# Eye Shape in Emmetropia and Myopia

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**Purposes.** To determine axial, vertical, and horizontal eye dimensions in myopic and emmetropic eyes by using magnetic resonance imaging (MRI) and to relate these to different ocular expansion models of myopia development.

**Methods.** The internal length (cornea to retina), height and width (both retina to retina) were measured in emmetropic and myopic eyes (up to −12 D) of 88 participants aged 18 to 36 years. Participants were positioned supine in a clinical MRI scanner. The fixation target was imaged straight ahead of the subject by an overhead 45° inclined mirror. Eye images were acquired with a 7.5-cm receive-only radio frequency surface coil. Axial (horizontal through middle of eye) and sagittal (vertical through visual axis) sections were taken with a $T_1$-weighted fast spin-echo sequence.

**Results.** With an increase in myopic refractive correction, myopic eyes became much larger in all three dimensions, but more so in length (0.35 mm/D, 95% confidence interval [CI] 0.28–0.40) than in height (0.19 mm/D, 95% CI 0.09–0.29) and more so in height than in width (0.10 mm/D, 95% CI 0.01–0.20). Based on height and length dimensions, 25% and 29% of myopic eyes exclusively fitted global expansion and axial elongation models, respectively. Based on width and length dimensions, 17% and 39% of myopic eyes exclusively fitted the global expansion and axial elongation models, respectively.

**Conclusions.** Although there are considerable individual variations, in general myopic eyes are elongated relative to emmetropic eyes, more in length than in height and even less in width. Approximately a quarter of the myopic participants fitted each of the global expansion or axial elongation model exclusively. The small proportions are due primarily to the large variability in the dimensions of emmetropic eyes. (*Invest Ophthalmol Vis Sci.* 2004;45:3380–3386) DOI:10.1167/iovs.04-0292

Many people need spectacles or other ophthalmic corrections because the optical elements of their eyes are different from those of emmetropic (normal sighted) eyes. Myopic eyes usually have longer vitreous chambers than do emmetropic eyes,[1–3] although the reason is still not understood. Many measurements of eye size have been made along the axial direction (optical axis and visual axis) with ultrasonography and partial coherence interferometry, but few measurements have been made along other directions.

There is evidence to suggest that the retinal location where the ocular expansion occurs and produces the longer vitreous chambers varies between individuals—that is, there may be different types of myopia in terms of retinal region affected. Some suggested changes to the structure of the eye, which can result in myopia, include equatorial stretching in which axial elongation occurs because of stretching in the periphery parallel to the visual axis,[4] posterior pole elongation,[5] and global expansion of the vitreous chamber[4] (Fig. 1). Myopes may thus be classified according to where the myopic changes occur: equatorial (peripheral) stretching, posterior pole (central) elongation, or global expansion (both central and peripheral). As both equatorial stretching and posterior pole elongation cause axial elongation, these classifications can be combined together as axial elongation.

There is a limited number of published studies investigating ocular shape. Deller et al.[6] used an x-ray technique involving subjective responses from participants to determine lengths, heights (retina to retina), and widths (retina to retina) of eyes. For most emmetropic eyes, these dimensions were similar, but lengths increased at approximately twice the rate of increases in height and width as myopia increased. Vohra and Good[7] measured axial lengths and widths with B-scan echography in both eyes of 50 patients. Eyes were categorized by axial length rather than refractive error, but as 60% of eyes had lengths greater than 27 mm, it can be concluded that most were highly myopic. Lengths increased at more than three times the rate of increases in width. These results suggest that expansion of highly myopic eyes may be predominantly axial rather than global, at least for comparison in the horizontal meridian. Zhou et al.[8] measured the transverse axial (horizontal) plane using computerized x-ray tomography, finding that emmetropic eyes usually have similar lengths and widths, but that myopic eyes are greater in length than in width and that the dimension differences increases quickly with increase in myopia.

Magnetic resonance imaging (MRI) has been used in more recent studies. A small MRI study of eight hypermetropes, six emmetropes, and seven myopes found a variety of different three-dimensional eye shapes in myopic eyes.[9] Chau et al.[10] explored the relationship between eye and orbital volumes, but found no relationship between the volume of the orbit and either the volume or axial length of the eye. A larger scale MRI study ($n = 89$) measuring transverse axial sections found that lengths of eyes were generally greater than widths and that the differences were greater in myopes than in emmetropes and hypermetropes (Miller JM, et al. *IOVS* 2004;45:ARVO E-Abstract 2388), whereas a smaller scale MRI study found that myopic eyes were more prolate in shape than emmetropic eyes in the transverse axial section.[11]

MRI is ideal to investigate ocular dimensions because it facilitates three-dimensional measurements. We report a large-scale MRI study investigating the three-dimensional shapes of emmetropic and myopic eyes.

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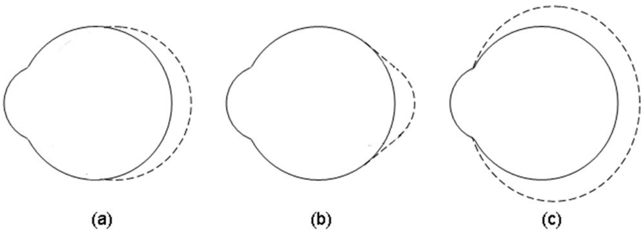


**FIGURE 1.** Models of myopia: (**a**) equatorial stretching, (**b**) posterior pole elongation, and (**c**) global expansion.

## METHODS

The research adhered to the tenets of the Declaration of Helsinki and was approved by both the Queensland University of Technology (QUT) University Human Research Ethics Committee and Prince Charles Hospital Human Research Ethics Committee. Informed consent was obtained from all participants. They were all in good general and ocular health, with corrected visual acuity of 6/6 or better in the tested eye. They consisted of 22 emmetropes (best sphere corrections −0.50 to +0.75D) and 66 myopes to −12.00 D, aged between 18 and 36 years, with small amounts of astigmatism (≤0.75 D) except for five participants (astigmatism 1.00–2.00 D). There were 53 females and 35 males. Eighty-four percent (74/88) and 16% (14/88) of participants were white and Asian, respectively. Right eyes were used, unless they were outside refraction or acuity criteria. Contralateral eyes were occluded during MRI.

MRI was performed on a 1.5-T clinical system (Signa Twin Speed; GE Medical Systems, Milwaukee, WI) with a 7.5-cm receive-only surface coil positioned over the eye. To ensure minimum eye movement during imaging, participants were scanned while lying supine and looking vertically upward at the image of a 5-mm diameter light emitting diode (LED) reflected in a mirror mounted at an angle 45° to the horizontal inside the bore of the magnet. The LED was placed approximately 6 m in front of the magnet along the axis of the magnet tunnel and patient table. Each subject was advised to restrict blinking while keeping the eye as still as possible and focused on the LED (46% of eyes wore a best sphere contact lens). A series of scout scans were obtained and examined to check that the subject was looking vertically upward. Failing this, the mirror was adjusted and scout images rescanned. Sagittal and axial images containing the line of sight, were acquired using a fast spin-echo (FSE) sequence with the following imaging parameters: receiver bandwidth of ±15 kHz, slice thickness 3 mm, field of view 80 mm$^2$, pulse flip angle 90°, repetition time (TR) 400 ms, echo time (TE) 16.9 ms, echo train length 4, four averages, acquisition matrix 320 × 320 (interpolated with zero-filling to 512 × 512). Acquisition time was 130 seconds. Sagittal FSE images were acquired with fat suppression to minimize chemical shift artifact in the inferior region of the sclera.

Before the study, tests were performed to determine the extent to which image artifacts arising from the proximity of air in the sinuses, might generate spatial distortion of the images. The significant magnetic susceptibility difference between air and soft tissue is known to result in significant image distortion in MRI.[12] Images were obtained of a phantom constructed from a 12-cm diameter Perspex cylinder filled with 0.7 mM $CuSO_4$ solution to simulate the head, enclosing a 1.9-cm precision diameter glass tube, also filled with 0.7 mM $CuSO_4$ (simulating the orbit), with a piece of bubble wrap tethered approximately 1 cm from the glass test tube to simulate air in the sinuses. In spin-echo images acquired with bandwidths between ±13.9 and ±62.5 kHz, no distortion in the apparent shape or position of the glass tube was detected. We concluded that differences in magnetic susceptibility between the sinus and surrounding tissue did not significantly affect the orbit region in our study.

Measures of ocular dimensions were made from the axial and sagittal images at approximately 50× magnification on a computer monitor with a standard resolution (1024 × 768 pixels). Using a graphic device interface program written using a commercial application programming interface (WIN32; Microsoft, Redmond, WA), the DICOM (Digital Imaging and Communications in Medicine) image of the cross section through the eye was displayed and contrast adjusted until the edges of interest were most clearly defined. Distances were measured with a line caliper, and the distance between the two points in pixels was converted to the distance in millimeters (using the resolution of the original DICOM image and its magnification on screen).

For both the axial and sagittal sections of the eye, eye length was recorded as the distance between the anterior cornea and the approximate location of the fovea along the line that bisected the eye in the axial plane (Fig. 2). Eye length dimensions reported are those measured from the axial image (unless otherwise stated). Eye width was measured retina to retina across the axial image at the point that visually appeared the widest (Figs. 2b, 2d). Eye height (retina to retina) was measured from the image through the sagittal section of the eye (Figs. 2a, 2c).

Measurements were made to two decimal places and averages were taken of three measures of each dimensional parameter (eye length, height, and width). The mean standard deviation of the three repeated measures of each parameter from one scan was approximately 0.1 mm. To investigate differences between two different scans (images) of the same section, we examined three repeated measures of alternate images from five participants. The mean difference between images was approximately 0.3 mm for eye length, height, and width. To investigate observer repeatability, differences (of another five participants) in eye length, height, and width were compared in the two observers. The mean difference between observers was approximately 0.2 mm. From these data, we concluded our measures were accurate to approximately 0.3 mm, as this was the maximum amount of error we observed (i.e., between image repeatability). For 83 of the 88 participants, axial

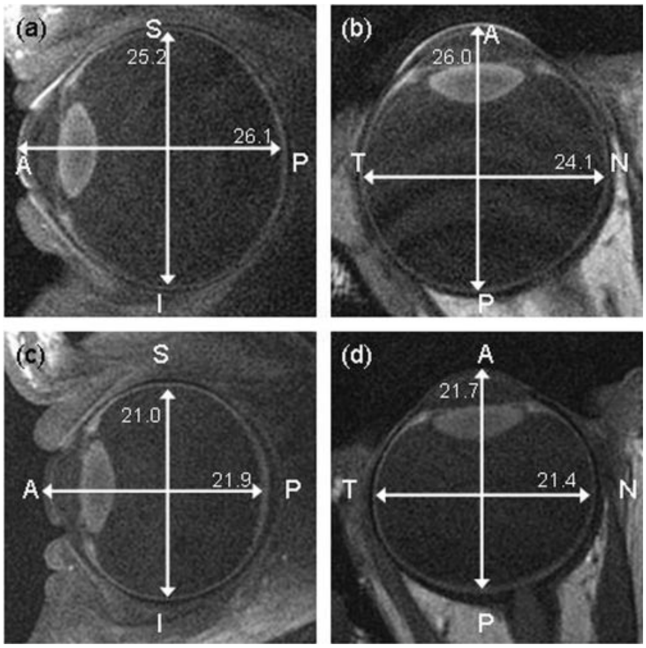


**FIGURE 2.** MRI slices of typical emmetropic and myopic eyes. The *top* images are those of a myopic eye (best sphere correction, −7.63 D) of a male participant (**a**, **b**) and the *lower* images of an emmetropic eye (best sphere correction, −0.13 D) of a female participant (**c**, **d**). Scans were taken in the sagittal plane (**a**, **c**) and through the axial section (**b**, **d**) of the eye. Length measures (millimeters) were taken from both the axial and sagittal sections, height from the sagittal image, and width from the axial image. In this example the greater length, height, and width of the myopic eye are easily observed. A, anterior; P, posterior; N, nasal; T, temporal; S, superior; I, inferior.

**TABLE 1.** Ocular Dimensions Measured from Axial and Sagittal MRI Sections in Various Refractive Error Groups

| Ref. Corr. Group | Best Sphere Correction (D) | Length (Axial Image) | Height | Width | Length (Sagittal Image) | Length (Ultrasonography) |
|---|---|---|---|---|---|---|
| 0 | +0.75 to −0.50 | 23.0 ± 0.7 | 22.4 ± 1.0 | 22.7 ± 0.9 | 23.1 ± 0.8 | 23.3 ± 0.7 |
| | | 21.4–24.3 | 20.4–24.0 | 20.6–24.6 | 21.6–24.3 | 21.8–24.2 |
| | | 22 | 21 | 22 | 21 | 18 |
| 1 | −0.61 to −1.50 | 23.8 ± 0.8 | 23.3 ± 0.9 | 23.0 ± 1.1 | 23.9 ± 0.6 | 24.0 ± 0.7 |
| | | 22.6–25.4 | 22.1–25.1 | 21.1–24.6 | 22.6–25.5 | 23.0–25.6 |
| | | 18 | 18 | 18 | 19 | 18 |
| 2 | −1.61 to −2.50 | 24.5 ± 0.6 | 23.5 ± 1.1 | 23.4 ± 1.0 | 24.6 ± 0.7 | 24.6 ± 0.7 |
| | | 23.6–25.6 | 21.8–25.1 | 21.5–25.1 | 23.6–25.7 | 23.5–25.5 |
| | | 12 | 11 | 11 | 12 | 12 |
| 3 | −2.61 to −3.50 | 24.6 ± 0.5 | 23.2 ± 0.6 | 23.1 ± 0.8 | 24.7 ± 0.4 | 24.7 ± 0.5 |
| | | 24.1–25.5 | 22.3–24.2 | 21.2–24.0 | 24.2–25.6 | 23.8–25.4 |
| | | 11 | 10 | 11 | 11 | 11 |
| 4 | −3.61 to −4.50 | 24.6 ± 0.5 | 23.4 ± 1.0 | 22.9 ± 0.5 | 24.8 ± 0.5 | 24.9 ± 0.5 |
| | | 24.0–25.1 | 22.0–24.4 | 21.9–23.6 | 24.2–25.1 | 24.3–25.4 |
| | | 7 | 6 | 7 | 6 | 7 |
| 5 | −4.61 to −5.50 | 24.5 ± 1.5 | 23.4 ± 1.4 | 22.9 ± 1.7 | 24.8 ± 1.4 | 24.8 ± 1.5 |
| | | 22.1–26.2 | 21.1–25.3 | 20.8–25.5 | 22.4–26.3 | 22.3–26.4 |
| | | 6 | 6 | 6 | 6 | 6 |
| 6 | −5.61 to −6.50 | 25.7 ± 1.0 | 23.8 ± 0.5 | 23.5 ± 1.5 | 25.4 ± 0.6 | 25.7 ± 0.9 |
| | | 24.6–27.3 | 22.9–24.3 | 22.2–26.1 | 24.9–26.4 | 24.9–27.1 |
| | | 6 | 5 | 6 | 5 | 6 |
| 7 | −6.61 to −12.00 | 26.1 ± 0.5 | 24.2 ± 1.6 | 23.9 ± 0.5 | 26.3 ± 0.5 | 26.4 ± 0.6 |
| | | 25.3–26.6 | 22.4–25.9 | 23.3–24.5 | 25.7–27.0 | 25.5–27.1 |
| | | 5 | 4 | 4 | 4 | 5 |

Mean ± standard deviation (mm), range (mm), and number of cases are presented for each refractive error group. Ref. Corr., refractive correction.

length measurements were also made by A-scan ultrasonography (Echograph Axis-II; Quantel Medical, Clermont-Ferrand, France) for comparison to the MRI data. The means of 10 measures were recorded.

Measurements of the eye dimensions of length, height, and width were recorded in mm and are expressed as the mean ± standard deviation, unless stated otherwise. A subjective refraction was performed on each participant. Regression was performed to determine the relationships between eye dimensions and best sphere correction. Refractive correction groups in 1-D steps up to −6.50 D were also used to describe the population, with the five participants with higher refractive corrections (−7.25 to −12.00 D) combined into one group. Paired *t*-tests were used to compare eye dimensions within the same subjects and to compare axial length dimensions measured using different techniques. ANOVA was used to make comparisons between refractive correction groups. Probabilities <0.05 were considered to be statistically significant.

# RESULTS

## Emmetropic and Myopic Eye Dimensions

Myopic eyes were longer in the axial, vertical, and horizontal meridians (i.e., length, height, and width, respectively) than emmetropic eyes. The measured ocular dimensions for emmetropes and myopes based on severity are reported in Table 1. On average, emmetropic eyes ($n = 22$) were 23.0 mm long, 22.4 mm high, and 22.7 mm wide. Myopic eyes ranged from 22.1 (−4.63D) to 27.3 (−6.00 D) mm long, 21.1 (−4.63 D) to 25.9 (−7.50 D) mm high, and 20.8 (−4.63 D) to 26.1 (−6.38 D) mm wide. Some asymmetry (i.e., in the appearance of eye shape) was noted in most eyes, and a small number of eyes showed very steep retinal boundaries particularly on the nasal side.

For comparison purposes, sagittal and axial sections of a −7.63 D eye of a male participant and an emmetropic eye of a female participant are shown in Figure 2. The male myopic eye clearly had greater length, height, and width than the female emmetropic eye. Eyes of male emmetropes and myopes were on average 0.7 ± 0.3 and 0.6 ± 0.3 (mean ± SE) mm longer than eyes of female emmetropes and myopes, respectively (independent *t*-test emmetropes, $P = 0.013$ and myopes, $P = 0.031$). In the vertical and horizontal meridians, similar results were observed. Eyes of emmetropic and myopic males were 1.0 ± 0.4 and 0.7 ± 0.3 mm greater vertically and 0.8 ± 0.4 and 0.7 ± 0.3 mm greater horizontally than eyes of emmetropic and myopic females, respectively ($P < 0.05$). The differences between male and female eyes for all three dimensions measured were not dependent on refractive error group (two-factor ANOVA, $P = 0.738$, $P = 0.096$, $P = 0.242$ for length, height, and width, respectively).

All three measured ocular dimensions (i.e., length, height, and width) correlated significantly with best sphere correction (Fig. 3), so that the greater the myopic refractive correction the greater the dimension. In terms of millimeter increase in size per diopter of myopia, the change was greatest for length (0.35 mm/D, 95% confidence interval [CI] 0.28–0.42), than for height (0.19 mm/D, 95% CI 0.09–0.29) and least for width (0.10 mm/D, 95% CI 0.01–0.20).

The heights and widths of emmetropic eyes were not significantly different ($P = 0.125$); however, lengths of emmetropic eyes were greater than the heights and widths ($P = 0.001$ and 0.009, respectively). Similarly, myopic eyes had significantly greater length than height and width ($P < 0.001$). Unlike emmetropic eyes, myopic eyes had significantly greater height and width ($P = 0.011$). Differences between lengths and heights, between lengths and widths, and between heights and widths were also compared as a function of best sphere correction. The regression slopes were all significant (lengths minus heights $P < 0.001$, lengths minus widths $P < 0.001$, and heights minus widths $P = 0.04$, respectively). The slope of length minus widths was approximately 40% greater than that of the slope of lengths minus heights (Fig. 4).

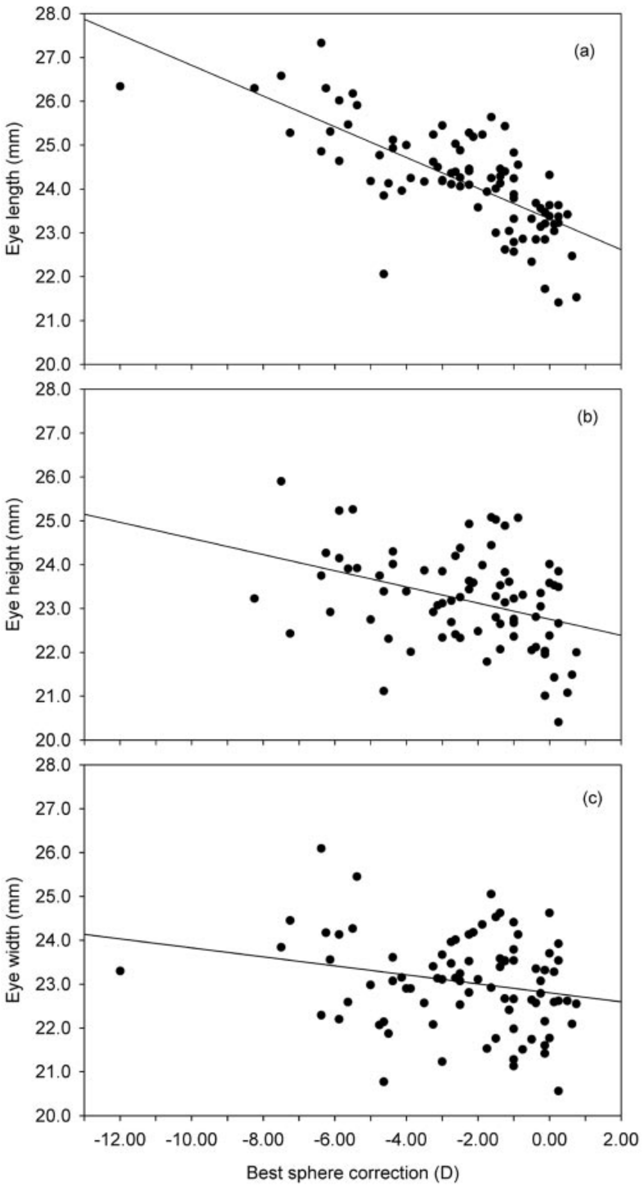


**FIGURE 3.** Dimensions of eyes as a function of the best sphere correction. Linear regression fits are shown for (**a**) length ($y = -0.35x + 23.31$, $R^2 = 0.53$, $n = 87$, $P < 0.001$), (**b**) height ($y = -0.19x + 22.74$, $R^2 = 0.15$, $n = 81$, $P < 0.001$), and (**c**) width ($y = -0.10x + 22.80$, $R^2 = 0.05$, $n = 85$, $P = 0.032$). The number of datapoints varies in (**a**), (**b**) & (**c**) because data could not be obtained from a few images. Regression fits change only slightly if results for common participants only ($n = 79$) are plotted.

## Axial Elongation versus Global Expansion Models

We investigated how well our data fit models of myopic growth. For this purpose, the myopes were grouped by refractive correction (Table 1). It is not possible to distinguish between the equatorial stretching and posterior pole elongation models (Fig. 1) on the basis of the dimensions, because this would require a more sophisticated analysis of the curvature of the posterior retina, and so we combined these two models as an axial elongation model.

The global expansion model predicts that the dimensions of length, height, and width of myopic eyes maintain the same relationships as those of emmetropic eyes (i.e., eyes expand similarly in all directions). We first determined the differences between the length and each of the height and width within which 90% of our emmetropic eyes fitted (length minus height: −0.47 to +1.61 mm; length minus width: −0.30 to +1.32 mm). We then determined the proportion of participants in each myopic group that fitted within these emmetropic difference limits.

The axial elongation model predicts that the lengths of myopic eyes, but not the heights and widths, increase. We first determined the height and width limits within which 90% of our emmetropes fitted (height, 21.0–23.9 mm; width, 21.4–23.9 mm). We then determined, for both height and width, the proportion of eyes in each myopic group that fitted within these emmetropic limits.

Figure 5 shows the proportion of eyes in each refractive error group that fitted each ocular expansion model exclusively, fitted both models, or fitted neither model. Figure 5a shows this comparison based on height, and Figure 5b shows it for the width. Based on height data, 30% and 26% of myopes exclusively fitted the global expansion and axial elongation models, respectively. Based on width data, more myopes exclusively fitted the axial elongation model (47%) than fitted the global expansion model (18%). Based on height data, with increasing levels of myopia, the trend is for increasing proportions of eyes to fit each model exclusively (Fig. 5a). Based on width, the proportion of eyes fitting the global expansion model do not vary much with refractive error group, but the proportions of eyes fitting the axial elongation model tended to increase as myopia increased (Fig. 5b).

## Axial Length Measured from Different MRI Sectional Images and Ultrasonography

Eye lengths from the axial images were compared to the lengths measured from the sagittal images, as well as to those measured by ultrasonography (Table 1). The lengths of the eyes were 0.1 ± 0.3 mm (range, −0.9 to +1.1) greater using sagittal images, and 0.2 ± 0.3 mm (range, −1.5 to +0.4) greater using ultrasonography than using the axial images. Although the differences between lengths measured using axial images and sagittal images, or ultrasonography were significant (paired *t*-tests, $P = 0.001$ and $P < 0.001$, respectively), the differences in both instances were smaller than the accuracy of the MRI measurement technique (0.3 mm) as described

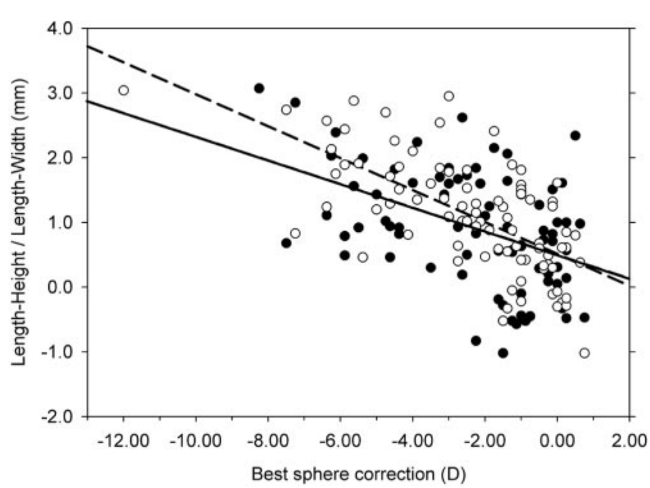


**FIGURE 4.** Differences between lengths and heights (●) and between lengths and widths (○) of eyes as a function of best sphere correction. Linear regression fits are shown for length minus height ($y = -0.17x + 0.52$, $R^2 = 0.19$, $n = 80$, $P < 0.001$) and length minus width ($y = -0.24x + 0.51$, $R^2 = 0.44$, $n = 85$, $P < 0.001$) by the *solid* and *dashed lines*, respectively.

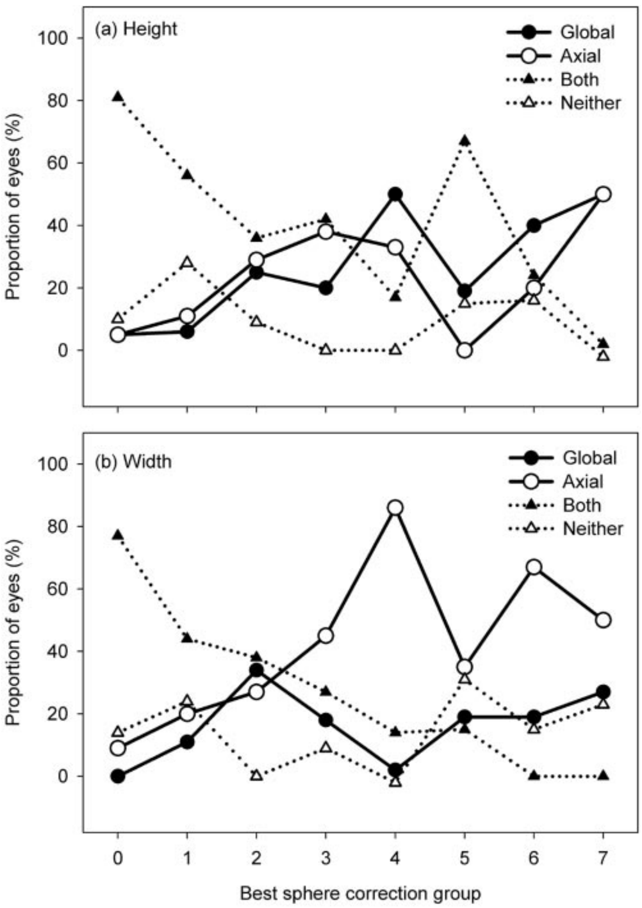


**FIGURE 5.** Proportion of eyes (%) fitting each of the global expansion and axial elongation models exclusively, fitting both models, or fitting neither model, for (**a**) height and (**b**) width as a function of refractive error group (Table 1).

in the Methods section. The differences between lengths measured with axial images and sagittal images and between lengths measured with axial images and ultrasonography were not dependent on refractive error group (one-way ANOVA $P = 0.661$, $P = 0.137$, respectively).

## DISCUSSION

This study shows that although myopic eyes tend to expand in all directions relative to emmetropic eyes, they are elongated more in the axial than in the vertical dimension and are elongated much less in the horizontal dimension. The increase in length of myopic eyes (0.35 mm/D) was sufficient to account for the change in refractive correction (Fig. 3a) and is similar to that observed in studies of Carroll[13] (0.39 mm/D, using data of Stenstrom[14]), Grosvenor and Scott[15] (0.28 mm/D, early-onset myopia group) and Chau et al.[10] (0.40 mm/D). Previous studies have shown differences between lengths and widths[6–8,11] (Miller JM, et al. *IOVS* 2004;45:ARVO E-Abstract 2388), but this is the first study to find differences between the rates of increase in the heights and widths of eyes with increases in myopia.

There are at least two possible reasons that differences in axial and equatorial dimensions with myopia may occur. The altered shape of myopic eyes may be due to the anatomic constraint of the location of the bony orbital walls, or it may be due to regional variations in the eye's susceptibility to some factor that causes ocular expansion. Our data suggest that the former is more likely. It is hard to conceive how the second option would result in the height and width differences we observed. We describe these two options in more detail in the following discussion.

Considering the hypothesis of anatomic constraint, the orbital walls are much closer to the sides of eyes than behind the eyes,[16] and thus an eye's ability to expand is much greater in the axial direction. The MRI scans of our participants' eyes showed clearly that there is more space between the eye and the wall vertically than there is horizontally, and so eye expansion may be constrained more in the horizontal direction than the vertical direction by the soft tissues (extraocular muscles, connective tissue, and orbital fat) surrounding the eye. This possibility depends on the bony orbital walls limiting the expansion. The fact that some equatorial expansion occurs may mean that the soft tissue between the globe and the walls is compacted or that the orbital walls slowly expand outward. The orbital volume increases by approximately 80% from the age of 1 month to 15 years (from 13–15 to 24–26 $cm^3$).[17] It is also known that, even in adults, bony tissue can redistribute itself,[18] leading to increases[19] or decreases in orbital volume.[20,21] However, Chau et al.[10] found no relationship between the volume of the orbit and either the volume or axial length of the eye, suggesting that in humans the eye expands within the existing orbital constraints and that the expanding myopic eye does not alter the orbital volume to a measurable degree. This contrasts with the findings in studies of neonatal animals showing that when eye size is manipulated with lenses, longer myopic eyes have larger orbits and shorter hyperopic eyes have smaller orbits.[22]

Considering the second possibility of regional variations in the eye's susceptibility to some factor that causes ocular expansion to occur, there is evidence from animal models that local retinal regions control the growth of the eye (e.g., if only half of the chick eye is deprived of high-quality form vision with a hemifield occluder, then only that half of the eye elongates).[23] Localized changes have also been observed with hemifield spectacle lenses.[24] Our results may suggest that although all myopic eyes are more susceptible to expansion in the axial direction, the susceptibility to local expansion is slightly greater in the vertical than in the horizontal meridian. Whether this variable susceptibility is due to the peripheral retina being less sensitive to defocus or to the varied concentration of some growth-promoting factor across the retina is not known. This possibility would also mean that defocus sensitivity or growth factor gradients vary horizontally and vertically.

Neither the global expansion model nor the axial elongation model is adequate to define our entire myopic population (Fig. 5). Approximately 40% of the myopic participants did not fit either model exclusively, apparently due to the considerable variability in the size and shape of emmetropic eyes. Both models are similarly successful when the determination is made based on the height dimension, with 30% and 26% of eyes exclusively fitting the global expansion and axial elongation models, respectively. However, the axial elongation model much better represents the shape of eyes when the determination is based on the width dimension, with 47% of myopic eyes exclusively fitting this model (compared with 18% exclusively fitting the global expansion model). Approximately 50% and 25% of the myopic group with refractive errors greater than −6.50 D fit the global expansion model based on height and width dimensions, respectively. Approximately 50% of this group fitted the axial elongation model in both dimensions.

Our finding that myopic eyes are elongated more in the axial than in the vertical dimension and are elongated much less in the horizontal dimension seems to conflict with the earlier MRI study by Cheng et al.,[9] who reported that myopic eyes were longer horizontally than axially and longer axially than vertically. However, they presented results of measurements of the outside of the sclera, and when their data are adjusted for measurement to the retina using their scleral and choroidal thickness measurements, then relative to the emmetropic group, the changes in dimensions for the myopic group are greater axially (mean, 2.1 mm) than vertically or horizontally, which is similar to our findings. However, in their study the change in width (1.2 mm) was greater than the change in height (1.0 mm). We are confident our methodology and sample size give a reasonable evaluation of eye shape.

Our findings conflict with the x-ray study by Deller et al.[6] Calculations using their data of 14 male emmetropes ($<+0.75$ D best spherical correction) and 12 male myopes gives similar rates of changes in height and width of 0.14 mm/D (compared with 0.19 and 0.10 mm/D, respectively, in the present study). A significant limitation of their study compared with the present study was its reliance on subjective responses of participants for alignment.

Indirect measurements have been made of eye shape by using peripheral refraction, but these have been mainly along the horizontal meridian. Although there is considerable intersubject variation, as myopia increases the mean peripheral refraction along the horizontal meridian moves increasingly in the hypermetropic direction relative to the central refraction.[25,26] Assuming that the refractive components (cornea and lens) are unaffected by refractive error, Charman and Jennings[27] and Dunne et al.[28] showed that this finding is consistent with equatorial stretching, one of the two axial elongation models, in myopia. It is consistent with posterior pole elongation, but only over a limited range of angles and is not consistent with global expansion, which gives only small changes in mean peripheral refraction. This is consistent with our finding that, for width, more myopic eyes (68%) fitted the axial elongation model than fitted the global expansion model (46%).

Along with the finding of greater heights than widths in myopic eyes, we would expect to find smaller relative hypermetropic shifts along the vertical meridian than along the horizontal meridian of myopic eyes. We are aware of only two studies that have measured peripheral refraction along both meridians. Seidemann et al.[29] actually found an increased hypermetropic shift in the superior visual field (inferior retina) of myopes; however, the shift in the inferior visual field was similar to that in the nasal visual field. These patterns were also found in an emmetropic group, and so this does not fit our expectation. In a study with children, Schmid[30] found hypermetropic shifts along both inferior and superior fields that did not occur along the horizontal meridian (nasal visual field only used), whereas in the emmetropic and hypermetropic groups, there were myopic shifts along temporal, inferior, and superior fields. This fits our expectation, but measurements were taken only at 15° eccentricity, and subject numbers were small. Schmid also used optical coherence reflectometry to estimate eye length at different eccentricities. The changes in lengths, relative to the on-axis length, correlated significantly with peripheral changes in refraction only for the nasal visual field, but the overall decreases support the equatorial stretching model of myopia.

This study has given useful information about the dimensions of human emmetropic and myopic eyes, but only a large longitudinal study can tell us about the pattern of expansion that occurs in individual eyes as myopia develops. It is possible that the pattern of expansion changes at some level of myopia (e.g., as the myopia progresses, global expansion is replaced by purely equatorial stretching).

The advantages of MRI technology for measuring eye dimensions include its independence from parameter assumptions such as refractive index, the ability to image the eye through any desired meridian, and the relatively good image resolution. The similarity of eye lengths between those measured from the MRI scans and those obtained using the traditional method of A-scan ultrasonography is reassuring. Although statistically the difference between the methods was significant, this difference was determined to be less than the estimated accuracy of the procedure and is therefore of no clinical relevance. The disadvantages of using MRI for ocular shape measures include cost, the reproducibility of the scan locations in the eye, and the amount of time necessary for manual measurement of the scans. A computer-assisted device for measurement of eye dimensions would help this procedure.

## Conclusion

Although myopic eyes tend to be greater in all dimensions than emmetropic eyes, they are elongated more in the axial than the vertical dimension and are elongated much less in the horizontal dimension. We suggest this difference is most likely due to anatomic constraints of the orbital walls. Approximately a quarter of the myopic participants fitted each of the global expansion and axial elongation models exclusively, with a limitation of these models being the large variability of shape and size of emmetropic eyes.

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