were examined, operated and followed up by the same clinical team. Clinical tests and recording of data were performed by team members that did not perform surgery. These individuals remained unaware of the type of PCIOL implanted in each case.

Patient Allocation/Selection

Patients were assigned into one of three surgical groups where the type of PCIOL implanted depended on the availability at the time of surgery. Group I patients received mix-and-match surgery (between 2016 and 2018), group II were implanted with a trifocal PCIOL (between 2018 and 2020) and group III were implanted with an extended depth of focus PCIOL.

Inclusion criteria were presbyopic cases with either clear lenses or slight traces of cataract requesting to be spectacle free. All patients were older than 35 years with estimated postoperative astigmatic power between −1.00D and zero.

Exclusion criteria included corneal astigmatism worse than −1.00D, history of eye disease and/or surgery, orthoptic treatment, tropias, amblyopia and corrected distance or near logMAR visual acuity greater than 0.30 in one eye. A control group (group IV), of age and gender matched spectacle wearers with stable refraction and no history of ocular disease or surgery, was recruited for comparison.

The investigator assessing binocular function remained unaware of the patient's group allocation.

Description of the Implanted Presbyopia Correcting Intraocular Lenses (PCIOLs)

Group I were implanted with Tecnis MF ZKB00 in the dominant eye and Tecnis ZLB00 (Johnson & Johnson Surgical) in the non-dominant eye. These are foldable one-piece PCIOLs with a biconvex aspheric anterior surface and diffractive posterior surface. Additions in the IOL plane are +2.75D and +3.25D providing reading distances of 50cm and 42cm for ZKB00 and ZLB00, respectively. Both PCIOLs share identical spherical and chromatic aberration characteristics.

Group II were implanted with AT LISA tri 839 MP (Carl Zeiss Meditec) one-piece diffractive aspheric PCIOL where the optical zone is divided into a central 4.34mm trifocal zone and peripheral 4.34-to-6mm bifocal zone. It provides additions of +3.33D and +1.66D for near (40cm) and intermediate (80cm) distances, respectively.

Group III were implanted with TECNIS Synergy OU (Johnson&Johnson Surgical) one-piece diffractive PCIOL. The optical profile of this PCIOL is aimed to optimize distance vision providing clear vision from far to near.

In all cases, the target refraction was emmetropia, and PCIOL power was calculated using the Barrett Universal II formula.[24]

Surgical Procedure and Postoperative Care

Routine phacoemulsification surgery was performed in all cases. Cefuroxime was instilled intracamerally after lens implantation. Topical antibiotic and steroid were prescribed for postoperative use four times daily and tapered over one month.

Preoperative and Postoperative Assessment

The preoperative examination of each patient including, uncorrected (UDVA) and corrected (CDVA) distance visual acuity, uncorrected (UNVA), near corrected (CNVA) and distance corrected (DNVA) near visual acuity, subjective and objective refraction (back vertex distance fixed at 12mm), tonometry, orthoptic status, distant and near stereoacuity, aniseikonia, slit-lamp assessment, fundoscopy, corneal topography, biometry (IOL Master 700, Carl Zeiss Meditec AG, Jena, Germany), aberrometry, endothelial microscopy, OCT of macula and optic nerve. Where applicable, patients discontinued contact lens wear for up to four weeks, depending on the type of contact lenses, prior to the examination. Where necessary, the dominant eye was determined by asking the patient to look at a target 6m away with both eyes open, form a circle with the thumb and fingers of one hand, extend the arm, look at the object through the circle, and close one eye then the other. The dominant eye is the one aligned with the circle and object. The patients were examined one day, one week, one month, three and six months after surgery. UDVA, CDVA, distance corrected near refraction, tonometry, biomicroscopy and dilated fundus assessments were performed during each follow-up visit. Additionally, assessments of stereoacuity, aniseikonia and aberrometry were undertaken at three and six months.

Stereoacuity

Stereoacuity was assessed, with patient wearing the best correction, at 6m using a Randot Stereotest (CSO, VisioChart CVC03 v2.0.0, Firenze, Italy) with a range from 20-to-640 arcsecs (″) in 20″ steps. Near stereoacuity was measured at 40cm (with +2.50D binocular near addition at pre- and no addition at postoperative stages) using a Randot Stereotest (Precision Vision, Woodstock, USA) ranging from 20-to-400″ in 20″ steps. The patient was asked to identify which target, in a set, stood out as closer or further away from the rest. The test was stopped when the patient made two consecutive mistakes. The stereoacuity value recorded was the setting where the patient correctly identified the target just before the consecutive mistakes.

Aniseikonia

Aniseikonia was assessed, with patient wearing the best correction, at 6m using the Awaya aniseikonia test (Awaya, 6m CSO vision chart, Firenze, Italy).[25] The aniseikonia was the size of the image viewed by the right eye as a percentage (larger or smaller) compared with the size of the image viewed by the left eye. The sizes could be adjusted in steps of 1%. When aniseikonia was detected, the percentage value was recorded as positive/negative when the target seen by the right eye was perceived as being larger/smaller than the target seen by the left eye. The test was modified to assess the aniseikonia along the vertical and then the horizontal meridian. A single figure description of the total, or resultant, aniseikonia (A_R) was calculated by subjecting each pair of vertical and horizontal measurements to the Pythagorean theorem.

Aberrometry

A Shack-Hartmann type aberrometer (L80 wave+™, Luneau SAS, Prunay-le-Gillon, France), was used to measure ocular HOAs after the patient was dark adapted for ten minutes. Coma, trefoil, and spherical aberration for 3mm and 5mm pupils were assessed with this aberrometer. The value of coma was the root mean square (RMS) of Z^{-1}_3 and Z^1_3 coefficients, trefoil was the RMS of Z^{-3}_3 and Z^3_3 coefficients, and spherical aberration was the Z^0_4 coefficient.

Data Collection and Analysis

Data were analyzed to determine if there were significant interocular differences in CDVA, CNVA, DNVA (groups I, II & III), refraction, HOAs and axial lengths (at preop) within each group at each stage (Wilcoxon signed-rank or paired *t*-test), and changes in the magnitude of any interocular differences during the study (Friedman test or 1-way ANOVA for repeat measures); changes in CDVA, near acuity (CNVA at preop minus DNVA in groups I, II & III), stereoacuity, aniseikonia and HOAs within each group during the study (Friedman test or 1-way ANOVA for repeat measures); intergroup differences in CDVA, CNVA, DNVA, refraction, HOAs, axial lengths (at preop), stereoacuity and aniseikonia at each stage of the study (Kruskal Wallis test or 1-way ANOVA for independent measures).

Should any intergroup differences be detected, then the analysis would be extended to determine the significance of differences between pairs of groups (Mann Whitney U or unpaired *t*-test).

If a significant change (in CDVA, near acuity, stereoacuity, aniseikonia or any of the HOAs) was detected then the analysis would be extended to determine if the change [a] occurred between any two stages of the study (Wilcoxon signed-rank or paired *t*-test), [b] correlated with the value at the start of the study (Spearman's rho or Pearson correlation), and if significant correlations were found, then the difference between actual and estimated changes would be calculated.

Also, inter-ocular differences in preoperative values of HOAs, CDVA, CNVA and axial lengths were tested to determine if they were associated with postoperative values of stereoacuity and aniseikonia (Spearman's rho or Pearson correlation).

Non-parametric tests were applied when data were not normally distributed (Kolmogorov–Smirnov test of normality). Changes, differences and comparisons were considered statistically significant when $p<0.05$ after adjusting for the Bonferroni correction.

Results

Twenty patients underwent mix-and-match surgery (group I, 15 females and 5 males), 17 patients were implanted with the AT LISA tri 839 MP trifocal (group II, 11 females and 6 males) and 18 with the TECNIS Synergy OU (group III, 11 females and 7 males) PCIOLs. Group IV consisted of 14 females and 7 males. Intergroup differences for age, spherical and astigmatic refractive errors were not significant. The main details are shown in Table 1 and key results now follow where $p <0.001$ unless otherwise stated.

Visual Acuity, Refraction, and Axial Length

In each group, interocular differences in visual acuities, refractive errors and axial lengths were neither significant nor changed during the study. In group III there was a significant improvement in CDVA at left eyes ($p = 0.003$). Comparing the four groups, at preop there was a significant difference in the CDVA at the left eyes, but this was not significant after excluding group IV (the control). There were no other significant differences between groups I, II & III. At 3 and 6 months, the best spherical equivalent (BSE) refractive errors were within ±0.50D except in three eyes of group I cases where the BSE was ±1.00D at 6months.

Higher Order Aberrations (HOAs)

Chief details of HOAs are shown in Table 2. In each group, interocular differences in HOAs were not significant. In group I, the magnitude of interocular differences in coma (3mm pupil), trefoil (3 and 5mm pupil) and spherical aberration (3mm pupil) changed significantly during the study ($p < 0.02$). The magnitude of interocular differences did not change

Table 1 Breakdown of Age, Refractive Errors, Axial Lengths and LogMAR Visual Acuities

Preoperative Stage											
Group	**Age [years]**	**OD**			**OS**			**OD**		**OS**	
		Sphere [D]	**Cyl [D]**	**AL [mm]**	**Sphere [D]**	**Cyl [D]**	**AL [mm]**	**CDVA**	**CNVA**	**CDVA**	**CNVA**
I	58.9 (7.7)	0.91 (2.43)	0.68 (0.41)	23.12 (1.10)	0.92 (2.41)	0.70 (0.43)	23.12 (1.12)	0.02,0.02 (0.00–0.02)	0.00,0.00 (0.00–0.02)	0.02,0.00 (0.00–0.02)	0.00,0.00 (0.00–0.02)
II	57.3 (8.9)	0.79 (2.38)	0.69 (0.24)	23.54 (1.56)	0.74 (1.88)	0.78 (0.22)	23.43 (1.40)	0.00,0.00 (0.00–0.13)	0.00,0.00 (0.00–0.13)	0.00,0.00 (0.02–0.02)	0.00,0.00 (0.00–0.00)
III	56.6 (8.4)	1.15 (1.60)	0.65 (0.34)	23.00 (0.88)	1.24 (1.72)	0.83 (0.44)	23.10 (1.09)	0.00,0.00 (0.00–0.05)	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.13)	0.00,0.00 (0.00–0.13)
IV	52.4 (7.9)	0.42 (1.08)	0.90 (0.65)	23.43 (1.01)	0.71 (1.92)	0.88 (0.75)	23.29 (1.17)	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.00)

Postoperative Stage								
Group	**3 Months**				**6 Months**			
	OD		**OS**		**OD**		**OS**	
	CDVA	**DNVA**	**CDVA**	**DNVA**	**CDVA**	**DNVA**	**CDVA**	**DNVA**
I	0.00,0.00 (0.00–0.02)	0.00,0.00 (0.00–0.05)	0.00,0.00 (0.00–0.02)	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.02)	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.02)	0.00,0.00 (0.00–0.00)
II	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.00)
III	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.00)	0.00,0.00 (0.00–0.00)

Notes: Mean (±sd) spherical and astigmatic (cyl, in plus format) powers in diopters. Mean (±sd) age in years. Median, mode and interquartile ranges (in parentheses) of acuity values are shown.

Abbreviations: I, group I (Mix-and-match cases); II, group II (Trifocal cases); III, group III (Synergy OU cases); IV, control group; CDVA, corrected distance visual acuity; CNVA, corrected near visual acuity; DNVA, distance corrected near visual acuity; Cyl, astigmatic power at Preoperative stage; AL, axial length.

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Table 2 Higher Order Aberrations (HOAs) Before and After Phacoemulsification and Implantation of PCIOLs

Group	OD						OS					
	Coma (μ)		Trefoil (μ)		Spherical Aberration (μ)		Coma (μ)		Trefoil (μ)		Spherical Aberration (μ)	
	3mm	5mm	3mm	5mm	3mm	5mm	3mm	5mm	3mm	5mm	3mm	5mm
Preoperative												
I	0.051±0.039 (0.034,0.068)	0.124±0.083 (0.088,0.160)	0.052±0.035 (0.037,0.067)	0.106±0.057 (0.081,0.131)	0.021±0.028 (0.009,0.033)	0.060±0.068 (0.030,0.090)	0.064±0.054 (0.040,0.088)	0.149±0.086 (0.111,0.187)	0.063±0.069 (0.033,0.093)	0.122±0.077 (0.088,0.156)	−0.006±0.052 (−0.029,0.017)	0.034±0.081 (−0.002,0.070)
II	0.034±0.017 (0.026,0.042)	0.092±0.063 (0.062,0.122)	0.035±0.021 (0.025,0.045)	0.065±0.044 (0.044,0.086)	0.018±0.032 (0.003,0.033)	0.042±0.053 (0.017,0.067)	0.045±0.030 (0.031,0.059)	0.100±0.069 (0.067,0.133)	0.040±0.032 (0.025,0.055)	0.094±0.059 (0.066,0.122)	0.008±0.021 (−0.002,0.18)	0.026±0.032 (0.011,0.041)
III	0.047±0.025 (0.036,0.059)	0.089±0.057 (0.063,0.155)	0.047±0.025 (0.078,0.100)	0.090±0.058 (0.063,0.117)	0.022±0.054 (−0.003,0.047)	0.057±0.080 (0.020,0.094)	0.050±0.038 (0.032,0.068)	0.126±0.077 (0.090,0.162)	0.054±0.030 (0.040,0.068)	0.124±0.082 (0.086,0.162)	0.015±0.053 (−0.010,0.040)	0.023±0.091 (0.019,0.065)
3 months postoperative												
I	0.042±0.022 (0.032,0.052)	0.111± 0.096 (0.069,0.153)	0.042±0.028 (0.030,0.054)	0.102± 0.085 (0.065,0.139)	−0.009±0.016 (−0.016,-0.002)	−0.019±0.037 (−0.035,-0.003)	0.041±0.027 (0.029,0.053)	0.090±0.058 (0.065,0.115)	0.048±0.033 (0.034,0.063)	0.092±0.037 (0.076,0.108)	−0.015± 0.032 (−0.029,-0.001)	−0.024±0.042 (0.042,-0.006)
II	0.041±0.023 (0.030,0.052)	0.087±0.050 (0.063,0.111)	0.046±0.026 (0.034,0.058)	0.084±0.039 (0.070,0.098)	−0.007±0.024 (−0.018,0.004)	0.017±0.043 (−0.003,0.037)	0.036±0.024 (0.025,0.047)	0.073±0.056 (0.046,0.010)	0.049±0.029 (0.035,0.063)	0.093±0.077 (0.056,0.130)	−0.007±0.020 (−0.017,0.003)	−0.005±0.035 (0.022,0.012)
III	0.043±0.028 (0.030,0.056)	0.092±0.061 (0.064,0.120)	0.036± 0.025 (0.025,0.048)	0.076±0.040 (0.058,0.095)	−0.021±0.035 (−0.037,-0.005)	0.014±0.052 (−0.010,0.038)	0.047±0.080 (0.010,0.084)	0.090±0.084 (0.051,0.129)	0.048±0.082 (0.010,0.086)	0.101±0.075 (0.066,0.136)	−0.025 ±0.032 (−0.040,-0.010)	0.00±0.051 (0.024,0.024)
6 months postoperative												
I	0.036±0.024 (0.026,0.047)	0.099±0.074 (0.067,0.131)	0.045±0.032 (0.031,0.059)	0.067±0.045 (0.047,0.087)	−0.018±0.019 (−0.026,-0.010)	−0.017±0.033 (−0.032,-0.003)	0.037±0.024 (0.027,0.048)	0.082±0.050 (0.060,0.104)	0.044±0.024 (0.036,0.055)	0.083±0.032 (0.069,0.097)	−0.018±0.015 (−0.025,-0.011)	−0.013±0.027 (0.025,-0.001)
II	0.028±0.017 (0.020,0.036)	0.062±0.026 (0.050,0.074)	0.041±0.025 (0.029,0.053)	0.067±0.028 (0.054,0.080)	−0.011±0.021 (−0.021,-0.001)	0.013±0.053 (−0.012,0.038)	0.028±0.011 (0.023,0.033)	0.068±0.050 (0.044,0.092)	0.040±0.024 (0.029,0.051)	0.083±0.047 (0.061,0.105)	−0.008±0.026 (−0.020,0.004)	0.008±0.038 (0.010,0.026)
III	0.038±0.025 (0.027,0.050)	0.079±0.050 (0.056,0.102)	0.034±0.017 (0.026,0.042)	0.073±0.039 (0.055,0.091)	−0.018±0.031 (−0.032,-0.004)	0.007±0.050 (−0.016,0.030)	0.044±0.054 (0.019,0.069)	0.080±0.056 (0.054,0.106)	0.037±0.043 (0.017,0.057)	0.086±0.061 (0.058,0.114)	−0.026±0.026 (−0.038,-0.014)	−0.001±0.044 (0.021,0.019)

Notes: Mean ±sd, 95% CI limits (in parentheses) for 3 and 5mm pupils. The respective values for coma, trefoil and spherical aberration in the control group at the start of the study were OD: 0.059 ± 0.083 (0.024–0.095) and 0.148 ± 0.165 (0.090–0.206), 0.066 ± 0.116 (0.016–0.116) and 0.133 ± 0.175 (0.058–0.208), −0.002 ± 0.057 (−0.026–0.022) and 0.037 ± 0.085 (0.001–0.073). OS: 0.041 ± 0.028 (0.029–0.053) and 0.132 ± 0.107 (0.086–0.178), 0.046 ± 0.045 (0.027–0.065) and 0.091 ± 0.057 (0.067–0.115), 0.007 ± 0.025 (0.000–0.018) and 0.047 ± 0.068 (0.018–0.076). These values did no change significantly during the study.
Abbreviations: I, group I (Mix-and-match cases); II, group II (Trifocal cases); III, group III (Synergy OU cases); μ, units for higher order aberrations are in micrometers.

significantly in groups II, III & IV. Intergroup differences in spherical aberration (5mm pupil, right eyes) were found at 3 months ($p = 0.026$).

Change Within Each Group

Significant changes were found in; group I, spherical aberration (3 and 5mm pupil) and coma (5mm pupil, $p = 0.006$) in the right eyes and spherical aberration (5mm pupil, $p = 0.002$) in the left eyes; group II spherical aberration (3mm pupil, $p = 0.005$) in the right eyes; group III spherical aberration in both eyes (3mm pupil, right eyes $p = 0.005$ and left eyes, $p = 0.003$).

Stereoacuity and Aniseikonia

Change Within Each Group

Table 3 shows that there were significant changes in the distance and near stereoacuities in groups I, II & III. Changes between 3 and 6 months were not significant except for the near stereoacuity in group I ($p = 0.002$). Changes in median and mode values of aniseikonia were not significant. The change in the resultant aniseikonia (A_R) was significant in group III. Changes in

Table 3 Stereoacuity (″) and Aniseikonia (%) Before and After Phacoemulsification and Implantation of PCIOLs

Group		Preop	3 months	6 months	Significance
		Me, mo, IQ	Me, mo, IQ	Me, mo, IQ	p
Distance Stereoacuity (″)					
I		160,320,(140–320)	160,160,(80–160)	120,80,(80–160)	0.027
II		160,160,(160–200)	80,80,(80–160)	80,80,(80–120)	0.006
III		160,160,(160–320)	80,80,(80–160)	80,80,(80–160)	0.003
Near Stereoacuity (″)					
I		70,70,(37.5–80)	50,25,(29–60)	35,25,(25–40)	0.008
II		70,70,(60–80)	40,50,(30–50)	40,40,(25–40)	<0.001
III		70,70,(70–140)	60,60,(40–63)	50,40,(40–60)	0.002
Aniseikonia (%)					
I	V	−1.0,3.0,(−2.3 to 2.0)	0.0,1.0,(−2 to 1)	1.0,1.0,(−2.0 to 2.0)	>0.05
	H	0.0,0.0,(−1.3 to 3.0)	1.0,1.0,(−2 to 1.0)	0.0,0.0,(0.0 to 1.0)	1.0
	A_R	4.1,3.2,(2.2 to 5.8)	2.2,2.2,(2.2 to 3.6)	2.2,1.0,(1.0 to 3.6)	0.046*
II	V	0.0,0.0,(−1.0 to 1.0)	0.0, 1.0,(0.0, to 1.0)	0.0,0.0,(−1.0 to 0.5)	>0.05
	H	0.0,0.0,(−2.0 to 0.0)	−1.0,0.0,(−1.0 to 0.0)	0.0,0.0,(−1.0,0.0)	>0.05
	A_R	1.4,1.0,(1.0 t 3.3)	1.4,1.0,(1.0 to 2.2)	1.0,1.0,(1.0 to 1.4)	>0.05
III	V	−1.0,-1.0,(−1.8 to 3.5)	−1.0,-1.0,(−1.0 to 1.0)	0.0,0.0,(−1.0 to 1.0)	>0.05
	H	−0.5,-1.0(1.0 to 2.0)	0.0,0.0,(−0.8 to 1.3)	0.0,0,0,(0.0 to 1.0)	>0.05
	A_R	3.0,3.2,(1.6 to 5.4)	1.4,1.0,(1.0 to 3.4)	1.0,1.0,(1.0 to 2.4)	0.003

Notes: In the control group (group IV), the values for the median (mode and interquartile ranges) stereoacuity at distance and near, followed by the resultant aniseikonia (A_R) values, were 80″ (160, 80–160), 40″ (70, 30–70) and 2.0% (1.0, 1.0–3.0). These did not change significantly over the course of the study. Minus sign indicates image at right eye was perceived as smaller compared with the image at left eye. A_R, resultant aniseikonia according to Pythagorean theorem. *Rendered not significant after applying Bonferroni correction.

Abbreviations: I, group I (Mix-and-match cases); II, group II (Trifocal cases); III, group III (Synergy OU cases); Me, median; mo, mode; IQ, inter-quartile range; p, significance of Friedman test; V, aniseikonia in vertical meridian; H, aniseikonia in horizontal meridian.

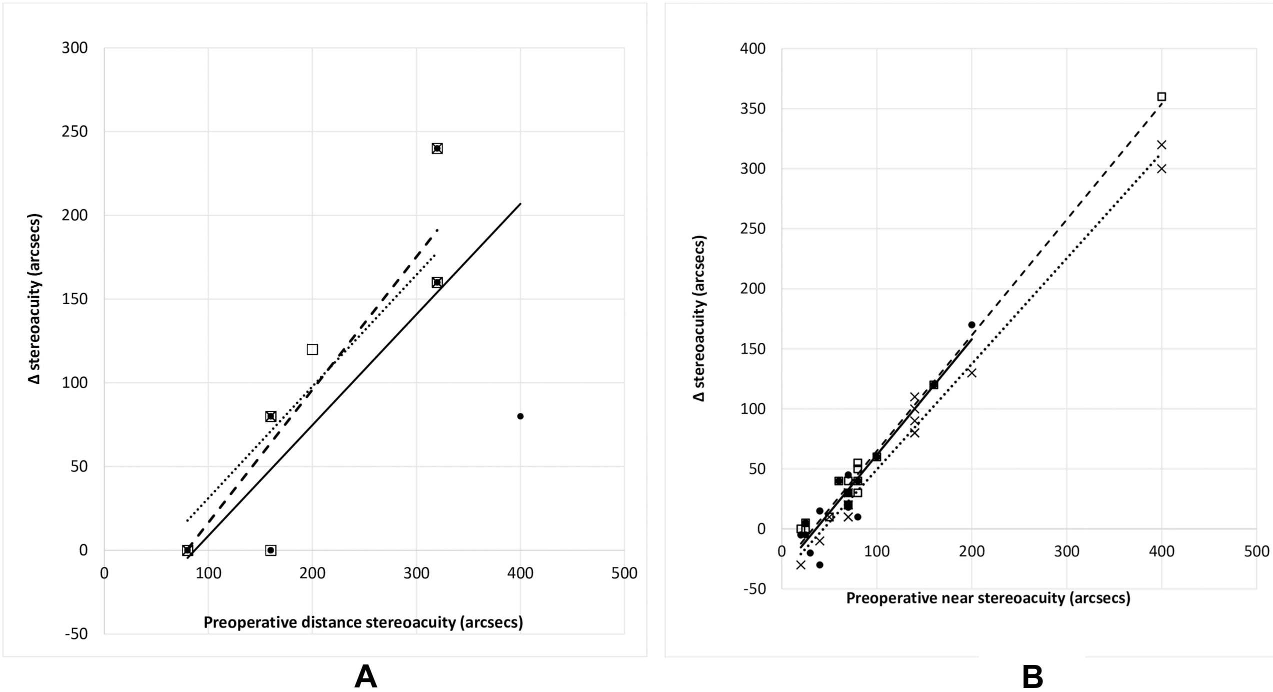

Figure 1 (**A**) Comparison between preoperative distance stereoacuity (x) and change (y) at 6 months. Characteristics of the least squares lines are, group I (mix-and-match, filled circles [•], solid line) y=0.66x-57.47, n =20, r_s = 0.832, p<0.001; group II (trifocal, empty squares [□], broken line) y=0.79x-62.91, n=17, r_s=0.916, p<0.001; group III (synergy OU, crosses [x], dotted line) y=0.67x-35.50, n=18, r_s =0.991, p<0.001. N.B. some data points overlap. (**B**) Comparison between preoperative near stereoacuity (x) and change (y) at 6 months. Characteristics of the least squares lines are, group I (mix-and-match, filled circles [•], solid line) y=0.96x-34.59, n=20, r_s=0.821, p<0.001; group II (trifocal, empty squares [□], broken line) y= 0.96x-31.49, n=17, r_s=0.892, p<0.001; group III (synergy OU, crosses [x], dotted line) y=0.88x-38.51, n=18, r_s=0.988, p<0.001. N.B. some data points overlap.

stereoacuity and aniseikonia significantly correlated with the preop value as shown in Figures 1A, B and 2. Table 4 shows the least squares expressions describing the relationships between changes in stereoacuity and A_R and the respective preop values. These expressions were used to compute the expected changes in stereoacuity and A_R. The RMS difference (DAE) and limits of agreement (LoA) between the actual and expected changes in stereoacuity and A_R are included in Table 4.

In group IV, the median (mode and interquartile range) distance and near stereoacuity, and A_R values, were, respectively, 80″ (160,80–160), 40″ (70,30–70) and 2.0% (1.0,1.0–3.0). These values did not change significantly during the study.

Comparison Between Groups

At preop, there were significant differences between the four groups in stereoacuity (distance stereoacuity, p = 0.008; near stereoacuity, p = 0.012). These differences were rendered not significant after excluding group IV. There were no other significant differences between groups at 3 and 6 months in distance stereoacuity. There were significant differences in the near stereoacuity between groups at 6 months (p = 0.004) but not at 3 months. There was a significant difference in the near stereoacuity between groups I & III at 6 months (p = 0.003), between groups II & III at 3 (p = 0.010) and 6 months.

There were significant differences in A_R values between groups at the start of the study (p = 0.013), at 6 months (p = 0.024) but not at 3 months. The differences were not significant after excluding group IV from the comparisons. Comparing pairs of groups, significant differences in A_R values were revealed between groups I & II at 6 months (p = 0.007). Differences between groups for the vertical and horizontal aniseikonia values were not significant.

Association Between Aniseikonia and Stereoacuity

Significant correlations between aniseikonia and stereoacuity were not found either within each group or after pooling data from all groups. Changes in aniseikonia were not associated with changes in stereoacuity.

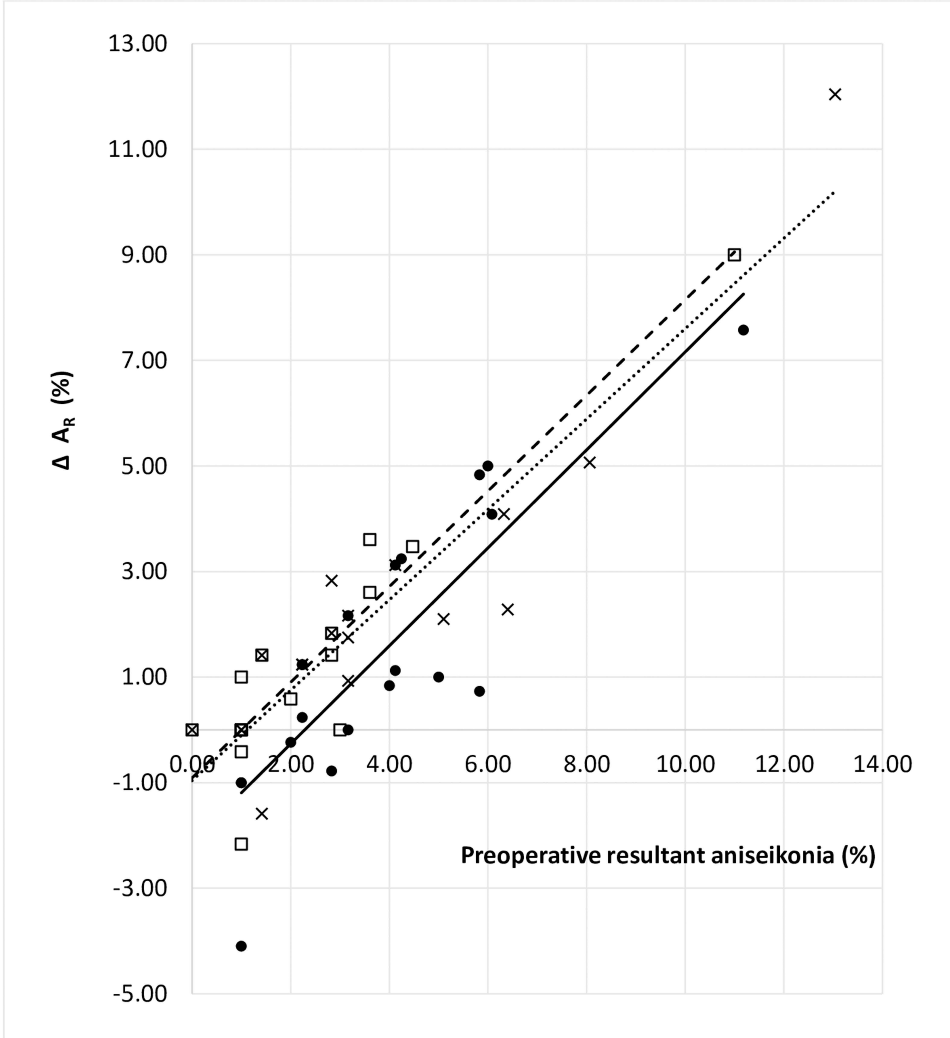

Figure 2 Comparison between preoperative resultant aniseikonia (A_R) and change (y) at 6 months. Characteristics of the least squares lines are, group I (mix-and-match, filled circles [•], solid line) y=0.93A_R-2.12, n=20, r_s=0.795, p<0.001; group II (trifocal, empty squares [□], broken line) y=0.91A_R-0.91, n=17, r_s =0.839, p<0.001; group III (synergy OU, crosses [x], dotted line) y=0.86A_R-0.96, n=18, r_s=0.900, p<0.001).

Association Between Interocular Differences in CDVA, CNVA, DNVA, Refractive Error, HOAs and Stereoacuity, and Aniseikonia

Significant correlations were not detected between any interocular differences and either stereoacuity or aniseikonia at any stage.

Association Between Interocular Differences in the Preoperative Values of CDVA, CNVA, Refractive Error, HOAs, Axial Lengths and Postoperative Measurements of Stereoacuity and Aniseikonia

In group I, a significant association was revealed between distance stereoacuity at 6 months and RMS interocular difference in preop measures of coma (5mm pupil, r_s= −0.456, p = 0.043) and axial lengths (r_s= 0.483, p = 0.031). The former was rendered as not significant after applying the Bonferroni correction. In group II, a significant link was revealed between distance stereoacuity at 6 months and RMS interocular difference in preop measures of spherical aberration (5mm pupil, r_s= 0.631, p = 0.007). There were no other significant correlations between any interocular differences in the preoperative values and stereoacuity or aniseikonia at any stage.

Table 4 Least Squares Linear Expressions Describing the Best Fit Relationships Between Changes in Stereoacuity and Aniseikonia with Preoperative Values

Group	PoS	Indices of Best Fit Linear Expressions	DAE	±LoA	**
Change in stereoacuity (″): Distance					
I	3 months	Δ=0.68x-94.25, r_s=0.745	54.2	81.0	15
	6 months	Δ=0.66x-57.47, r_s=0.832	32.1	66.4	48
II	3 months	Δ=0.73x-64.47, r_s=0.843	29.0	37.1	52
	6 months	Δ=0.79x-62.91, r_s=0.916	24.1	38.1	64
III	3 months	Δ=0.56x-26.67, r_s=0.750	29.1	70.3	63
	6 months	Δ=0.67x-35.50, r_s=0.991	15.8	23.7	72
Change in stereoacuity (″): Near					
I	3 months	Δ=0.78x-34.75, r_s=0.679	16.2	20.7	20
	6 months	Δ=0.96x-34.59, r_s=0.821	11.8	16.9	32
II	3 months	Δ=0.96x-37.59, r_s=0.903	10.4	10.2	30
	6 months	Δ=0.96x-31.49, r_s=0.892	8.3	8.04	36
III	3 months	Δ=0.86x-40.01, r_s=0.954	10.5	13.2	20
	6 months	Δ=0.88x-38.51, r_s=0.988	8.7	10.6	23
Resultant (A_R) Aniseikonia (%)					
I	3 months	Δ=0.95A_R-2.37, r_s=0.797	0.73	1.22	1.4
	6 months	Δ=0.93A_R-2.12, r_s=0.795	1.11	1.44	1.4
II	3 months	Δ=0.69A_R-0.80, r_s=0.729	0.58	1.11	2.0
	6 months	Δ=0.91A_R-0.91, r_s=0.839	0.62	1.27	2.7
III	3 months	Δ=0.70A_R-1.19, r_s=0.709	1.19	1.99	1.6
	6 months	Δ=0.86A_R-0.96, r_s=0.900	0.83	1.28	2.5

Notes: Column **shows the predicted changes (preoperative minus postoperative) according to the preceding least squares expressions for a preoperative distance stereoacuity of 160", near stereoacuity of 70" and resultant aniseikonia (A_R) of 4%. DAE, RMS difference between actual and estimated values of Δ according to the preceding linear expression. LoA= limits of agreement between actual and estimated values, ie 1.96x(±sd of DAE).

Abbreviations: I, group I (Mix-and-match cases); II, group II (Trifocal cases); III, group III (Synergy OU cases); PoS, postoperative stage; x, preoperative value; Δ, preoperative – postoperative value; A_R, preoperative resultant aniseikonia; r_s, value of Spearman's rho.

Association Between Change (Δ) in the Interocular Differences in CDVA, CNVA, DNVA, Refractive Error, HOAs and Change in Stereoacuity (ΔSA) or Aniseikonia (ΔA)

In group I, significant associations were revealed between the change in the interocular difference for; trefoil (5mm pupil) and distance ΔSA at 3months (r_s=−0.595); coma (5mm pupil) and distance ΔSA at 6months (r_s=−0.634). These results are shown in Figure 3. There were no other significant correlations between changes in interocular differences and either ΔSA or ΔA.

Discussion

Stereoacuity improved in the treated groups, and this supports previous reports on bilateral implantation of MFIOLs.[1–9] Hayashi et al[8] found that implantation of bifocal MIOLs with unidentical near additions resulted in poorer stereoacuity

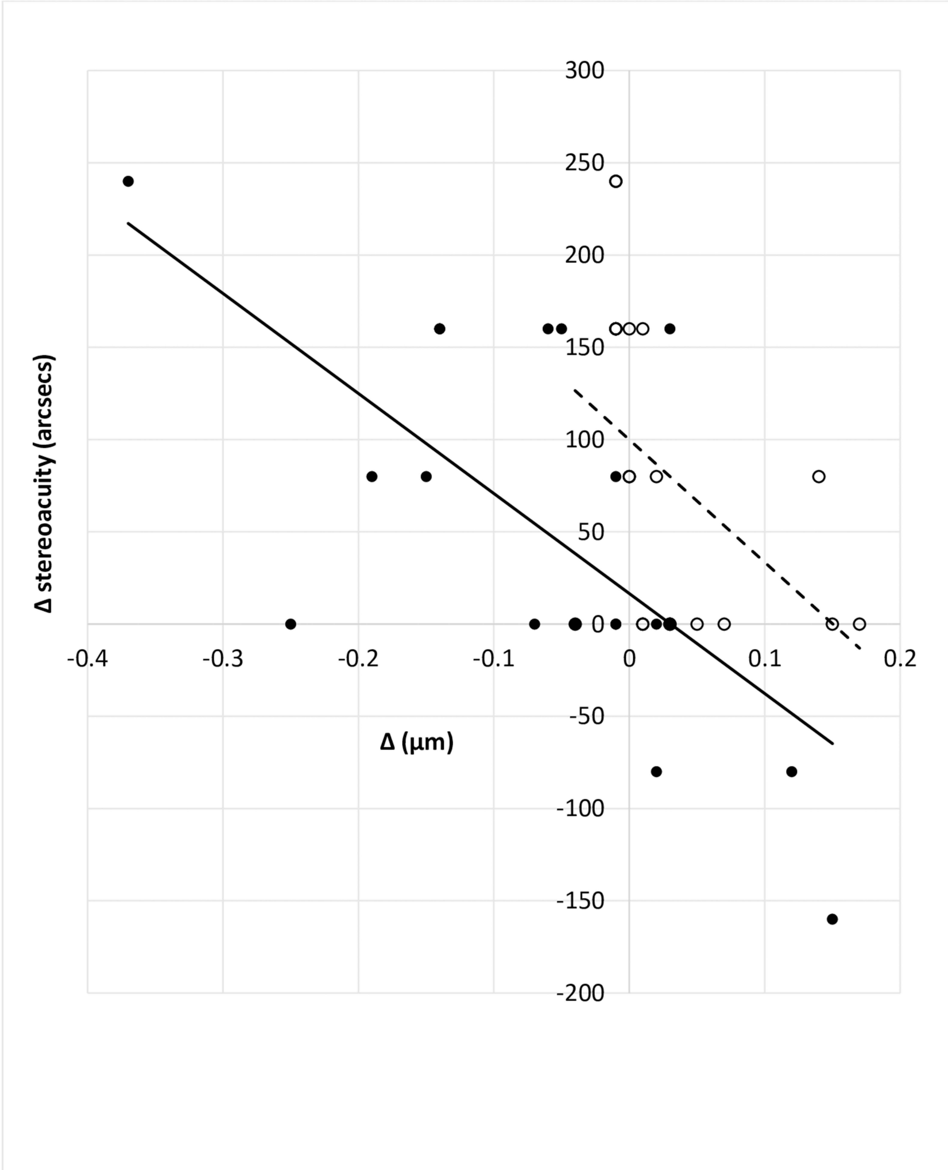

Figure 3 Comparison between changes in distance stereoacuity and corresponding changes in the interocular differences of coma and trefoil in group I (mix-and-match cases). Characteristics of the least squares line between change in stereoacuity (y) and change in the interocular difference (x) of coma (5mm pupil, empty circles, broken line) at 6 months = 99.94–664.62x, n=20, r_s=−0.595, p=0.006; and trefoil (5mm pupil, filled circles, solid line) at 3 months =16.56–542.12x, n=20, r_s=−0.634, p=0.003.

compared with cases implanted with trifocal MFIOLs. Glancing over Tables 1 and 3, the postoperative distance near visual acuities (DNVA) in the three groups were more-or-less the same, but the near stereoacuity was best in group I where the interocular difference in the near addition was +0.50D. This was a counter-intuitive finding suggesting other factors were responsible for the intergroup differences. Table 4, Figure 1A and B show that changes in stereoacuity were highly dependent upon the preoperative values. For the example in Table 4 (column **), the differences in the estimated changes between groups II and III are less than the 20” scale division in the stereoacuity tests. The linear expressions for these different presbyopia-correcting intraocular lenses (PCIOL) are, within practical clinical limits, interchangeable. The DAE and LoA values raise two key points; firstly, changes (Δ) in near stereoacuity (SAN) are more predictable than changes in distance stereoacuity (SAD); secondly, mix-and-match cases are less predictable in comparison with groups II and III.

The values for aniseikonia shown in Table 3 are comparable with previous reports observed in bilaterally treated cases[4,10,26] and the normal population.[27] The resultant aniseikonia (A_R) tended to reduce after PCIOL implantation, but the change reached statistical significance in just group III. A possible reason for this change in A_R is considered in the last paragraph of this Discussion. Table 4 shows, for individual cases, the change in A_R was associated with the preoperative value, and the estimated change (column**) in each group was more-or-less the same as the corresponding change shown in Table 3.

In Figure 2 there are some data points below the abscissa indicating that aniseikonia increased in these individual cases. These were mainly group I cases, and the linear expression predicts >2% change in A_R when the preoperative value is zero. There is a greater risk of *inducing* aniseikonia with the mix-and-match procedure when aniseikonia is not present before surgery. This is not unexpected when the mix-and-match procedure involves bilateral implantation of PCIOLs of unidentical optical design.

The DAE and LOA values, for both stereoacuity and aniseikonia, are greater in group I compared with groups II and III. Thus, the postoperative stereoacuity and aniseikonia values are less predictable in cases that undergo the group I procedure compared with either group II or III. Paradoxically, at 6 months, the near stereoacuity was better in group I even though this group had the highest magnitude of A_R. In keeping with previous reports on unilateral cases[26] and within the normal population,[27] significant associations between aniseikonia and stereoacuity were not detected. Therefore, other factors must be responsible for the observed improvements in stereoacuity.

The interocular differences in coma and trefoil reduced in group I, as noted in Table 2, alongside improvements in distance and near stereoacuity. So, as shown in Figure 3, it is reasonable to assume that reducing the interocular disparity contributed to improvements in stereoacuity. This should be viewed with caution because one of the expressions predicts a change in stereoacuity when the change in the interocular difference of the HOA is zero. In groups II and III, significant changes in the interocular HOA differences were not found, yet stereoacuity improved. Changes in aniseikonia and interocular differences of certain HOAs may be in tandem with changes in stereoacuity, but for the cases enrolled in this study, there were no clear-cut definitive cause-and-effect outcomes.

The lack of any definitive clinical associations between interocular differences in axial lengths, HOAs, refractive errors, aniseikonia and stereoacuity implies that another factor is, or other factors are, responsible for the improvements in stereoacuity. Proposing an explanation to account for this would be conjectural. Nevertheless, interocular differences associated with the heterogeneous optical properties of the natural crystalline lenses are expected to contribute to the measured interocular differences in HOAs, refractive errors, aniseikonia and other aspects of visual performance such as contrast sensitivity. Bilateral phacoemulsification and replacement with optically clear homogeneous PCIOLs may have improved stereoacuity by reducing any pre-existing interocular differences in contrast sensitivity coupled with an overall improvement in the contrast sensitivity. Cancelling out this potential source of interocular difference may account for the reduction in the A_R in group III.

Conclusion

Stereoacuity improved and aniseikonia tended to reduce following bilateral implantation with presbyopia-correcting intraocular lenses. The three sets of linear expressions for estimating ΔSAD are, to some extent, interchangeable. The same applies for the estimation of ΔSAN and ΔA_R. However, only the differences in the predicted changes between groups II and III are less than ±20” and ±1%.

Within our cohort of cases, there were no significant associations between preoperative measurements of inter-ocular differences in HOAs, corrected visual acuities and axial lengths with the pre- or postoperative stereoacuity and aniseikonia values.

Ethics Approval and Informed Consent

The study was approved by the presiding Ethics Committee. The tenets of the Helsinki agreement were followed throughout. Signed informed consent was obtained from all patients after fully explaining all the procedures, risks, and benefits.

Author Contributions

All authors meet the International Committee of Medical Journal Editors (ICMJE) criteria for authorship for this article All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

The authors report no conflicts of interest in this work.

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