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Orthokeratology reshapes eyes to be less prolate and more symmetric

Yingying Huang [a,b], Xue Li [a,b], Chenglu Ding [a], Yunyun Chen [a], Hao Chen [a,*], Jinhua Bao [a,b,*]

[a] Eye Hospital and School of Ophthalmology and Optometry, Wenzhou Medical University, Wenzhou, Zhejiang, China
[b] Key Laboratory of Vision Science, Ministry of Health P.R. China, Wenzhou, Zhejiang, China

A R T I C L E I N F O

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A B S T R A C T

Purpose: This prospective study assessed the influence of wearing and then discontinuing orthokeratology (OK) lenses on retinal shape and peripheral refraction in myopic children.
Methods: Fifty-eight myopic children (age 8–12 years) were equally divided into an OK group and a single vision spectacles (SVS) group. After 12 months of OK, it was discontinued for 1 month. Peripheral eye length (PEL), relative peripheral refraction (RPR), and corneal parameters were measured in the right eye on the nasal and temporal retinal sides at baseline, 6 months, and 12 months (13 months in OK group) visits.
Results: In the SVS group, faster elongation of the temporal side PEL made the eyes more asymmetric and prolate, developing a temporal pointed shape. In the OK group, the nasal retinal side PEL grew faster, the nasal RPR developed less hyperopic defocus, and the eye shape became more symmetric and less prolate. The central cornea became thinner and flattened, while the peripheral cornea became steeper. Changes in corneal thickness, relative peripheral corneal power, and K-values were no significant differences for the OK and SVS groups at 12 months.
Conclusions: The cornea reverted to be no difference with myopic children with SVS after 1 month discontinuation of OK. The retinal shape of SVS eyes became more asymmetric and prolate with myopia progression. OK remodelled retinal shape to be less asymmetric and less prolate.

1. Introduction

After birth, refractive components of the eye develop in a coordinated way and develop a state of emmetropia. After 6 years of age, there is very little potential to compensate refractively for the growing eye length by flattening the corneal curvature [1]. If flattening and thinning of the crystalline lens curvature fail to produce sufficient refractive power to compensate for the loss due to eye growth, the emmetropic state will transition to myopia [2,3]. The crystalline lens and other anatomic factors restrict the growth of the globe in the equatorial plane. Thus, as growth occurs in the axial direction, it causes the development of myopia [3,4].

Animal studies have shown that the peripheral retina exhibits a visual feedback response to defocus and that hyperopic defocus can promote central refractive error and axial length growth to become more myopic, whereas myopic defocus can make eyes more hyperopic [5–7]. Because of the axial extension, the eyes of myopic children develop a prolate shape that is steeper, more asymmetric, and more irregular than observed in emmetropic eyes [8,9]. This eye shape causes more peripheral hyperopic defocus than does emmetropia [10,11] and may promote myopia progression [12]. However, whether or not peripheral hyperopic defocus is a reason for myopia progression or a result is a topic of debate [13,14]. Furthermore, how eye shape and peripheral refraction change during myopia development has not been explored. Previous studies have measured differences in eye shape between myopia and emmetropia based on magnetic resonance imaging [15–18] or optical methods [4,19–24]. Dr. Atchison and his colleague followed changes of peripheral refraction with myopia development and progression over two years [25]. However, they did not measure the changes in eye shape and the relationship with peripheral defocus during myopia progression.

Thus “peripheral defocus” forms the basis of a hypothesis in which reduction of peripheral hyperopic defocuses or enhancement of peripheral myopic defocuses slows the progression of myopia in children. The overnight use of orthokeratology (OK) lens is a reversible way to reshape the cornea to correct refractive error [26]. It is also a commonly used method for controlling clinical myopia, slowing progression by 32%-63% relative to control eyes [26]. The myopic OK lens has a reverse geometry design including a flattening of the central cornea that corrects the central myopic refraction and a steep mid-peripheral cornea that causes peripheral myopic defocus. The peripheral myopic defocus is

* Corresponding authors at: Eye Hospital and School of Ophthalmology and Optometry, Wenzhou Medical University, Wenzhou, Zhejiang, China.
E-mail addresses: chenhao@mail.eye.ac.cn (H. Chen), baojessie@163.com (J. Bao).

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considered an important mechanism whereby OK lenses slow myopia progression [27–29]. Several studies have reported peripheral defocus changes after wearing OK lenses [27–30], and all of them were found to be from hyperopic defocus to myopic defocus or to be more myopic defocus. Only one study measured the changes in peripheral defocus during OK lens wear by children for 9 months [31]. However, the authors did not include a control group to determine if the observed peripheral defocus changes were due to myopia progression or OK lens wearing.

The main goal of this study was to describe changes in eye shape and peripheral defocus that occur after wearing OK lenses or single vision spectacles (SVS) for 12 months to determine how retinal shape and peripheral defocus change during myopia progression.

2. Methods

2.1. Subjects and study design

Sixty-one primary school children with progressive myopia (myopia progression ≥ −0.75 diopter (D)/12 months or ≥ −0.50 D/6 months based on the previous records from each subject in the hospital) were included in the study. The inclusion criteria required that the subjects be 8–12 years old with central refraction (spherical equivalent) between –1.00 D and –4.00 D with less than –0.75 D of astigmatism and anisometropia of <1.00 D. They were further required to be in good ocular health and free from ocular disease. Subjects were assigned to either the OK group or control SVS group mainly based on the personal desire of the children and their guardians. This study was approved by the institutional review board of the Eye Hospital of Wenzhou Medical University, and all work was carried out in accordance with the tenets of the Declaration of Helsinki. Informed assent was obtained from the children, and consent was obtained from their parents after verbal and written explanations of the objectives and possible consequences of the study.

2.2. Sample size

Change of axial length (AL) was the primary outcome in this study. The sample size was predicated on the expectation of at least a 30% reduction in the mean progression of myopia in the OK group compared with the SVS group. This, along with a previous study that found a mean myopia progression of 0.38 (SD = 0.13) mm over one year in Chinese children wearing SVS was the basis of determining the sample size [32]. With at least a 90% statistical power, type 1 error probability of 0.05, and based on a two-tailed *t*-test, the minimum sample size was estimated to be 28 for each group.

2.3. OK lenses

Subjects were fitted with OK lenses (Euclid, Sterling, VA, USA) that were worn overnight, with no lens wear during the day. The lenses were fabricated with Boston Equalens II (oprifocon A) material (Dk ISO/Fatt 85). The total lens diameter was 10.6 mm with a 6.2-mm diameter optic zone. Because the OK lenses were customized for each subject, the lenses were dispensed to the participants one month after baseline examination. Measurements were performed after five months of actual lens wear, which was six months after the baseline measurements were made. The six months measurements were made within 2 h after the removal of the OK lenses. At 12 months after the baseline measurements were taken, during which the lenses had been worn for the last 11 months, the subjects were asked to stop wearing the lenses for one month. At that time, i.e., the 13th month of the study, the final follow-up measurements were made. Subjects in the SVS group had follow-up visits at 6 and 12 months.

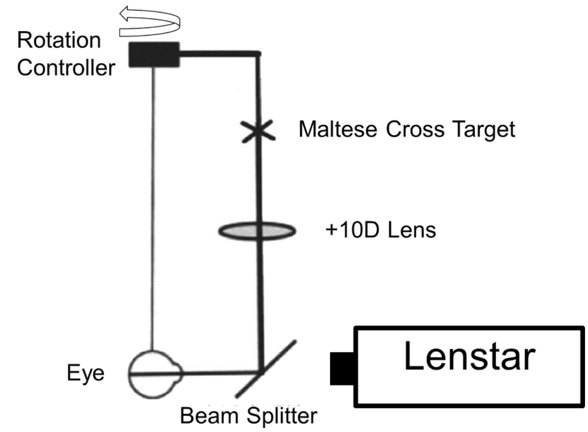

Fig. 1. Schematic diagram of peripheral eye length measurement apparatus attached to the Lenstar.

2.4. Measurements

Cycloplegia objective refraction and eye length measurements were performed at the 6-month follow-up for the OK and SVS groups, at 12 months for the SVS group, and at 13 months for the OK group. Cycloplegia was achieved with one drop of 0.5% proparacaine and two drops of 1% cyclopentolate separated by 5 min each. The measurements were performed at least 30 min after the last drop was applied. All peripheral measurements were performed on the right eyes while the left eyes were covered.

Central AL and peripheral eye length (PEL) were measured using a Lenstar optical biometer (LS 900, Haag-Streit, Koeniz, Switzerland) with the optical apparatus attached to the headrest. The system was composed of a circular goniometer mounted on the headrest bracket to control the peripheral gaze position accurately, a beam splitter placed at 45° to change the path of light from the target system and to pass the infrared laser beam from the Lenstar, and a Maltese cross as a fixation target (Fig. 1 [23]). Eye lengths were measured at the central 0° and at the horizontal meridian peripheral 10°, 20°, and 30° for the nasal (N) and temporal (T) retina. These were designated as PELs at N10°, N20°, and N30°, and as T10°, T20°, and T30° respectively. Three readings were recorded for each direction of gaze with differences no more than 0.02 mm.

Peripheral refractions (PR) were obtained from an open-view Grand Seiko binocular auto-refractor (WAM-5500, Rexxam CO. LTD, Kagawa, Japan). Refractive errors were measured at the central 0° (primary gaze) and the horizontal peripheral 10°, 20°, and 30° gazes for the nasal and temporal retina. Ten readings were recorded for each direction of gaze in which neither the sphere nor the cylinder differed from the median by more than 0.50 D. Relative peripheral refraction (RPR) was determined by subtracting the central refraction values from different positions of PR values. Spherical equivalent refraction was used to analyse refraction errors.

Three corneal topographies were performed by Scheimpflug corneal topography (Sirius, CSO, Florence, Italy). Central and peripheral corneal thicknesses were obtained from corneal thickness maps, and the refractive power of the anterior corneal surface was calculated based on sagittal anterior refractive power maps. Central anterior chamber depth and lens thickness were acquired by the Lenstar and used to calculate the corresponding corneal distance at 10°, 20°, and 30°. The mean position of anterior nodal point was calculated using a Gaussian optical system based on the measured central corneal thickness, central anterior chamber depth, and lens thickness [33,34]. Then the corneal anterior surface sites corresponding to each angle were calculated by sine function. In order to be consistent with the direction of PEL and RPR, retinal eccentricity was also used on the corneal parameters, that is, opposite to

Table 1
Group baseline data.

Parameter		OK group	SVS group	p
Age (y)		9.86 ± 1.27	9.97 ± 0.98	0.68
Male/Female		13/16	16/13	0.44
Refractive error (D)		−2.51 ± 0.74	−2.61 ± 0.75	0.60
Axial length (mm)		24.85 ± 0.90	24.85 ± 0.73	0.99
RPR (D)	N30	1.83 ± 1.01	2.10 ± 0.88	0.29
	N20	1.02 ± 0.66	1.02 ± 0.66	0.98
	N10	0.21 ± 0.39	0.26 ± 0.28	0.57
	T10	−0.08 ± 0.44	−0.03 ± 0.27	0.72
	T20	0.10 ± 0.80	0.13 ± 0.60	0.86
	T30	0.30 ± 1.17	0.45 ± 1.09	0.61
PEL (mm)	N30	23.67 ± 0.89	23.58 ± 0.76	0.67
	N20	24.07 ± 1.03	24.04 ± 0.84	0.89
	N10	24.64 ± 0.91	24.64 ± 0.79	0.99
	T10	24.70 ± 0.91	24.70 ± 0.72	0.97
	T20	24.23 ± 0.89	24.23 ± 0.71	0.98
	T30	23.54 ± 0.86	23.51 ± 0.71	0.89
Corneal thickness (mm)	N30	646.65 ± 39.12	650.21 ± 32.76	0.71
	N20	585.82 ± 30.57	588.00 ± 26.28	0.77
	N10	556.94 ± 28.04	559.24 ± 25.01	0.74
	C	551.79 ± 27.78	554.55 ± 25.15	0.69
	T10	570.84 ± 28.54	573.39 ± 26.66	0.73
	T20	614.12 ± 30.97	617.12 ± 29.58	0.71
	T30	706.35 ± 40.64	709.91 ± 36.23	0.73
RPCP (D)	N30	−0.49 ± 0.48	−0.67 ± 0.40	0.12
	N20	0.04 ± 0.38	−0.12 ± 0.33	0.08
	N10	0.15 ± 0.23	0.07 ± 0.26	0.22
	T10	0.17 ± 0.70	−0.04 ± 0.21	0.13
	T20	−0.38 ± 0.54	−0.55 ± 0.38	0.18
	T30	−1.53 ± 0.73	−1.68 ± 0.59	0.40
Kf at 3 mm (D)		42.35 ± 1.49	42.74 ± 1.18	0.28
Ks at 3 mm (D)		43.39 ± 1.60	43.79 ± 1.29	0.30
Kf at 5 mm (D)		42.29 ± 1.48	42.63 ± 1.16	0.33
Ks at 5 mm (D)		43.27 ± 1.59	43.66 ± 1.28	0.31
Kf at 7 mm (D)		42.11 ± 1.47	42.43 ± 1.16	0.35
Ks at 7 mm (D)		43.04 ± 1.56	43.41 ± 1.28	0.33

OK = orthokeratology, SVS = single vision spectacle, D = diopter, RPR = relative peripheral refraction, PEL = peripheral eye length, C = central cornea, RPCP = relative peripheral corneal power, Kf = flat keratometry, Ks = steep keratometry, N = nasal retina (temporal cornea), T = temporal retina (nasal cornea).

the corneal direction, N10, N20, N30 on the temporal side of cornea, T10, T20, T30 on the nasal side of cornea. The relative peripheral corneal power (RPCP) was defined as the peripheral refractive power minus the corneal apex refractive power. Flat keratometry (Kf) and steep keratometry (Ks) values were expressed for the 3-, 5-, and 7 mm diameter rings of the cornea to represent the different design zones of the OK lens.

2.5. Data analysis

Second-order polynomial fits were applied to PELs for each participant: $y = ax^2 + bx + c$, where "*x*" was the retinal angle in degrees and was designated as positive for temporal retina, one unit of "*x*" was the equivalent to 10° on the x-axis [35]. Retinal shape was represented by the coefficient "*a*", larger absolute values of "a" indicate a more prolate retinal shape. The location of the axis of symmetry "*s*" was determined by the equation $s = (-2a/b)*10°$. Positive values of "*s*" indicated that the axis of symmetry passed through the temporal retina.

Independent *t*-tests compared differences between the OK and SVS groups, and repeated-measured ANOVA was used to compare differences between visits. Bonferroni corrections were applied for post hoc pairwise comparisons. A critical p-value of 0.05 was taken to indicate a statistical significance.

3. Results

Thirty subjects in the OK group and 31 in the SVS group were included in the study, and all finished the follow-ups; however, one subject in the OK group and two subjects in the SVS group refused to do cycloplegia at the last visit. Therefore, only twenty-nine subjects in each group completed all of the peripheral measurements. There were no differences in baseline data between the OK and SVS groups in age, sex, central refractive error, axial length, RPR, PEL, and corneal parameters (Table 1).

3.1. Myopia control

After 13 months of OK lens wear, the AL increased by 0.28 ± 0.16 mm. After 12 months of SVS wear, the AL increased by 0.36 ± 0.18 mm. The myopia control effect of OK was 0.08 mm (22%) for one year.

3.2. PEL

PEL-N30 and PEL-N20 elongated faster in the OK group than in the SVS group at both 6 and 12 months (Fig. 2, Tables 2 and 3). PEL-T20 and PEL-T10 elongated faster in the SVS group at 12 months. In the OK group, both at 6 and 12 months, the PEL of the nasal side grew faster than the AL (all $p < 0.05$). In the OK group, PEL-N20° grew faster than all of the other PELs and ALs (all $p < 0.05$), PEL-T10 grew slower than all other PELs and ALs (all $p < 0.05$). In the SVS group, PEL-N30 and PEL-N20 grew slower than all temporal side PELs and ALs (all $p < 0.05$) both at 6 months and 12 months.

3.3. Coefficients "a", "s", and symmetry

At baseline, there was no difference in the coefficient "*a*", which expresses the degree of prolateness, between the OK and SVS groups (Table 4). Similarly, there was no difference in "s", which indicates the location of the axis of symmetry, between the two groups (Table 4). Coefficient "a" was larger (the absolute value was smaller) after wearing OK lenses (p = 0.02), but it became smaller in the SVS group without statistical significance. Coefficient "s" tended to become more negative in the OK group, indicating that the axis of symmetry moved slightly to

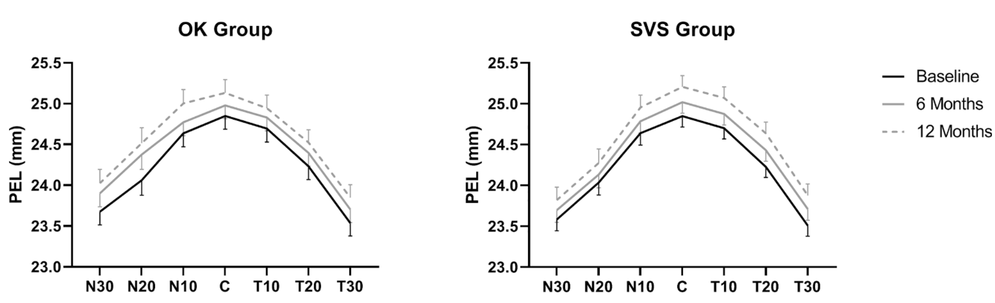

Fig. 2. PEL of the OK and SVS group at baseline, 6 months, and 12 months. PEL = peripheral eye length, OK = orthokeratology, SVS = single vision spectacles, N = nasal retina, C = central, T = temporal retina.

Table 2
Comparisons of PEL, RPR and RPCP among three visits in each group.

	OK Group						SVS Group					
	Baseline	6 Months	12 Months	P^a	P^b	P^c	Baseline	6 Months	12 Months	P^a	P^b	P^c
PEL (mm)												
N30	23.67 ± 0.89	23.90 ± 0.91	24.03 ± 0.93	<0.001	<0.001	<0.001	23.58 ± 0.76	23.70 ± 0.82	23.82 ± 0.87	<0.001	0.004	<0.001
N20	24.07 ± 1.03	24.38 ± 1.00	24.52 ± 1.04	<0.001	<0.001	<0.001	24.04 ± 0.84	24.13 ± 0.89	24.28 ± 0.94	<0.001	0.021	<0.001
N10	24.64 ± 0.91	24.77 ± 0.90	25.00 ± 0.94	<0.001	<0.001	<0.001	24.64 ± 0.79	24.79 ± 0.78	24.95 ± 0.84	<0.001	<0.001	<0.001
C	24.85 ± 0.90	24.98 ± 0.89	25.13 ± 0.88	<0.001	<0.001	<0.001	24.85 ± 0.73	25.02 ± 0.74	25.21 ± 0.76	<0.001	<0.001	<0.001
T10	24.70 ± 0.91	24.83 ± 0.88	24.95 ± 0.87	<0.001	<0.001	<0.001	24.70 ± 0.72	24.88 ± 0.75	25.07 ± 0.75	<0.001	<0.001	<0.001
T20	24.23 ± 0.89	24.40 ± 0.89	24.52 ± 0.86	<0.001	<0.001	<0.001	24.23 ± 0.71	24.43 ± 0.75	24.64 ± 0.75	<0.001	<0.001	<0.001
T30	23.54 ± 0.86	23.70 ± 0.88	23.85 ± 0.87	<0.001	<0.001	<0.001	23.51 ± 0.71	23.71 ± 0.75	23.88 ± 0.77	<0.001	<0.001	<0.001
RPR(D)												
N30	1.83 ± 1.01	−1.36 ± 1.69	1.46 ± 1.04	<0.001	<0.001	0.007	2.10 ± 0.88	2.22 ± 0.97	2.44 ± 1.08	0.20	/	/
N20	1.02 ± 0.66	−2.70 ± 1.48	0.56 ± 0.78	<0.001	<0.001	0.001	1.02 ± 0.66	1.16 ± 0.69	1.32 ± 0.68	0.21	/	/
N10	0.21 ± 0.39	−1.09 ± 1.45	0.07 ± 0.49	<0.001	<0.001	0.61	0.26 ± 0.28	0.38 ± 0.40	0.34 ± 0.32	0.33	/	/
T10	−0.08 ± 0.44	−2.70 ± 1.74	−0.04 ± 0.28	<0.001	<0.001	1.00	−0.03 ± 0.27	−0.09 ± 0.26	−0.05 ± 0.30	0.52	/	/
T20	0.10 ± 0.80	−2.40 ± 1.82	0.11 ± 0.68	<0.001	<0.001	1.00	0.13 ± 0.60	0.10 ± 0.62	0.04 ± 0.62	0.64	/	/
T30	0.30 ± 1.17	−1.55 ± 1.47	0.16 ± 0.94	<0.001	<0.001	1.00	0.45 ± 1.09	0.42 ± 1.00	0.22 ± 1.03	0.45	/	/
RPCP(D)												
N30	−0.49 ± 0.48	0.98 ± 0.74	−0.67 ± 0.42	<0.001	<0.001	0.05	−0.67 ± 0.40	−0.65 ± 0.34	−0.74 ± 0.45	0.39	/	/
N20	0.04 ± 0.38	0.52 ± 1.06	−0.11 ± 0.25	0.009	0.10	0.09	−0.12 ± 0.33	−0.11 ± 0.23	−0.16 ± 0.32	0.68	/	/
N10	0.15 ± 0.23	−0.10 ± 1.05	0.02 ± 0.20	0.31	/	/	0.07 ± 0.26	0.08 ± 0.20	0.03 ± 0.21	0.55	/	/
T10	0.17 ± 0.70	0.70 ± 1.04	−0.01 ± 0.21	0.008	0.14	0.43	−0.04 ± 0.21	−0.01 ± 0.17	−0.04 ± 0.27	0.87	/	/
T20	−0.38 ± 0.54	2.41 ± 1.48	−0.48 ± 0.40	<0.001	<0.001	0.71	−0.55 ± 0.38	−0.48 ± 0.31	−0.53 ± 0.28	0.58	/	/
T30	−1.53 ± 0.73	0.09 ± 0.99	−1.65 ± 0.67	<0.001	<0.001	0.42	−1.68 ± 0.59	−1.62 ± 0.50	−1.64 ± 0.48	0.72	/	/

OK=orthokeratology, SVS=single vision spectacle, D=diopter, PEL=peripheral eye length, RPR=relative peripheral refraction, C=central cornea, RPCP=relative peripheral corneal power, P^a=RM-ANOVA among three visits, P^b=post hoc comparison between 6 months and baseline, P^c=post hoc comparison between 12 months and baseline.

Table 3
Change in PEL after wearing OK or SVS lenses.

		Change in PEL (mm)		
Eccentricity	Follow-up	OK group	SVS group	p
N30	6 months	0.23 ± 0.16	0.11 ± 0.17	0.01
	12 months	0.35 ± 0.20	0.24 ± 0.21	0.045
N20	6 months	0.30 ± 0.23	0.10 ± 0.18	<0.001
	12 months	0.45 ± 0.27	0.24 ± 0.25	0.002
N10	6 months	0.13 ± 0.14	0.15 ± 0.16	0.72
	12 months	0.37 ± 0.21	0.31 ± 0.23	0.53
T10	6 months	0.13 ± 0.14	0.17 ± 0.11	0.23
	12 months	0.25 ± 0.18	0.37 ± 0.17	0.01
T20	6 months	0.16 ± 0.12	0.21 ± 0.14	0.23
	12 months	0.29 ± 0.15	0.41 ± 0.19	0.009
T30	6 months	0.17 ± 0.14	0.20 ± 0.16	0.38
	12 months	0.31 ± 0.16	0.37 ± 0.18	0.21

PEL = peripheral eye length, OK = orthokeratology, SVS = single vision spectacle, N = nasal retina, T = temporal retina. The 12-month follow-up for the OK group was performed at 13 months because OK therapy was begun one month after baseline measurements were made.

the nasal side; however, the change was not statistically significant (Table 4). For the SVS group, coefficient "s" became more positive over the study period ($p = 0.001$), indicating that the axis of symmetry moved to the temporal side of the retina. Thus, during the 12-month period of lens wear, the ocular symmetry shifted differently for the OK and SVS groups (Table 5). For the OK group, the nasal side became more elongated, while for the SVS group, the temporal side became more elongated.

Table 4
Changes in coefficients "a" and "s" after wearing OK or SVS lenses.

Coefficient	Time	OK group	SVS group	p*
a	Baseline	−0.14 ± 0.03	−0.14 ± 0.03	0.29
	6 months	−0.13 ± 0.03	−0.14 ± 0.03	0.03
	12 months	−0.13 ± 0.03	−0.15 ± 0.03	0.03
	p**	0.02	0.12	
s	Baseline	−0.32 ± 2.16	0.18 ± 1.76	0.33
	6 months	−0.80 ± 2.02	0.74 ± 2.05	0.005
	12 months	−0.97 ± 2.41	1.02 ± 2.15	0.002
	P**	0.07	0.001	

OK = orthokeratology, SVS = single vision spectacle. The coefficient "a" represents the steepness of retinal shape. Larger absolute values of "a" mean that the eye shape is more prolate. Coefficient "s" represents the symmetry of retinal shape. Positive values of "s" indicate that the axis of symmetry is located at the temporal retina. *, column p-values represent comparison between different groups in one visit. **, row p-values represent comparisons of different visits with the baseline value within each group. The 12-month follow-up for the OK group was performed at 13 months because OK therapy was begun one month after baseline measurements were made.

Table 5
Symmetry of PEL change after wearing OK or SVS lenses.

Temporal to Nasal	Time	OK group	SVS group	p*
PEL-T30 minus PEL-N30	Baseline	−0.14 ± 0.27	−0.08 ± 0.23	0.33
	6 months	−0.20 ± 0.24	0.01 ± 0.30	0.005
	12 months	−0.18 ± 0.28	0.06 ± 0.35	0.007
	p**	0.19	0.008	
PEL-T20 minus PEL-N20	Baseline	0.17 ± 0.40	0.19 ± 0.32	0.84
	6 months	0.02 ± 0.32	0.30 ± 0.38	0.004
	12 months	0.01 ± 0.38	0.36 ± 0.39	0.001
	p**	0.001	<0.001	
PEL-T10 minus PEL-N10	Baseline	0.06 ± 0.19	0.06 ± 0.14	0.93
	6 months	0.06 ± 0.14	0.09 ± 0.16	0.41
	12 months	−0.06 ± 0.17	0.12 ± 0.19	0.001
	p**	0.001	0.12	

PEL = peripheral eye length, OK = orthokeratology, SVS = single vision spectacle, N = nasal retina, T = temporal retina. The 12-month follow-up for the OK group was performed at 13 months because OK therapy was begun one month after baseline measurements were made. *, column p-values represent comparison between different groups in one visit. **, row p-values represent comparisons of different visits with the baseline value within each group.

3.4. RPR

In the OK group, all eccentricities in the RPR at 6 months were more myopic than at baseline, thus increasing the myopic defocus. However, one month after discontinuance of OK, all RPRs had returned to the hyperopic defocus. For the SVS group, there were no significant changes in RPR during the study period. Comparisons between the OK and SVS groups at 12 months showed that RPR-N30 and RPR-N20 in the OK group had less hyperopic defocus than the SVS group (Fig. 3, Tables 2 and 6).

3.5. Corneal topography

Based on the mean baseline values for all subjects of both treatment groups, the central corneal thickness was 0.55 mm, the anterior chamber depth was 3.29 mm, and the lens thickness was 3.33 mm. At the horizontal meridional angles of 10°, 20°, and 30° from the cornea, the corresponding corneal distances were calculated to be 1.25 mm, 2.45 mm, and 3.59 mm. The corneal data were acquired by Scheimpflug topography at intervals of 0.2 mm and 1.4°. Thus the measured N30, N20, and N10 distances (nasal retina and temporal cornea) were 1.2 mm, 2.4 mm, and 3.6 mm at 180°, and the T30, T20, and T10 distances (temporal retinal and nasal cornea) were 1.2 mm, 2.4 mm, and 3.6 mm at 0°.

After wearing OK lenses for 6 months, the central corneal thickness of the OK group was thinner than in the SVS group (Table 7) After discontinuation of OK lens wear for one month, the corneal thickness increased, but was still thinner than in the SVS group. All changes of central and peripheral corneal thickness were far <20 μm in the two groups. Thus the changes in corneal thickness are unlikely to influence the AL and PEL measurements because the measurement error was 20 μm.

For the OK group at the 6-month visit, measurement of the RPCP showed that the peripheral cornea refractive power was more myopic than at baseline (Fig. 4, Tables 2 and 8). All RPCPs in the OK group produced a more myopic defocus than in the SVS group except at N10° and T10°. The largest myopic defocus change occurred at N20°. At the

Table 6
Change of RPR after wearing OK or SVS lenses.

Eccentricity	Time	OK group	SVS group	p
N30	6 months	−3.19 ± 1.88	0.12 ± 1.16	<0.001
	12 months	−0.37 ± 0.59	0.34 ± 1.20	0.006
N20	6 months	−3.72 ± 1.77	0.13 ± 1.03	<0.001
	12 months	−0.46 ± 0.63	0.29 ± 1.01	0.001
N10	6 months	−1.29 ± 1.35	0.13 ± 0.54	<0.001
	12 months	−0.14 ± 0.57	0.08 ± 0.46	0.11
T10	6 months	−2.61 ± 1.75	−0.06 ± 0.29	<0.001
	12 months	0.04 ± 0.42	−0.02 ± 0.54	0.55
T20	6 months	−2.49 ± 1.86	−0.03 ± 0.69	<0.001
	12 months	0.02 ± 0.54	−0.09 ± 0.71	0.53
T30	6 months	−1.85 ± 1.59	−0.04 ± 1.41	<0.001
	12 months	−0.14 ± 1.00	−0.24 ± 1.35	0.77

RPR = relative peripheral refraction, OK = orthokeratology, SVS = single vision spectacle, N = nasal retina, C = central cornea, T = temporal retina. The 12-month follow-up for the OK group was performed at 13 months because OK therapy was begun one month after baseline measurements were made

Table 7
Central and peripheral corneal thickness change after wearing OK or SVS lenses.

Eccentricity	Time	OK	SVS	p
N30 (μm)	6 months	5.96 ± 11.04	4.01 ± 9.84	0.48
	12 months	1.97 ± 8.76	4.05 ± 8.24	0.36
N20 (μm)	6 months	3.18 ± 9.96	3.39 ± 8.15	0.93
	12 months	−0.27 ± 6.63	2.10 ± 6.41	0.17
N10 (μm)	6 months	−3.48 ± 7.53	2.21 ± 7.39	0.005
	12 months	−2.19 ± 5.67	0.93 ± 5.95	0.046
C (μm)	6 months	−4.42 ± 7.69	1.78 ± 7.44	0.003
	12 months	−2.65 ± 5.35	0.55 ± 6.16	0.04
T10 (μm)	6 months	2.96 ± 9.73	2.10 ± 8.38	0.72
	12 months	−1.85 ± 6.18	1.14 ± 6.96	0.09
T20 (μm)	6 months	3.37 ± 10.41	2.12 ± 10.00	0.64
	12 months	−0.50 ± 7.62	2.24 ± 8.37	0.20
T30 (μm)	6 months	5.26 ± 12.23	1.81 ± 14.27	0.33
	12 months	0.92 ± 9.72	4.10 ± 12.11	0.26

OK = orthokeratology, SVS = single vision spectacle, N = nasal retina (temporal cornea), T = Temporal retina (nasal cornea). The 12-month follow-up for the OK group was performed at 13 months because OK therapy was begun one month after baseline measurements were made

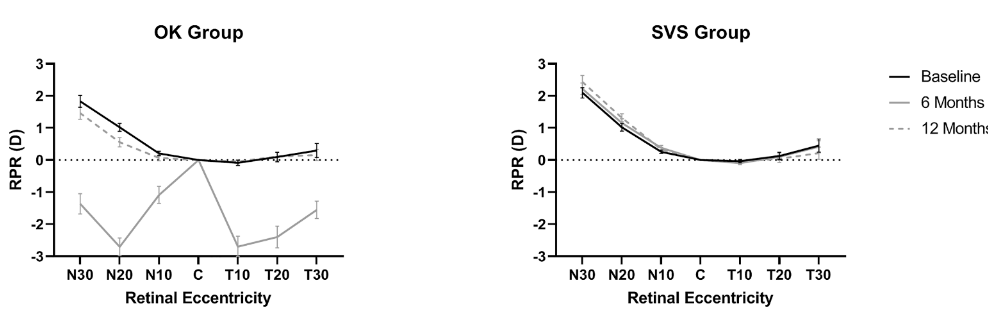

Fig. 3. RPR of the OK and SVS group at baseline, 6 months, and 12 months. RPR = relative peripheral refraction, OK = orthokeratology, SVS = single vision spectacles, D = diopter, N = Nasal retina, C = central, T = Temporal retina.

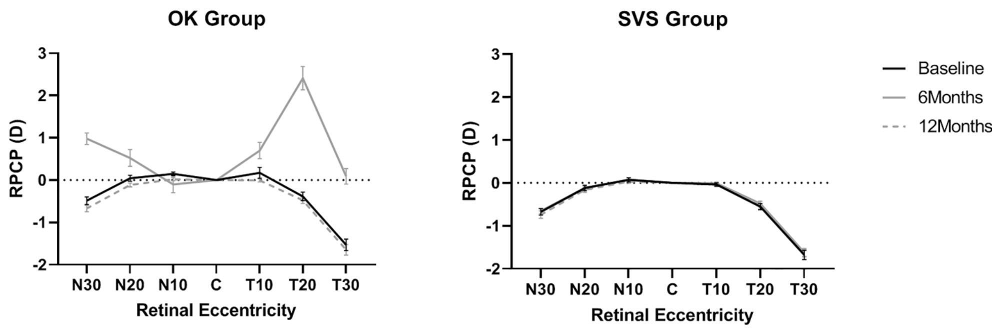

Fig. 4. RPCP of the OK and SVS group at baseline, 6 months, and 12 months. RPCP = relative peripheral corneal power, OK = orthokeratology, SVS = single vision spectacles, D = diopter, N = Nasal retina (temporal cornea), C = central, T = Temporal retina (nasal cornea).

Table 8
Changes of RPCP after wearing OK or SVS lenses.

Eccentricity	Time	OK (D)	SVS (D)	p
N30	6 months	1.47 ± 1.00	0.02 ± 0.38	<0.001
	12 months	−0.18 ± 0.39	−0.07 ± 0.36	0.24
N20	6 months	0.48 ± 1.15	0.01 ± 0.35	0.04
	12 months	−0.16 ± 0.38	−0.04 ± 0.32	0.21
N10	6 months	−0.25 ± 1.10	0.01 ± 0.29	0.22
	12 months	−0.13 ± 0.27	−0.04 ± 0.24	0.18
T10	6 months	0.05 ± 1.35	0.03 ± 0.27	0.06
	12 months	−0.18 ± 0.64	−0.00 ± 0.37	0.20
T20	6 months	2.80 ± 1.78	0.07 ± 0.36	<0.001
	12 months	−0.09 ± 0.41	0.02 ± 0.42	0.30
T30	6 months	1.62 ± 1.19	0.06 ± 0.40	<0.001
	12 months	−0.12 ± 0.42	0.04 ± 0.42	0.17

RPCP = relative peripheral corneal power, OK = orthokeratology, SVS = single vision spectacle, D = diopter, N = nasal retina (temporal cornea), T = temporal retina (nasal cornea). The 12-month follow-up for the OK group was performed at 13 months because OK therapy was begun one month after baseline measurements were made

Table 9
Changes in flat and steep keratometry after wearing OK or SVS lenses.

Keratometry	Time	OK	SVS	p
Kf within 3 mm	6 months	−1.65 ± 0.62	−0.01 ± 0.22	<0.001
	12 months	−0.02 ± 0.33	−0.06 ± 0.29	0.63
Ks within 3 mm	6 months	−1.80 ± 0.75	0.16 ± 0.26	0.000
	12 months	0.10 ± 0.32	0.16 ± 0.23	0.41
Kf within 5 mm	6 months	−0.97 ± 0.54	−0.00 ± 0.19	<0.001
	12 months	−0.04 ± 0.27	−0.06 ± 0.24	0.79
Ks within 5 mm	6 months	−1.13 ± 0.59	0.15 ± 0.22	<0.001
	12 months	0.14 ± 0.26	0.15 ± 0.18	0.81
Kf within 7 mm	6 months	−0.60 ± 0.37	0.00 ± 0.18	<0.001
	12 months	−0.06 ± 0.24	−0.06 ± 0.20	0.97
Ks within 7 mm	6 months	−0.69 ± 0.36	0.13 ± 0.20	<0.001
	12 months	0.16 ± 0.24	0.14 ± 0.18	0.67

OK = orthokeratology, SVS = single vision spectacle. Kf = keratometry reading along the flat meridian, Ks = keratometry reading along the steep meridian. The 12-month follow-up for the OK group was performed at 13 months because OK therapy was begun one month after baseline measurements were made.

12-month visit, the RPCP of the OK group was not significantly different from the SVS group (Table 8).

The decreases in Kf values and Ks values indicated a flatter cornea after wearing OK lenses for 6 (Table 9). One month after discontinuance of OK lens wear, Kf and Ks reverted to the baseline values. For the SVS group, Kf values decreased, and Ks values increased as myopia progressed, leading to increased corneal toricity of about 0.20 D/year.

4. Discussion

This study described the changes in myopic retinal shape and peripheral defocus that occurred after wearing OK lenses. Then compared these changes with those that occurred in eyes wearing SVS lenses to clarify how peripheral defocus affects the retinal shape. For the purpose of this study, the SVS group was considered to represent normal eyes that exhibit the predictable progression of myopia. Wearing OK lenses can bring different myopic defocuses at different retinal eccentricities. Furthermore, the cornea reverts to normal myopic condition after discontinuation of OK lens wear for 1 month. In the SVS group, the eyes elongated faster on the temporal side; thus, the retinal shape became tapered to the temporal side, and the axis of symmetry moved slightly to the temporal side. In the OK group, the nasal side grew faster, compensating for previous temporal growth, and the retinal shape became more symmetric and less prolate.

During the normal progression of myopia, the cornea also undergoes changes in shape and thickness. In the SVS group, the Kf values decreased, and Ks values increased as myopia progressed. These changes led to an increase in corneal toricity of about 0.20 D/year. Therefore, to minimize the impact of myopia progression, the corneal changes were compared after wearing OK lenses with the SVS control group instead of with the baseline data of the OK eyes. After discontinuation of OK lens wear for one month, corneal thickness, curvature, and K-values reverted to the normal myopic conditions, i.e., there were no differences between the corneas of the OK and SVS groups, except for the thickness at the central and N10° positions. The changes of K-values after stopping OK lens for a month were not different with the control group at the different corneal diameter ranges, and the increase of toricity was mainly due to Ks. Subjects in the OK group indeed increased corneal toricity, but it was not different from the SVS group. Therefore it was speculated that the increased toricity was due to the progression of myopia and not the OK lens wear. Chen et al. [36] showed that in eyes treated by OK lenses for two years, the Kf at one month after wear discontinuance was flattened compared to baseline, and there was an increase in corneal toricity. Different outcomes may be dependent on different OK lens wear periods. Thus in their study, the one month of discontinuation may not have been enough time for corneal reversion.

The present observations demonstrate that at baseline, the RPR was asymmetric in both groups, with the nasal side having a greater hyperopic defocus than the temporal side. This asymmetry was due to the asymmetric retinal shape, with the temporal side having a longer PEL and was closer to the AL than the nasal side, resulting in less hyperopic defocus. The OK lens-induced peripheral myopic defocus in the whole cornea and the retina, with defocus ranges and amounts that were similar to those reported in previous studies [30,31,37–39]. The defocus was more myopic on the nasal cornea and temporal retina after OK due to the temporal decentration of the OK lenses [39–41]. In previous clinical studies, temporal decentration of OK lenses was common due to the flatter curvature of the nasal cornea [42–44].

In this study, SVS eyes without intervention to control myopia tended to elongate on the temporal side and become more asymmetric, pointed towards the temporal side of the eye. Eyes wearing the OK lens were more likely to elongate faster on the nasal side, PEL-N20° elongated faster than any other PEL or AL. As 20° was the most asymmetric area at baseline, this growth pattern reshaped the eyes to be more symmetric after one year of treatment. However, there is a concern that longer treatment by OK would cause too much elongation on the nasal side, causing the eyes to become pointed on the nasal side. The OK lenses caused a fast elongation of PEL-N20 and PEL-N30, leading to a decrease of hyperopic retinal defocus of more than 0.7 D at the nasal side. This can benefit myopia control and even stop the necessity of wearing OK lenses if the peripheral hyperopic defocus promotes central myopia. Faria-Ribeiro et al. [21] compared retinal contours between progressing and stable young-adult myopes. They found that stable myopes had a more symmetric shape than progressive myopes. The remodelling of retinal shape to be more symmetric may be a goal for the next step of myopia control.

An unexpected result was that wearing an OK lens could remodel retinal shape to be less prolate. Coefficient “a” represents the degree of eye prolateness. The absolute value of “a” was smaller at 6 months and 12 months than at baseline in the OK group, indicating that the eyes had become less prolate. Myopic eyes have a more prolate shape than emmetropic eyes, resulting in peripheral hyperopic defocus [8–11]. The OK lenses reshaped the eyes to be more oblate and thereby reduced hyperopic defocus. In the SVS group, the retinal shape did not change significantly, but there was a tendency to become more prolate. Some studies of high myopia have found that a steeper or more prolate retinal shape is a risk factor for myopic traction maculopathy [45] and that an asymmetric and irregular retinal shape is associated with the incidence of posterior staphyloma [46]. The remodelling of retinal shape by OK causes it to be less prolate and more symmetric, and this may reduce the incidence of serious retinal shape-related diseases.

Previous studies showed that OK lenses could exhibit a reduction of axial elongation by more than 30% compared to SVS or soft contact lenses [26]. The myopia control effect of OK, 22% in this study, was lower than previously published data. Two reasons can explain this non-ideal control effect. One is that the follow-up period of the OK group was 13 months, which was one month longer than for the SVS group. The extra month was required because the discontinuance of OK lenses was necessary to determine the real morphological characteristics of the eyes after OK. Thus the time and rebound after treatment [47] are two possible influencing factors present during the one month of discontinued OK lens wear. Another is that, because of the lens customization that required a month to complete, the subjects wore the OK lenses for only 11 months.

A potential limitation of this study is that the participants were not randomly assigned to the OK and SVS groups. Instead, to achieve better compliance, the study respected the individual wishes of the parents and children regarding the choice of OK of SVS lenses. However, all of the basic data and measured parameters were matched against baseline values, which tended to ameliorate this limitation.

5. Conclusions

The retinal shape became more asymmetric and prolate with myopia progression if there was no interference. A new finding is that treatment of myopic eyes with OK lenses for one year remodeled retinal shape, causing it to become less asymmetric and prolate, and to have reduced nasal retinal hyperopic defocus.

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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.

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