Original Article

Ocular dimensions by three-dimensional magnetic resonance imaging in emmetropic versus myopic school children

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ABSTRACT

Background: Magnetic resonance imaging (MRI) has been used to investigate eye shapes; however, reports involving children are scarce. This study aimed to determine ocular dimensions, and their correlations with refractive error, using three-dimensional MRI in emmetropic versus myopic children.

Methods: Healthy school children aged < 10 years were invited to take part in this cross-sectional study. Refraction and best-corrected distance visual acuity (BCDVA) were determined using cycloplegic refraction and a logarithm of the minimum angle of resolution (logMAR) chart, respectively. All children underwent MRI using a 3-Tesla whole-body scanner. Quantitative eyeball measurements included the longitudinal axial length (LAL), horizontal width (HW), and vertical height (VH) along the cardinal axes. Correlation analysis was used to determine the association between the level of refractive error and the eyeball dimensions.

Results: A total of 70 eyes from 70 children (35 male, 35 female) with a mean (standard deviation [SD]) age of 8.38 (0.49) years were included and analyzed. Mean (SD) refraction (spherical equivalent, SEQ) and BCDVA were -2.55 (1.45) D and -0.01 (0.06) logMAR, respectively. Ocular dimensions were greater in myopes than in emmetropes (all $P < 0.05$), with no significant differences according to sex. Mean (SD) ocular dimensions were LAL 24.07 (0.91) mm, HW 23.41 (0.82) mm, and VH 23.70 (0.88) mm for myopes, and LAL 22.69 (0.55) mm, HW 22.65 (0.63) mm, and VH 22.94 (0.69) mm for emmetropes. Significant correlations were noted between SEQ and ocular dimensions, with a greater change in LAL (0.46 mm/D, $P < 0.001$) than in VH (0.27 mm/D, $P < 0.001$) and HW (0.22 mm/D, $P = 0.001$).

Conclusions: Myopic eyeballs are larger than those with emmetropia. The eyeball elongates as myopia increases, with the greatest change in LAL, the least in HW, and an intermediate change in VH. These changes manifest in both sexes at a young age and low level of myopia. These data may serve as a reference for monitoring the development of refractive error in young Malaysian children of Chinese origin.

KEYWORDS

myopia, emmetropia, ocular, eye axial length, vertical, horizontal, dimension, children, magnetic resonance image, MRI scan, Malaysia

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INTRODUCTION

Myopia is the most common refractive error worldwide. Its highest prevalence is in East Asian countries such as Singapore, China, and Japan [1-3]. Myopia has received far more attention because of its increasing prevalence in the last few decades. Estimates show that 50% of people worldwide will be myopic by the year 2050, with 10% likely having high myopia, which could accompany serious and potentially blinding ocular diseases such as retinal detachment, macular degeneration, and glaucoma [4-7].

Eyeball shape has received growing attention as a biomarker for myopia. Direct *in vivo* investigations of eyeball shape are now possible with the advancement of magnetic resonance imaging (MRI) and computer software for three-dimensional (3D) modeling. Atchison et al. [8] compared the retinal shapes of emmetropes and myopes and found that both are oblate, although to a lesser degree in myopic eyes. A similar study found that myopic eyes are elongated, but that approximately equal proportions of myopic eyes exclusively fit the global expansion and axial elongation models [9]. Ishii et al. [10] evaluated eye shape changes in children with emmetropia and myopia using MRI and elliptic Fourier descriptors. Their analysis showed that myopia development in children accompanies a transition in shape from oblate to prolate. Lim et al. [11] used MRI to investigate the changes in eye volume, surface area, and shape according to refractive error in young children, and they found axial globe enlargement in myopic eyes, causing a less oblate shape. Non-myopic eyes enlarged globally in length, width, and height.

Few reports on ethnic variations in eye shape are available in the literature. Pope et al. [12] investigated racial variations in the shape of eyeballs with varying degrees of myopia. Their results indicated that with each increment in myopia, eye dimensions increased in all directions such that the increase in length was significantly greater than in width and height. However, race is unlikely to have any systematic effect. Lim et al. [13] evaluated posterior eye shape variations using MRI in a multi-ethnic cohort in Singapore. Their results showed that a less oblate posterior eye shape correlated with myopia. Regarding ethnicity, Chinese individuals had less oblate eyeballs than Malay and Indian individuals, specifically in non-myopic eyes.

Reports involving MRI examination of eyeball sizes and shapes in children are scarce [10, 11]. Such important data provides the earliest information that policymakers use to plan suitable intervention programs. Malaysia has a multi-ethnic population consisting mainly of Malays, Chinese, and Indians. This study focuses on Chinese children, as myopia is more prevalent in the Chinese than in other races [14].

Therefore, we aimed to determine the ocular dimensions in emmetropic and myopic children of Chinese origin living in the Kuala Lumpur, Malaysia using MRI analysis. The association between refractive error and ocular dimensions was also evaluated.

METHODS

Primary school children of Chinese origin, aged less than 10 years and living in the Kuala Lumpur area, were screened to be included in this cross-sectional study. Parents were interviewed at the outset to determine whether the children were descended from two consecutive generations of Chinese parents living in Kuala Lumpur. Following Flintcroft et al., myopia was classified as a spherical equivalent (SEQ) of equal or more than -0.5 D, and emmetropia was classified as SEQ less than -0.5 D [15, 16]. The other inclusion criteria were 1) astigmatism of less than or equal to 1.50 D, 2) best-corrected distance visual acuity (BCDVA) of 0.00 logarithm of the minimum angle of resolution (logMAR) in each eye, 3) birth weight ≥ 2000 g, 4) no history of ocular or systemic diseases, myopia treatment, or contact lens use. We excluded individuals for whom MRI was contraindicated, including those with metallic implants, braces, pacemakers, and claustrophobia. The study received ethical approval from the Universiti Kebangsaan Malaysia (UKM) research ethics committee and followed the tenets of the Declaration of Helsinki. After briefing the parents and participants on the study measures and nature of the procedures, written informed consent was obtained from the parents or legal guardians of the included children.

BCDVA was determined using a logMAR chart (Precision Vision, Illinois, USA). Cycloplegic refraction was conducted using an open-field autorefractor (Grand Seiko WAM-5100, Hiroshima, Japan) and subjective refinement. Following instillation of two drops of 1% cyclopentolate (Cyclogyl, Alcon, TX, USA), and with a pupil diameter > 5 mm, refraction was conducted. Detailed anterior and posterior segments examination was performed using a slit lamp biomicroscope (Righton MW50D LED, Tokyo, Japan).

For MRI acquisition and segmentation, an experienced pediatric radiologist and radiographer performed all measurements at the Radiology Department, Hospital Canselor Tuanku Muhriz, Kuala Lumpur, using a whole-body MRI scanner (3-Tesla Trio; Siemens, Erlangen, Germany). Parameters for the T2-weighted scan were: 176 sagittal slices with 516 pixels × 512 matrices of 1-mm thickness without gaps (250 mm × 250 mm field of view [FOV], echo time [TE] = 409 ms, repetition time [TR] = 3200 ms, and flip angle [FA] = 120°); 60 axial slices with 381 pixels × 384 matrices of 0.8-mm thickness without gaps (199 mm × 199 mm FOV, TE = 132 ms, TR = 1270 ms, and FA = 120°). To reduce motion artifact during the fast image acquisition, children were instructed to maintain a supine position with eyes closed. They were given earplugs and headphones to reduce noise throughout the procedure.

Using a commercially available graphics program [17], the cross-sectional image of the eye was displayed at 50 × magnification on a computer screen, and the contrast was adjusted to clearly define the edges of interest. Left and right eye segmentation (Figure 1) was implemented based on the level set segmentation method [18, 19], which is a nonparametric version of image segmentation techniques that steer an initially defined curve/rectangle to the boundaries of the intended object according to the edge/region information. Detailed methods of MRI acquisition and segmentation are described elsewhere [20]. Based on the results of the segmentation technique, the pertinent lines used to analyze the eyeball shape (length and width) were automatically measured. However, the height of the eyeball was measured from the sagittal view.

Three ocular dimensions from the MRI images were evaluated: longitudinal axial length (LAL), vertical height (VH), and horizontal width (HW), as shown in Figure 2. LAL was measured on the axial image, HW was measured retina-to-retina across the center of the axial length at the widest point, and VH was measured on the sagittal section of the eyeball.

To validate the MRI measurements, Pearson's correlation analysis was conducted between LAL measurements taken from the same participant using MRI and ultrasound A-scan (PacScan Plus; Sonomed Escalon, New Hyde Park, NY, USA). The analysis revealed that the measurements were similar and had a highly positive and significant correlation ($r = +0.95$; $P < 0.001$).

The data were collected and analyzed using IBM SPSS Statistics for Windows, version 21.0 (IBM Corp., Armonk, NY, USA). The right eye data were used for analyses. Normality of data distribution was determined using the Shapiro–Wilk test. Participant demographics are presented using descriptive statistics. Student's *t*-test

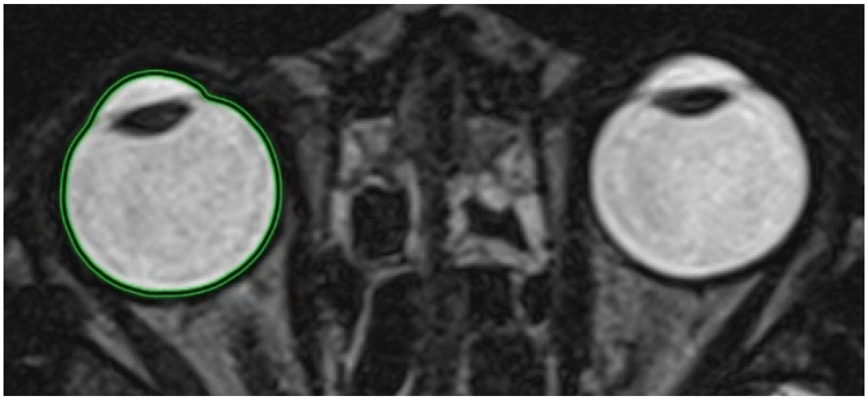

Figure 1. The green pertinent line was used to analyze the shape of the right eyeball.

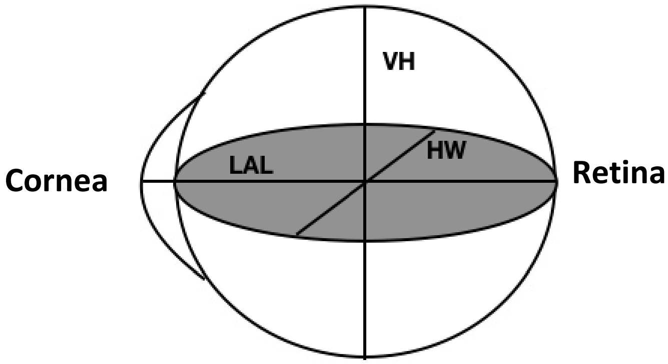

Figure 2. Schematic diagram of ocular dimensions, namely longitudinal axial length (LAL), vertical height (VH), and horizontal width (HW), which were measured using magnetic resonance imaging analysis.

Table 1. Comparison of participants in the emmetropia and myopia groups

Variables	Emmetrope (n = 10)	Myope (n = 60)	P-value
Age (y), Mean ± SD	8.04 ± 0.02	8.07 ± 0.03	0.063
Height (cm), Mean ± SD	122.61 ± 5.10	125.5 ± 7.80	0.145
Body weight (kg), Mean ± SD	27.92 ± 3.70	26.70 ± 6.01	0.544
SEQ (D), Mean ± SD	+0.05 ± 0.16	- 2.97 ± 1.08	**< 0.001**
BCDVA (logMAR), Mean ± SD	0.00 ± 0.02	- 0.01 ± 0.07	0.316
LAL (mm), Mean ± SD	22.69 ± 0.55	24.07 ± 0.91	**< 0.001**
HW (mm), Mean ± SD	22.65 ± 0.63	23.41 ± 0.82	**0.006**
VH (mm), Mean ± SD	22.94 ± 0.69	23.70 ± 0.88	**0.012**

Abbreviations: n, number; y, years; SD, standard deviation; cm, centimeter; kg, kilogram; SEQ, spherical equivalent of refractive error in cycloplegic refraction; D, diopters; BCDVA, best-corrected distance visual acuity; logMAR, logarithm of the minimum angle of resolution; LAL, longitudinal axial length; mm, millimeter; HW, horizontal width; VH, vertical height. *P*-values < 0.05 are shown in bold. Note: All reported data are from the right eye. Emmetrope, SEQ less than -0.5 D; Myope, SEQ equal or more than -0.5 D.

Table 2. Comparison of participants in the emmetropia, low myopia, and moderate myopia groups

Parameters	Emmetrope (n = 10)	Low Myope (n = 30)	Moderate Myope (n = 30)	P-value
Age (y), Mean ± SD	8.04 ± 0.02	8.02 ± 0.01	8.01 ± 0.03	0.089
Height (cm), Mean ± SD	122.61 ± 5.10	123.65 ± 4.30	122.76 ± 5.20	0.543
BW (kg), Mean ± SD	27.92 ± 3.70	26.92 ± 4.70	27.72 ± 2.70	0.654
SEQ (D), Mean ± SD	+ 0.05 ± 0.16	- 2.03 ± 0.58	- 3.92 ± 0.45	**0.003**
BCDVA (logMAR), Mean ± SD	0.00 ± 0.02	- 0.01 ± 0.05	- 0.01 ± 0.04	0.452
LAL (mm), Mean ± SD	22.69 ± 0.55	23.60 ± 0.81	24.55 ± 0.75	**< 0.001**
HW (mm), Mean ± SD	22.65 ± 0.63	23.20 ± 0.80	23.63 ± 0.81	**0.003**
VH (mm), Mean ± SD	22.94 ± 0.69	23.44 ± 0.72	23.95 ± 0.95	**0.002**

Abbreviations: n, number; y, years; SD, standard deviation; cm, centimeter; kg, kilogram; SEQ, spherical equivalent of refractive error in cycloplegic refraction; D, diopters; BCDVA, best-corrected distance visual acuity; logMAR, logarithm of the minimum angle of resolution; LAL, longitudinal axial length; mm, millimeter; HW, horizontal width; VH, vertical height. Note: All the reported data were from the right eye only. *P*-values < 0.05 are shown in bold. Note: Emmetrope, SEQ less than -0.5 D; Low myopia, SEQ equal or more than -0.5 D and less than -3.00 D; Moderate myopia, SEQ equal to or more than -3.00 D and less than -5.00 D.

and one-way analysis of variance (ANOVA) was used to compare ocular dimensions between groups. Pearson's correlation analysis was used to determine the associations between ocular dimensions and refractive error. A P-value < 0.05 was deemed statistically significant.

RESULTS

A total of 70 Chinese children (35 male, 35 female) participated in this study. The mean (standard deviation [SD]) age was 8.38 (0.49) years (range: 8–9 years). Mean (SD) SEQ and BCDVA were -2.55 (1.45) D (range: +0.50 to -4.50 D) and -0.01 (0.06) logMAR, respectively. Mean (SD) height was 125.12 (7.53) cm and mean (SD) body weight was 26.82 (5.72) kg. The mean (SD) ocular dimensions for all participants were as follows: LAL, 23.88 (0.99) mm; HW, 23.30 (0.84) mm; and VH, 23.59 (0.89) mm.

We allocated participants to one of two groups according to the degree of refraction: *emmetropes* (SEQ less than -0.5 D) and *myopes* (SEQ equal or more than -0.5 D). Comparing the two groups, the mean LAL, HW, and VH were significantly greater in the myopic group (all P < 0.05) (Table 1). Regarding eyeball shape, the analysis revealed no significant differences in LAL, HW, and VH measurements in emmetropic eyeballs (P > 0.05), indicating an oblate shape. However, in myopic eyeballs, the LAL was significantly greater (P < 0.05) than HW or VH, implying a more prolate shape.

For further analysis, the participants with myopia were allocated to one of two groups: *low myopia* (SEQ equal or more than -0.5 D and less than -3.00 D) and *moderate myopia* (SEQ equal to or more than -3.00 D and less than -5.00 D) [16]. As shown in Table 2, mean ocular dimensions significantly differed between the three subgroups (all P < 0.05), with greater values in the moderate myopia subgroup and lesser values in the emmetropia subgroup (Table 2).

The association between ocular dimensions and SEQ was analyzed using Pearson's correlation. Significant negative correlations were noted between all ocular dimensions and SEQ (LAL: r = - 0.676, $P < 0.001$; HW: r = - 0.388, $P = 0.001$; and VH: r = - 0.433, $P < 0.001$). For every 1-D change in SEQ, increments of 0.46 mm in LAL ($P < 0.001$), 0.22 mm in HW ($P = 0.001$), and 0.27 mm in VH ($P < 0.001$) were observed.

DISCUSSION

In this study of children of Chinese origin, we found a significant difference in ocular dimensions between those with emmetropia and those with myopia. Our results indicate that axial elongation manifests as the eye changes from emmetropic to myopic. Significant correlations were noted between SEQ and ocular dimensions, with a greater change in LAL than in VH and HW. In myopic eyes, the eyeball was larger and asymmetrically longer, rendering a prolate shape. These changes manifested in both sexes at a young age and a low level of myopia.

Eyeball shape has recently been associated with myopia [21], and MRI is the best tool to determine the 3D characteristics of the eyeball [8]. A few ocular MRI studies are available in the literature; however, data from the pediatric population are scarce for obvious logistic reasons [11]. To the best of our knowledge, this study is the first to evaluate the ocular dimensions of Malaysian children of Chinese origin using MRI analysis. Overall, the results showed that the eyeballs of myopes were larger than those of emmetropes. The ocular dimensions in emmetropic eyeballs indicated a more oblate shape, whereas those in myopic eyeballs implied a prolate shape (LAL > VH > HW). As myopia increased, all ocular dimensions became greater, with the highest increment in LAL, the least in HW, and an intermediate increment in VH. These changes were noted in both sexes at a young age and a low level of myopia.

Atchison et al. [8] examined ocular dimensions of 88 emmetropes and myopes aged 18–36 years using MRI. They considered three possible theories of eyeball enlargement in myopia to explain their results: the *global expansion model* (proportionate increases in all three ocular dimensions), the *equatorial elongation model* (expansion in length but not in width or height), and the *posterior polar elongation model* (expansion in the most posterior part of the eyeball). Based on the ocular height and length measurements, 25% of the myopic individuals exclusively fit the global expansion model and 29% exclusively fit the equatorial elongation model. However, based on width and length dimensions, 17% and 39% of myopic eyes exclusively fit the global expansion and axial elongation models, respectively. The authors concluded that despite considerable individual variations in eyeball shapes, myopic eyes tend to be greater in all dimensions than emmetropic eyes, with more elongation in the axial dimension than the vertical, and much less elongation in the horizontal dimension [8]. In another adult study [9] comparing the shape of the retinal surface in 66 myopes to that of 21 emmetropes, most emmetropic eyeballs were oblate, having proportionally lesser axial dimensions compared with the vertical and horizontal dimensions. The present study demonstrated similar findings, in that longer measurements were found in VH than in LAL or HW in emmetropic eyeballs, indicating a more oblate shape. However, with increasing myopia, ocular dimensions became greater, but with different proportions of elongation. Our results showed that as the degree of myopia increases, LAL elongates the most, then VH and HW (LAL > VH > HW), creating a prolate shape. This is possible because the sides of the eyeball are closer to the orbital wall than the posterior part [22]. With each myopia increment, ocular dimensions increase, with axial elongation increasing more than the vertical or horizontal, signifying a decreasingly oblate profile.

Nevertheless, Lim et al. [11] found no correlation between refractive error and height of the eyeball. They evaluated 3D changes in the eyeball shapes of Singaporean Chinese boys with mean (SD) age of 77.9 (3.9) months (134 eyes from 67 participants) in the population-based Strabismus, Amblyopia, and Refractive Error study. They found that refractive error is correlated with axial length and width of the eyeball, but not eyeball height, with a greater change in length than height per diopter of SEQ.

Our results also demonstrated that changes in eyeball dimensions occurred at a young age, implying that eyeball size and shape at birth may influence eyeball growth, yet should be verified by future longitudinal studies. Lim et al. [23] investigated whether eyeball size and shape at birth are associated with its shape and refractive error 3 years later. They found that eyeball shape and size influence subsequent eye growth, but not development of refractive error. Ishii et al. [10] analyzed eyeball shape using MRI and elliptic Fourier descriptors in children (age 1–19 years). A significant correlation was found between an oblate-to-prolate change and refractive error in children aged ≥ 7 years. The authors hypothesized that the change in eyeball shape is more prominent after completing emmetropization at around 6 years of age. The results of the present study concur with this hypothesis, as changes in eyeball dimensions were observed in children aged approximately 8 years and with a low level of myopia. In a later study [24] on the relationship between variations in crystalline lens shape and axial length increase in children aged 1 month to 6 years, Ishii et al. found that crystalline lens shape changes dramatically during ocular development, and that axial length increase is linked to the entire contour of the crystalline lens as part of the emmetropization process. Therefore, it is possible that changes in the eyeball shape with refractive error are more noticeable after the process completes.

This study included well-adjusted young Chinese children who cooperated well during MRI scans. Obtaining MRI scans in young children is difficult; however, we managed to obtain their full cooperation with the help of their parents and experienced investigators. We are aware that there were fewer participants with emmetropia than with myopia, which may cause bias in the analysis. It was more difficult to enroll emmetropic children in this study because of the high prevalence of myopia among Chinese school children. However, our analysis and results were consistent with those of previous investigations. Notwithstanding, our study is limited by a small sample size, a lack of prospective longitudinal follow-up, and the exclusion of other Malaysian ethnicities. Longitudinal MRI studies, with larger sample sizes and more ethnically diverse participants, are needed to determine the impact of eyeball shapes and sizes on the development of refractive error in young children of differing ages and racial backgrounds.

CONCLUSIONS

Myopic eyeballs are larger and longer than emmetropic eyeballs in children of Chinese ethnicity. As myopia increases, the eyeball becomes larger and asymmetrically longer, rendering a more prolate shape. These changes manifest in both sexes at a young age and a low level of myopia. The data presented here represent the first reported measurements of ocular dimensions in young Malaysian children of Chinese origin using 3D MRI. Thus, further studies are necessary to understand the relationship of eyeball shapes and sizes with the development of refractive error in young children.

ETHICAL DECLARATION

Ethical approval: The study received ethical approval from the UKM research ethics committee and followed the tenets of the Declaration of Helsinki. After briefing the parents and participants on the study measures and nature of the procedures, written informed consent was obtained from the parents or legal guardians of the included children.
Conflict of interests: None.

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