Heliyon 10 (2024) e36020

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Analysis of the peripheral refraction in myopic adults using a novel multispectral refraction topography

Wu Qiuxin [a,b,c], Zhang Xiuyan [a,b,c], Tian Qingmei [a,c], Feng jiaojiao [b], Guo Xiaoxiao [b], Liu yijie [b], Guo Dadong [c], Song Jike [b,c,**], Bi Hongsheng [a,b,c,*]

[a] *Affiliated Eye Hospital of Shandong University of Traditional Chinese Medicine, No.48#, Yingxiongshan Road, Jinan, 250002, PR China*
[b] *Shandong University of Traditional Chinese Medicine, No. 16369#, Jingshi Road, Jinan, 250014, PR China*
[c] *Shandong Provincial Key Laboratory of Integrated Traditional Chinese and Western Medicine for Prevention and Therapy of Ocular Diseases, Key Laboratory of Integrated Traditional Chinese and Western Medicine for Prevention and Therapy of Ocular Diseases in Universities of Shandong, Shandong Academy of Eye Disease Prevention and Therapy , No. 48#, Yingxiongshan Road, Jinan, 250002, PR China*

A R T I C L E I N F O

Keywords:
Peripheral refraction
Relative peripheral refraction
Adult
Myopia
Refractive error

A B S T R A C T

Purpose: To determine the distribution and characteristics of peripheral refraction in adults with myopia using the novel multispectral refraction topography.
Method: A total of 187 adults with myopia were recruited for this study. This study was conducted in two stages. Part I: participants were divided into 6 groups based on the central refraction of the right eyes, Part II: according to the interocular differences in refractive error (IOD) of the central refraction, we divided the participants into isomyopia group (IOD<1.00 D) and anisomyopia group (IOD≥1.0 D). We surveyed the characteristics of peripheral refraction and relative peripheral refraction (RPR), as well as the correlation between RPR and central refraction, age, sex, and axial length.
Result: Part I: With an increase in the degree of myopia, relative peripheral hyperopia developed from the center to the periphery. A statistically significant hyperopia shift compared to the center ($P < 0.05$) was first observed on the temporal side within a 40° field of view at the posterior pole of the retina. The RPR of the temporal, superior, and inferior retinas positively correlated only with age. Part II: In the isomyopic participants, there was no difference in peripheral refraction between the eyes ($P < 0.05$). In the anisomyopic participants, the RPR of the more myopic eyes was more hyperopic than that of the less myopic eyes in NRDV40-50, SRDV10-20, SRDV30-50, TRDV20-30, TRDV40-50, and IRDV10-40.
Conclusion: With an increase in the degree of myopia, relative peripheral hyperopia developed from the center to the periphery, and peripheral refraction progressed at different rates in various retinal zones.

1. Introduction

Myopia is one of the most common eye diseases worldwide and has become a global public health issue. Myopia affects 28.3 % of

* Corresponding author. Affiliated Eye Hospital of Shandong University of Traditional Chinese Medicine, No.48#, Yingxiongshan Road, Jinan, 250002, PR China.
** Corresponding author. Shandong University of Traditional Chinese Medicine, No. 16369#, Jingshi Road, Jinan, 250014, PR China.
E-mail addresses: edusjk@163.com (S. Jike), hongshengbi1@163.com (B. Hongsheng).

https://doi.org/10.1016/j.heliyon.2024.e36020
Received 16 September 2023; Received in revised form 5 August 2024; Accepted 8 August 2024
Available online 10 August 2024

the global population and is predicted to increase to 49.8 % by 2050 [1,2]. Myopia is one of the main causes of vision impairment and is related to eye diseases, including choroidal neovascularization, retinal detachment, and glaucoma [3]. The incidence of myopia is gradually increasing and has a significant negative impact on society, the economy, and education [4]. Understanding the possible causes of myopia is important for its prevention and control.

In 1971, Hoogerheide et al. [5] suggested that peripheral refraction affected myopia development. In recent decades, several studies have focused on the relationship between myopia and peripheral refraction. Peripheral refraction is considered a stimulating factor for the onset and progression [6]. The concept has been supported by animal studies in which peripheral morphological deprivation and imposed local retinal defocus appear to induce central axial myopia [7–9]. It has also been hypothesized that the relative hyperopic blurring of the peripheral retina is a risk factor for the development of central myopia in children and adults [10, 11]. The peripheral retina controls eye growth [12,13]. Recently, there has been an increasing interest in the area of peripheral visual field refraction, as peripheral refraction is believed to play an important role in the development of myopia.

In recent decades, researchers have used different methods to detect peripheral refraction. The open-field autorefractometer [14] and commercial Hartmann-Shack wavefront sensor technique [15,16] appear to be the most commonly used instruments to measure peripheral refraction. However, research on peripheral refraction has been limited to the horizontal or vertical longitudes.

There are few reports on the characteristics of the peripheral refractive plane distribution. Wang et al. [17] used a custom-made Hartmann–Shack wavefront sensor to measure the two-dimensional peripheral refractive distribution of myopic eyes in a 60° × 36° visual field. Osuagwu et al. [18] used a COAS-HD Hartmann–Shack aberrometer to determine the differences in peripheral aberrations in hyperopic, emmetropic, and myopic groups for a 42° × 32° visual field. However, these instruments have the disadvantages of complex operation and long inspection times for peripheral refraction detection.

Multispectral refraction topography (MRT) is a newly developed instrument designed to measure the spherical equivalent refraction (SER) of a 53° retinal field of view within 2–3 s. MRT collects fundus images successively using single-spectrum light of different wavelengths. Using a computer algorithm developed in-depth, the lens-compensated multi-spectral images were compared and analyzed, and the corresponding topographic map was drawn after calculating and summarizing the actual refractive value of each pixel. The novel multispectral refraction topography demonstrated good repeatability in central and peripheral refraction [19,20], has been used in peripheral refractive detection [21], and guided the clinical prevention and control of myopia [21,22]. To better understand the distribution and characteristics of peripheral refraction in myopic adults and provide a theoretical basis for the prevention and control of myopia, we designed this experiment to measure peripheral refraction using the MRT.

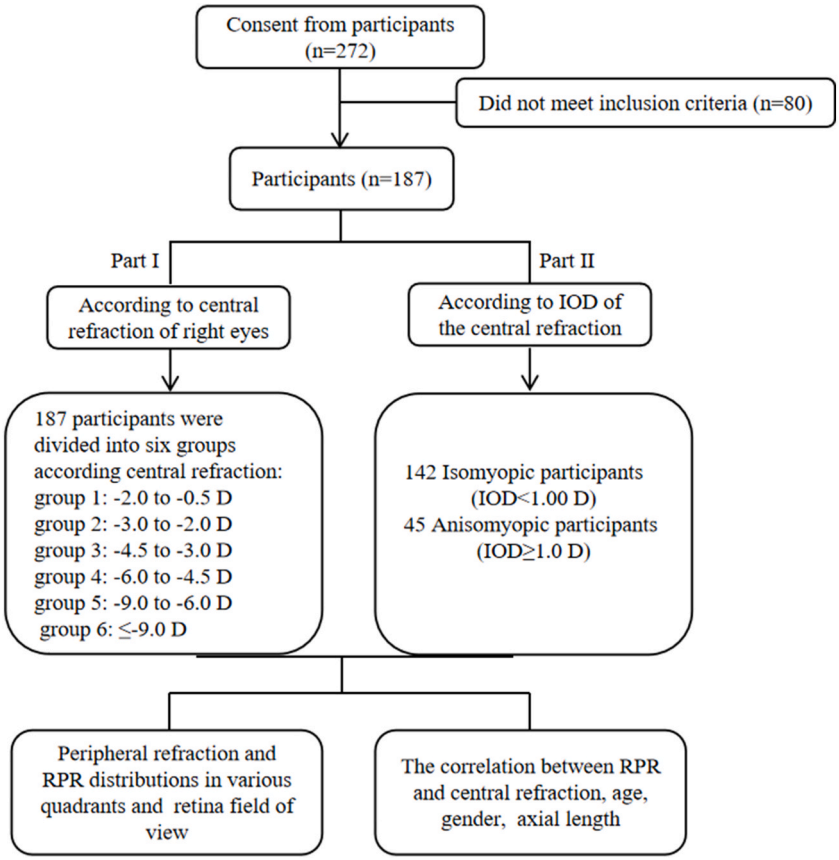


Fig. 1. Study flowchart: Flow chart of participants in the study. IOD: interocular differences in refractive error. RPR: relative peripheral refraction.

2. Methods and materials

2.1. Participants and study design

This study followed the principles of the Declaration of Helsinki and was approved by the Affiliated Eye Hospital of Shandong University of Chinese Medicine before study commencement (HEC-HY-2023004KY). All participants gave written consent to participate in the study after being informed of the nature and possible consequences of participating in the study.

Volunteers were recruited from the Affiliated Eye Hospital of the Shandong University of Traditional Chinese Medicine according to the following inclusion criteria.

(1) Participants between 18 and 45 years old (inclusive).
(2) Participants had the best corrected visual acuity of $\geq$20/20.
(3) Cycloplegic SER of $\leq$ –0.5 D, and astigmatism of $\leq$2.0 D in both eyes.

The exclusion criteria were as follows.

(1) History of ocular disease or previous ocular surgery.
(2) History of wearing orthokeratology lenses in the previous month.

In this study, 272 adults signed informed consent forms, 187 of whom met the inclusion and exclusion criteria. To explore the relative peripheral refraction (RPR) distribution in myopic adults, this study was conducted in two parts.

Part I: 187 participants were divided into six groups based on the central refraction of right eyes (Group 1: 2.0 to −0.5 D, Group 2: 3.0 to −2 D, Group 3: 4.5 to −3.0 D, Group 4: 6.0 to −4.5 D, Group 5: 9.0 to −6.0 D, Group 6: $\leq$–9.0 D). We surveyed the characteristics of peripheral refraction and RPR in the six groups from different quadrants and fields of view as well as the correlation between RPR and central refraction, age, sex, and axial length (AL). A schematic of the study is shown in Fig. 1.

Part II: Based on the interocular differences in central refractive error (IOD), the 187 participants were divided into participants

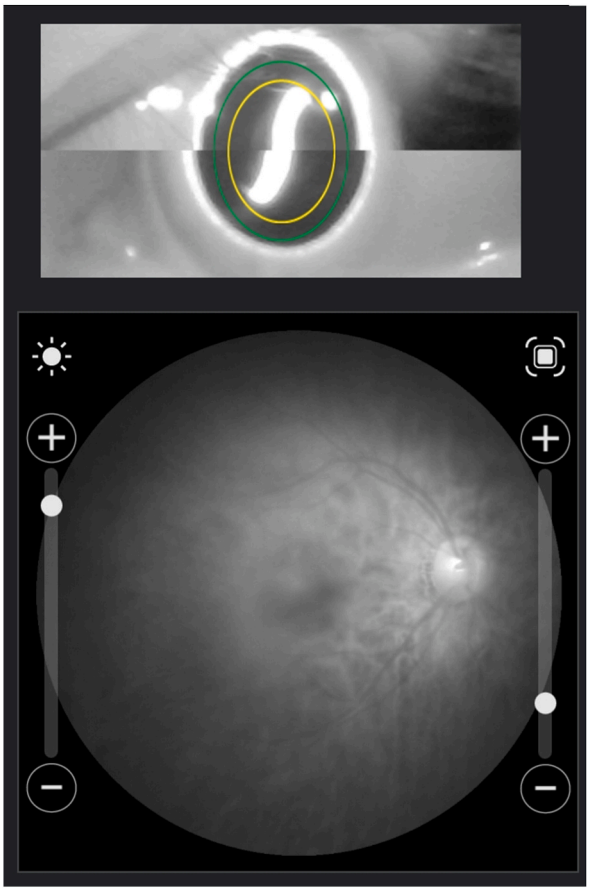


Fig. 2. The operational interface of Multispectral Refraction Topography (MRT) Instrument.

with isomyopia (IOD<1.00 D) and participants with anisomyopia (IOD≥1.0 D), and then the characteristics of peripheral refraction and RPR of both eyes were analyzed.

2.2. Cycloplegia and ocular examinations

Cycloplegia was induced using one drop of 0.4 % oxybuprocaine hydrochloride eye drops (Benoxil; Santen Pharmaceuticals, Japan), followed by three drops of 1 % cyclopentolate hydrochloride eye drops (Cyclogyl; Alcon, Japan) applied 5 min apart. The pupillary light reflex was examined 30 min after the final drop of cyclogyl. If the light reflex was still present, another drop of cyclogyl was instilled, and the following measurement was not performed until the best possible cycloplegia was obtained. The procedure was performed by an experienced operator in a dark room between 9:00 a.m. and 5:00 p.m. to avoid the potential effects of diurnal variations [23].

Astigmatism was determined using an autorefractometer (ARK-1; NIDEK, Tokyo, Japan) AL was measured via optical biometry using an IOL Master 500 (Carl Zeiss Meditec, Dublin, CA, Stati Uniti). The peripheral refraction of both eyes was measured using MRT (version 1.0.5T05C; Thondar, Inc.) after mydriasis.

2.3. Multispectral refraction topography

The MRT detection process is as follows: (1) Instruct the participant to fully open their eyes, adjust the joystick to align the interface with one of the eyes, keep the pupil at the center of the interface and push forward to make the interface of the retinal image appear intact, and then fine-tune to achieve the alignment of the upper and lower pupils of the positioning interface, with no light leakage at the edge of the shooting interface (Fig. 2). The gray value of GrayAVG is limited to 100–140 by adjusting the brightness of the retinal illumination; (2) the patient was asked to look at the gaze label and blink gently to ensure that the tear film was complete, and then image collection began. After 2–3 s of the focusing scanning process, the retinal image screening interface appears, and click save to complete the monocular shooting process; (3) by moving the joystick, repeat the above process for the other eye, and then complete the data storage. Each participant required approximately 3 min.

The MRT can determine the SER of 128 × 128 points in a 53° fundus field of view, and the data point between them is 0.5°. After each data point was collected, a set of custom compensation software-processed images were color-coded. Macular foveal refraction measured at the equator (parallel to 0°) was defined as the central refraction. The absolute peripheral refraction for a given eccentric area is the SER of the eccentric area. The RPR was calculated by subtracting the central refraction of the fovea from that obtained at each eccentric location and was translated into color images.

The analyzed parameters were divided into three different types (Fig. 3): (1) the refraction difference value (RDV) of circle areas centered on macular with an increment of 10°, RDV-10, RDV-20, RDV-30, RDV-40, and RDV-50, which represent the average peripheral retinal refraction from the center to 10°, 20°, 30°, 40°, and 50° (Fig. 3A); (2) the retina was centered on the macula and divided into inferior, superior, nasal, and temporal (RDV-I, RDV-S, RDV-N, and RDV-T) (Fig. 3B); (3) the annular refraction difference value with intervals of 10°, RDV 10–20, RDV 20–30, RDV 30–40, and RDV 40–50.

2.4. Statistics and data analysis

Statistical analysis was conducted using SPSS (version 20.0; SPSS Inc., Chicago, IL, USA). First, we divided the 187 participants into six groups according to the central refraction of the right eye, and the differences in RPR between various retinal zones were analyzed using one-way ANOVA, and multiple linear regression was used to analyze the correlation between RPR and central refraction, age,

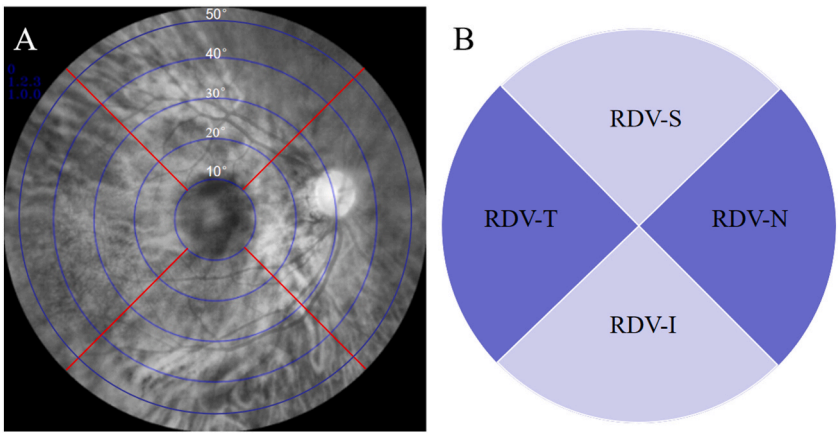


Fig. 3. Section segmentation in multispectral refraction topography (MRT) images. The MRT image of the right eye fundus is divided into 17 sections by five ring and two vertical intersecting lines (A), and divided into four sections (B).

sex, and AL.

Second, based on the interocular difference in refractive error (IOD) of the central refraction, we divided the 187 participants into participants with isomyopia (IOD<1.00 D) and participants with anisomyopia (IOD≥1.0 D), and then the difference of peripheral refraction between two eyes was analyzed using paired *t*-test, the difference of RPR between various retina zones were analyzed using one way ANOVA. A critical $P < 0.05$ was used to represent statistical significance.

3. Results

3.1. Participant characteristics

A total of 187 adults with myopia participated in the study, with a mean age of 24.20 ± 6.51 years old. The central refraction was −5.17 ± 2.01 D (range from −1.25 to −12.125 D) and −4.94 ± 1.99 D (range from −0.5 to −11.625 D) in the right and left eye, respectively. According to the IOD of the central SER, 142 participants were isomyopes (IOD<1.00 D) and 45 were anisomyopes (IOD≥1.0 D). Therefore, the isomyopic participants had a mean central refraction of −4.98 ± 1.88 D (range from −0.62 to −10.75 D) in both eyes, and an average IOD of 0.35 ± 0.25 D. In contrast, the anisomyopic participants had a mean central refraction of −5.30 ± 2.34 D (range from −0.5 to −12.125 D) in both eyes and an average IOD of 1.98 ± 1.36 D. The demographic information of the participants is presented in Table 1.

3.2. Distribution of RPR by different eccentric fields of view in all adults with myopia

We analyzed the distribution characteristics of the RPR in different eccentric fields of view. The RDV-10, 20, 30, 40, and 50 were 0.07 ± 0.03, 0.33 ± 0.08, 0.56 ± 0.17, 0.75 ± 0.27, and 0.84 ± 0.38 D, respectively. From Table 2, we determined that the RDV increased with increasing eccentric field of view, and the difference was statistically significant ($P < 0.05$). Within the same eccentric fields of view, there was no significant difference in RDV between the different degrees of myopia ($P > 0.05$).

A multiple regression model was used to analyze the correlation between the RDV of various eccentric fields of view and central refraction, age, sex, and AL. The results showed that the RDV-30, -40, and −50 were positively correlated with age (RDV-30: regression coefficient B = 0.005, standardized coefficients β = 0.193, $P = 0.017$; RDV-40: regression coefficient B = 0.009, standardized coefficients β = 0.208, $P = 0.010$; RDV-50: regression coefficient B = 0.013, standardized coefficients β = 0.227, $P = 0.005$), but not correlated with central refraction, gender and AL (all $P > 0.05$). There was no correlation between RDV-10 and RDV-20 and central refraction, age, sex, or AL ($P > 0.05$).

3.3. Distribution of peripheral refraction and RPR by quadrants in all adults with myopia

To analyze the distribution characteristics of peripheral refraction and RPR in the myopic eyes, we further analyzed the right eye of all 187 participants. Based on central SER, the patients were divided into six groups. Fig. 4 shows the mean peripheral refraction (Fig. 4A) and RPR (Fig. 4B) values of all eyes of the myopic participants in the visual field. In −0.5 to −2.0 D mild myopic eyes, the RPR was homogeneous across the visual field (compared to the center, all $P < 0.05$) (Fig. 4B, Group 1). With an increase in the degree of myopia, relative peripheral hyperopia develops from the center to the periphery, and peripheral refraction progresses at different rates in various retinal zones. A statistically significant hyperopia shift compared to the center ($P < 0.05$) first appeared on the temporal side within a 40° field of view at the posterior pole of the retina (Fig. 4B). When the central SER is between −9.0 and −12.5 D, the phenomenon of relative peripheral hyperopia becomes irregular (Fig. 4B, Group 6). The RDV of the 20–30/40–50 nasal and temporal retinas, as well as the 10–20/30–40 superior and inferior retinas, were significantly different among the groups (all $P < 0.05$, Table 3).

The nasal, superior, temporal, and inferior retina mean RDV was 1.21 ± 0.60, 0.65 ± 0.68, 0.58 ± 0.72, and 0.94 ± 0.67 D, respectively. The relative peripheral hyperopia shift was most evident in the nasal retina. There were significant differences in RPR between the temporal and nasal, as well as the superior and inferior retinas (all $P < 0.05$). This indicates that the RPR of the nasal retina is asymmetrical compared to that of the temporal, superior, and inferior retinas.

Table 1
The demographic information of the participants.

	Anisomyopes		Isomyopes		Total myopia	
	MM	LM	OD	OS	OD	OS
Number participants (eyes)	45 (90)		142 (284)		187(374)	
Sex number participants (eyes)						
Male	17 (34)		81 (162)		98 (196)	
Female	28 (56)		61 (122)		89 (178)	
Age, y, mean ± SD	25.02 ± 7.88		24.08 ± 6.24		24.20 ± 6.51	
central refraction[a], D, mean ± SD [range]	−6.29 ± 2.16 [-2.5 to −12.13]	−4.32 ± 2.10 [-0.50 to −8.38]	−5.03 ± 1.91 [-1.25 to −10.75]	−4.97 ± 1.85 [-0.62 to 10.38]	−5.17 ± 2.01 [-1.25 to −12.13]	−4.94 ± 1.99 [-0.50 to −11.63]

D:diopters; MM = more myopic eyes; LM = less myopic eyes; SD: Standard Deviation.

[a] The macular fovea refraction was defined as the central refraction.

Table 2
The relative peripheral refraction (RPR) (D, mean ± SD) in different circles of the six myopia groups.

Retina field of view[c]	*Total*	group 1[a]	group 2[a]	group 3[a]	group 4[a]	group 5[a]	group 6[a]	P_1 value[b]
RDV-10	0.07 ± 0.03	0.05 ± 0.04	0.07 ± 0.04	0.07 ± 0.03	0.07 ± 0.03	0.07 ± 0.03	0.08 ± 0.03	0.584
RDV-20	0.33 ± 0.08	0.26 ± 0.09	0.33 ± 0.09	0.33 ± 0.08	0.32 ± 0.08	0.33 ± 0.07	0.36 ± 0.06	0.382
RDV-30	0.56 ± 0.17	0.41 ± 0.19	0.54 ± 0.17	0.57 ± 0.17	0.56 ± 0.18	0.55 ± 0.15	0.60 ± 0.11	0.354
RDV-40	0.75 ± 0.27	0.55 ± 0.30	0.72 ± 0.26	0.77 ± 0.28	0.76 ± 0.28	0.74 ± 0.26	0.77 ± 0.21	0.530
RDV-50	0.84 ± 0.38	0.53 ± 0.41	0.75 ± 0.36	0.86 ± 0.39	0.88 ± 0.39	0.82 ± 0.40	0.85 ± 0.30	0.374
P_2 value[b]	<0.001	0.020	<0.001	<0.001	<0.001	<0.001	<0.001	

SD: Standard Deviation; RDV: relative refraction difference value.
[a] We divided them into 6 groups according to the degree of central refraction, group 1: −2.0 to −0.5 D, group 2: −3 to −2 D, group 3: −4.5 to −3.0 D, group 4: −6.0 to −4.5 D, group 5: −9.0 to −6.0 D, group 6: ≤-9.0 D.
[b] Significant difference was tested by one-way ANOVA.
[c] RDV10/20/30/40/50: relative defocus values of 10°/20°/30°/40°/50° around the macula.

A multiple regression model was used to analyze the correlation between the RDV of the four quadrants and central refraction, age, sex, and AL. The results showed that the RDV of the temporal, superior, and inferior retinas was positively correlated with age (RDV-T: regression coefficient B = 0.019, standardized coefficients β = 0.172, $P = 0.034$; RDV-S: regression coefficient B = 0.022, standardized coefficients β = 0.211, $P = 0.008$; RDV-I: regression coefficient B = 0.023, standardized coefficients β = 0.226, $P = 0.006$), but not correlated with central refraction, gender and AL (all $P > 0.05$). There was no correlation between RDV-N and central refraction, age, sex, or AL ($P > 0.05$).

3.4. Distribution of peripheral refraction and RPR in adults with isomyopia

Fig. 5A shows the mean peripheral refractive values in the visual field of adults with isomyopia. To facilitate comparison, we obtained a distribution map of RPR by subtracting the refraction of the macular fovea from the refraction of the retina in different directions (Fig. 5B). There was a significant difference in the RPR of the right and left eye peripheral zones compared to the central zone, and the nasal and temporal RPR were asymmetrical (Fig. 5B). The mean values of the peripheral refraction for each zone are displayed in Table 4. In participants with isomyopia, there was no difference in the peripheral refraction between the right and left eyes. In each zone, the difference in peripheral refraction between the left and right eyes was not statistically significant (F = 0.520, $P = 0.938$).

3.5. Distribution of peripheral refraction and RPR in adults with anisomyopia

For convenience of comparison, in the anisometropic myopia group, we defined eyes with more degrees of myopia as more myopic (MM) and those with less myopia as less myopic (LM). The central refraction of the MM eyes and the LM eyes were −6.29 ± 2.16 D and −4.32 ± 2.10 D. The distribution of peripheral refraction in the MM and LM eyes is shown in Fig. 6A. There were significant differences in the peripheral refraction between the MM and LM eyes, except for NPR 40–50 (Table 4). As shown in Fig. 6B, the RPR of both MM and LM eyes tended to be hyperopic. Hyperopic RPR in NRDV40-50, SRDV10-20, SRDV30-50, TRDV20-30, TRDV 40–50, and IRDV10-40 were more pronounced in MM eyes than in LM eyes.

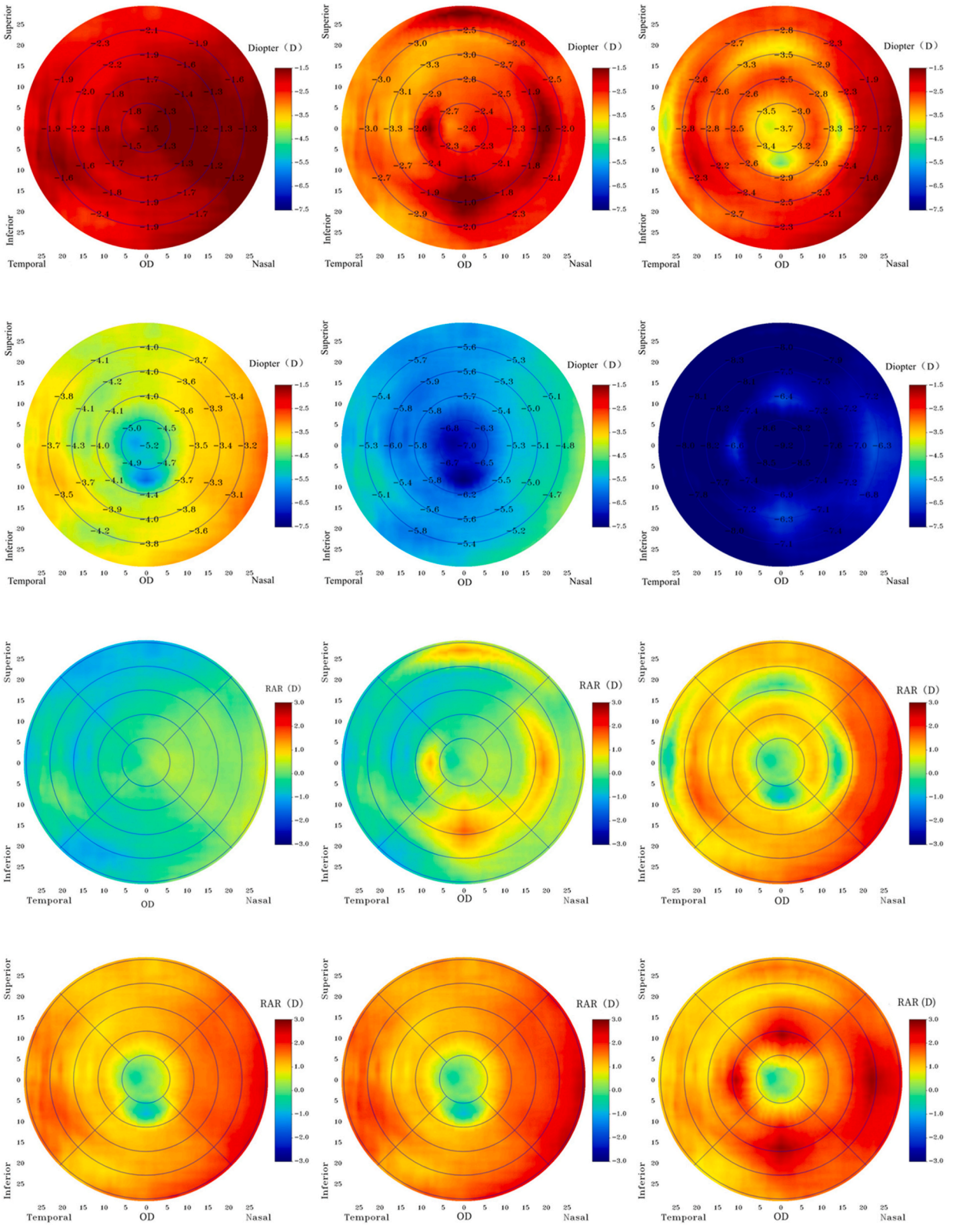
4. Discussion

In the current study, we first discussed the distribution characteristics of peripheral refraction in adults with myopia through different visual fields and quadrants, we then discussed the distribution characteristics of peripheral refraction in adults with isomyopia and anisometropia.

Anisomyopes have different central refractions between the eyes; therefore, we speculated that anisometropic eyes have different peripheral refractions. Even in isomyopic eyes, peripheral refraction varies with central refraction [24,25].

By examining the peripheral refraction of isomyopic eyes, we found that the right and left eye peripheral refractions were completely symmetric. These results are consistent with those of Wang et al. [17] and Osuagwu [26]. They reported mirror-symmetrical RPR patterns in the fellow eyes of participants with isomyopia. This justifies the common practice of measuring only one eye in peripheral refraction studies.

Chen et al. [27] reported that the RPR of the MM eye with anisomyopia shifted hyperopically, as observed in isomyopic eyes with similar central refraction. The RPR of the LM eyes in the anisomyopic group shifted less hyperopically than that of the corresponding isomyopic eyes. They suggested that such an RPR pattern in LM eyes may be a factor that slows the progression of myopia. However, our results were not completely consistent with the observation by Chen et al. In the current study, the results showed that, in anisometropia, the RPR of MM eyes was more prone to hyperopia than that of LM eyes only in partial retinal zones. In this study, the LM eyes in the anisomyopic and isomyopic eyes had similar central refraction, and the LM eyes showed less hyperopia shift in the retinal regions of the 40–50° nasal, 10–20° and 40–50°superior, 10–20° temporal, and 20–40° inferior regions. This result differs from that reported by Wang et al. [17], who suggested that LM eyes showed a smaller hyperopic shift in the inferior retina than isomyopic eyes with similar central refraction.



(caption on next page)

Fig. 4. Characteristics of peripheral refraction (PR) (A) and relative peripheral refraction (RPR) (B) distribution in different degree of central refraction. We divided them into 6 groups according to the degree of central refraction, group 1: −2.0 to −0.5 D, group 2: −3 to −2 D, group 3: −4.5 to −3.0 D, group 4: −6.0 to −4.5 D, group 5: −9.0 to −6.0 D, group 6: ≤-9.0 D. Compared with center, the asterisk (*) indicated that there was statistically significant difference in relative hyperopia defocus, $*P < 0.05$, $**P < 0.001$. The x-axis values represent the nasal retina and temporal retina, and the y-axis represents the superior retina and inferior retina. The colour scales vary in the light of the diopters.

Table 3
Comparison of relative peripheral refraction (RPR, D, mean ± SD) in 6 myopia group between 17 zones.

RPR indexes	group 1[a]	group 2[a]	group 3[a]	group 4[a]	group 5[a]	group 6[a]	*P* value[b]
RDV-10	0.05 ± 0.04	0.07 ± 0.04	0.07 ± 0.03	0.07 ± 0.03	0.07 ± 0.03	0.08 ± 0.03	0.584
Nasal RDV							
NRDV 10-20	0.26 ± 0.58	0.26 ± 0.29	0.41 ± 0.32	0.41 ± 0.35	0.43 ± 0.31	0.42 ± 0.22	0.428
NRDV 20-30	−0.06 ± 0.27	0.47 ± 0.54	0.26 ± 0.46	0.5 ± 0.48	0.41 ± 0.3	0.43 ± 0.26	0.009
NRDV 30-40	0.71 ± 0.84	1.29 ± 0.65	1.03 ± 0.59	1.02 ± 0.61	0.93 ± 0.5	1.11 ± 0.42	0.259
NRDV 40-50	1.51 ± 0.83	0.78 ± 0.67	1.38 ± 0.55	1.24 ± 0.58	1.13 ± 0.65	1.04 ± 0.29	0.007
Superior RDV							
SRDV 10-20	0.54 ± 0.28	0.26 ± 0.5	0.54 ± 0.28	0.41 ± 0.27	0.43 ± 0.21	0.52 ± 0.11	0.015
SRDV 20-30	0.32 ± 0.76	0.34 ± 0.41	0.58 ± 0.45	0.58 ± 0.51	0.61 ± 0.44	0.59 ± 0.31	0.294
SRDV 30-40	−0.12 ± 0.32	0.47 ± 0.7	0.3 ± 0.56	0.61 ± 0.64	0.51 ± 0.43	0.52 ± 0.43	0.013
SRDV 40-50	0.37 ± 0.9	1.22 ± 0.78	0.93 ± 0.69	0.95 ± 0.79	0.88 ± 0.62	1.04 ± 0.5	0.238
Temporal RDV							
TRDV 10-20	0.71 ± 0.44	0.87 ± 0.38	0.75 ± 0.46	0.75 ± 0.65	0.65 ± 0.28	0.77 ± 0.22	0.710
TRDV 20-30	0.81 ± 0.49	0.42 ± 0.52	0.81 ± 0.32	0.65 ± 0.36	0.65 ± 0.32	0.67 ± 0.15	0.008
TRDV 30-40	0.44 ± 0.95	0.49 ± 0.44	0.72 ± 0.55	0.74 ± 0.61	0.75 ± 0.55	0.74 ± 0.41	0.512
TRDV 40-50	−0.11 ± 0.4	0.51 ± 0.92	0.42 ± 0.71	0.80 ± 0.81	0.64 ± 0.60	0.64 ± 0.56	0.020
Inferior RDV							
IRDV 10-20	−0.15 ± 0.28	0.22 ± 0.41	0.01 ± 0.35	0.17 ± 0.33	0.14 ± 0.20	0.11 ± 0.17	0.021
IRDV 20-30	0.71 ± 0.71	1.1 ± 0.52	0.86 ± 0.49	0.86 ± 0.45	0.8 ± 0.36	0.97 ± 0.31	0.228
IRDV 30-40	1.39 ± 0.63	0.79 ± 0.52	1.26 ± 0.45	1.08 ± 0.48	1.03 ± 0.45	0.96 ± 0.24	0.005
IRDV 40-50	0.19 ± 1.05	0.29 ± 0.56	0.61 ± 0.69	0.73 ± 0.72	0.69 ± 0.69	0.73 ± 0.57	0.140

SD: Standard Deviation; RDV: relative refraction difference value.

[a] We divided them into 6 groups according to the degree of central refraction, group 1: −2.0 to −0.5 D, group 2: −3 to −2 D, group 3: −4.5 to −3.0 D, group 4: −6.0 to −4.5 D, group 5: −9.0 to −6.0 D, group 6: ≤-9.0 D.

[b] Significant difference was tested by one-way ANOVA.

The RPR was affected by field eccentricity [24,28]. In this study, we found that the relative RDV gradually increased as the retinal field of view increased in all participants with myopia. This finding is consistent with those of the previous studies. Chen et al. [24] and Sng et al. [28] reported that along the horizontal and vertical meridians, the hyperopic RPR gradually increased with increasing eccentricity. Zheng et al. [29] used MRT to detect the RPR distribution characteristics of young Chinese people with emmetropia, low myopia, and moderate myopia, and they found that RPR increased with eccentricity and showed a growing trend with the increase in the degree of myopia among the emmetropia, low myopia, and moderate myopia groups.

Our results are consistent with those of most previous investigations showing that myopic eyes tend to exhibit relative peripheral hyperopia [30,31]. With an increase in the degree of myopia, relative peripheral hyperopia develops from the center to the periphery, and peripheral refraction progresses at different rates in various retinal zones. When the myopia was between −0.5 D and −9.0 D, The retinal area showing hyperopic RPR gradually increased with the aggravation of myopia. However, the degree of hyperopia shift does not seem to be affected by the amount of myopia exceeding approximately −9.0 D. The peripheral refraction observed during the examination was consistent with the changes in the shape of the eyes during the progression of myopia. Peripheral refractive error in adults is associated with ocular shape; myopic eyes tend to be prolate, whereas hyperopic eyes tend to be oblate. Atchison et al. [32] found that eye length, height, and width increased at a ratio of approximately 3:2:1 as myopia increased; therefore, the increase in length corresponded roughly to the length required for myopia to develop. The shape of the posterior retinal surface can be modeled as an asymmetrical ellipsoid with only a slight variation in the width half diameter, whereas the vertical half diameter increases with increasing myopia. The characteristics of ocular myopia development are consistent with the earlier development of hyperopic RPR in the nasotemporal region than in the superior-inferior region within a 40° field of view at the posterior pole of the retina.

For highly myopic eyes, such as spherical equivalent refraction ≤–6.0 D, the hyperopic RPR is correlated to its ocular shape deformation [33]. High myopia is characterized by an abnormal eyeball shape, which follows the elongation of the AL and usually forms a posterior staphyloma [34]. Moriyama M et al. [35] studied the shapes of highly myopic eyes (refractive error ≤–8.00 D) with high-resolution magnetic resonance (MR), the results indicated that, compared with emmetropic eyes, 97.4 % of the eyes with pathologic myopia were analyzed to have deformity by their software. In our study, we observed an abnormal shape of the eye, which may be the cause of irregular peripheral refraction around high myopia (central refraction was ≤–9.0 D).

Along the horizontal axis, there is an asymmetry between the nasal and temporal RPP [18]. In this study, we found that greater changes in RPR occurred in the nasal visual field than in the temporal visual field. Li et al. [36] and Furuse et al. [37] used an open-field autorefractor to analyze peripheral refraction in children with myopia and their conclusions were consistent with our results. However, Kuo et al. [33] and Osuagwu et al. [18] believed that temporal hyperopic RPR is more obvious than nasal RPR in patients with

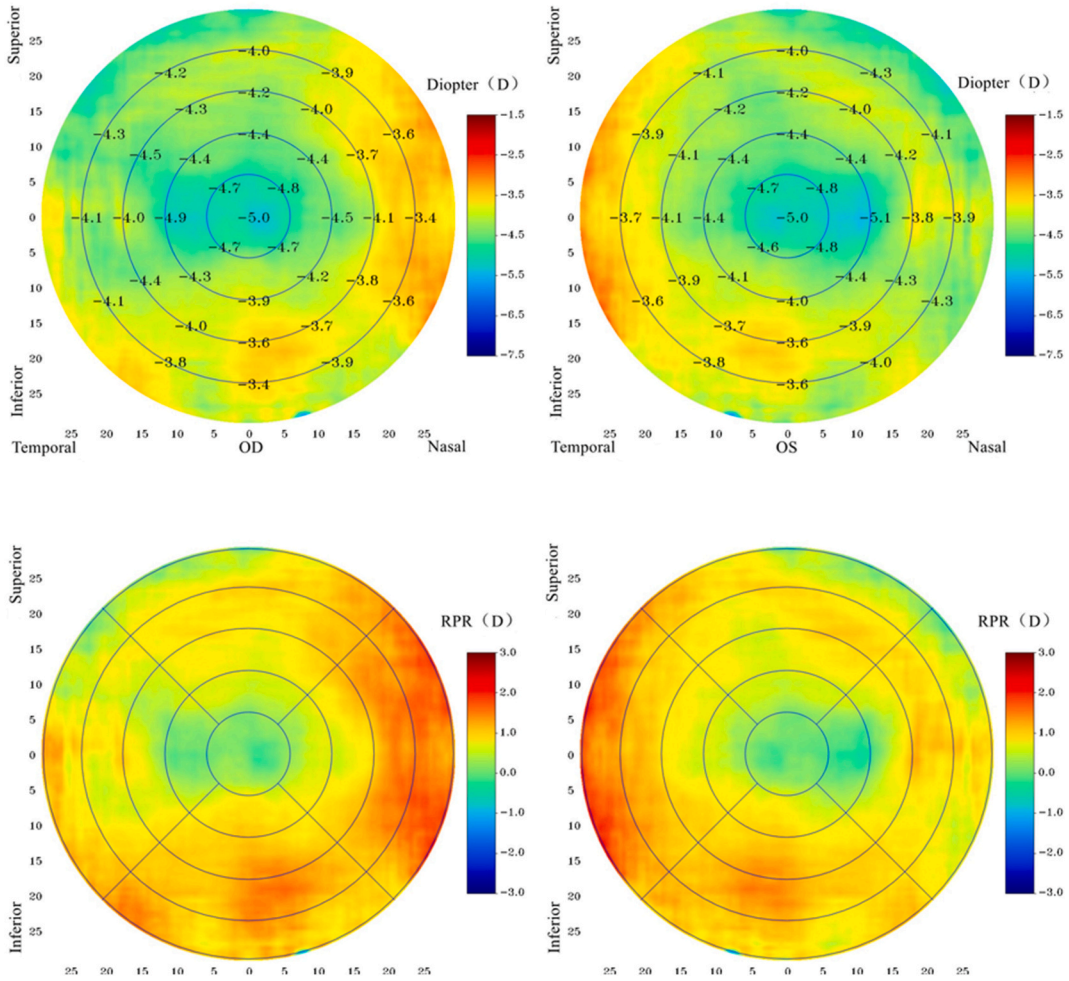


Fig. 5. (A) Distribution diagram of peripheral refraction of participants with isomyopia. Based on the flexion values of 1 million (1000 × 1000) different points, from inside to outside, the first concentric circle represents the refractive values of the corresponding points of the 10° field angle in each position. 20°, 30°, 40° in turn, the outermost circle 50° is not accurately measured. The peripheral refraction of different endpoints of concentric circles are displayed in each concentric circle. (B) The characteristics of isomyopia relative peripheral refraction distribution in 17 sections. The x-axis values represent the nasal retina and temporal retina, and the y-axis represents the superior retina and inferior retina. The colour scales vary in the light of the diopters. The asterisk (*) indicated that there was significant difference in RPR compared with central, $*P < 0.05$, $**P < 0.001$; the hash (#) indicated that there was significant difference in RPR of nasal compared with temporal ($P < 0.05$).

myopia. There is no consensus on which side has a more obvious hyperopic RPR: nasal or temporal.

Compared to mild myopia, those with moderate to high myopia have greater hyperopic RPR shifts [24,28,36]. However, we found no significant correlation between RPR and central refraction or AL. In this study, we found that RDV-T, RDV-S, RDV-I, RDV-30, RDV-40, and RDV-50 positively correlated with age. Li [36] indicated that 14-year-old children with myopia showed more relative peripheral hyperopia than 7-year-old children. Furuse [37] used a multiple regression model to analyze the relationship between age, sex, and RPR; they did not find any factors that significantly influenced RPR. Atchison et al. [38] suggested that peripheral refraction in patients with moderate myopia is relatively unaffected by age in healthy eyes with similar refractive errors. The conclusions of that study were not consistent with those of our study. The possible reasons are as follows: first, in this study, we measured the average value of RPR in different directions, while in the other two studies, we measured the RPR value of a site on the horizontal axis; second, there were differences in the age of the included participants; and third, the range of central refraction was different among the participants.

Presently, peripheral refraction is thought to promote myopia development and progression, although some longitudinal studies have reported that baseline peripheral refraction cannot predict the onset or progression of myopia [10,39]. Lam et al. [40] reported that daily wear of Defocus Incorporated Multiple Segments (DIMS) spectacle lenses significantly retarded myopia progression and axial elongation in myopic children. Their results suggest that simultaneous clear vision with constant myopic defocus can slow the progression of myopia. Orthokeratology can significantly reduce central myopia in children with myopia, transform relative peripheral hyperopia measured at baseline into relative peripheral myopia, and control myopia [41,42]. Multifocal soft contact lenses designed to

Table 4
Comparison of peripheral refraction (PR, D, mean ± SD) in 17 Zones Between Eyes.

	Isomyopes (N = 142)				Anisometropia (N = 45)			
PR indexes	OD	OS	d (OD-OS)	*P* Value[a]	MM	LM	IOD (MM-LM)	*P* Value[a]
PR-10	−4.92 ± 1.90	−4.96 ± 1.85	0.03 ± 0.99	0.709	−5.69 ± 1.74	−4.70 ± 2.05	−1.00 ± 1.23	<0.001
Nasal PR								
NPR10-20	−4.62 ± 1.96	−4.62 ± 1.92	0.00 ± 1.11	0.996	−5.30 ± 1.78	−4.26 ± 2.05	−1.04 ± 1.28	<0.001
NPR20-30	−4.60 ± 1.95	−4.58 ± 1.92	−0.01 ± 1.13	0.879	−5.45 ± 1.69	−4.38 ± 1.97	−1.07 ± 1.19	<0.001
NPR30-40	−3.95 ± 1.94	−4.00 ± 1.89	0.06 ± 0.97	0.493	−4.86 ± 1.68	−3.87 ± 2.02	−0.99 ± 1.49	<0.001
NPR40-50	−3.86 ± 2.05	−3.85 ± 1.90	−0.01 ± 1.26	0.952	−4.28 ± 1.9	−3.97 ± 2.25	−0.31 ± 1.37	0.14
Superior PR								
SPR10-20	−4.57 ± 1.92	−4.56 ± 1.82	−0.01 ± 1.14	0.926	−5.20 ± 1.77	−4.52 ± 2.01	−0.68 ± 1.3	0.001
SPR20-30	−4.47 ± 2.01	−4.45 ± 1.95	−0.02 ± 1.18	0.842	−5.10 ± 1.76	−4.01 ± 2.03	−1.09 ± 1.21	<0.001
SPR30-40	−4.53 ± 1.98	−4.39 ± 1.98	−0.13 ± 1.22	0.196	−5.36 ± 1.72	−3.96 ± 2.19	−1.40 ± 1.53	<0.001
SPR40-50	−4.02 ± 1.96	−4.11 ± 1.90	0.08 ± 1.07	0.349	−4.92 ± 1.69	−4.14 ± 2.04	−0.78 ± 1.26	<0.001
Temporal PR								
TPR10-20	−4.23 ± 1.92	−4.33 ± 1.87	0.09 ± 0.96	0.240	−5.12 ± 1.7	−4.20 ± 2.09	−0.93 ± 1.42	<0.001
TPR20-30	−4.35 ± 1.96	−4.39 ± 1.82	0.04 ± 1.15	0.681	−4.93 ± 1.78	−4.10 ± 2.12	−0.84 ± 1.28	<0.001
TPR30-40	−4.34 ± 2.04	−4.33 ± 1.95	−0.01 ± 1.18	0.950	−4.95 ± 1.78	−4.04 ± 2.02	−0.91 ± 1.31	<0.001
TPR40-50	−4.39 ± 2.04	−4.46 ± 2.02	0.07 ± 1.39	0.534	−5.31 ± 1.72	−3.86 ± 1.93	−1.46 ± 1.24	<0.001
Inferior PR								
IPR10-20	−4.87 ± 1.93	−5.00 ± 1.89	0.13 ± 1.06	0.160	−5.75 ± 1.71	−4.49 ± 2.12	−1.26 ± 1.3	<0.001
IPR20-30	−4.11 ± 1.92	−4.14 ± 1.88	0.03 ± 0.96	0.748	−4.96 ± 1.66	−4.13 ± 2.02	−0.83 ± 1.27	<0.001
IPR30-40	−3.95 ± 2.04	−4.11 ± 1.85	0.17 ± 1.20	0.098	−4.51 ± 1.85	−4.09 ± 1.94	−0.43 ± 1.32	0.036
IPR40-50	−4.42 ± 2.04	−4.41 ± 1.97	−0.01 ± 1.25	0.900	−4.99 ± 1.78	−3.91 ± 2.02	−1.08 ± 1.33	<0.001

MM: more myopic eyes; LM: less myopic eyes.
d:right eyes peripheral refraction subtract left eyes peripheral refraction.
IOD: more myopic eyes peripheral refraction subtract less myopic eyes peripheral refraction.
SD: Standard Deviation; PR: peripheral refraction.
[a] Significant difference was tested by paired *t*-test.

decrease relative peripheral hyperopia have also been shown to decrease myopia progression [43,44]. In summary, we believe that a study on the peripheral refractive distribution of myopia has profound implications for myopia prevention and control. MRT is convenient to perform, and the refraction of the detection center and peripheral retina were consistent with previous research results. This study provides a theoretical basis for the application of MRT for the prevention and control of myopia.

The current study had some limitations. On the one hand, MRT cannot accurately locate the optic disc, and the influence of the optic disc location on peripheral refraction was ignored in this study. On the other hand, the adults included were mainly people who came to our hospital for myopia refractive surgery, fewer participants have myopia between −0.5 D and −2.0 D; Third, we included audult participants, which can not represent the distribution of peripheral refraction in children. Finally, this was only a cross-sectional study on adults, and longitudinal observations should be conducted on children to further study the influence of peripheral refraction on the progression of myopia.

5. Conclusion

In summary, we used the MRT to analyze the characteristics of peripheral refraction in adults with myopia. We found that with an increase in the degree of myopia, relative peripheral hyperopia developed from the center to the periphery, first appearing on the temporal side within a 40° field of view at the posterior pole of the retina, and the peripheral refraction progressed at different rates in the varied retinal zones. The RPR was affected by the field eccentricity, and the relative RDV gradually increased as the retinal field of view increased. In isomyopic eyes, the right and left eye peripheral refractions were completely symmetric. In anisometropia, the RPR of MM eyes is more prone to hyperopia than that of LM eyes in the partial retinal zones. Greater myopia and a longer AL were not associated with a greater hyperopic RPR.

Ethics approval and consent to participate

This study was reviewed and approved by the Affiliated Eye Hospital of the Shandong University of Chinese Medicine (approval number: HEC-HY-2023004KY). All the participants provided informed consent to participate in the study.

Funding

This study was supported by the National Natural Science Foundation of China (grant no.82104937). National Key Research and Development Project (2021YFC2702100, 2021YFC2702103, 2021YFC2702104). Shandong TCM Science and Technology Development Project (M−2023010), and the Medical and health science and technology development plan of Shandong province (202207020876). Key Research and Development plan of Shandong province (2021LCZX09).

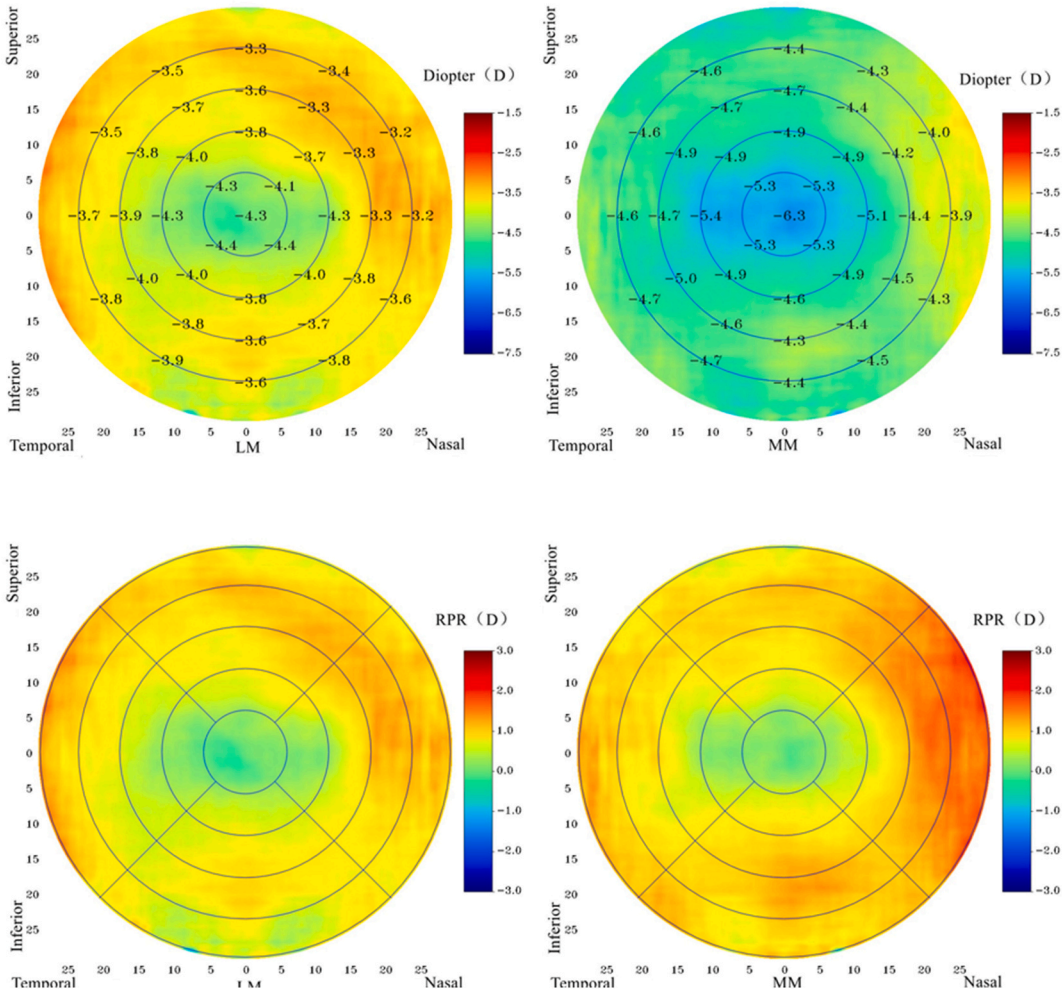


Fig. 6. (A) Distribution diagram of peripheral refraction of participants with anisometropia. (B) The characteristics of anisometropia relative peripheral refraction distribution in less myopic (LM) and more myopic (MM) eye. The x-axis values represent the nasal retina and temporal retina, and the y-axis represents the superior retina and inferior retina. The colour scales vary in the light of the diopters.The asterisk (*) indicated that there was significant difference in RPR compared with central, $*P < 0.05$, $**P < 0.001$.

Data availability statement

The authors do not have permission to share data.

CRediT authorship contribution statement

Wu Qiuxin: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation. **Zhang Xiuyan:** Writing – review & editing, Methodology, Investigation, Data curation. **Tian Qingmei:** Writing – review & editing, Methodology, Investigation. **Feng jiaojiao:** Formal analysis, Data curation. **Guo Xiaoxiao:** Methodology, Investigation, Formal analysis, Data curation. **Liu yijie:** Formal analysis, Data curation. **Guo Dadong:** Project administration, Methodology. **Song Jike:** Supervision, Project administration. **Bi Hongsheng:** Supervision, Project administration.

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.

Acknowledgements

We would like to thank Editage (www.editage.cn) for English language editing.

References

[1] B.A. Holden, T.R. Fricke, D.A. Wilson, M. Jong, K.S. Naidoo, P. Sankaridurg, T.Y. Wong, T.J. Naduvilath, S. Resnikoff, Global prevalence of myopia and high myopia and temporal trends from 2000 through 2050, Ophthalmology 123 (2016) 1036–1042, https://doi.org/10.1016/j.ophtha.2016.01.006.
[2] S. Hopf, N. Pfeiffer, [Epidemiology of myopia], Ophthalmologe 114 (2017) 20–23, https://doi.org/10.1007/s00347-016-0361-2.
[3] Q. Zhu, Y. Liu, S. Tighe, Y. Zhu, X. Su, F. Lu, M. Hu, Retardation of myopia progression by multifocal soft contact lenses, Int. J. Med. Sci. 16 (2019) 198–202, https://doi.org/10.7150/ijms.30118.
[4] Y. Shapira, M. Mimouni, Y. Machluf, Y. Chaiter, H. Saab, E. Mezer, The increasing burden of myopia in Israel among young adults over a generation: analysis of predisposing factors, Ophthalmology 126 (2019) 1617–1626, https://doi.org/10.1016/j.ophtha.2019.06.025.
[5] J. Hoogerheide, F. Rempt, W.P. Hoogenboom, Acquired myopia in young pilots, Ophthalmologica 163 (1971) 209–215, https://doi.org/10.1159/000306646.
[6] W.N. Charman, H. Radhakrishnan, Peripheral refraction and the development of refractive error: a review, Ophthalmic Physiol. Opt. 30 (2010) 321–338, https://doi.org/10.1111/j.1475-1313.2010.00746.x.
[7] D. Guo, M. Ding, X. Song, Y. Sun, G. Li, Z. Li, H. Wei, J. Wu, W. Jiang, H. Bi, Regulatory roles of differentially expressed microRNAs in metabolic processes in negative Lens-induced myopia Guinea pigs, BMC Genom. 21 (2020) 13, https://doi.org/10.1186/s12864-020-6447-x.
[8] Y. Liu, C. Wildsoet, The effect of two-zone concentric bifocal spectacle lenses on refractive error development and eye growth in young chicks, Invest. Ophthalmol. Vis. Sci. 52 (2011) 1078–1086, https://doi.org/10.1167/iovs.10-5716.
[9] K. Thomson, C. Karouta, R. Ashby, Form-deprivation and lens-induced myopia are similarly affected by pharmacological manipulation of the dopaminergic system in chicks, Invest. Ophthalmol. Vis. Sci. 61 (2020) 4, https://doi.org/10.1167/iovs.61.12.4.
[10] H. Radhakrishnan, P.M. Allen, R.I. Calver, B. Theagarayan, H. Price, S. Rae, A. Sailoganathan, D.J. O'Leary, Peripheral refractive changes associated with myopia progression, Invest. Ophthalmol. Vis. Sci. 54 (2013) 1573–1581, https://doi.org/10.1167/iovs.12-10278.
[11] E.P. Tarutta, E.N. Iomdina, N.G. Kvaratskheliya, S.V. Milash, G.V. Kruzhkova, [Peripheral refraction: cause or effect of refraction development?], Vestn. Oftalmol. 133 (2017) 70–74, https://doi.org/10.17116/oftalma2017133170-74.
[12] E.L. Smith, J. Huang, L.-F. Hung, T.L. Blasdel, T.L. Humbird, K.H. Bockhorst, Hemiretinal form deprivation: evidence for local control of eye growth and refractive development in infant monkeys, Invest. Ophthalmol. Vis. Sci. 50 (2009) 5057–5069, https://doi.org/10.1167/iovs.08-3232.
[13] E.L. Smith, L.-F. Hung, J. Huang, T.L. Blasdel, T.L. Humbird, K.H. Bockhorst, Effects of optical defocus on refractive development in monkeys: evidence for local, regionally selective mechanisms, Invest. Ophthalmol. Vis. Sci. 51 (2010) 3864–3873, https://doi.org/10.1167/iovs.09-4969.
[14] N.Y. Koomson, E. Kobia-Acquah, M. Abdul-Kabir, U.M. Aderonke, R.J. Kwaw, E.E. Arkhurst, Relationship between peripheral refraction, axial lengths and parental myopia of young adult myopes, J. Opt. 15 (2022) 122–128, https://doi.org/10.1016/j.optom.2020.10.007.
[15] R.C. Bakaraju, C. Fedtke, K. Ehrmann, A. Ho, Comparing the relative peripheral refraction effect of single vision and multifocal contact lenses measured using an autorefractor and an aberrometer: a pilot study, J. Opt. 8 (2015) 206–218, https://doi.org/10.1016/j.optom.2015.01.005.
[16] C. Fedtke, K. Ehrmann, B.A. Holden, A review of peripheral refraction techniques, Optom. Vis. Sci. 86 (2009) 429–446, https://doi.org/10.1097/OPX.0b013e31819fa727.
[17] S. Wang, Z. Lin, X. Xi, Y. Lu, L. Pan, X. Li, P. Artal, W. Lan, Z. Yang, Two-dimensional, high-resolution peripheral refraction in adults with isomyopia and anisomyopia, Invest. Ophthalmol. Vis. Sci. 61 (2020) 16, https://doi.org/10.1167/iovs.61.6.16.
[18] U.L. Osuagwu, M. Suheimat, D.A. Atchison, Peripheral aberrations in adult hyperopes, emmetropes and myopes, Ophthalmic Physiol. Opt. 37 (2017) 151–159, https://doi.org/10.1111/opo.12354.
[19] Y. Liao, Z. Yang, Z. Li, R. Zeng, J. Wang, Y. Zhang, Y. Lan, A quantitative comparison of multispectral refraction topography and autorefractometer in young adults, Front. Med. 8 (2021) 715640, https://doi.org/10.3389/fmed.2021.715640.
[20] W. Lu, R. Ji, W. Ding, Y. Tian, K. Long, Z. Guo, L. Leng, Agreement and repeatability of central and peripheral refraction by one novel multispectral-based refractor, Front. Med. 8 (2021) 777685, https://doi.org/10.3389/fmed.2021.777685.
[21] N.-J. Ni, F.-Y. Ma, X.-M. Wu, X. Liu, H.-Y. Zhang, Y.-F. Yu, M.-C. Guo, S.-Y. Zhu, Novel application of multispectral refraction topography in the observation of myopic control effect by orthokeratology lens in adolescents, World J Clin Cases 9 (2021) 8985–8998, https://doi.org/10.12998/wjcc.v9.i30.8985.
[22] T. Li, Z. Chen, M. She, X. Zhou, Relative peripheral refraction in myopic children wearing orthokeratology lenses using a novel multispectral refraction topographer, Clin. Exp. Optom. (2022) 1–6, https://doi.org/10.1080/08164622.2022.2113330.
[23] W. Lu, Z. Peng, W. Ding, R. Ji, Y. Tian, C. Zhao, L. Leng, The influence of accommodation on retinal peripheral refraction changes in different measurement areas, J Ophthalmol 2023 (2023) 5553468, https://doi.org/10.1155/2023/5553468.
[24] X. Chen, P. Sankaridurg, L. Donovan, Z. Lin, L. Li, A. Martinez, B. Holden, J. Ge, Characteristics of peripheral refractive errors of myopic and non-myopic Chinese eyes, Vis. Res. 50 (2010) 31–35, https://doi.org/10.1016/j.visres.2009.10.004.
[25] T.-T. Lee, P. Cho, Relative peripheral refraction in children: twelve-month changes in eyes with different ametropias, Ophthalmic Physiol. Opt. 33 (2013) 283–293, https://doi.org/10.1111/opo.12057.
[26] U.L. Osuagwu, M. Suheimat, D.A. Atchison, Mirror symmetry of peripheral monochromatic aberrations in fellow eyes of isomyopes and anisomyopes, Invest. Ophthalmol. Vis. Sci. 57 (2016) 3422–3428, https://doi.org/10.1167/iovs.16-19267.
[27] J. Chen, J.C. He, Y. Chen, J. Xu, H. Wu, F. Wang, F. Lu, J. Jiang, Interocular difference of peripheral refraction in anisomyopic eyes of schoolchildren, PLoS One 11 (2016) e0149110, https://doi.org/10.1371/journal.pone.0149110.
[28] C.C.A. Sng, X.-Y. Lin, G. Gazzard, B. Chang, M. Dirani, A. Chia, P. Selvaraj, K. Ian, B. Drobe, T.-Y. Wong, S.-M. Saw, Peripheral refraction and refractive error in Singapore Chinese children, Invest. Ophthalmol. Vis. Sci. 52 (2011) 1181–1190, https://doi.org/10.1167/iovs.10-5601.
[29] X. Zheng, D. Cheng, X. Lu, X. Yu, Y. Huang, Y. Xia, C. Lin, Z. Wang, Relationship between peripheral refraction in different retinal regions and myopia development of young Chinese people, Front. Med. 8 (2021) 802706, https://doi.org/10.3389/fmed.2021.802706.
[30] D.O. Mutti, R.I. Sholtz, N.E. Friedman, K. Zadnik, Peripheral refraction and ocular shape in children, Invest. Ophthalmol. Vis. Sci. 41 (2000) 1022–1030.
[31] A. Seidemann, F. Schaeffel, A. Guirao, N. Lopez-Gil, P. Artal, Peripheral refractive errors in myopic, emmetropic, and hyperopic young subjects, J. Opt. Soc. Am. Opt Image Sci. Vis. 19 (2002) 2363–2373, https://doi.org/10.1364/josaa.19.002363.
[32] D.A. Atchison, C.E. Jones, K.L. Schmid, N. Pritchard, J.M. Pope, W.E. Strugnell, R.A. Riley, Eye shape in emmetropia and myopia, Invest. Ophthalmol. Vis. Sci. 45 (2004) 3380–3386, https://doi.org/10.1167/iovs.04-0292.
[33] H.-Y. Kuo, J.C.-J. Hsiao, J.-J. Chen, C.-H. Lee, C.-C. Chuang, H.-Y. Sun, The correlations between horizontal and vertical peripheral refractions and human eye shape using magnetic resonance imaging in highly myopic eyes, Healthcare (Basel) 9 (2021) 966, https://doi.org/10.3390/healthcare9080966.
[34] B. Wen, G. Yang, J. Cheng, X. Jin, H. Zhang, F. Wang, C. Yan, D. Zheng, T. Xu, Using high-resolution 3D magnetic resonance imaging to quantitatively analyze the shape of eyeballs with high myopia and provide assistance for posterior scleral reinforcement, Ophthalmologica 238 (2017) 154–162, https://doi.org/10.1159/000477466.
[35] M. Moriyama, K. Ohno-Matsui, T. Modegi, J. Kondo, Y. Takahashi, M. Tomita, T. Tokoro, I. Morita, Quantitative analyses of high-resolution 3D MR images of highly myopic eyes to determine their shapes, Invest. Ophthalmol. Vis. Sci. 53 (2012) 4510–4518, https://doi.org/10.1167/iovs.12-9426.
[36] S.-M. Li, S.-Y. Li, L.-R. Liu, Y.-H. Zhou, Z. Yang, M.-T. Kang, H. Li, X.-Y. Yang, Y.-P. Wang, S.-Y. Zhan, P. Mitchell, N. Wang, D.A. Atchison, Anyang childhood eye study group, peripheral refraction in 7- and 14-year-old children in central China: the anyang childhood eye study, Br. J. Ophthalmol. 99 (2015) 674–679, https://doi.org/10.1136/bjophthalmol-2014-305322.

[37] T. Furuse, S. Hasebe, T. Tokutake, Peripheral refraction in Japanese schoolchildren with low to moderate myopia, Jpn. J. Ophthalmol. 66 (2022) 74–80, https://doi.org/10.1007/s10384-021-00880-2.
[38] D.A. Atchison, N. Pritchard, S.D. White, A.M. Griffiths, Influence of age on peripheral refraction, Vis. Res. 45 (2005) 715–720, https://doi.org/10.1016/j.visres.2004.09.028.
[39] D.O. Mutti, L.T. Sinnott, G.L. Mitchell, L.A. Jones-Jordan, M.L. Moeschberger, S.A. Cotter, R.N. Kleinstein, R.E. Manny, J.D. Twelker, K. Zadnik, CLEERE Study Group, Relative peripheral refractive error and the risk of onset and progression of myopia in children, Invest. Ophthalmol. Vis. Sci. 52 (2011) 199–205, https://doi.org/10.1167/iovs.09-4826.
[40] C.S.Y. Lam, W.C. Tang, D.Y.-Y. Tse, R.P.K. Lee, R.K.M. Chun, K. Hasegawa, H. Qi, T. Hatanaka, C.H. To, Defocus Incorporated Multiple Segments (DIMS) spectacle lenses slow myopia progression: a 2-year randomised clinical trial, Br. J. Ophthalmol. 104 (2020) 363–368, https://doi.org/10.1136/bjophthalmol-2018-313739.
[41] K.L. Gifford, P. Gifford, P.L. Hendicott, K.L. Schmid, Stability of peripheral refraction changes in orthokeratology for myopia, Cont Lens Anterior Eye 43 (2020) 44–53, https://doi.org/10.1016/j.clae.2019.11.008.
[42] P. Kang, H. Swarbrick, Peripheral refraction in myopic children wearing orthokeratology and gas-permeable lenses, Optom. Vis. Sci. 88 (2011) 476–482, https://doi.org/10.1097/OPX.0b013e31820f16fb.
[43] C. Fedtke, K. Ehrmann, V. Thomas, R.C. Bakaraju, Peripheral refraction and aberration profiles with multifocal lenses, Optom. Vis. Sci. 94 (2017) 876–885, https://doi.org/10.1097/OPX.0000000000001112.
[44] J. Shen, F. Spors, D. Tsang, L.E. McNaughton, D.J. Egan, In-vivo evaluation of peripheral refraction changes with single vision and multifocal soft contact lenses, Med Hypothesis Discov Innov Ophthalmol 7 (2018) 112–118.