Optik - International Journal for Light and Electron Optics 273 (2023) 170401

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.com/locate/ijleo

Relative peripheral refraction, higher-order aberrations, and visual quality with single-vision, progressive-multifocal, multifocal, and dual-focus soft contact lenses

Mike Chih-Wei Yeh [a], John Ching-Jen Hsiao [a,b,1], Dorcas Tsang [c], Frank Spors [c,*], Ching-Ying Cheng [a,b,**]

[a] Department of Optometry, Chung Shan Medical University, Taichung 402, Taiwan
[b] Department of Ophthalmology, Chung Shan Medical University Hospital, Taichung 402, Taiwan
[c] College of Optometry, Western University of Health Sciences, Pomona, CA, USA

ARTICLE INFO

Keywords:
Relative Peripheral Refraction
Higher-Order Aberrations
Visual Quality
Single-Vision
Progressive-Multifocal
Multifocal
And Dual-Focus Soft Contact Lenses
Myopia Control

ABSTRACT

Purpose: The purpose of this study was to measure relative peripheral refraction, higher-order aberrations, horizontal coma, and visual quality in young myopic adults wearing progressive-multifocal and multifocal center-distance soft contact lenses, dual-focus soft contact lenses, and single vision soft contact lenses for four days.
Methods: The eyes of 34 young, healthy adults ages 20–35 were analyzed while the participants wore progressive-multifocal and multifocal center-distance soft contact lenses (ArtMost SoftOK SMR and SEED 1dayPure UP Multistage daily disposable, respectively), dual-focus soft contact lenses (CooperVision MiSight 1 Day), and single vision soft contact lenses (iLens Aqua Bi-weekly). Non-cycloplegic central and relative peripheral refractions were determined at 10, 20, 25, and 30 degrees along the nasal and temporal meridians of the horizontal visual field. In addition, visual acuity, stereoacuity, accommodative amplitude, accommodative posture, spherical aberration, and horizontal coma were measured.
Results: Relative peripheral refractions showed that myopic defocus and myopic J_0 astigmatism both were highest with the SoftOK and the MiSight contact lenses. Accommodative amplitude was slightly reduced with the MiSight contact lens and spherical aberration was significantly higher with the SoftOK lens compared to the other lenses. Horizontal coma was higher and more variable with the SoftOK lens compared to the other lenses, although no statistical significance was determined.
Conclusions: The contact lenses used in this study displayed differences in relative peripheral defocus and myopic J_0 astigmatism, accommodative amplitude, and spherical aberration. The relevance of these differences in the context of myopia progression control remains to be determined.

* Corresponding author.
** Corresponding author at: Department of Optometry, Chung Shan Medical University, Taichung 402, Taiwan.
E-mail addresses: fspors@westernu.edu (F. Spors), ldiioul.tw@gmail.com (C.-Y. Cheng).
[1] The author's contribution was equal to the first author

https://doi.org/10.1016/j.ijleo.2022.170401
Received 1 July 2022; Received in revised form 12 November 2022; Accepted 9 December 2022
Available online 11 December 2022

1. Introduction

Myopia is a refractive error that occurs when distant images are focused in front of the retina. It's also a common cause of blindness. Holden et al. predicted in 2016 that by 2050, the prevalence of myopia would rise to 49.8 % of the global population, with 9.8 % suffering from high myopia, posing a significant risk of developing eye diseases such as myopic maculopathy and retinal detachment. [1] Controlling the progression of myopia has become an important topic for eye care practitioners in recent years in order to reduce the risk of eye diseases caused by myopia [2].

Animal studies have shown that myopic peripheral defocus caused by wearing plus power lenses can reduce axial length elongation. [3,4] According to Smith and Arumugam, the central retina's image quality has less of an effect on refractive development than the peripheral retina's image quality [5–7].

According to Mutti et al., relative peripheral hyperopia defocus can be used to predict the occurrence of myopia, and according to Faria Ribeiro et al., relative peripheral hyperopia defocus can be used to predict the progression of myopia. [8,9] Furthermore, Mutti et al. and Queirós et al. found that peripheral retinal myopic defocus and astigmatism could help to slow the progression of myopia and axial elongation. [8,10] Variations in relative peripheral retinal defocus are caused by wearing contact lenses with different optical designs. As a result, these differences may have an additional impact on the effectiveness of myopia control [11–15].

Clinical trials have shown that orthokeratology effectively slows the progression of a myopic refractive error while also reducing axial elongation. [16,17] Orthokeratology alters the corneal profile, causing peripheral retinal myopic defocus. Soft multifocal contact lenses with a center-distance design also produce peripheral myopic defocus, the amount of which depends on their add power. [18] When compared to single-vision contact lenses, wearing multifocal, center-distance soft contact lenses can reduce myopia progression and delay axial elongation in children. [11,19,20] Walline et al. proposed that a more pronounced peripheral retinal myopic defocus caused by multifocal center-distance contact lenses may result in a better myopia control effect based on the findings of the BLINK study [12].

Dual-focus contact lenses have a central distance zone, surrounded by multiple concentric alternating zones of add power and distance refractive power. These lenses also demonstrated their efficacy in slowing myopia progression and axial elongation compared to single-vision contact lenses. [11,21] Extended depth of focus contact lenses utilizes a front surface design that provides alternating areas of positive and negative power and induces primary and secondary spherical aberration. In one study, these lenses demonstrated myopia control potential, though it was not as pronounced as with the previously mentioned contact lens modalities [21].

Findings of a retrospective study showed a significant negative correlation of spherical aberration and axial elongation in school-age children. [22] In this context, it has been suggested that the presence of wavefront aberrations in human eyes is linked to the development of the central refractive error, however, the findings of different studies are inconclusive. [23–25] Ocular aberrations are typically expressed as Zernike polynomials and are grouped into lower-order aberrations and higher-order aberrations. Relevant lower-order aberrations are defocus M and refractive astigmatisms J_0 and J_{45}. A number of articles proposed analyzing relative peripheral defocus and higher-order aberrations in multifocal or bifocal contact lenses, as well as the interaction between peripheral retinal defocus and higher-order aberrations for myopia development. [26–30] Positive spherical aberration will be increased in a multifocal contact lens design that provides a progressive increase in positive power across the wearer's entrance pupil. Since this lens design also provides an extended depth of focus, it may be useful in controlling myopia progression. [31] Spherical aberration and horizontal coma are higher-order aberrations with analytical importance in eyes wearing contact lenses, according to the literature. [32,33] Therefore, consideration should be given to how soft contact lenses affect spherical aberration and horizontal coma of the eye when assessing their optical performance.

With the continuous innovation of multifocal and bifocal contact lens designs, it was pointed out that poor visual quality is one of the possible reasons for myopia progression. [32] Visual quality is influenced by visual acuity, contrast sensitivity, aberrations, stereoacuity, glare, visual field, accommodative amplitude, and accommodative posture. [34–38] Schulle et al. discovered no significant difference in visual acuity between spectacle lenses and soft multifocal contact lenses when the distance power of the multifocal contact lenses was increased by − 0.50 D to − 0.75 D. [39] Gong et al. found that, in addition to better accommodative amplitude and facility, single-vision lenses improved visual acuity, contrast sensitivity, and phoria status when compared to multifocal lenses in high and low illuminance settings. Wearing multifocal contact lenses, on the other hand, resulted in reduced accommodative responses and more exophoria at increasing accommodative demands than single vision contact lenses. [40] If multifocal or bifocal contact lenses can maintain visual quality comparable to single vision lenses, patient satisfaction and compliance will almost certainly ensure long-term use of these lenses for myopia progression management.

The purpose of this study was to compare relative peripheral refractions, spherical aberration, horizontal coma, and visual quality in young myopic adults wearing progressive multifocal and multifocal center-distance soft contact lenses, dual focus contact lenses, and single vision soft contact lenses for four days, based on the findings and recommendations of previous studies.

2. Methods

A single-blinded, randomized prospective study was conducted to measure relative peripheral refractions, spherical aberration, horizontal coma, and visual quality in healthy, young myopic adults wearing two different types of multifocal, center-distance soft contact lenses, one dual-focus soft contact lens, and one single vision soft contact lens.

2.1. Research subjects

Healthy adults between the ages of 20 and 35 were recruited from Chung Shan Medical University, Taichung, Taiwan, participated in this study. The inclusion criteria were spherical refractive error ≥-6.00 D, astigmatism ≥-1.00 D, monocular and binocular visual acuity ≤0.1 logMAR, and normal binocular visual function. The exclusion criteria were (a) the sphere-equivalent difference between right eye and left eye > 1.00D, (b) current wearing of rigid contact lenses, (c) eye surgery, (d) eye-related diseases, and (e) systemic diseases. Using G*Power analysis, a sample size of 32 patients was determined, with an effect size of d = 0.8, α = 0.05, power (1-β) = 0.95. A total of 35 subjects were enrolled in the study: 12 males and 23 females. The average age of all subjects was 21.86 (SD ± 2.14). Two eyes were excluded because the refractive errors did not meet the inclusion criteria. Therefore, 34 right eyes with an average spherical equivalent power of − 3.58 (SD ± 1.68) and 34 left eyes with an average spherical equivalent power of − 3.45 (SD ± 1.80) were included. The study was conducted in accordance with the Declaration of Helsinki and informed consent was obtained from all subjects prior to their participation in the study. Ethical approval was obtained from the Institutional Review Board of the Chung Shan Medical University Hospital, Taichung, Taiwan. (Approval number: CS2–20089).

2.2. Subjective refraction and visual quality measurements

A Topcon VT-10 phoropter (Topcon, Tokyo, Japan) and a View-M digital visual acuity chart were used to measure subjective refraction and visual acuity in a typically lit examination room (Quan Chin Industrial Co., Taiwan). The subjective refraction approach employed the Jackson cross-cylinder technique and maximum plus to maximum visual acuity procedure. To measure near visual acuity at a distance of 40 cm, a TMV near point card (Brighten Optix Co., Taiwan) was utilized. The near point card's stimulus was a 20/25 letter size.

Visual quality was assessed through monocular distance and near visual acuities, monocular accommodative amplitude, binocular accommodative posture, and stereoacuity. Using the Topcon VT-10 Phoropter and TMV Near Point Card, we employed the fused cross-cylinder technique to assess the accommodative posture. During this test, the near stimulus was a letter with a size of 0.1 logMAR. The accommodative amplitude was measured with an RAF ruler (Bernell Co., Mishawaka, IN) using the binocular push-up method while the individuals wore their subjective refractions in a trial frame. A Titmus Stereo Test was then used to test the stereoacuity (Bernell Co., Mishawaka, IN).

2.3. Objective refraction and aberration measurements

The baseline central and peripheral refractions were determined using a Shin-Nippon K5001 open-field autorefractor (Rexxam Co., Osaka, Japan). All subjects were instructed to fixate luminous visual targets (Fig. 1) with sizes corresponding to 0.3 logMAR visual acuity. The central visual target's fixation distance was 7.5 m. To ensure adequate pupil diameters, the measurements were performed in a dark room without cycloplegia (Fig. 1). Following the measurement of the central refraction, peripheral refractions were measured at 10, 20, 25, and 30 degrees in the nasal and temporal visual fields across the horizontal meridian. To avoid decentration of the contact lenses, participants were asked to turn their heads toward the peripheral target during these measurements. Spherical aberration and horizontal coma were measured for a 5 mm pupil diameter under central fixation using a Nidek OPD Scan 3 wavefront aberrometer (Nidek Inc., Tokyo, Japan).

2.4. Contact lenses, wearing sequence, and measurements over contact lenses

Four types of soft contact lenses were used in this study. The iLens Aqua Bi-weekly soft contact lens (Seinoh Optical Co., Taipei, Taiwan) served as the single vision control lens. The progressive multifocal, center-distance soft contact lens was the ArtMost SoftOK

Fig. 1. Luminous visual targets in an illuminated room and in a dark room. Non-cycloplegic objective refraction measurements were conducted in the dark room.

SMR (Seinoh Optical Co., Taipei, Taiwan). The multifocal, center-distance soft contact lens was the SEED 1 day Pure UP Multistage daily disposable (SEED Co., Tokyo, Japan). The dual-focus soft contact lens was the MiSight 1 Day (Coopervision, San Ramon, CA). Throughout this article, the different lenses will be referred to as follows: iLens (iLens Aqua Bi-weekly soft contact lens), SoftOK (ArtMost SoftOK SMR soft contact lens), Pure UP (SEED 1dayPure UP Multistage daily disposable soft contact lens), and MiSight (MiSight 1 Day soft contact lens).

It is noteworthy that the add power of the SoftOK lens increases dynamically with its distance power, whereas the Pure UP and MiSight lenses have fixed add power values of + 1.50 D and + 2.00 D, respectively. This dynamic change mimics the peripheral add power effect achieved by orthokeratology. Specifications of the contact lenses used in this study are listed in Table 1.

The radial power value distributions of the different contact lenses with distance power values of − 2.00 D and − 5.00 D were analyzed with a Contest Plus lens analyzer (Rotlex, Omer, Israel). The findings are shown in Fig. 2 and are summarized below.

The iLens, shown in panel A, is a single-vision contact lens. Its power profile shows an increase in negative power in the periphery of the optic zone. For the − 2.00 D iLens, this increase in negative power starts at a radius of 1.8 mm from the optic center, while for the − 5.00 D lens it starts at the center.

The SoftOK lens, shown in panel B, is a progressive multifocal, center-distance contact lens that generates dynamic add power values based on its surface asphericity. Its power profile shows a constant increase in positive power from the center toward the periphery of the optic zone. For the − 2.00 D SoftOK lens, the add power is up to + 6.50 D. For the − 5.00 D SoftOK lens, the add power is up to + 10.00 D.

The Pure UP lens, shown in panel C, is a multifocal, center-distance contact lens. For the − 2.00 D lens, the add power reaches a maximum of + 2.00 D at a radius of 1.7 mm and then reduces to + 1.25 D at the periphery of the optic zone. For the − 5.00 D lens, the add power reaches a maximum of + 1.00 D at a radius of 1.6 mm, returns to the distance power at a radius of 2.3 mm, followed by an increase in negative power in the periphery of the optic zone.

The MiSight lens, shown in panel D, is a dual-focus contact lens. For the − 2.00 D lens, the add power shows two peaks. The first peak is at a radius of 1.7 mm, with an add power of + 1.75 D at a radius of 1.7 mm, after which the lens power reduced to the distance power, followed by an increase in negative power of up to − 2.25 D. The second peak is at a radius of 3.5 mm with an add power of + 5.00 D. For the − 5.00 D lens, the add power also shows two peaks. The first peak is at a radius of 1.7 mm, with an add power of + 1.50 D at a radius of 1.7 mm, after which the lens power reduces to the distance power, followed by an increase in negative power of up to − 7.00 D. The second peak is at a radius of 3.5 mm with an add power of + 1.00 D.

Each participant received a comprehensive eye examination. The distance power for each contact lens power was determined based on the corresponding refractive error. Then trial lenses were fitted and allowed to settle for 20 min. After the correct fit and centration of each lens were confirmed, an over-refraction was conducted to determine the final lens power. The corresponding contact lenses were then selected for each participant.

If the subjects wore contact lenses, the wash-out interval was 3 days prior to wearing the study lenses [41]. Each type of contact lens was worn for a period of 4 days for at least 6 h per day. The wearing sequence for the different contact lenses was randomly assigned. At the end of each wearing period, non-cycloplegic central and peripheral objective refractions and central ocular aberrations were obtained. The subjects' follow-up measurements were scheduled for the same times of day each time to ensure consistency.

2.5. Data analysis

For the purpose of data analysis, the sphero-cylindrical refractive errors that were obtained as sphere S, minus-cylinder C, and axis α were transposed into rectangular Fourier form and expressed as power vectors defocus M, astigmatism J_0, and astigmatism J_{45} [42] as follows:

Table 1
Lens specifications of the four types of contact lenses used in the study.

Contact lenses	Lens design	Add power (D)	Material	Water content (%)	Base curve (mm)	Diameter (mm)
iLens	Single vision (spherical)	0.00	Ocufilcon D	55	8.6	14.4
SoftOK	Progressive multifocal, center distance (aspheric)	Depends on distance power	Ocufilcon D	55	9.0	14.4
Pure UP	Multifocal, center-distance (concentric)	1.50	2-HEMA	58	8.8	14.2
MiSight	Dual-focus, center-distance (concentric)	2.00	Omafilcon A	60	8.7	14.2

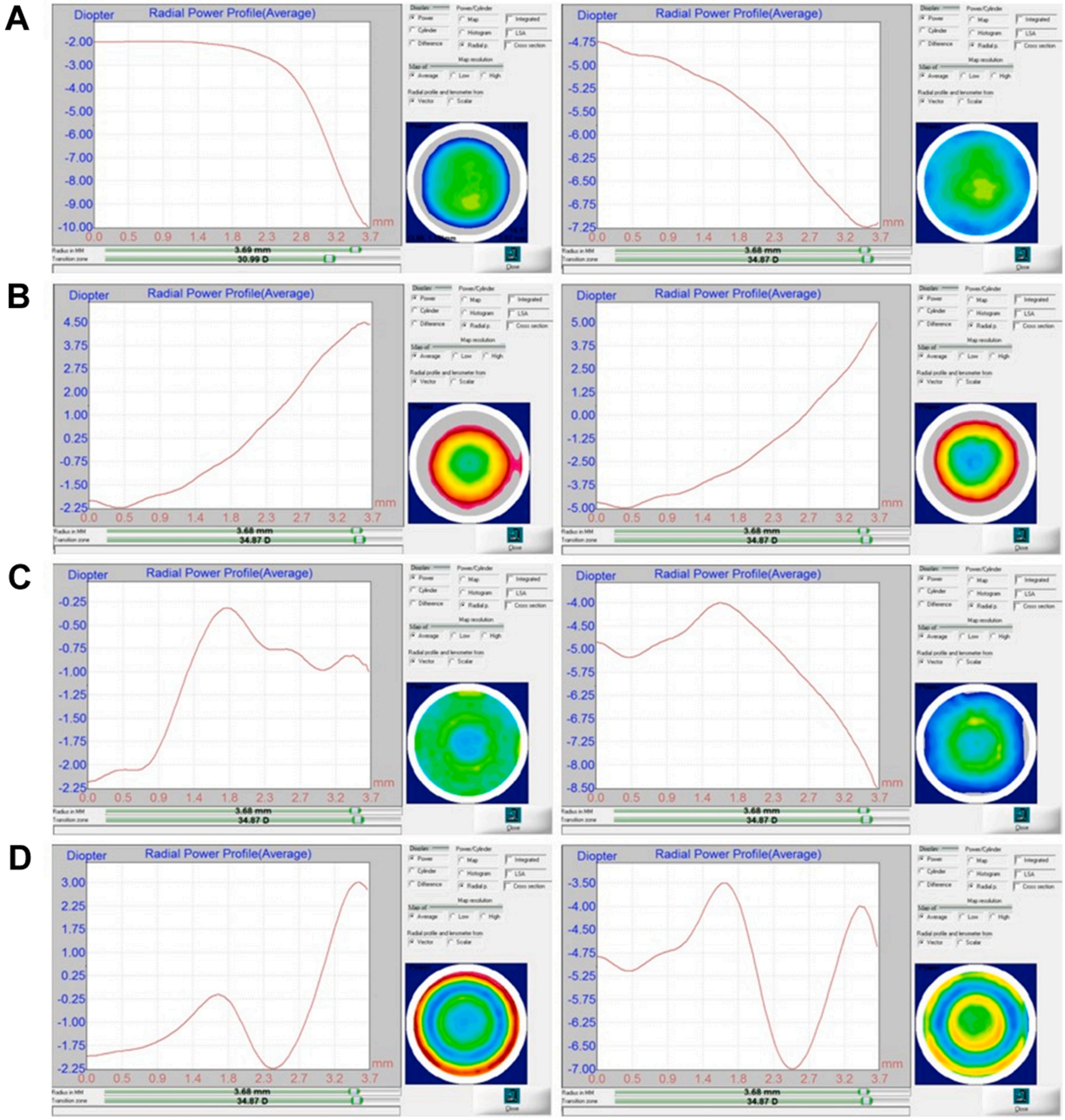

Fig. 2. Radial power profiles of the iLens (panel A), SoftOK (panel B), Pure UP (panel C), and MiSight (panel D) soft contact lenses. Power profiles were measured with a Contest Plus lens analyzer (Rotlex, Omer, Israel). Each graph displays the average power profile starting at the center of the lens (0.0 mm) and progressing toward the periphery of the optical zone, up until a radius of 3.7 mm. A decreasing slope indicates an increase in negative power. An increasing slope indicates an increase in positive power (add power). The small, colored images next to each power profile display a frontal view of the power distribution at the measured zone. This zone is 7.4 mm in diameter. The color scale utilizes blue for the lowest power measured at that lens and red for the highest power. The center of each lens corresponds to the distance power of the lens. Data shown on the left were obtained at lenses with a distance power of − 2.00 D. Data shown on the right were obtained at lenses with a distance power of − 5.00 D.

$$M = S + \frac{C}{2}$$

$$J_0 = -\frac{C}{2}\cos 2\alpha$$

$$J_{45} = -\frac{C}{2}\sin 2\alpha$$

Table 2
Relative peripheral defocus *M* data. Each cell displays the mean and standard deviation.

Condition	Visual field angle							
	Nasal (degrees)				Temporal (degrees)			
	30	25	20	10	10	20	25	30
Baseline (A)	+ 2.02 D ± 1.06	+ 1.42 D ± 0.86	+ 1.07 D ± 0.75	+ 0.21 D ± 0.43	+ 0.06 D ± 0.31	+ 0.39 D ± 0.61	+ 0.67 D ± 0.78	+ 1.33 D ± 1.10
ILens (B)	+ 2.22 D ± 2.21	+ 1.83 D ± 1.45	+ 1.13 D ± 0.99	+ 0.23 D ± 0.43	+ 0.04 D ± 0.34	+ 1.01 D ± 1.89	+ 0.72 D ± 2.70	+ 0.13 D ± 2.88
SoftOK (C)	-5.80D ± 2.10	-6.68 D ± 1.78	-3.45 D ± 1.64	-0.32 D ± 0.56	-2.43 D ± 0.50	-7.49 D ± 1.19	-5.73 D ± 3.26	-2.50 D ± 2.24
Pure UP (D)	+ 1.60 D ± 1.44	+ 1.34 D ± 1.06	+ 0.75 D ± 0.97	+ 0.38 D ± 0.56	-0.32 D ± 0.48	+ 0.40 D ± 1.23	+ 1.35 D ± 2.30	+ 1.47 D ± 2.48
MiSight (E)	+ 0.72 D ± 1.55	+ 0.52 D ± 0.97	+ 1.02 D ± 0.86	+ 0.20 D ± 0.63	+ 0.32 D ± 0.64	-1.46 D ± 1.05	-1.68 D ± 1.62	-1.07 D ± 1.53
ANOVA F	F = 81.176 $P < 0.001$	F = 192.954 $P < 0.001$	F = 87.638 $P < 0.001$	F = 6.093 $P < 0.001$	F = 142.178 $P < 0.001$	F = 159.202 $P < 0.001$	F = 42.914 $P < 0.001$	F = 9.211 $P < 0.001$
Post Hoc Significant	C< ABDE	C< ABDE E < B	C< ABDE	C< ABDE	C< ABDE D < E	C< ABDE E < ABD	C< ABDE E < ABD	C< ABD E < AD

For each condition (baseline, iLens, SoftOK, Pure Up, and MiSight), relative values for M, J_0, and J_{45} values were calculated for each eccentricity as the difference between the central refraction and the peripheral refraction. Independent and repeat measure one-way ANOVA with Bonferroni post-hoc comparison and Chi-square analysis were performed using SPSS 26.0 statistical software (IBM Corp., Armonk, NY). A value of $P < 0.05$ was considered statistically significant.

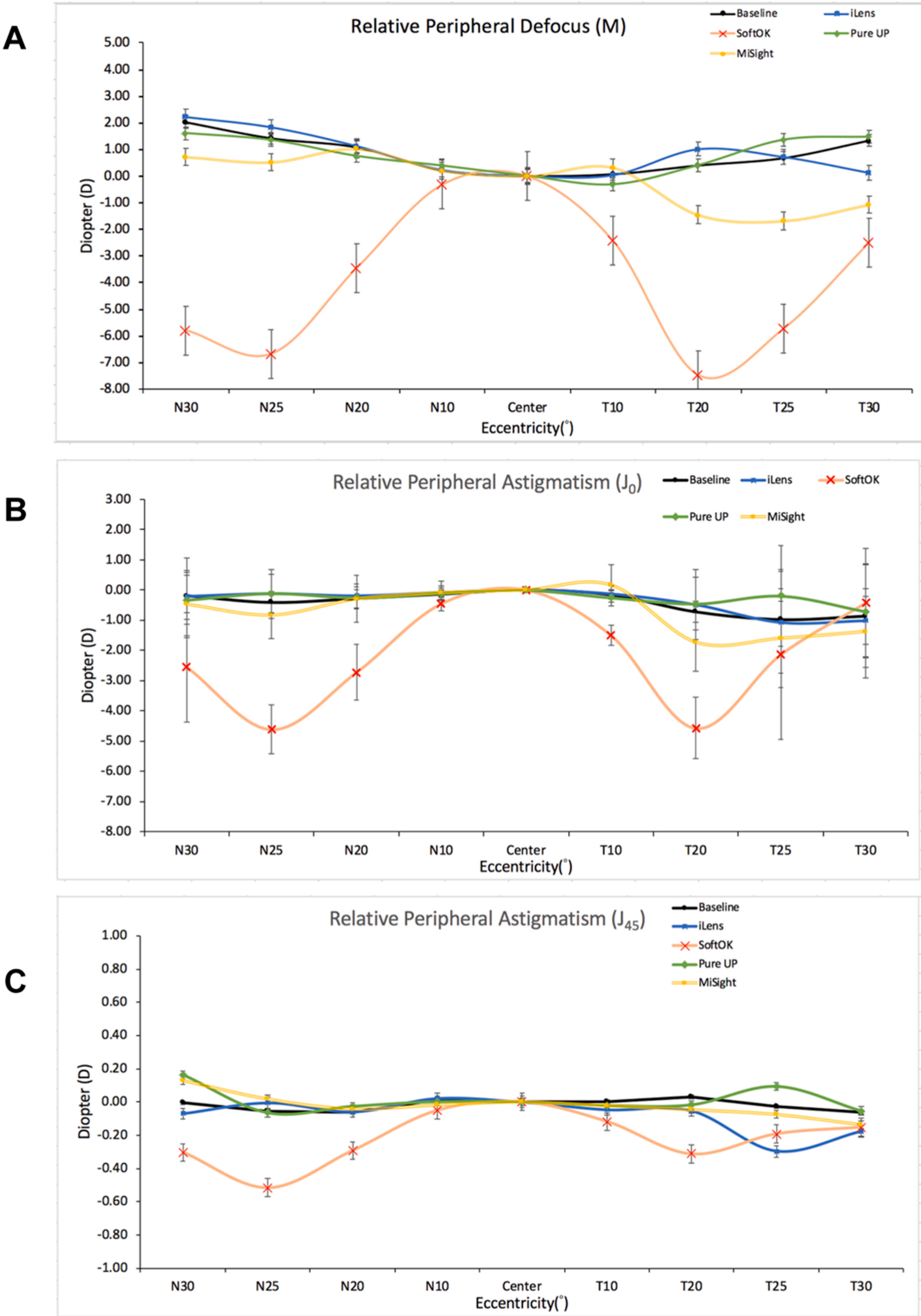

Fig. 3. Average values of relative power vectors measured as baseline and with iLens, SoftOK, Pure UP, and MiSight contact lenses. (A) relative peripheral defocus M; (B) relative astigmatism J_0; (C) relative astigmatism J_{45}. The bars show the margin of error around the point estimate, representing the 95 % confidence interval.

Table 3
Relative peripheral J_0 astigmatism data. Each cell displays the mean and standard deviation.

Condition	Visual field angle							
	Nasal (degrees)				Temporal (degrees)			
	30	25	20	10	10	20	25	30
Baseline (A)	-0.20 D ± 0.77	-0.41 D ± 0.36	-0.28 D ± 0.30	-0.14 D ± 0.15	-0.17 D ± 0.15	-0.72 D ± 0.36	-0.97 D ± 0.59	-0.86 D ± 0.92
ILens (B)	-0.21 D ± 1.29	-0.12 D ± 0.81	-0.19 D ± 0.40	-0.08 D ± 0.16	-0.13 D ± 0.27	-0.48 D ± 1.17	-1.07 D ± 1.69	-1.01 D ± 1.89
SoftOK (C)	-2.55 D ± 1.81	-4.61 D ± 0.82	-2.72 D ± 0.92	-0.45 D ± 0.24)	-1.50 D ± 0.33	-4.57 D ± 1.02	-2.14 D ± 2.82	-0.43 D ± 1.79
Pure UP (D)	-0.32 D ± 0.81	-0.11 D ± 0.64	-0.25 D ± 0.36	-0.10 D ± 0.24	-0.25 D ± 0.26	-0.45 D ± 0.88	-0.19 D ± 1.65	-0.70 D ± 1.53
MiSight (E)	-0.47 D ± 1.11	-0.83 D ± 0.78	-0.30 D ± 0.78	-0.09 D ± 0.39	+ 0.16 D ± 0.67	-1.73 D ± 0.97	-1.59 D ± 1.63	-1.37 D ± 1.17
ANOVA F	F = 12.063 $P < 0.001$	F = 190.600 $P < 0.001$	F = 80.746 $P < 0.001$	F = 9.685 $P < 0.001$	F = 70.787 $P < 0.001$	F = 73.684 $P < 0.001$	F = 4.378 $P = 0.002$	F = 0.868 $P = 0.485$
Post Hoc Significant	C < ABDE	C < ABDE E < BD	C < ABDE	C < ABDE	C < ABDE A < E D < E	C < ABDE E < ABD	C < D E < D	×

Table 4
Relative peripheral J_{45} astigmatism data. Each cell displays the mean and standard deviation.

Condition	Visual field angle							
	Nasal (degrees)				Temporal (degrees)			
	30	25	20	10	10	20	25	30
Baseline (A)	0.00 D ± 0.39	-0.05 D ± 0.32	-0.06 D ± 0.27	+ 0.01 D ± 0.21	0.00 D ± 0.19	+ 0.03 D ± 0.47	-0.03 D ± 0.62	-0.06 D ± 0.68
ILens (B)	-0.07 D ± 0.50	-0.01 D ± 0.41	-0.06 D ± 0.34	+ 0.02 D ± 0.18	-0.05 D ± 0.22	-0.05 D ± 0.62	-0.30 D ± 0.75	-0.18 D ± 0.82
SoftOK (C)	-0.30 D ± 0.54	-0.51 D ± 0.78	-0.29 D ± 0.52	-0.05 D ± 0.23	-0.12 D ± 0.31	-0.31 D ± 0.69	-0.19 D ± 0.95	-0.15 D ± 1.17
Pure UP (D)	+ 0.16 D ± 0.72	-0.06 D ± 0.46	-0.03 D ± 0.37	0.00 D ± 0.37	-0.02 D ± 0.29	-0.02 D ± 0.67	+ 0.09 D ± 0.94	-0.05 D ± 0.96
MiSight (E)	+ 0.13 D ± 0.88	+ 0.02 D ± 0.76	-0.04 D ± 0.63	-0.02 D ± 0.82	-0.02 D ± 0.67	-0.05 D ± 0.74	-0.08 D ± 0.86	-0.14 D ± 0.90
ANOVA F	F = 1.743 *P* = 0.144	F = 3.502 *P* = 0.009	F = 1.418 *P* = 0.230	F = 0.115 *P* = 0.977	F = 0.419 *P* = 0.795	F = 1.137 *P* = 0.340	F = 0.823 *P* = 0.512	F = 0.057 *P* = 0.994
Post Hoc Significant	×	C < BE	×	×	×	×	×	×

3. Results

A total of 35 subjects were enrolled in the study: 12 males and 23 females (70 eyes). The average age of all subjects was 21.86 (SD ± 2.14). Two eyes were excluded because the refractive errors did not meet the inclusion criteria. Therefore, 34 right eyes with an average spherical equivalent power of − 3.58 (SD ± 1.68) and 34 left eyes with an average spherical equivalent power of − 3.45 (SD ± 1.80) were included (68 eyes).

3.1. *Relative peripheral defocus M*

The data are shown in Table 2 and Fig. 3A. Compared to the central refraction, the iLens produced a relative peripheral hyperopic defocus at each position. The SoftOK lens provided relative peripheral myopic defocus values for all eccentricities, which went up to a maximum value of − 7.49 D ± 1.19 at the 20-degree temporal location. This was the largest relative peripheral myopic defocus produced by any of the lenses. The Pure UP lens showed a relative peripheral hyperopic defocus except at the 10-degree temporal location where it reached an average value of − 0.32 D ± 0.48. The MiSight lens provided relative peripheral myopic defocus values of − 1.46 D ± 1.05, − 1.68 D ± 1.62, and − 1.07 D ± 1.53 only at the 20-, 25-, and 30-degree temporal locations, respectively.

3.2. *Relative peripheral J_0 astigmatism*

The data are shown in Table 3 and Fig. 3B. The iLens data were relatively consistent with the baseline data. The SoftOK lens showed a substantial myopic increase in J_0 astigmatism. It peaked at the 20-degree temporal and 25-degree nasal locations with measurements of − 4.57 D ± 1.02 and − 4.61 D ± 0.82, respectively. The Pure UP lens data were relatively consistent with the baseline data and showed the least myopic J_0 astigmatism compared with the other groups. The MiSight lens showed a moderate increase in myopic J_0

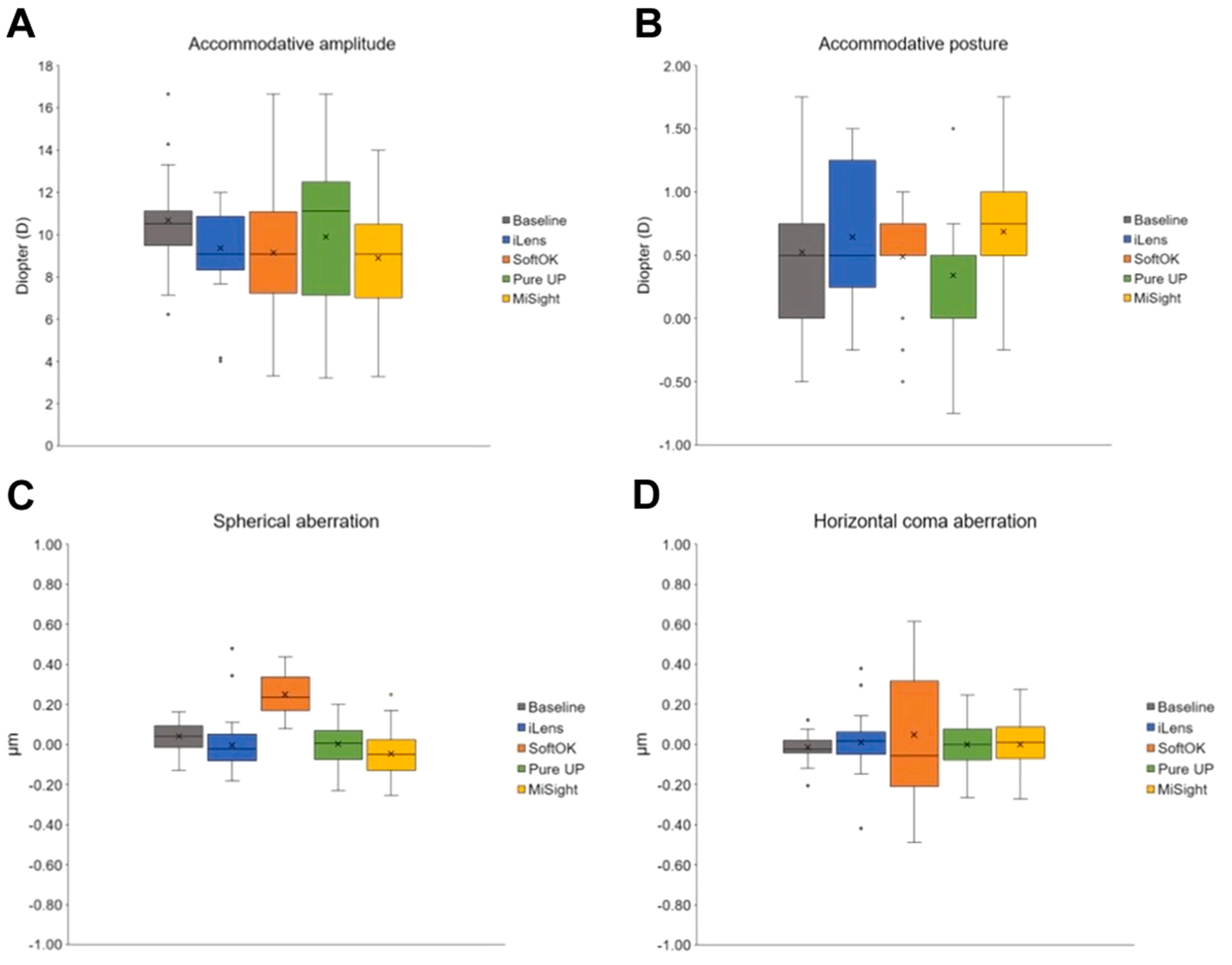

Fig. 4. Visual quality indicators for baseline and with iLens, SoftOK, Pure UP, and MiSight contact lenses. (A) Accommodative amplitude, (B) Accommodative posture, (C) Spherical aberration, (D) Horizontal coma aberration. The box and whisker plots show the values for the median (—), mean (×), interquartile range (□), minimum and maximum values (‗), and outliers (*).

astigmatism with peak values of − 1.73 D ± 0.97, − 1.59 D ± 1.63, and − 1.37 D ± 1.17 at the 20-, 25-, and 30-degree temporal locations, respectively.

3.3. Relative peripheral J_{45} astigmatism

The data are shown in Table 4 and Fig. 3C. In general, measurements obtained with all lens groups were relatively consistent with the baseline measurements. The iLens showed a slight increase in myopic J_{45} astigmatism at the 25-degree temporal location with a value of − 0.30 D ± 0.75. The SoftOK lens showed a slight increase in myopic J_{45} astigmatism at the 20-degree temporal, and 20-, 25-, 30-degree nasal locations with values of − 0.31 D ± 0.69, − 0.29 D ± 0.52, − 0.51 D ± 0.78, − 0.30 D ± 0.54, respectively.

3.4. Visual acuity

For the distance visual acuity, the average baseline value was − 0.04 logMAR ± 0.05. When wearing the study lenses, the average values were − 0.05 logMAR ± 0.05 for the iLens, − 0.04 logMAR ± 0.05 for the SoftOK lens, − 0.04 logMAR ± 0.04 for the Pure UP lens, and − 0.04 logMAR ± 0.04 for the MiSight lens. One-way ANOVA analysis showed no statistically significant difference in distance visual acuity between baseline and the four contact lenses (F = 0.321, $P = 0.864$). For the near visual acuity, the average baseline value was 0.00 logMAR ± 0.06, 0.01 logMAR ± 0.04 for the iLens, 0.02 logMAR ± 0.05 for the SoftOK lens, − 0.03 logMAR ± 0.05 for the Pure UP lens, and 0.01 logMAR ± 0.03 for the MiSight lens. One-way ANOVA analysis showed no statistically significant difference in near visual acuity between baseline and the four contact lenses (F = 1.175, $P = 0.321$).

3.5. Stereoacuity

The average value of baseline stereoacuity was 43.7″ ± 6.6. When wearing the study lenses, the average stereoacuity values were 41.6″ ± 2.7 for the iLens, 40.5″ ± 1.0 for the SoftOK lens, 41.6″ ± 2.8 for the Pure UP lens, and 40.5″ ± 1.0 for the MiSight lens. This indicates that all average values were clustered close to approximately 40″, which is considered a clinically normal value. For analysis, the data were grouped into 40″ and less as well as greater than 40″. According to Chi-square analysis ($\chi^2 = 1.718$, $P = 0.787$), stereoacuity was not significantly affected by the different lenses.

3.6. Accommodative amplitude

The average value of the baseline accommodative amplitude was 10.67 D ± 1.53. When wearing the study lenses, the average accommodative amplitude values were 9.38 D ± 1.21 for the iLens, 9.14 D ± 2.48 for the SoftOK lens, 9.89 D ± 2.97 for the Pure UP lens, and 8.88 D ± 2.34 for the MiSight lens. The data are visualized in Fig. 4A. One-way ANOVA analysis showed a statistically significant difference between baseline measurements and measurements with the four lenses (F = 2.562, $P = 0.040$). Using Bonferroni's post-hoc comparison, only the MiSight lens showed a statistically significant change in accommodative amplitude compared to the baseline value ($P = 0.047$).

3.7. Accommodative posture

The average value of the baseline accommodative posture was 0.53 D ± 0.48. When wearing the study lenses, the average accommodative posture values were 0.64 D ± 0.43 for the iLens, 0.49 D ± 0.28 for the SoftOK lens, 0.34 D ± 0.32 for the Pure UP lens, and 0.68D ± 0.41 for the MiSight lens. As shown in Fig. 4B, SoftOK, Pure UP, and MiSight lenses showed less variation. For analysis, the data were grouped into normal accommodation (+0.25 D to +0.75 D), accommodative lag (greater than +0.75 D), and accommodative lead (less than +0.25 D). According to Chi-square analysis ($\chi^2 = 1.718$, $P = 0.787$), there was no statistically significant difference between the baseline values and the values measured with the four lenses.

3.8. Spherical aberration

The average value of the baseline spherical aberration was + 0.0404 μm ± 0.0551. When wearing the study lenses, the average spherical aberration values were − 0.0037 μm ± 0.0824 for the iLens, + 0.2497 μm ± 0.0775 for the SoftOK lens, + 0.0017 μm ± 0.0800 for the Pure UP lens, and − 0.0469 μm ± 0.0910 for the MiSight lens. The data are visualized in Fig. 4C. Since the baseline spherical aberration of the uncorrected eye will be changed after correction, it is reasonable to only include the four lenses in the statistical analysis. With this approach, one-way ANOVA showed a statistically significant difference between the four lenses (F = 51.672, $P < 0.001$). The high positive spherical aberration of the SoftOK lens was statistically significantly different from the spherical aberration values of the iLens ($P < 0.001$), the Pure Up lens ($P < 0.001$), and the MiSight lens ($P < 0.001$).

3.9. Horizontal coma

The average value of baseline horizontal coma aberration was − 0.0158 μm ± 0.0434. When wearing the study lenses, the average coma aberration values were + 0.0084 μm ± 0.0794 for the iLens, 0.0478 μm ± 0.2779 for the SoftOK lens, − 0.0019 μm ± 0.0837 for the Pure UP lens, and + 0.0003 μm ± 0.0877 for the MiSight lens. The data are visualized in Fig. 4D. Although the standard deviation was wider for the SoftOK lens, one-way ANOVA indicated that there was no statistically significant difference between the four lenses (F = 0.818, $P = 0.515$).

4. Discussion

The history of peripheral refractive measurement can be traced back to Ferree et al. in 1931. [43] Over the course of almost a century, both the measuring equipment and the measuring method have substantially changed. In the last 20 years, open-field autorefractors became available, which allow the assessment of peripheral refractions up to 40 degrees. [44] When using optical treatment strategies such as multifocal contact lenses and orthokeratology to manage myopia progression, these measurements are critical.

Multifocal center-distance and dual-focus soft contact lenses have demonstrated their efficacy in decreasing the progression of myopic refraction as well as reducing axial elongation. Multifocal center-distance contact lenses are also known to produce relative peripheral myopic defocus, which, among other factors, is hypothesized to be linked to the myopia control exhibited by these lenses [26,45].

The analysis of peripheral refraction patterns showed that the myopic subjects at baseline had relative hyperopic peripheral refractions, which is consistent with findings reported in the literature. [9,46–48] When wearing the iLens single-vision contact lenses, the relative peripheral refractions remains hyperopically defocused. This is in accordance with findings of other single-vision soft contact lens studies and may be a possible cause of myopia progression. [49] It is known that single-vision contact lenses do not slow down the progression of myopia, which is why these lenses are used as controls in clinical trials.

In this study, the progressive-multifocal, center-distance SoftOK lenses demonstrated a pronounced shift toward relative peripheral myopic defocus all locations. The dual-focus MiSight lenses and the multifocal, center-distance Pure Up lenses created slight peripheral myopic defocus values at some, but not all locations. Findings on orthokeratology patients published by Kang and Swarbrick indicate that peripheral myopic defocus may result in a dose-dependent slowing of myopia progression. That is, the greater the peripheral myopic defocus, the more effectively myopia progression slows. [13] In multifocal, center-distance soft contact lenses, the peripheral myopic defocus increases when the add powers of the lenses increase. Since multifocal, center-distance soft contact lenses with higher add power values have shown an improved myopia control effect compared to lenses with lower add power values, it is reasonable to assume that a more pronounced peripheral myopic defocus obtained with soft contact lenses will have the same effect. [12].

Furthermore, in this study, myopic relative peripheral J_0 astigmatism increased significantly with the SoftOK lens and moderately with the MiSight lens, whereas relative peripheral J_{45} astigmatism remained largely unchanged with all lenses. The findings obtained with the SoftOK lens have also been reported in patients wearing orthokeratology lenses. [50] Since the SoftOK lens is designed to mimic the peripheral add power effect achieved by orthokeratology, this similarity is not surprising.

There was no significant difference in distance and near visual acuity between baseline measurements and when the four study lenses were worn in this study. Especially for the multifocal and dual-focus contact lenses, this is an important outcome since these lenses possess optical designs that place different power zones in front of the wearers' entrance pupils. Even with these intricate optical designs, visual acuities must be good to ensure patient satisfaction and long-term use of these lenses. This study's findings are consistent with those of Schulle et al. and Przekoracka et al., who concluded that multifocal contact lenses should not cause significant changes in visual acuity or vision decline. [39,51] Stereoacuity was also unaffected by any of the contact lenses used in the current study. This is consistent with the findings of Kang and Wildsoet, who compared the visual quality of young patients fitted with single-vision and multifocal soft contact lenses. [52].

Contrary to the findings of Ruiz-Pomeda et al., the MiSight contact lens was found to have an average reduction in accommodative amplitude by 1.79 D from baseline. The average accommodative posture was also lower in the current study, both at baseline and with all study lenses. The age difference between the subjects in both studies could be one explanation for the disparate outcomes. The MiSight group in the Ruiz-Pomeda et al. study had an average age of 10.94 years (SD ± 2.14), but the average age in the current study was 21.86 years (SD ± 2.14). Furthermore, the techniques used to measure accommodative posture differed between the two studies. While the subjective fused cross-cylinder technique was used in this study, the accommodative posture was calculated using objective measurements obtained with a Grand Seiko WAM-5500 autorefractor by Ruiz-Pomeda et al. [53].

Furthermore, the current study showed a significant increase in positive spherical aberration with the SoftOK lenses, which is due to the progressive-multifocal design of these lenses. It is known that increased positive spherical aberration is associated with reduced myopia progression. [54] Since an increase in positive spherical aberration will extend the depth of focus, it was suggested using soft contact lenses with positive spherical aberration to enhance the effectiveness of myopia control. [55] This makes the SoftOK lens an excellent choice for myopia control in children, although a randomized clinical trial is required to investigate whether this lens design has better myopia control efficacy compared to multifocal and dual-focus contact lenses. In this study, no significant difference was found in horizontal coma between wearing lenses and baseline, even though the standard deviation increased with wearing the lenses.

The type of equipment and its measurement accuracy, the environmental setting, and the subjects' pupil sizes all have an impact on the data collected when measuring peripheral refractions and higher-order aberrations in a clinical study. While calibrated equipment and standard measurement procedures were used, there are several limitations to this study:

(1) The measurements of relative peripheral refractions, higher-order aberrations, and visual quality indicators were limited to four-day intervals per lens type, rather than the one- or two-year intervals reported in most myopia control studies. (2) Peripheral refractions were measured without cycloplegia. To facilitate natural mydriasis, the environment was dark. Measurements at the 30-degree nasal and 30-degree temporal locations, however, were difficult to conduct and might be prone to measurement errors. [56] (3) The Shin-Nippon NVision K5001 autorefractor's measurement spot is approximately 2.3 mm in diameter. Because the MiSight

lens's power is provided by an alternating concentric ring design, the autorefractor's measurement spot will overlap the concentric rings, influencing the amount of detected defocus. (4) Subjective visual quality measures such as contrast sensitivity and the perception of halos and glare may vary when wearing multifocal contact lenses with different optical designs. These indicators were not assessed in this study. (5) Stereoacuity was measured with a traditional stereoscopic vision test that was limited to a minimum angle of 40 s of arc. Its accuracy might not be enough to produce true analytical differences.

How the variations in relative peripheral refraction, spherical aberration, and amplitude of accommodation found with the contact lenses used in this study, especially with the SoftOK lens, influence the course of myopia progression remains to be investigated in future studies.

Funding

This research was funded by Chung Shan Medical University research projects CSMU-INT-101-24 and FCU/CSMU 110-003 in Taiwan.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ching-Ying, Cheng reports financial support was provided by Chung Shan Medical University.

Data Availability

The data that has been used is confidential.

Acknowledgments

na.

Author contributions

Conceptualization, C.-Y.C., J.C.-J.H. and. M.C.-W.Y.; Investigation, Data curation, and Formal analysis, C.-Y.C., J.C.-J.H. and. M.C.-W.Y.; Writing – original draft preparation, C.-Y.C.; Writing – review & editing, C.-Y.C., J.C.-J.H. D.T. and F.S. All authors have read and agreed to the published version of the manuscript.

Institutional review board statement

The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Ethics Committee of Chung Shan Medical University Hospital (Taichung, Taiwan) (approval number: CS2–20089).

Informed consent statement

Informed consent was obtained from all subjects involved in the study.

References

[1] B.A. Holden, T.R. Fricke, D.A. Wilson, M. Jong, K.S. Naidoo, P. Sankaridurg, T.Y. Wong, T.J. Naduvilath, S. Resnikoff, Global prevalence of myopia and high myopia and temporal trends from 2000 through 2050, Ophthalmology 123 (2016) 1036–1042.
[2] P. Cho, Q. Tan, Myopia and orthokeratology for myopia control, Clin. Exp. Optom. 102 (2019) 364–377.
[3] E.L. Irving, J.G. Sivak, M.G. Callender, Refractive plasticity of the developing chick eye, Ophthalmic Physiol. Opt. 12 (1992) 448–456.
[4] X. Zhu, J.A. Winawer, J. Wallman, Potency of myopic defocus in spectacle lens compensation, Invest Ophthalmol. Vis. Sci. 44 (2003) 2818–2827.
[5] E.L.3rd Smith, L.F. Hung, J. Huang, Relative peripheral hyperopic defocus alters central refractive development in infant monkeys, Vis. Res 49 (2009) 2386–2392.
[6] E.L.3rd Smith, L.F. Hung, J. Huang, B. Arumugam, Effects of local myopic defocus on refractive development in monkeys, Optom. Vis. Sci. 90 (2013) 1176–1186.
[7] B. Arumugam, L.F. Hung, C.H. To, B. Holden, E.L.3rd Smith, The effects of simultaneous dual focus lenses on refractive development in infant monkeys, Invest Ophthalmol. Vis. Sci. 55 (2014) 7423–7432.
[8] D.O. Mutti, J.R. Hayes, G.L. Mitchell, et al., Refractive error, axial length, and relative peripheral refractive error before and after the onset of myopia, Invest Ophthalmol. Vis. Sci. 48 (2007) 2510–2519.
[9] M. Faria-Ribeiro, A. Queirós, D. Lopes-Ferreira, J. Jorge, J.M. González-Méijome, Peripheral refraction and retinal contour in stable and progressive myopia, Optom. Vis. Sci. 90 (2013) 9–15.
[10] A. Queirós, J.M. González-Méijome, J. Jorge, C. Villa-Collar, A.R. Gutiérrez, Peripheral refraction in myopic patients after orthokeratology, Optom. Vis. Sci. 87 (2010) 323–329.
[11] P. Chamberlain, S.C. Peixoto-de-Matos, N.S. Logan, C. Ngo, D. Jones, G. Young, A 3-year randomized clinical trial of MiSight lenses for myopia Control, Optom. Vis. Sci. 96 (2019) 556–567.
[12] J.J. Walline, M.K. Walker, D.O. Mutti, L.A. Jones-Jordan, L.T. Sinnott, A.G. Giannoni, K.M. Bickle, K.L. Schulle, A. Nixon, G.E. Pierce, D.A. Berntsen, Effect of high add power, medium add power, or single-vision contact lenses on myopia progression in children: the BLINK randomized clinical trial, JAMA 324 (2020) 571–580.

[13] P. Kang, H. Swarbrick, New perspective on myopia control with orthokeratology, Optom. Vis. Sci. 93 (2016) 497–503.
[14] E.L.3rd Smith, M.C. Campbell, E. Irving, Does peripheral retinal input explain the promising myopia control effects of corneal reshaping therapy (CRT or Ortho-K) & multifocal soft contact lenses? Ophthalmic Physiol. Opt. 33 (2013) 379–384.
[15] J.J. Walline, G.A. Gaume, L.T. Sinnott, M.A. Chandler, J. Huang, D.O. Mutti, L.A. Jones-Jordan, D.A. Berntsen, A randomized trial of soft multifocal contact lenses for myopia control: baseline data and methods, Optom. Vis. Sci. 94 (2017) 856–866.
[16] Y.C. Lee, J.H. Wang, C.J. Chiu, Effect of orthokeratology on myopia progression: twelve-year results of a retrospective cohort study, BMC Ophthalmol. 17 (2017) 243.
[17] X. Li, I.B. Friedman, N.B. Medow, C. Zhang, Update on orthokeratology in managing progressive myopia in children: efficacy, mechanisms, and concerns, J. Pedia Ophthalmol. Strabismus 54 (2017) 142–148.
[18] P. Sankaridurg, Contact lenses to slow progression of myopia, Clin. Exp. Optom. 100 (2017) 432–437.
[19] J.J. Walline, K.L. Greiner, M.E. McVey, L.A. Jones-Jordan, Multifocal contact lens myopia control, Optom. Vis. Sci. 90 (2013) 1207–1214.
[20] Remon, et al., Bifocal and multifocal contact lenses for presbyopia and myopia control, J. Ophthalmol. 2020 (2020), 8067657, https://doi.org/10.1155/2020/8067657.
[21] P. Sankaridurg, R.C. Bakaraju, T. Naduvilath, X. Chen, R. Weng, D. Tilia, P. Xu, W. Li, F. Conrad, E.L. Smith III, K. Ehrmann, Myopia control with novel central and peripheral plus contact lenses and extended depth of focus contact lenses: 2 year results from a randomised clinical trial, Ophthalmic Physiol. Opt. 39 (4) (2019) 294–307 (Jul).
[22] J.K. Lau, S.J. Vincent, M.J. Collins, S.-W. Cheung, P. Cho, Ocular higher-order aberrations and axial eye growth in young Hong Kong children, Sci. Rep. 8 (2018) 1–10.
[23] T. Buehren, D.R. Iskander, M.J. Collins, B. Davis, Potential higher-order aberration cues for sphero-cylindrical refractive error development, Optom. Vis. Sci. 84 (2007) 163–174.
[24] A. Hartwig, D.A. Atchison, H. Radhakrishnan, Higher-order aberrations and anisometropia, Curr. Eye Res 38 (2013) 215–219.
[25] R.P. Hughes, S.J. Vincent, S.A. Read, M.J. Collins, Higher order aberrations, refractive error development and myopia control: a review, Clin. Exp. Optom. 103 (2020) 68–85.
[26] P. Kang, Y. Fan, K. Oh, K. Trac, F. Zhang, H.A. Swarbrick, The effect of multifocal soft contact lenses on peripheral refraction, Optom. Vis. Sci. 90 (2013) 658–666.
[27] C. Fedtke, K. Ehrmann, R.C. Bakaraju, Peripheral refraction and spherical aberration profiles with single vision, bifocal and multifocal soft contact lenses, J. Optom. 13 (2020) 15–28.
[28] C. Fedtke, K. Ehrmann, V. Thomas, R.C. Bakaraju, Peripheral refraction and aberration profiles with multifocal lenses, Optom. Vis. Sci. 94 (2017) 876–885.
[29] J. Pauné, S. Thivent, J. Armengol, L. Quevedo, M. Faria-Ribeiro, J.M. González-Méijome, Changes in peripheral refraction, higher-order aberrations, and accommodative lag with a radial refractive gradient contact lens in young myopes, Eye Contact Lens 42 (2016) 380–387.
[30] J. Shen, F. Spors, D. Tsang, L.E. McNaughton, D.J. Egan, In-vivo evaluation of peripheral refraction changes with single vision and multifocal soft contact lenses, Med Hypothesis Disco Innov. Ophthalmol. 7 (2018) 112.
[31] D. Lopes-Ferreira, P. Fernandes, A. Queirós, J.M. González-Meijome, Combined effect of ocular and multifocal contact lens induced aberrations on visual performance: center-distance versus center-near design, Eye Contact Lens 44 (2018) S131–S137. Sep 1.
[32] S. Patel, M. Fakhry, J.L. Alió, Objective assessment of aberrations induced by multifocal contact lenses in vivo, CLAO J. 28 (2002) 196–201.
[33] C. Fedtke, R.C. Bakaraju, K. Ehrmann, J. Chung, V. Thomas, B.A. Holden, Visual performance of single vision and multifocal contact lenses in non-presbyopic myopic eyes, Cont. Lens Anterior Eye 39 (2016) 38–46.
[34] A.D. Miller, M.J. Kris, A.C. Griffiths, Effect of small focal errors on vision, Optom. Vis. Sci. 74 (1997) 521–526.
[35] J.V. García-Marqués, R.J. Macedo-De-Araújo, A. Cerviño, S. García-Lázaro, C. McAlinden, J.M. González-Méijome, Comparison of short-term light disturbance, optical and visual performance outcomes between a myopia control contact lens and a single-vision contact lens, Ophthalmic Physiol. Opt. 40 (2020) 718–727.
[36] P. Kang, C. McAlinden, C.F. Wildsoet, Effects of multifocal soft contact lenses used to slow myopia progression on quality of vision in young adults, Acta Ophthalmol. 95 (2017) e43–e53.
[37] T. Buehren, M.J. Collins, Accommodation stimulus-response function and retinal image quality, Vis. Res 46 (2006) 1633–1645.
[38] J. Ruiz-Alcocer, D. Madrid-Costa, H. Radhakrishnan, T. Ferrer-Blasco, R. Montés-Micó, Changes in accommodation and ocular aberration with simultaneous vision multifocal contact lenses, Eye Contact Lens 38 (2012) 288–294.
[39] K.L. Schulle, D.A. Berntsen, L.T. Sinnott, K.M. Bickle, A.T. Gostovic, G.E. Pierce, L.A. Jones-Jordan, D.O. Mutti, J.J. Walline, Visual acuity and over-refraction in myopic children fitted with soft multifocal contact lenses, Optom. Vis. Sci. 95 (2018) 292–298.
[40] C.R. Gong, D. Troilo, K. Richdale, Accommodation and phoria in children wearing multifocal contact lenses, Optom. Vis. Sci. 94 (2017) 353–360.
[41] M.J. Lipson, A. Sugar, D.C. Musch, Overnight corneal reshaping versus soft disposable contact lenses: vision-related quality-of-life differences from a randomized clinical trial, Optom. Vis. Sci. 82 (10) (2005) 886–891. Oct 1.
[42] L.N. Thibos, W. Wheeler, D. Horner, Power vectors: an application of fourier analysis to the description and statistical analysis of refractive error, Optom. Vis. Sci. 74 (1997) 367–375.
[43] C.E. Ferree, G. Rand, C. Hardy, Refraction for the peripheral field of vision, Arch. Ophthalmol. 5 (1931) 717–731.
[44] P. Sankaridurg, B. Holden, E. Smith 3rd, T. Naduvilath, X. Chen, P.L. de la Jara, A. Martinez, J. Kwan, A. Ho, K. Frick, J. Ge, Decrease in rate of myopia progression with a contact lens designed to reduce relative peripheral hyperopia: one-year results, Invest Ophthalmol. Vis. Sci. 52 (13) (2011) 9362–9367.
[45] D.A. Berntsen, C.D. Barr, D.O. Mutti, K. Zadnik, Peripheral defocus and myopia progression in myopic children randomly assigned to wear single vision and progressive addition lenses, Invest. Ophthalmol. Vis. Sci. 54 (8) (2013) 5761–5770. Aug 1.
[46] D.O. Mutti, J.R. Hayes, G.L. Mitchell, L.A. Jones, M.L. Moeschberger, S.A. Cotter, R.N. Kleinstein, R.E. Manny, J.D. Twelker, K. Zadnik, Refractive error, axial length, and relative peripheral refractive error before and after the onset of myopia, Invest Ophthalmol. Vis. Sci. 48 (2007) 2510–2519.
[47] W. Neil Charman, H. Radhakrishnan, Peripheral refraction and the development of refractive error: a review, Ophthalmic Physiol. Opt. 30 (2010) 321–338.
[48] D.A. Atchison, R. Rosén, The possible role of peripheral refraction in development of myopia, Optom. Vis. Sci. 93 (2016) 1042–1044.
[49] P. Kang, Y. Fan, K. Oh, K. Trac, F. Zhang, H. Swarbrick, Effect of single vision soft contact lenses on peripheral refraction, Optom. Vis. Sci. 89 (7) (2012) 1014–1021. Jul 1.
[50] P. Kang, H. Swarbrick, Peripheral refraction in myopic children wearing orthokeratology and gas-permeable lenses, Optom. Vis. Sci. 88 (4) (2011) 476–482. Apr 1.
[51] K. Przekoracka, K. Michalak, J. Olszewski, F. Zeri, A. Michalski, J. Paluch, A. Przekoracka-Krawczyk, Contrast sensitivity and visual acuity in subjects wearing multifocal contact lenses with high additions designed for myopia progression control, Cont. Lens Anterior Eye 43 (2020) 33–39.
[52] P. Kang, C.F. Wildsoet, Acute and short-term changes in visual function with multifocal soft contact lens wear in young adults, Cont. Lens Anterior Eye 39 (2016) 133–140.
[53] A. Ruiz-Pomeda, B. Pérez-Sánchez, P. Cañadas, F.L. Prieto-Garrido, R. Gutiérrez-Ortega, C. Villa-Collar, Binocular and accommodative function in the controlled randomized clinical trial MiSight® assessment study Spain (MASS), Graefes Arch. Clin. Exp. Ophthalmol. 257 (2019) 207–215.
[54] T. Hiraoka, J. Kotsuka, T. Kakita, F. Okamoto, T. Oshika, Relationship between higher-order wavefront aberrations and natural progression of myopia in schoolchildren, Sci. Rep. 7 (2017) 1–9.
[55] X. Cheng, J. Xu, K. Chehab, J. Exford, N. Brennan, Soft contact lenses with positive spherical aberration for myopia control, Optom. Vis. Sci. 93 (2016) 353–366.
[56] C. Fedtke, K. Ehrmann, B.A. Holden, A review of peripheral refraction techniques, Optom. Vis. Sci. 86 (2009) 429–446.