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Two-dimensional peripheral refraction and retinal image quality in orthokeratology lens wearers

ZHENGHUA LIN,[1] RAUL DUARTE-TOLEDO,[3] SILVESTRE MANZANERA,[3] WEIZHONG LAN,[1,2,4] PABLO ARTAL,[3,1] AND ZHIKUAN YANG[1,2,5]

[1]Aier School of Ophthalmology, Central South University, Changsha, China
[2]Aier School of Optometry, Hubei University of Science and Technology, Xianning, China
[3]Laboratorio de Óptica, Universidad de Murcia, Campus de Espinardo, 30100, Murcia, Spain
[4]lanweizhong@aierchina.com
[5]yangzhikuan@aierchina.com

Abstract: Orthokeratology (O-K) is a common procedure that uses rigid contact lenses to reshape the cornea while worn overnight. Beyond the correction of refractive error, it has been suggested that this approach can also be used to reduce myopia progression, possibly because it induces changes in peripheral optics. As this hypothesis remains unproven, the aim of the present study was to explore changes in peripheral retinal optical quality in a group of myopic children following O-K treatment. We provide a comprehensive description of optical characteristics in a group of myopes before and after achieving stable corneal reshaping using overnight O-K lenses. These characteristics extended across the central visual field (60° horizontal x 36° vertical) as measured with a custom Hartmman-Shack wavefront sensor. After corneal reshaping, peripheral refraction was found to be asymmetrically distributed, with a myopic relative refraction of approximately 3D in the temporal retina. Astigmatism and higher order aberrations also increased in the temporal side. Based on corneal topography following treatment, subjects were divided into two groups: Centred Treatment (CT, decentration $\in [-0.5 + 0.5]$ mm) and Slightly Decentred Treatment (subjects with more decentred lenses). The process was also modelled by ray-tracing simulation. The results indicate that increased myopia in the temporal retina is caused by the decentration of lenses towards the temporal side. Peripheral optics differ significantly following O-K lens treatment, but further research is required to determine whether this is likely to affect myopia progression.

1. Introduction

As an ocular disorder that develops mainly in teenagers, myopia is increasingly prevalent across the world, especially in East Asia [1]. In the past, the consequences of myopia were commonly underestimated because of the ease of correction with prescription glasses. However, the condition can lead to serious complications, especially in cases of high myopia, including retinal detachment, open-angle glaucoma, cataracts and macular degeneration [2–5], accompanied by an increasing social and economy burden [1].

Due to the differing increase of the dimensions during the development of the eye ball [6,7], varied refractions occur at different retinal locations. In myopic eyes specifically, relative peripheral hyperopia (mean refraction in the periphery is hyperopic relative to the central refraction) was observed commonly in the horizontal meridian [6,8–13]; some studies. such as Atchison et al. [14] and Verkicharla [6] et al. have found that mean patterns have a relative peripheral myopia (mean refraction in the periphery is myopic relative to the central refraction) in the vertical meridian. Those results seemed to suggest that peripheral defocus may trigger

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the progression of myopia, which has also been investigated in animal models [15–19] and in clinical studies [20–23].

A number of studies have reported the efficacy of orthokeratology (O-K) in reducing myopia progression; on average, orthokeratology seems to retard axial elongation by between 30% and 70% when compared to single vision glasses [20,24–26]. O-K employs a rigid contact lens worn overnight to reshape the cornea [27]. The O-K lens has a peripheral reversal geometry curve on the back surface and a flat central treatment zone for correcting refractive error [28]. As a result, the cornea is reshaped with thicker mid-peripheral epithelium and thinner central epithelium [29]. Charman et al. [30] were the first to determine peripheral refraction accompanying orthokeratology and revealed that induced a relative myopic defocus in the peripheral retina, which gained consistent support from later studies using both optical modeling [26,31,32] and actual measurement [33–36]. They also suggested this could be linked to myopia progression [30]. Although it has been widely cited [20–23,37], this assumption is not fully validated yet, in part because the associated optical properties across the retina have not been clearly quantified.

To further validate this assumption, we used a scanning Hartmann-Shack wavefront sensor to measure peripheral optical properties of myopic subjects in detail before and after orthokeratology treatment. In addition, we investigated the impact of O-K lens decentration on peripheral refraction, as this is a common occurrence in clinical practice. The experimental results were compared with theoretical predictions based on a ray-tracing optical model.

2. Methods

2.1. Subjects

The indications for O-K lens treatment were as follows: age 8–17 years, spherical equivalent > -6.00 D, cylinder less than 1.5 D, best corrected visual acuity (BCVA) 20/20 or better, mean keratometry value 40 D–46 D, no history of any systemic or eye disease. The standard orthokeratology assessment process included slit-lamp examination, tear breakup time, fundus examination, cover test, corneal endothelium cells test, and measurement of subjective refraction, keratometry and corneal topography (Pentacam, Oculus Inc., Germany).

Subjects who sought orthokeratology for myopia control and who met the above criteria were invited to participate. The study was carried out at the Aier Eye Hospital, Changsha, China. After receiving information about the nature and purpose of the study, 25 subjects were enrolled. As two of those subjects were excluded because of large decentration of cornea reshaping or poor after-treatment visual acuity, the final sample included 23 subjects (male = 14 (60.9%), mean age = 11.8 ± 2 years, ranging from 8 to 17 years, mean baseline refractive error = -3.29 ± 0.99D, ranging from -1.67 to -5.36D).

After participants and their guardians were informed about the study, those who wished to proceed signed a consent form prior to commencement. All procedures followed the requirements set out in the Declaration of Helsinki, and the study was approved by the Institutional Review Board of AIER Eye Hospital Groups (AIER2019IRB06).

2.2. O-K lens fitting

The O-K lenses (Alpha Corporation, Nagoya, Japan) used in the study featured a 4-zone reverse geometry design and were manufactured in fluorosilicone acrylate (Boston EM), with oxygen permeability (Dk) of 104×10^{-11} ($cm^2\times mLO_2$)/ ($s\times mL\times mmHg$). Lens fitting was performed in accordance with the manufacturer's guidelines. To determine the back optical zone radius (BOZR) and alignment curve (AC) radius, we measured subjective refraction, corneal flat-K, horizontal visible iris diameter and corneal eccentricity. Overall lens diameter was 10.0 to 11.0 mm, the optic zone diameter was 6.0 mm, the reverse curve (RC) width was 0.6 mm and the central thickness was 0.22 mm. Lens fitting evaluations were performed 30 minutes after

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insertion, using fluorescein, a slit-lamp biomicroscope and a corneal topographer. To be deemed an acceptable fitting, the lens had to be well centred on the cornea, with no more than 1-2 mm movement on blinking. Over-refraction was performed before the final lenses were ordered. To stabilize refractive error correction, each subject was instructed to wear the selected O-K lens for at least 8 hours overnight and to avoid wearing any other type of lens during the follow-up procedure.

2.3. Measurements of peripheral optics

Peripheral refraction and aberrations in the right eye of all subjects were assessed using a customized open-view fast scanning Hartmann-Shack peripheral wavefront sensor (VPR, Voptica SL, Murcia, Spain). The wavelength of measuring light was 780 nm. The sensor is mounted on a motorized optical arm that scans a 60° horizontal visual field (in 1° steps) in 1.3 seconds while the subject looks straight at a distant on-axis target. To measure refraction in the vertical visual field, 9 additional fixation targets were evenly distributed above and below the on-axis target. Fixating on the top target facilitated measurement at 20° in the superior retina; fixating on the bottom target corresponded to 16° in the inferior retina. Wavefront aberrations were estimated for a 3-mm circular pupil diameter within the natural elliptical eccentric pupil. The 2D refraction maps were captured by completing a total of 10 scans (1 central + 9 peripheral), fixating at different heights (10 scans x 61 meas./scan = 610 meas.). To reduce the error caused by the different sampling rates in the horizontal (1°) and vertical (4°) meridians, spline-based interpolation was applied to the matrix to produce the final refraction map ($37 \times 61 = 2251$ points). The detailed procedure for generating the 2D maps [38] and a more detailed description of the instrument have been published elsewhere [39].

Peripheral optical characteristics were measured prior to O-K lens fitting and repeated ~ 1–2 months after participants received the lenses. This time interval ensured that relatively stable refraction was achieved [31,40].

2.4. Data processing and statistical analyses

Data were analyzed using Matlab (MathWorks, USA). In the 2-D refraction map, positive values on the x- or y-axis indicate the nasal retina or superior retina, respectively; negative values on the x- or y-axis indicate the temporal retina or inferior retina. On the colour-coded maps, the units are dioptres (D) in the refraction maps and microns in the higher-order aberration maps. Previous studies have reported that changes in peripheral refraction relative to the central measure are significant only for eccentricities around 20° of the peripheral visual field [33,34,36]. On that basis, we divided the 2-D refraction maps into 8 regions, segmenting the visual field using the standard nasal, temporal, superior and inferior quadrants for 2 eccentricity ranges: ~20°–25° and > 25° (Fig. 1). The mean value in each region was calculated for each subject and was then used in the subsequent analysis.

Data were presented as mean ± 1 standard deviation or otherwise stated separately. Using paired-t tests, we first examined the symmetricity of peripheral refraction distribution before and after the Orthokeratology. An experienced O-K lens practitioner was then invited to divide the subjects into two groups based on centration of the lens fitting. Two subjects were excluded from this stratified analysis because of the difficulty of assignment. Accordingly, 14 subjects with relatively good fixation were assigned to the Centred Treatment (CT) group, and the other 7 (with relative suboptimal lens location) were assigned to the Slightly Decentred Treatment (SDT) group. The averaged centration values for the CT group were horizontal -0.2 ± 0.23 mm and vertical -0.4 ± 0.26 mm; for the SDT group, the values were horizontal -0.85 ± 0.26 mm and vertical -0.43 ± 0.16 mm (a positive value means the decentration is toward nasal or superior cornea, while a negative value means the decentration is toward temporal or inferior cornea). For all subjects, the range of decentration (horizontal orientation) was [−1.19, 0.4] mm. The range of

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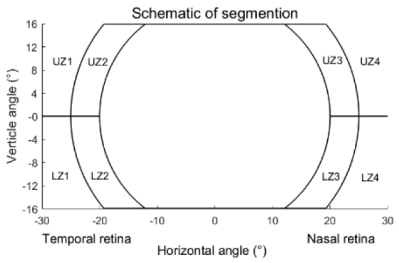

Fig. 1. Schematic of 2-D refraction map segmentation. The map was divided into 8 regions, based on 2 circles of radius 20° or 25° and a central horizontal line (y = 0°). The regions were labelled UZ1 (upper zone 1), UZ2, UZ3, UZ4 and LZ1 (lower zone 1) and LZ2, LZ3, LZ4 (for superior retina or inferior retina from temporal side to nasal side, respectively). Values beyond the superior 16° were removed to achieve a more uniformly distributed matrix.

decentration for CT in horizontal orientation was [−0.4, 0.4], and the range for SDT was [−1.19, −0.51]. Mean SER prior to O-K lens treatment was −3.42 ± 1.12D for CT and −3.13 ± 0.82D for SDT, decreasing to −1.02 ± 0.74D and −0.79 ± 0.58D, respectively, after O-K lens treatment. Rank-sum testing was used to compare differences between the two groups in corresponding sub-divided regions. A two-tailed $p < 0.05$ is set statistically significant.

2.5. Estimation of O-K lens decentration

A senior O-K lens practitioner was invited to determine the location of the lens by through careful observation of the correlation between the treatment zone (the edge of power increased area in difference map) and reserve zone (the edge of power reversal zone in post-fitting map) based on the front corneal tangential refraction map. Then the decentration was determined by comparing the practitioner's decision and the vertex of the cornea given by the topographer (Pentacam, Oculus Inc., Germany). The process was assisted by a customized Matlab script and repeated three times.

2.6. Ray-tracing modelling

To better understand the causes of peripheral refraction changes after O-K treatment, we used ray-tracing modeling (Zemax, Radiant Zemax, US), to simulate peripheral optics with and without the O-K lens. Based on the schematic eye model proposed by Navarro et al [41], the effect of O-K was introduced by placing a 2D power annular lens (inside diameter = 6.4 mm, outside diameter = 8 mm; no power in treatment zone) on the front corneal surface. The wavelength for the model is 780 nm and the pupil diameter was set to 3 mm as in the experimental measurements. The model was also used to predict the change of relative peripheral refraction induced by different levels of O-K lens decentration from 0 mm to 1.5 mm in the horizontal direction, at intervals of 0.05 mm.

3. Results

3.1. Relative peripheral refraction (RPR) after orthokeratology

Figure 2 shows the RPR before and after subjects were treated with O-K lenses. Before O-K treatment, myopic subjects presented with almost symmetrically distributed relative hyperopia in the horizontal direction (+1.0D to + 1.7D at 25° to 30°) between the temporal and nasal retina, and almost flat refraction across the central 20° (Figs. 2(a) and 2(d)). After O-K corneal reshaping, however, the peripheral refraction pattern became asymmetrically distributed, with more relative myopia in the temporal retina (around 1.7D to 1.9D relative myopia in temporal 25°

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to 30°) than in the nasal retina (around 0.6D to 0.3D in nasal 25° to 30°) (Figs. 1(b) and 1(e)). The difference map confirms that the myopic RPR of the peripheral refraction occurred primarily in the temporal retina (2.7D to 3.4D myopic RPR in temporal 25° to 30°) (Figs. 2(c) and 2(f)). The difference pattern is analogous to a circle of radius 20° of flat refraction, but with a centre at approximately 6 °.

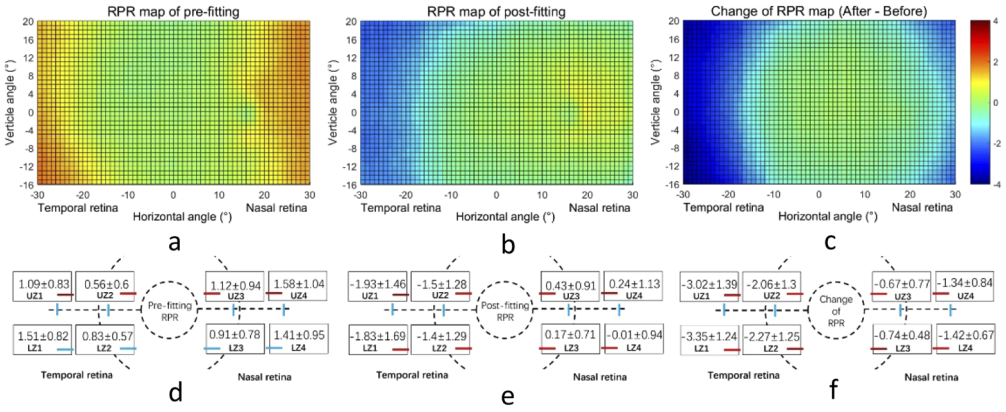

Fig. 2. Relative peripheral refraction before and after treatment with O-K lenses. Panels a and b represent the refraction map before and after subjects were treated, respectively. Panel c represents the differences in a and b (after - before). Panels d–f represents the averaged refraction in each retinal region (segmented as described in Fig. 1). The symmetry of refraction between corresponding regions (e.g. UZ2 vs UZ3, UZ2 vs LZ2) was examined by paired t-tests. A red line indicates a significant difference; a blue line indicates an insignificant difference.

3.2. *Retinal image quality and higher order aberrations after orthokeratology*

Figure 3 shows the changes in optical aberrations induced by the O-K treatment. As a metric of image quality, Strehl ratio increased significantly following the treatment. However, the values did not peak at the centre but decentred approximately 10° to the nasal retina. The pattern of spherical refraction prior to treatment was similar to that for RPR as shown in Fig. 2. However, the difference map indicates that the spherical component contributed little to the significant myopic RPR in the temporal retina. The change in astigmatism induced by the O-K lens occurred primarily along horizontal orientation for the J0 component but along both diagonal directions for J45. A significant decrease in J0 and an increase in J45 were noted in the temporal retina.

Before treatment, spherical aberration (Z12) was distributed almost evenly across the retina. After wearing O-K lenses, this pattern remained unchanged in most regions of the retina, but a significant negative shift was observed in the temporal region. Interestingly, while coma (Z8) values tended to increase from temporal to nasal across all horizontal meridians prior to treatment, this pattern was completely reversed following O-K treatment, resulting in a significant increase in coma on the temporal side.

3.3. *Effect of lens decentration on relative peripheral refraction*

For the purposes of stratified analysis, subjects were divided into CT and SDT groups (Fig. 4). Although no significant difference was observed between these two groups for each pair of corresponding retinal regions before O-K lens treatment (Figs. 4(a) and 4(b)), the temporal regions differed significantly between the two groups following O-K lens treatment (Figs. 4(c), 4(d), 4(e), 4f).

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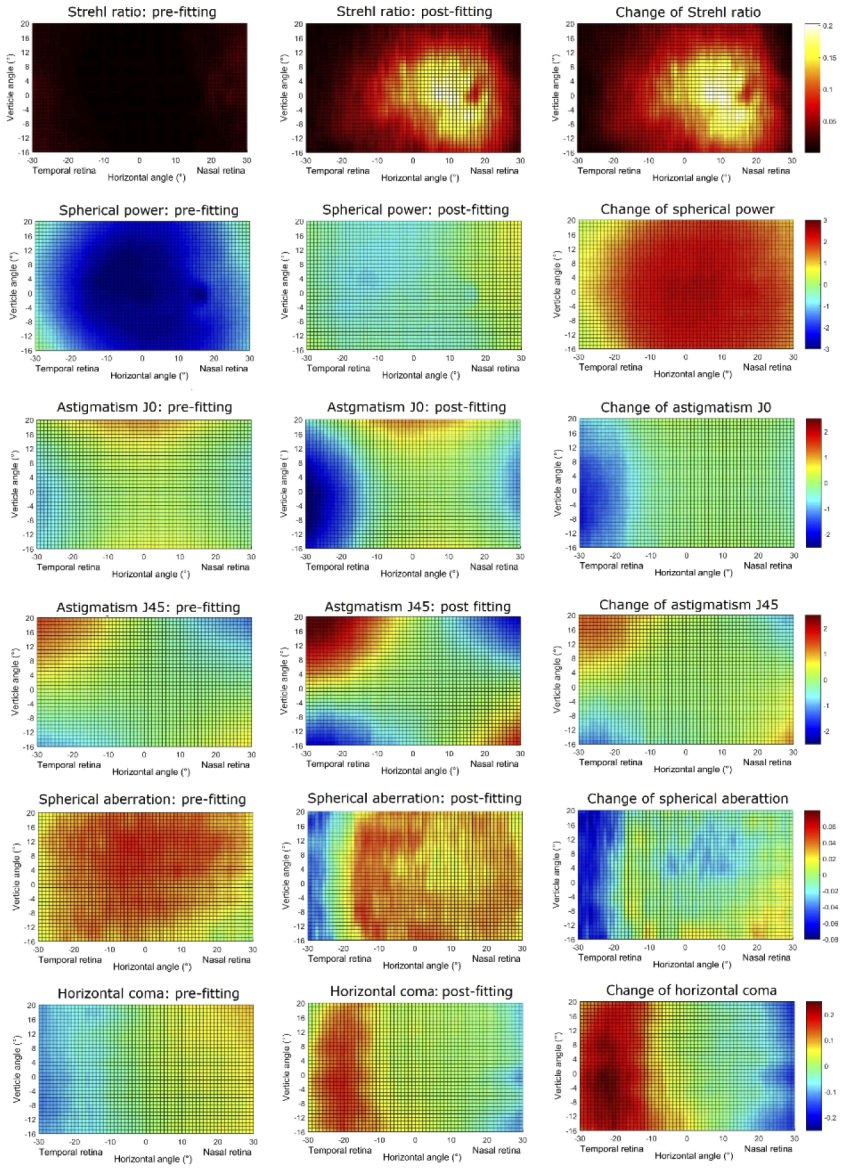

Fig. 3. Averaged refraction maps of image quality and higher-order aberrations of all subjects. Left column: pre-fitting maps. Middle column: post-fitting maps. Right column: difference maps (post-fitting map minus pre-fitting map).

Figure 5 shows the effects of the O-K lens on peripheral refraction (perfectly centred) for the CT and SDT groups in the simulation based on the schematic eye model. To determine whether the pattern of refractive change in the simulation agreed with the actual values, we compared the refractive values for CT (decentration = −0.2 in the model) and SDT (decentration = −0.85 in the model) with an eccentricity of 25° between measured and simulated values. We selected an eccentricity of 25° because there is no transition between the edge of reverse curve and alignment curve (or peripheral curve) in the O-K lens model, and this setting would reduce any error caused by this edge impact. As a result, the differences in refraction between CT and SDT at this

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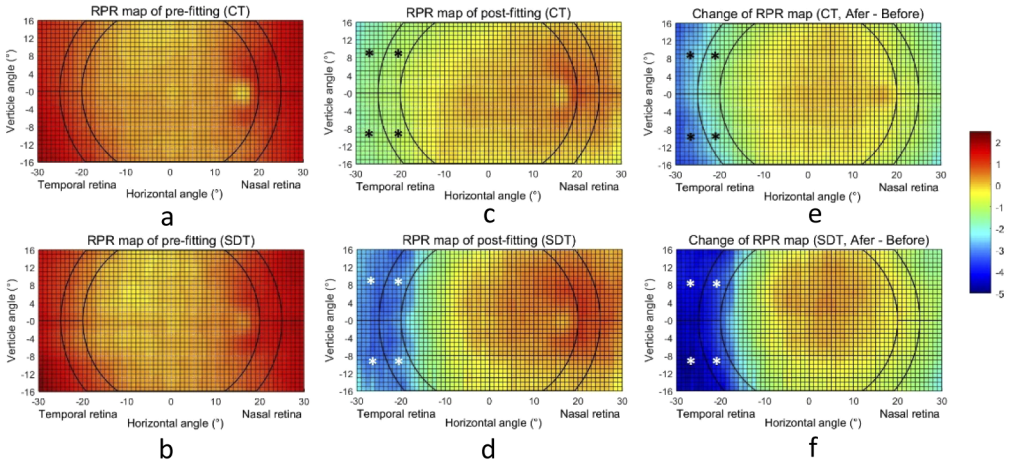

Fig. 4. Relative peripheral refraction map for the Centred Treatment (CT, upper) and Slightly Decentred Treatment groups (SDT, lower). Panels a and b: pre-fitting map; c and d: post-fitting map; e and f: difference map. $*p < 0.05$.

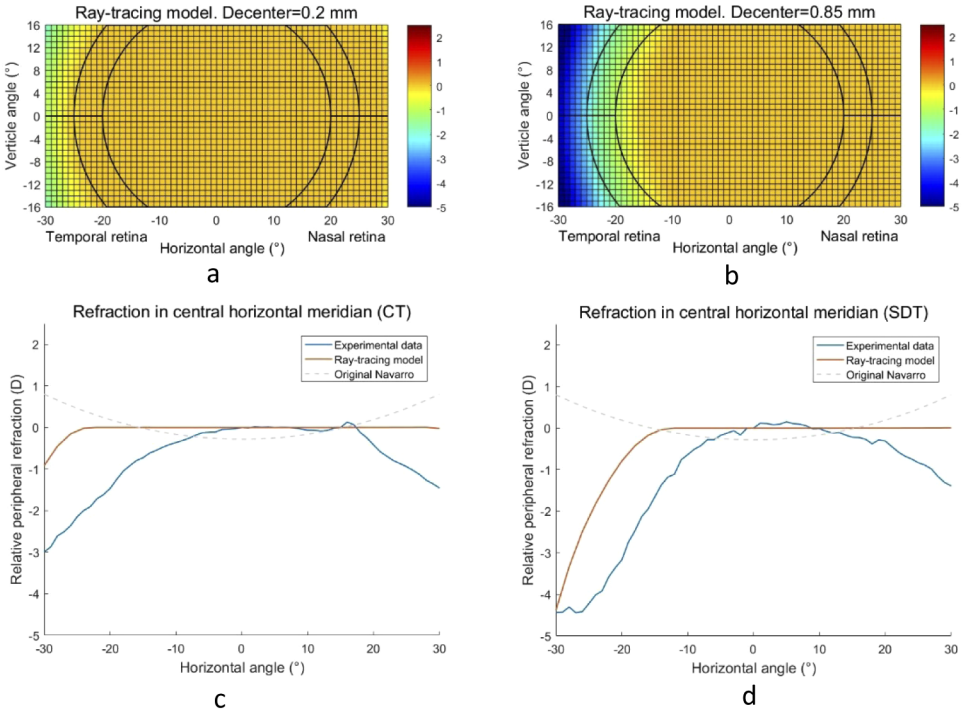

Fig. 5. Simulation of change of relative peripheral refraction (RPR) based on ray-tracing model at differing magnitudes of decentration (RPR with O-K lens minus RPR without O-K lens on front corneal surface) in the schematic eye model proposed by Navarro et al [41]. a: decentre = −0.2 mm (as in the averaged decentration magnitude of the Centred Treatment group, CT); b: decentre= −0.85 mm (as in the averaged decentration magnitude of the Slightly Decentred Treatment group, SDT); c & d: change of RPR in central horizontal meridian in modelling (brown line) and measured data (blue line) with situation as CT (left) or SDT (right). The gray dash line is the original of peripheral refraction profile of Navarro eye model.

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retinal location are very similar for the two approaches (2.07 D and 1.7 D for the measured and theoretical values, respectively).

The impact on RPR at different levels of decentration as predicted by modelling is shown in Fig. 6. It appears, for instance, that when the O-K lens decentres towards the temporal cornea, the magnitude of relative myopic RPR increases with the eccentricity of the retina location to the centre. However, this effect is observable only on the same side of retina as the direction of decentration (in this case, the temporal retina) and is very limited on the contralateral side (in this case, the nasal retina).

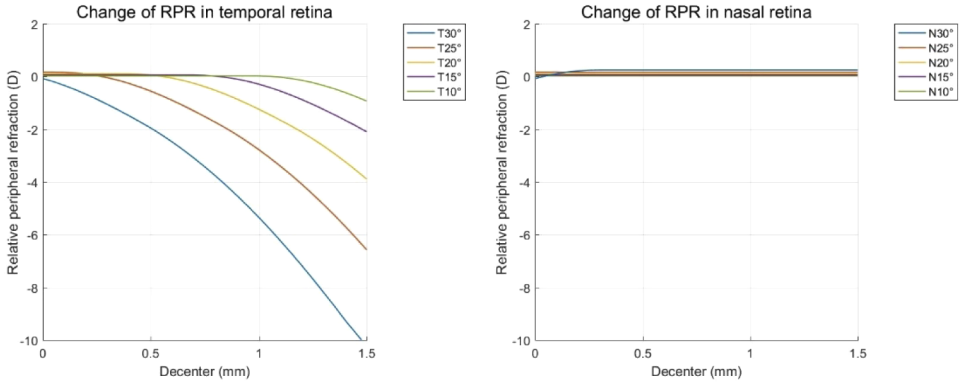

Fig. 6. Change of Relative peripheral refraction in central horizontal meridian at differing levels of decentration. Left: 2-D demonstration of change of RPR in the temporal retina as a function of O-K lens decentration. Right: 2-D demonstration of change of RPR in the nasal retina as a function of O-K lens decentration.

4. Discussion

In a group of O-K lens wearers, we found a consistent myopic RPR in the temporal retina (i.e. nasal visual field) for eccentricities greater than 20°. This asymmetric pattern was induced by a non-perfectly centred corneal reshaping and was verified by evaluating subjects according to the decentration of corneal treatment. More myopic RPR was observed in the temporal retina in the SDT group after corneal reshaping.

The change of peripheral optics induced by O-K lenses has been reported previously [32–34,36]. However, because of the limitations of the measurement techniques applied, most of these studies could only provide data for the horizontal principal median at certain retinal locations. As far as we know, the present study is one of the few to capture a comprehensive change in peripheral optics induced by O-K lenses in high-resolution across a wide area of the visual field. In line with previous evidence, we found that myopic RPR modified by O-K treatment occurred primarily beyond 20° of eccentricity as a result of reverse cure of the lens.

As well as refraction, other optical aberrations also changed following O-K treatment. As expected, Strehl ratio was significantly increased by O-K treatment, indicating that this technique is effective in correcting unaided vision in myopes. The dislocation of the Strehl ratio peak also aligns with the direction of lens decentration. The special design of the treatment zone and the reverse zone in the O-K lens resulted in corresponding modification of both the spherical and astigmatic components of refraction. Measuring peripheral refraction in the horizontal meridian, Queiros et al [33] reported that O-K primarily affected J0, with a limited impact on J45. While our results were similar for the horizontal meridian, we found that O-K also significantly impacted J45 beyond the horizontal meridian. The reason for this is that distortion of J45 is along the diagonals rather than the horizontal. The use of traditional instruments to

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measure along limited meridians would have missed important information. It is interesting that orthokeratology had a mild effect on the distribution of spherical aberration but completely reversed the distribution pattern of coma. We suspect that this is because the reverse zone of the decentred O-K lens caused a relatively steeper cornea on the nasal side than on the temporal side, leading subsequently to a larger angle between the incident ray from the instrument and the front surface of the nasal cornea, ultimately altering the pattern of coma distribution. The pattern of flipping coma was also found in LAISK [42] and O-K [32].

In contrast to the previously reported finding of symmetrical change in RPR induced by O-K treatment [33,34,36], we found that the change of RPR in our subjects was more apparent in the temporal than in the nasal retina. This may relate to better centration of the O-K lens in previous studies; unfortunately, this information was unavailable, but this speculation is supported by the results predicted by the simulation in the present study. In clinical practice, perfect centration (i.e. zero deviation from the cornea centre) is rare; a small magnitude of decentration is much more common, with decentration occurring most frequently in the temporal quadrant [43–45]. In line with the reported averaged magnitude of 0.50 ~ 1.00 mm [43–47], our subjects' mean decentration in the horizontal orientation was -0.42 ± 0.39 mm (ranging from 0.4 to −1.19 mm). Wang et al [46]. and Chen et al [47]. recently reported that O-K lens decentration was associated with greater anti-myopia efficacy. Wang et al [46]. suggested that the greater reduction in myopia progression might relate to the greater range or degree of myopic defocus experienced in the relatively central retina. However, they admitted that this was pure speculation because the available instruments cannot accurately measure peripheral defocus. The instrument used in this study confirms that the myopic RPR in peripheral refraction moved in the direction of lens decentration. We also found that, for the cases of decentration of 0.85 mm towards temporal cornea, the magnitude of myopic RPR was 4.22 ± 1.21 D at a retinal location of 25° of temporal side. Simulation based on the schematic eye model further showed that the magnitude of myopic RPR increases with eccentricity of the retinal location. This means that if the relative myopic defocus imposed in the peripheral retina contributes to slowing myopia progression [20–23,37], O-K lens decentration that imposes the myopic defocus in a less peripheral part of the retina is likely to inhibit myopia progression more than in well-centred cases.

The strengths of the present study include high-resolution capture of optical aberrations across a relatively wide visual field, providing intensive and comprehensive data that help to explain the impact of O-K. The inclusion of cases involving differing magnitudes of lens decentration better reflects the real-world situation in clinical practice and facilitates comparison of the varied outcomes of optics induced by O-K. In addition, the applied ray-tracing model further confirm that the change in RPR are induced by lens decentration. However, it must be noted that as the sample size in the stratified analysis is relatively small, especially for decentred cases, the quantitative results must be interpreted with caution. As a further limitation, the study's cross-sectional design cannot prove that the induced change in RPR with lens decentration impacts the efficacy of orthokeratology treatment, and a longitudinal study with a larger sample is warranted.

In conclusion, we found asymmetrical change of myopic RPR in relative peripheral refraction after orthokeratology, leading to increased myopic defocus in the peripheral retina. This asymmetrical change was induced by decentration of the O-K lens, which is very common in clinical practice. These findings may explain why decentred O-K lenses are associated with a slowing of myopia progression.

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Disclosures

The authors declare no conflicts of interest

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