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Contact Lens and Anterior Eye xxx (xxxx) xxx

Contents lists available at ScienceDirect

Contact Lens and Anterior Eye

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

The effects of base curve aspheric orthokeratology lenses on corneal topography and peripheral refraction: A randomized prospective trial

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A R T I C L E I N F O

Keywords:
Orthokeratology lens
Aspheric base curve
Relative corneal refractive power change
Relative peripheral refraction

A B S T R A C T

Background: To investigate the effects of orthokeratology (*ortho*-k) lenses with aspheric and spherical base curve designs on corneal refractive power (CRP) and peripheral refraction.

Methods: Children aged 8 to 12 years with myopia between −0.75 D to −4.00 D, astigmatism ≤1.00 D, and corneal astigmatism ≤1.50 D were randomly assigned to the base curve aspheric (BCA) and base curve spherical (BCS) *ortho*-k lens groups. CRP was assessed for the central 8 mm cornea along horizontal and vertical meridians, and peripheral refraction was measured at 10°, 20°, and 30° along the nasal and temporal retina. Primary measurements included relative corneal refractive power change (RCRPC) and relative peripheral refraction change (RPRC).

Results: The 3-month results of the 33 and 29 subjects (right eye only) in the BCA and BCS groups, respectively, were obtained. Nonsignificant differences were found in the baseline data between the two groups ($p > 0.05$). At the 3-month follow-up visit, the mean RCRPC in the BCA group (2.08 ± 0.65 D) was significantly greater than that in the BCS group (1.32 ± 0.81 D) ($F_{1,51} = 25.25$, $p < 0.001$). The BCA group (-1.82 ± 0.65 D) exhibited a larger absolute RPRC than the BCS group (-0.98 ± 0.54 D) ($F_{1,57} = 33.73$, $p < 0.001$).

Conclusions: It was found that the BCA *ortho*-k lens resulted in a more aspheric treatment zone and a more myopic relative peripheral refraction (RPR) along the horizontal meridian. The more myopic RPR was contributed by a more hyperopic central refraction and a more myopic peripheral refraction in the BCA group.

1. Introduction

Myopia has become a global public health problem due to its increasing prevalence [1–3]. It is estimated that the prevalence of myopia will reach up to 50 %, and that of high myopia will reach up to 10 % worldwide by 2050 [4]. In East Asia, the prevalence of myopia is 69 % in 15-year-olds and 80 % in 18-year-olds [1]. The progression of myopia increases the risk of serious ocular complications, such as retinal detachment [5], glaucoma [6], and cataracts [7]. Thus, prevention of myopia progression is essential for children.

Approaches for controlling myopia mainly include optical and pharmacological interventions. The orthokeratology (*ortho*-k) lens is the most common optical device used in the clinic to slow axial elongation in children and has shown substantial efficacy relative to single vision spectacles[8,9]. The *ortho*-k lens is a rigid contact lens with a reverse geometric design in the back surface that can reshape the corneal morphology. After treatment, the corneal center tends to be flattened, and the mid-peripheral cornea tends to be steepened. In turn, this aspheric corneal change induces a hyperopic shift in central refraction as well as a relative myopic shift in peripheral refraction. Inducing peripheral myopic defocus has also been shown to inhibit ocular growth in marmosets, chicks, and infant monkeys [10–12]. It is possible that the peripheral myopic defocus induced by the *ortho*-k lens is the mechanism that slows myopia progression [13–15].

More recently, studies have suggested that corneal refractive power (CRP) and its distribution are crucial predictors of the efficacy of *ortho*-k lens treatment. Zhong et al. [16] found that axial elongation in children after *ortho*-k treatment was negatively correlated with the summed

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https://doi.org/10.1016/j.clae.2023.101814
Received 15 September 2022; Received in revised form 12 December 2022; Accepted 12 January 2023

relative corneal power change from the central cornea to the mid-peripheral cornea. Lee et al. [17] reported that the apex-periphery refractive power difference at the cornea was associated with axial elongation in *ortho*-k lens treatment. In addition, the spatial distribution of CRP may be a vital estimate of the validity of *ortho*-k lens treatment. It has been argued that a relative corneal refractive power change (RCRPC) closer to the corneal center contributes to better myopia control [18].

Furthermore, the aspheric change of CRP from the corneal center to the mid-peripheral region could cause a myopic shift of the peripheral refraction. It has been suggested that the CRP shift was consistent with the peripheral defocus shift [19]. A *meta*-analysis found that a dual-focus soft contact lens with defocus rings closer to the visual axis has greater efficacy in inhibiting myopia progression than a peripheral add multifocal soft contact lens [20]. One study on rhesus monkeys also demonstrated that imposing myopic defocus beyond 20° from the fovea had little consistent impact on central refractive development [21].

Importantly, the asphericity of the corneal optical surface after treatment is linked with CRP and its spatial distribution; moreover, it may impact the relative peripheral refraction. Theoretically, the change in the corneal optical surface may depend on the lens design and the corneal response. However, whether an *ortho*-k lens with an aspheric base curve could induce a more aspheric treatment zone remains unknown.

To the best of the knowledge, there have been no published studies investigating the impacts of *ortho*-k lenses with aspheric base curves on ocular optical properties. The aim of this prospective study is to investigate the effects on CRP and peripheral refraction in Chinese children after wearing base curve aspheric (BCA) *ortho*-k lenses compared to those after wearing base curve spheric (BCS) *ortho*-k lenses.

2. Method and materials

2.1. Study design

This was a randomized, controlled single-masked clinical trial. The study was approved by the Ethics Committee of West China Hospital of Sichuan University and was registered at https://www.chictr.org.cn with the identifier ChiCTR2000040990. All procedures followed the tenets of the Declaration of Helsinki. Subjects were masked from the lenses used during the study period. In the present study, the differences in CRP and peripheral refraction at the 3-month visit were compared between two groups of children, in which a different *ortho*-k lens (the BCA or BCS *ortho*-k lens) was used in each group.

2.2. Subjects

A total of 70 primary school children were enrolled in this study between December 2020 and July 2021 at West China Hospital of Sichuan University according to the criteria shown in Table 1. Subjects were randomly assigned at a 1:1 ratio to two groups using an interactive web response system (ebmedical-iwrs.com, Eyebright, China): the BCA and BCS (control) groups. Aspheric or spherical base curve *ortho*-k lenses were worn on both eyes, and the subjects were reminded to attend regular aftercare visits 1 day, 1 week, 1 month and 3 months after treatment.

2.3. Lenses

In this study, ProTong *ortho*-k lenses (Eyebright Co. ltd, Beijing, China) were used for the BCA and BCS groups. The lenses were composed of Roflufocon E, with an oxygen permeability (DK) of 125 (10^{-11} cm^2 × ml O_2)/(s × ml × mmHg). The diameter of the lenses ranged from 10.2 mm to 11.0 mm, and the compression factor was 0.75 D. In both groups, the *ortho*-k lens had a four-curve design, and the diameter of the back optical zone ranged from 6.0 mm to 6.4 mm with a step of 0.2 mm. An aspherical base curve design was used for the BCA group, whereas a spherical base curve design was used for the BCS group. In addition, the reverse curve, alignment curve and peripheral curve had aspherical designs in both groups.

Table 1
Subject inclusion criteria.

Inclusion criteria	
Age	8–12 years
Refractive error	Manifestation of ocular refraction in either eye • Myopia ≥ −4.00 D and ≤ −0.75 D • Astigmatism ≤ 1.00 D • Anisometropia ≤ 1.00 D • Corneal astigmatism ≤ 1.50 D with axis 180 ± 30
Visual acuity	Monocular best-corrected distance logMAR visual acuity equal to 0.1 or better
Health	No contraindications for wearing contact lenses No refractive surgery No systemic diseases
Others	No history of myopia control treatment (e.g., bifocal or multifocal spectacle lenses, soft multifocal contact lenses, orthokeratology, atropine eye drops, etc.) Willingness to make scheduled visits to the Hospital after wearing the orthokeratology lenses Willingness to wear orthokeratology lenses for at least eight hours per night and six days per week

2.4. Measurements

At baseline, best-corrected logMAR visual acuity (ETDRS charts; Precision Vision Inc., Illinois, USA), intraocular pressure (TX20, Canon Inc., Kawasaki, USA), corneal topography (TMS-4, Tomey Inc., Nagoya, Japan), central corneal thickness (SP-3000P, Topcon Corp, Tokyo, Japan), central refraction (KR-1, Topcon Corp, Tokyo, Japan), and peripheral refraction (WAM-5500, GrandSeiko Co. Ltd., Hiroshima, Japan) were assessed. At the 3-month visit, unaided logMAR visual acuity, corneal topography, and central and peripheral refraction were measured.

2.5. Corneal topography

Corneal topography was measured by Tomey TMS-4 (Tomey, Inc., Nagoya, Japan) at baseline and 1 day, 1 week, 1 month, and 3 months after wearing *ortho*-k lenses. All measurements were conducted within two hours after *ortho*-k lens removal and between 8 am and 10 am to minimize diurnal variations [22–24]. The flat-K and steep-K values were extracted from the corneal topography, and the corneal refractive power changes (CRPCs) were obtained by subtracting the pretreatment map from the posttreatment map. The CRPCs along the horizontal and vertical meridians were measured with reference to the visual axis and retrieved at 0.50-mm interval steps [25,26] to analyze the locations within a corneal area of an 8-mm diameter. In total, 17 locations were analyzed at the temporal and nasal cornea along the horizontal meridian in the power difference map. Similarly, 17 locations at the superior and inferior corneas along the vertical meridian were measured. The CRPC was assessed three times and the average was used for data analysis. Then, the RCRPC was calculated by subtracting the corneal apical refractive power change from each location where the CRPC was measured along the horizontal and vertical meridians. The data across the horizontal and vertical meridians were divided into central and paracentral regions; the corneal central 4 mm chord was considered the central region (nine locations), while the adjacent 2.5–4 mm areas were considered the paracentral region.

2.6. Refraction

Subjective and objective refractions were assessed 30 min after cycloplegia induction, which was achieved by one drop of 0.5 %

tropicamide instilled four times every 5 min. Peripheral refraction was measured by an open-field autorefractor (WAM-5500, GrandSeiko Co. ltd., Hiroshima, Japan). Peripheral refraction was measured in high-speed mode, and the results were recorded in spherical equivalent refraction (SER). Central refraction (0°) and peripheral refraction across the horizontal meridian at 10°, 20° and 30° on the nasal and temporal retina were obtained. Relative peripheral refraction (RPR) was extracted by subtracting the central refraction from each location where the peripheral refraction was measured. The relative peripheral refraction change (RPRC) was acquired by subtracting the baseline RPR from the RPR after wearing an *ortho*-k lens for 3 months.

2.7. Sample size

A sample size of 26 was calculated for each group based on the VOLTZ study [27]. An 80 % power was provided to detect a 0.44 D difference in the spherical equivalent refraction between the two groups, with a 5 % level of significance, based on the standard deviation of 0.56. The minimum number of subjects required to be enrolled was 32, assuming a 20 % drop-out rate during the study period.

2.8. Statistical analysis

Given the high degree of symmetry between the fellow eyes in terms of various ocular biometrics, including corneal parameters [28] and peripheral refraction [29], only right eye data of each subject were analyzed. The statistical analysis was performed by SPSS version 23.0 (IBM Corp., Armonk, New York, USA). The normality of the data was examined by the Shapiro–Wilk test. For normally distributed data, unpaired or paired t tests were used. For nonnormally distributed data, the Mann–Whitney *U* test was used. The sex composition of the groups was examined by the chi-square test. Bland-Altman analyses were used to assess the repeatability of the method for determining corneal refractive power change.

Repeated measures analysis of covariance (RM ANCOVA) adjusted for flat and steep meridian corneal curvature, eccentricity, central corneal thickness, intraocular pressure, myopia, astigmatism, and the diameter of the back optical zone was used to compare the difference in CRP between the two groups. RM ANCOVA adjusted for myopia, astigmatism, and the diameter of the back optical zone was performed to detect the difference in peripheral refraction between the two groups. Bonferroni corrections were applied for post hoc comparisons. A p value <0.05 was considered statistically significant.

3. Results

Of the 70 initially enrolled subjects, 33 subjects in the BCA group and 29 subjects in the BCS group completed the 3-month follow-up visit. Out of the BCA group, 2 subjects dropped out, due to unsatisfactory lens fitting and noncompliance with the care procedure. Out of the BCS group, 6 subjects dropped out, due to unsatisfactory lens fitting, noncompliance with the care procedure, and poor vision. The baseline data did not differ significantly between the two groups (Table 2).

Table 2
Baseline data of subjects in the BCA and BCS groups.

	BCA group (n = 33)	BCS group (n = 29)	P value
Age (years)	9.43 ± 1.94	9.62 ± 1.08	0.96
Male/Female	19/14	15/14	0.64
SER (D)	−2.65 ± 0.80	−2.55 ± 0.90	0.66
Myopia (D)	−2.44 ± 0.74	−2.37 ± 0.83	0.62
Astigmatism (D)	−0.42 ± 0.35	−0.36 ± 0.32	0.51
Flat-K (D)	42.52 ± 1.31	42.54 ± 1.19	0.58
Steep-K (D)	43.48 ± 1.37	43.39 ± 1.25	0.85
Es	0.57 ± 0.10	0.56 ± 0.11	0.71
Em	0.57 ± 0.07	0.54 ± 0.08	0.29
CCT (um)	528.97 ± 30.68	535.24 ± 28.57	0.41
IOP (mmHg)	16.47 ± 2.23	16.41 ± 2.98	0.93

Data are expressed as the mean ± standard deviation. BCA, base curve aspheric *ortho*-k lens; BCS, base curve spheric *ortho*-k lens; SER, spherical equivalent refractive error; Flat-K, flat meridian corneal curvature; Steep-K, steep meridian corneal curvature; Es, eccentricity of an ellipse approximating the corneal shape at the steep meridian; Em, eccentricity of an ellipse approximating the corneal shape at the meridian of minimum corneal curvature; CCT, central corneal thickness; IOP, intraocular pressure.

Corneal Refractive Power Change (CRPC) Bland-Altman analyses were performed to assess the repeatability of the method for determining the CRPC. The results showed that the 95 % limits of agreement were between −0.014 and 0.020 D, and the coefficient of repeatability was 0.018, which suggested that the method used for determining CRPC showed good repeatability. Fig. 1 shows the mean CRPC along the horizontal and vertical corneal meridians in the two groups after wearing an *ortho*-k lens for 3 months. The CRPC curve in the BCA group clearly follows a V-shape (*orange*), while that of the BCS group follows a U-shape (*green*) along both horizontal and vertical meridians (Fig. 1A & B). In general, an increase in the mean CRP at the nasal (Fig. 1A), superior, and inferior (Fig. 1B) paracentral corneal regions was observed, whereas a decrease in the mean CRP was found in the central cornea (Fig. 1A & B) in the two groups. Repeated measures ANCOVA was performed to detect the mean CRPC difference between the two groups. There was a significant difference in the mean CRPC between the BCA (-1.33 ± 0.41 D) and BCS (-1.13 ± 0.41 D) groups ($F_{1,51} = 10.28$, $p = 0.002$). Subsequently, the mean CRPC at each location along the horizontal and vertical meridians between the two groups was compared. In comparison with that of the BCS group, a significantly smaller mean CRPC was observed in the BCA group at the corneal vertex ($p < 0.001$), 0.5 mm ($p = 0.01$) and 1 mm ($p = 0.006$) along the temporal cornea, 1 mm ($p = 0.03$) along the nasal cornea, and 0.5 mm ($p = 0.007$), 1 mm ($p = 0.01$) and 1.5 mm ($p = 0.046$) along the inferior cornea. These results suggested that the central corneal region was flatter in the BCA group.

Furthermore, the difference in residual refractive errors after cycloplegia at the 3-month visit between the two groups was analyzed. The spheres were more hyperopic in the BCA group (0.42 ± 0.52 D) than in the BCS group (0.09 ± 0.34 D) ($p = 0.006$), and there was no significant difference in astigmatism between the BCA (-0.48 ± 0.46 D) and BCS groups (-0.60 ± 0.44 D) ($p = 0.24$).

To investigate whether the flatter central zone induced by the BCA *ortho*-k lens would impact subjective visual quality, the difference in unaided visual acuity between the BCA (−0.05 ± 0.08) and BCS (-0.05 ± 0.05) groups after treatment was analyzed. A nonsignificant difference was found between the two groups ($p = 0.77$), suggesting that the flatter central zone in the BCA group may not affect subjective visual quality.

In addition, an asymmetrical distribution of the mean CRPC along the horizontal and vertical meridians was observed in both the BCA ($p < 0.001$; $p = 0.003$, respectively) and BCS groups ($p < 0.001$; $p = 0.006$, respectively). A larger increase in the mean CRP was shown in the nasal paracentral cornea than in the temporal paracentral cornea (Fig. 1A & B). Additionally, there was a greater increase in the mean CRP in the superior paracentral cornea than in the inferior paracentral cornea (Fig. 1A & B).

Relative Corneal Refractive Power Change (RCRPC) The mean RCRPC along the horizontal and vertical meridians in the two groups after treatment is shown in Fig. 2. In line with the shape of the CRPC curve, RCRPC formed a V-shape (*orange*) in the BCA group and a U-shape (*green*) in the BCS group (Fig. 2). A hyperopic shift in the mean RCRPC at all locations along the horizontal and vertical meridians was observed in the BCA group. In contrast, in the BCS group, there was a hyperopic shift at most locations, except at 0.5 mm, 1 mm, and 1.5 mm along the temporal cornea and 0.5 mm and 1 mm along the inferior cornea, at which location the mean RCRPC instead showed subtle myopic shifts.

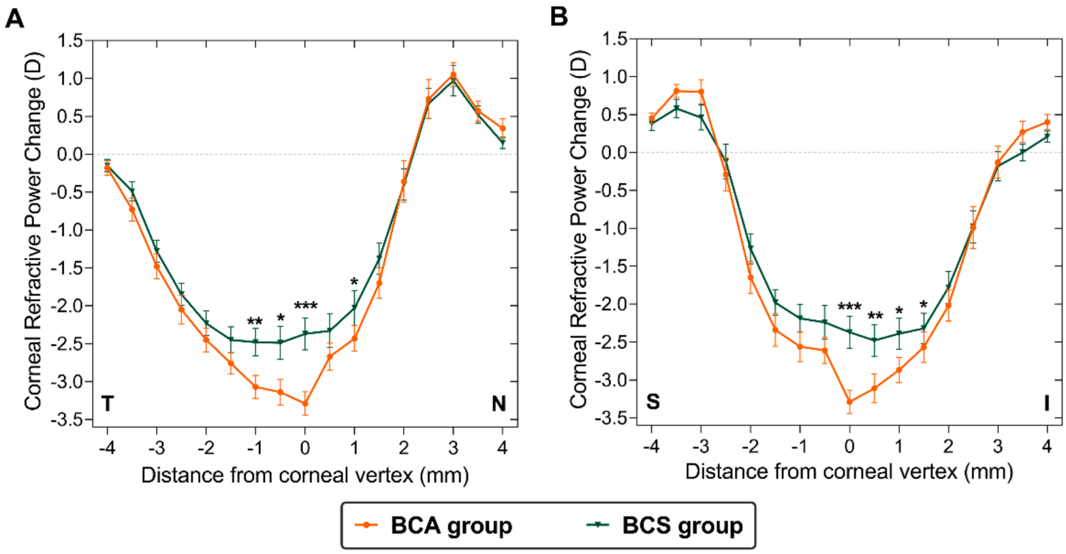

Fig. 1. The mean corneal refractive power change (CRPC) at the 3-month visit in the BCA and BCS groups along the horizontal meridian **(A)** and vertical meridian **(B)**. T, temporal cornea; N, nasal cornea; S, superior cornea; I, inferior cornea; BCA, base curve aspheric *ortho*-k lens; BCS, base curve spheric *ortho*-k lens. Error bars represent the standard error of the mean; ***p < 0.001; **p < 0.01; *p < 0.05.

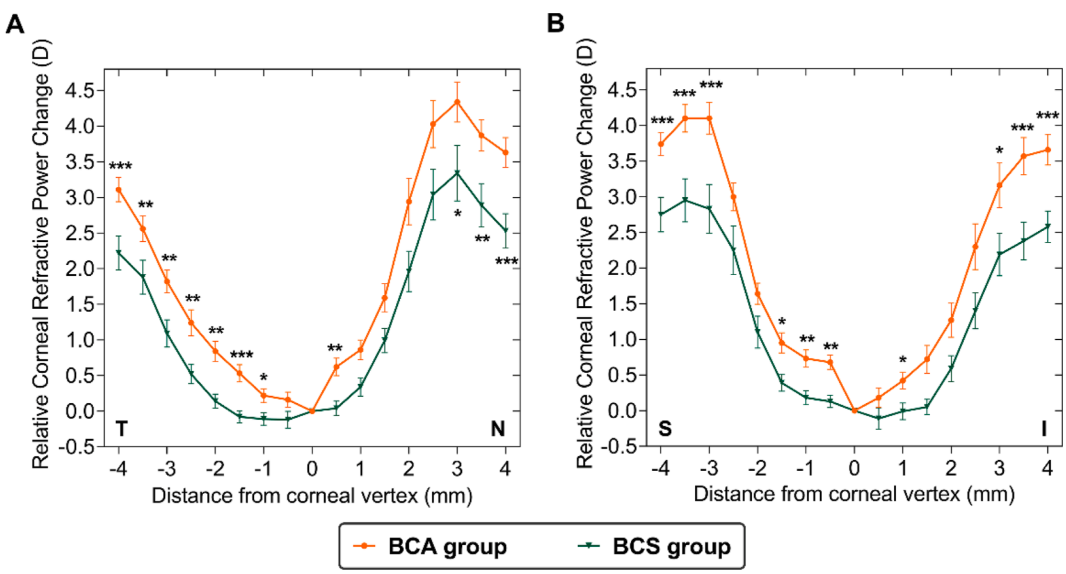

Fig. 2. The mean relative corneal refractive power change (RCRPC) at the 3-month visit in the BCA and BCS groups along the horizontal meridian **(A)** and vertical meridian **(B)**. T, temporal cornea; N, nasal cornea; S, superior cornea; I, inferior cornea; BCA, base curve aspheric *ortho*-k lens; BCS, base curve spheric *ortho*-k lens. Error bars represent the standard error of the mean; ***p < 0.001; **p < 0.01; *p < 0.05.

Then, the mean RCRPC differences between the two groups were compared. The results revealed that the mean RCRPC in the BCA group (2.08 ± 0.65 D) was significantly larger than that in the BCS group (1.32 ± 0.81 D) ($F_{1,51} = 25.25$, $p < 0.001$). Post hoc comparisons were made to further analyze the mean RCRPC at each location between the two groups. The difference in the mean RCRPC between the two groups was significant at most locations ($p \leq 0.03$) (Fig. 2A & B.) These results indicated that the BCA group manifested a greater mean RCRPC than the BCS group.

Peripheral Refraction (PR) The central and peripheral refraction before and after *ortho*-k lens treatment along the horizontal meridian in the two groups are shown in Fig. 3. At baseline, there was no significant difference in the PR between the BCA and BCS groups ($F_{1,60} = 0.003$, $p = 0.96$). After treatment, there was a significant hyperopic shift in the central refraction in both groups ($p < 0.001$), and the central refraction in the BCA (0.31 ± 0.56 D) group was more hyperopic than that in the BCS group (-0.07 ± 0.53 D) ($p = 0.008$).

Furthermore, after wearing the *ortho*-k lens, a hyperopic shift in PR was found at most locations, except at 30° along the temporal retina, in which a myopic shift was observed in the BCA and BCS groups (Fig. 3A & B). At most locations, the hyperopic or myopic shift along the horizontal meridian in the two groups was significant ($p < 0.04$, for all), while a nonsignificant shift was observed at 30° along the nasal retina ($F_{1,64} = 3.07$, $p = 0.09$) in the BCA group and 30° along the temporal retina in the BCS group ($F_{1,56} = 0.38$, $p = 0.54$). RM ANCOVA was performed to detect the differences in the PR along the horizontal meridian between the BCA and BCS groups, but nonsignificant differences were found ($F_{1,57} = 3.69$, $p = 0.06$). Additionally, the PR in the two groups exhibited an asymmetrical distribution between the temporal and nasal retina after treatment, suggesting that peripheral refraction was more myopic on the temporal retina than on the nasal retina ($p < 0.001$).

Relative Peripheral Refraction (RPR) The mean RPR values before

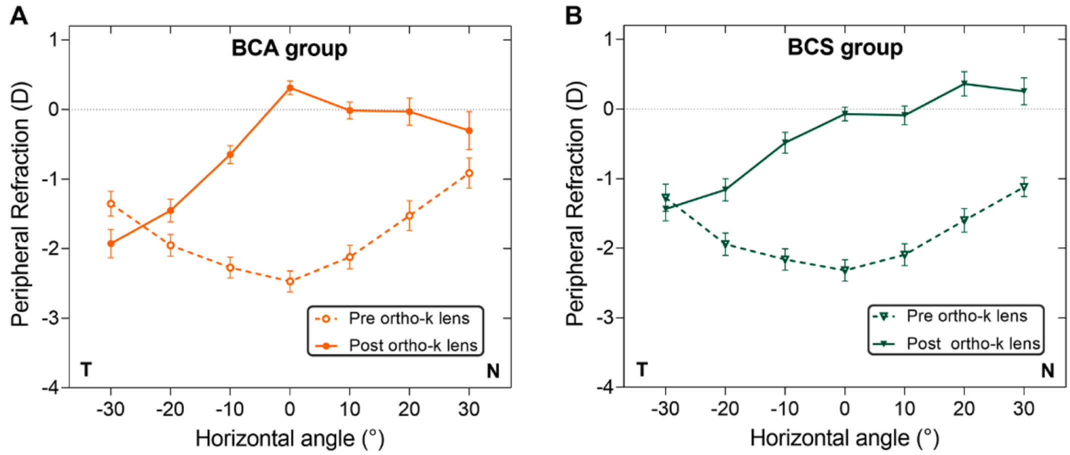

Fig. 3. Peripheral refraction (PR) before and after wearing the *ortho*-k lens along the horizontal meridian in the BCA group **(A)** and the BCS group **(B).** T, temporal retina; N, nasal retina. Error bars represent the standard error of the mean.

and after wearing the *ortho*-k lenses in the two groups along the horizontal meridian are shown in Fig. 4A & B. In the BCA group, the mean RPR exhibited myopic shift at all locations, and the difference between pre- and posttreatment was significant ($F_{1,64} = 227.89$, $p < 0.001$, Fig. 4A). In the BCS group, the mean RPR showed a myopic shift at all locations, and there were significant differences in the temporal retina and 10° and 30° along the nasal retina before versus after wearing the *ortho*-k lenses ($F_{1,56} = 101.41$, $p < 0.02$, Fig. 4B). Furthermore, there was relative peripheral myopic defocus on the temporal and nasal retina in the BCA group (Fig. 4A). However, in the BCS group, there was still relative peripheral hyperopic defocus on the nasal retina (Fig. 4B). The difference in the mean RPR between BCA (-1.03 ± 0.61 D) and BCS (-0.36 ± 0.44 D) groups was compared, and a significant difference was found between the two groups ($F_{1,57} = 24.36$, $p < 0.001$).

Relative Peripheral Refraction Change (RPRC) Fig. 5 illustrates the mean RPRC in the BCA and BCS groups. After *ortho*-k lens treatment, the mean RPR at all locations suggested a myopic shift in the two groups. The difference in RPRC between the two groups was compared, and a greater myopic shift in the mean RPRC was observed in the BCA group (−1.82 ± 0.65 D) than in the BCS group (−0.98 ± 0.54 D) ($F_{1,57} = 33.73$, $p < 0.001$). The mean RPRC at each location was also compared between the two groups. The results showed that the differences were significant at all locations ($p \le 0.003$; Fig. 5). In sum, the myopic shift in the RPR in the BCA group was greater than that in the BCS group.

4. Discussion

In the present study, the impacts of the BCA *ortho*-k lens on the CRP and peripheral refraction versus those of the BCS *ortho*-k lens were investigated. Compared with the BCS group, the BCA group exhibited a larger decrease in the mean CRPC in the central corneal region, a greater increase in the mean RCRPC in the central and paracentral corneal regions, and a more myopic RPR along the horizontal meridian.

Consistent with previous studies [26,30], it was observed that the corneal optical surface gradually changed from the corneal center to the mid-periphery after treatment in both the BCA and BCS groups. However, the corneal surfaces of the two groups were obviously different in the corneal central region. CRPC formed a "U" shape in the BCS group, while a V-shaped curve was observed in the BCA group (Fig. 1). It is likely that the discrepancies in the observations between the two groups may be due to the different lens designs. The peripheral shape in the aspherical base curve is steeper than that in the spherical base curve. Therefore, the aspheric base curve could produce a sharper decline in the central refractive power after lens wearing, causing a more aspheric treatment zone in the BCA group. The asphericity of the treatment zone has been linked with myopia control effects [31].

Additionally, CRPC was asymmetrically distributed in both groups (Fig. 1), which may be due to lens decentration resulting from the shape of the cornea [32–34]. These results showed that CRPC was asymmetrically distributed not only along the horizontal meridian, as previous studies reported [19,30,35], but also along the vertical meridian, which

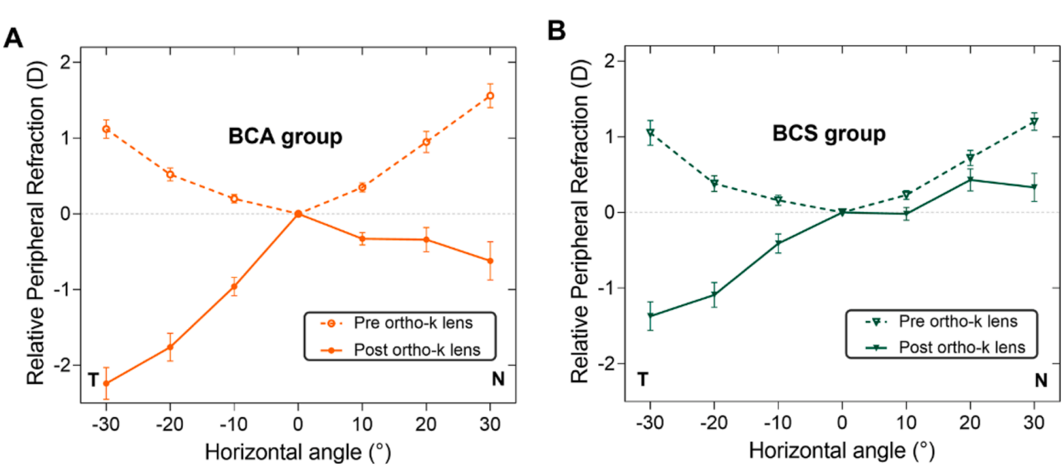

Fig. 4. Mean relative peripheral refraction (RPR) before and after wearing the *ortho*-k lens along the retinal horizontal meridian in the BCA group **(A)** and the BCS group **(B)**. T, temporal retina; N, nasal retina. Error bars represent the standard error of the mean.

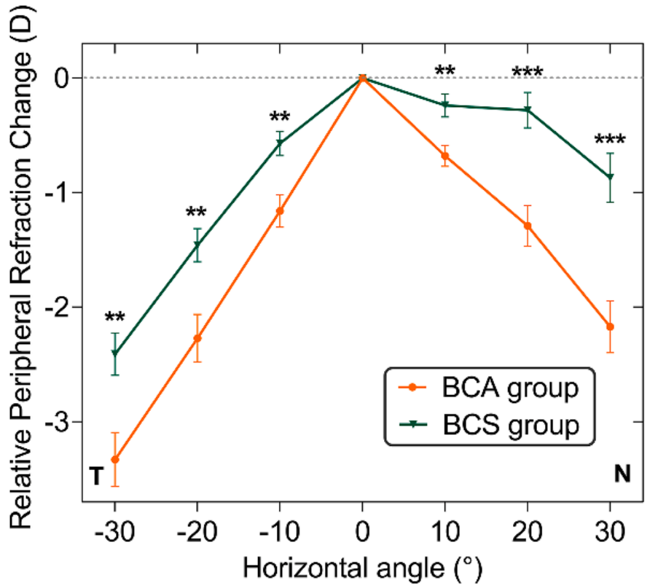

Fig. 5. Mean relative peripheral refraction change (RPRC) after wearing the *ortho*-k lens along the horizontal meridian in the BCA and BCS groups. BCA, base curve aspheric *ortho*-k lens; BCS, base curve spheric *ortho*-k lens; T, temporal retina; N, nasal retina; Error bars represent standard error of the mean. ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$.

differs from previous studies [19,30]. This distinctive finding may be due to the discrepancy in corneal shape among various ethnicities [36–38]. One investigation involving over 1000 Chinese subjects reported that the superior cornea is more prolate than the inferior cornea [34].

According to the results, the curves of the RCRPC were V-shaped and U-shaped in the BCA and BCS groups, respectively (Fig. 2). As observed here, the mean RCRPC at the central and paracentral corneal regions manifested a greater increase in the BCA group. It has been argued that the maximum corneal refraction difference within the central 4 mm diameter was negatively correlated with axial elongation in *ortho*-k lenses [39]. A recent investigation also demonstrated that a better efficacy of *ortho*-k lenses was correlated with an RCRPC closer to the corneal center [18]. It is likely that a larger RCRPC at the central corneal region could allow more of the myopic defocus to fall within the pupil margin, which may be associated with better myopia control. In addition, Hu et al. [40] found that the summed corneal refractive power shift within a 7.2 mm area was a crucial determinant of efficacy after treatment with an *ortho*-k lens in children, suggesting that the RCRPC at the paracentral region may also be a predictor for control efficacy.

It is well documented that defocus across the retina plays a vital role in refractive development [41–43]. Peripheral refraction along the retina has been shown to be altered by the *ortho*-k lens [14,15]. Observations in the present study exhibited a consistent myopic defocus along both the temporal and nasal retina in the BCA group (Fig. 3A). However, hyperopic defocus was present on the nasal retina in the BCS group (Fig. 3B). Several studies have demonstrated that the imposed local myopic or hyperopic defocus of the eye could produce regional alterations in ocular growth or choroidal thickness [44–46]. In other words, the ocular size could generate regional responses on its nasal side owing to the imposed temporal defocus, and vice versa. Tse et al. [47] investigated the difference in refractive development in chicks between integrated defocus (+10/−10 D) lenses and myopic defocus (+10 D) lenses and found that the refractive error was less hyperopic with the integrated defocus lenses. These results suggested that peripheral hyperopic defocus may decelerate the efficacy of inhibiting ocular growth.

RPR describes the refractive profile from the center to the peripheral visual field, with reference to central refraction. Based on the current results, a more myopic RPR along the horizontal meridian was observed in the BCA group, although the difference in the PR between the BCA and BCS groups was nonsignificant. It is possible that the discrepancies in the mean RPR and RPRC between the two groups may be contributed by the different central refractions mostly and to a lesser extent by PR. It has been argued that myopic RPR may be associated with refractive development [41,48]. Recent studies have reported that myopia progression in the treated eye of subjects who underwent unilateral corneal refractive surgery was slower than that in the untreated eye [49,50]. This may be because the flatter central cornea in the treated eye could lead to a more myopic RPR than that in the untreated eye. Li et al. [51] noted that the choroidal thickness was significantly thicker after myopic excimer laser surgery, which may be attributable to the RPR change. Additionally, Mutti et al. [52] suggested that the RPR was more hyperopic in myopic children than in emmetropes from 2 years before through 5 years after the onset of myopia. Thus, it is possible that myopes undergoing BCS *ortho*-k lens treatment may demonstrate a less ideal control effect since hyperopic PR and RPR on the nasal retina were found in the BCS group.

This is the first study to investigate the effects of the *ortho*-k lens with an aspherical base curve on corneal topography and peripheral refraction. Despite these advantages, a limitation of the current study was that the peripheral refraction was directly recorded with SER, and peripheral astigmatism was not assessed in terms of J0 and J45 in the two groups pre- and posttreatment.

In conclusion, the BCA *ortho*-k lens could result in a more aspheric treatment zone and a more myopic RPR along the horizontal meridian. The more myopic RPR was contributed by a more hyperopic central refraction and a more myopic PR in the BCA group. Whether these alterations in the BCA group would have a better effect of myopia control requires further investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research was supported by the National Natural Science Foundation of China Grants (82070996), Post-Doctor Research Project, West China Hospital, Sichuan University (2020HXBH167), and a Collaborative Research Agreement between West China Hospital, Sichuan University and Eyebright Corporation (Beijing) (grant number: HX-H2012261).

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