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Eye shape and retinal shape, and their relation to peripheral refraction

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Abstract

Purpose: We provide an account of the relationships between eye shape, retinal shape and peripheral refraction.

Recent findings: We discuss how eye and retinal shapes may be described as conicoids, and we describe an axis and section reference system for determining shapes. Explanations are given of how patterns of retinal expansion during the development of myopia may contribute to changing patterns of peripheral refraction, and how pre-existing retinal shape might contribute to the development of myopia. Direct and indirect techniques for determining eye and retinal shape are described, and results are discussed. There is reasonable consistency in the literature of eye length increasing at a greater rate than height and width as the degree of myopia increases, so that eyes may be described as changing from oblate/spherical shapes to prolate shapes. However, one study indicates that the retina itself, while showing the same trend, remains oblate in shape for most eyes (discounting high myopia). Eye shape and retinal shape are not the same and merely describing an eye shape as being prolate or oblate is insufficient without some understanding of the parameters contributing to this; in myopia a prolate eye shape is likely to involve both a steepening retina near the posterior pole combined with a flattening (or a reduction in steepening compared with an emmetrope) away from the pole.

Summary: In the recent literature, eye and/or retinal shape have often been inferred from peripheral refraction, and, to a lesser extent, vice versa. Because both the eye's optics and the retinal shape contribute to the peripheral refraction, and there is large variation in the latter, this inference should be made cautiously. Recently retinal shape has been measured independent of optical methods using magnetic resonance imaging. For further work on retinal shape, determining the validity of cheaper alternatives to magnetic resonance techniques is required.

Keywords: eye shape, peripheral refraction, retinal shape, conic sections

Introduction

With the recent interest in the possible roles of the shape of the eye and peripheral refraction in refractive development, it is timely to give a better explanation of eye and retinal shapes. It is likely that the eye shape will be related to the peripheral refraction as well as the latter depending on the optics of the eye, but the picture is often simplified by unwarranted linking of the two, e.g. a particular shape of the eye is taken to infer a particular pattern of refraction such as a prolate shape causes relative peripheral hyperopia or vice versa. Retinal shape may be confused with the more nebulous concept of eye shape, and in this paper we set out to explain the relative quantities. Retinal shape has been determined in different ways, and a review of this will be presented.

Most theories and investigations of myopia development have been concerned with the growth response to defocus signals corresponding to foveal vision, but Wallman and Winawer[1] indicated that the defocus signal at the periphery should be stronger than at the centre because of the presence of more neurons in the periphery than at centre, and that relative peripheral hyperopia might stimulate the eye to grow, dominating the central myopic refraction. This is supported by Ho et al.[2] who found that the electrical response of the human retina is sensitive to defocus, with the paracentral retina reacting more vigorously to optical defocus than the central retina. The mechanisms by which the retina might respond to a blurred signal in the periphery to produce axial elongation are beyond the scope of this paper (see Charman and Radhakrishnan,[3]; Charman,[4] for recent reviews). Also beyond the scope of this paper is an assessment of peripheral refraction treatments of myopia.

Shapes, axes and sections used to describe eye and retinal shape

Ocular surfaces are typically described by conic sections. A conic section rotated about one of its principal meridians becomes a rotationally symmetric conicoid. This can be described by the equation

$$X^2 + Y^2 + (1 + Q)\,Z^2 - 2ZR_v = 0 \qquad (1)$$

where Z is measured along the optical axis, X and Y are measured along axes perpendicular to the Z-axis and to each other, R_v is the vertex radius of curvature, and Q describes the asphericity (Figure 1). $Q > 0$ represents an oblate ellipse (steepening away from the vertex), $Q = 0$ represents a sphere, $-1 < Q < 0$ represents a prolate ellipse (flattening away from the vertex), $Q = -1$ represents a paraboloid and $Q < -1$ represents a hyperboloid. Alternative terms for oblate ellipsoid and prolate ellipsoid are oblate spheroid and prolate spheroid, respectively. Sometimes asphericity is represented by the quantity p where

$$p = 1 + Q \qquad (2)$$

and sometimes it is represented by the eccentricity e, where

$$e^2 = -Q \qquad (3)$$

An alternate equation to equation (1) that can be applied to ellipsoids is

$$(X^2 + Y^2)/R^2_{xy} + (Z - R_z)^2/R^2_z = 1 \qquad (4)$$

where R_{xy}, R_{xy} and R_z are the semi-axis lengths along the X, Y and Z directions, respectively (Figure 1). For an oblate ellipsoid $R_{xy} > R_z$ and for a prolate ellipsoid $R_z > R_{xy}$. The vertex radius of curvature R_v and the asphericity Q are related to R_z and R_{xy} by

$$R_v = R^2_{xy}/R_z \qquad (5)$$

$$Q = R^2_{xy}/R^2_z - 1 \qquad (6)$$

Non-rotationally symmetrical ellipsoids can be described by

$X^2/R^2_x + Y^2/R^2_y + (Z - R^2_z)/R^2_z = 1$

where R_x, R_y, and R_z are the semi-axis lengths along the X, Y and Z axes, respectively. For the X-Z section, the vertex radius of curvature R_{xv} and asphericity Q_x are given by

$$R_{xv} = R^2_x/R_z \quad (7)$$

$$Q_x = R^2_x/R^2_z - 1 \quad (8)$$

Similarly for the Y-Z section,

$$R_{yv} = R^2_y/R_z \quad (9)$$

$$Q_y = R^2_y/R^2_z - 1 \quad (10)$$

Further levels of sophistication would be to rotate and decentre the surfaces, and to have more complex surfaces, but we will not deal with these here.

Figure 2 shows sections and axes of the eye. Transverse axial sections are parallel to the XZ plane, and taking the visual axis as the Z axis, one is usually selected to match the XZ plane as well as possible. Sagittal sections are parallel to the YZ plane, and similarly for the transverse axial sections, one is usually selected to match the YZ plane as well as possible. Coronal sections are parallel to the XY plane, and one is usually selected where the X and Y dimensions are judged to be maximums.

The antero-posterior length is usually measured from the anterior corneal surface to the posterior pole at the inner retina, generally understood as the axial length, although in some studies it has been measured from the posterior cornea to the posterior pole and in others it has been measured from the anterior cornea to the outer sclera. This distance can be measured through either transverse axial or sagittal sections.

The vertical length, or height, is the widest distance between the top and bottom of the eye and can be obtained from either sagittal or coronal sections. The horizontal length, or width, is the widest distance between temporal and nasal sides of the eye and can be obtained from either transverse axial or coronal sections. The height and width can be measured from inner retina to inner retina or from outer sclera to outer sclera.

Eye shape can be quantified using the axial length, height and width, with a number of studies using the ratios of axial length to height and/or axial length to width as additional descriptors. Clearly this is an oversimplification as it ignores the rapid change in shape that occurs at the corneal-scleral intersection. Retinal shape can be similarly described by fitting ellipsoids to its posterior part, the functional part as far as imaging is concerned. The eye shape and retinal shape components will have similar heights and widths, but the lengths of the ellipsoids used to fit the retina are shorter than the axial length by about 3.1 mm.[5]

Models of retinal shape and their relation to peripheral refraction

Variations of retinal shape in myopic eyes can be related to models of the retinal stretching that accompanies the increase in axial length as shown in Figure 3. These include a global expansion model (a), a model where the stretching occurs parallel to the optical axis at the equatorial region (b), and a model where the stretching takes place only at the posterior pole (c). A hybrid model, called the axial expansion model is the combination of equatorial and posterior pole expansion models (d). The first three models are shown with spherical surfaces and the hybrid model is shown with a prolate ellipsoid surface.

A thin beam (pencil) of light from an off-axis object point on a plane surface, passing through a symmetrical optical system, will be focused as lines at two positions, one corresponding to light refracted in the (tangential) plane containing the object point and the optical axis and the other in the (sagittal) plane perpendicular to this plane. For a range of object points across the surface there will be two image shells as shown in Figure 4a. Taking the optical system as an emmetropic eye, we will assume that its normal retinal shape is a sphere with radius of curvature of about 12 mm and that the shell corresponding to the average of the tangential and sagittal shells coincides approximately with this sphere. Figure 4b shows this retinal shape (solid line) along with changes in retinal curvature that make the retina flatter or steeper. Light from a distant off-axis point converges to a point that coincides with the normal retina, is in front of the flatter retina causing peripheral myopia, and is behind the steeper retina causing peripheral hyperopia. The eye with the steeper retina might respond to the peripheral hyperopic defocus by elongating and thus causing myopia.

This description can be extended to a myopic eye. Assuming the optics of the eye are the same as those of the emmetropic eye described above apart from an increase in length, for the flatter retina an off-axis light beam's "mean" focus will be further in front of the retina than for the "normal" retina. The peripheral refraction corresponding to this is referred to as relative peripheral myopic refraction because a more negative correction is needed than for the normal retina. For the steeper retina, the off-axis light beam's "mean" focus will be closer to the retina than for the normal retina, resulting in a relative peripheral hyperopia. Similar to the emmetropic eye with a steep retina, the eye might respond to the relative hyperopic defocus by becoming yet more myopic.

The situation described above leading to myopia development might be turned around - "excessive" relative peripheral myopia in the young emmetropic or hyperopic eye might result in a "stop" signal to normal emmetropization and lead to an adult hyperopic eye.

The above situation is over-simplified: real eyes do not generally exhibit rotational symmetry and so peripheral refraction varies according to visual field meridian. Most emmetropic eyes have low levels of peripheral myopia, as will be discussed later. Most emmetropic retinas are oblate in shape rather than spherical,[5] but for the present we will ignore this.

Figure 5 shows how models of retinal stretching relate to image position and relative peripheral refraction. For all models, the image surface is closer to the retina in the periphery than in the centre, resulting in less myopia in the periphery than in the centre, that is, there is relative peripheral hyperopia. This effect is greatest for posterior polar expansion, followed by axial, equatorial and global expansion.

Peripheral refraction

Peripheral refraction studies date back to Thomas Young[7] who determined the tangential and sagittal image shells, for a 25 cm diameter circular object surface, for a schematic eye based on measurements of his left eye. This was followed by several studies in the late nineteenth and early twentieth centuries as reported by Ames and Proctor.[8] Ferree et al.[9-12] conducted a well-known study of peripheral refraction along the horizontal meridian up to 60° from fixation in 21 subjects using an objective refractometer. They identified three different patterns of peripheral refraction. The type A pattern had 'mixed' astigmatism in which the tangential refraction (refraction along the horizontal direction) became more myopic and sagittal refraction (refraction along the vertical direction) became more hyperopic, the type B pattern had relative hyperopic astigmatism in which both tangential and sagittal refraction became more hyperopic into the periphery, and the type C pattern had asymmetrical astigmatism with the peripheral refraction differing between nasal and temporal sides of the horizontal peripheral field.

Ferree and Rand[11] related the peripheral refraction patterns to the likely shapes of eyes. They did not use the terms “relative peripheral myopia” or “relative peripheral hyperopia” as are now used, but their assertions were equivalent to suggesting that a prolate ellipsoid shape would increase the relative peripheral hyperopia or decrease the relative peripheral myopia. As should be apparent from Figure 1, changing from a spherical shape to oblate elliptical and prolate elliptical shapes, but without changing the vertex curvature, will result in shifts towards relative peripheral hyperopia and relative peripheral myopia, respectively. These are in the opposite directions to Ferree and Rand’s suggestions, as they assumed that accompanying the change in asphericities would be a change in vertex curvature. This is made clear at one point only in the paper, when referring to an eye with a pattern of relative peripheral myopia, or “myopic astigmatism” because the nearly emmetropic eye has peripheral myopia in both principal meridians, they refer to “an eyeball flattened at the back, with a shape tending towards that of an oblate spheroid” (page 930). It is likely that Ferree and Rand did not consider that, accompanying differences in axial length and eye shape, eyes might have different equatorial dimensions as in the development of myopia according to the global model of myopia expansion. Figure 6 shows the effect of different shaped ellipsoids on peripheral refraction in which the equatorial diameter does not vary: both vertex curvature and asphericity differ between the ellipsoids.

By considering the amount of peripheral astigmatism (the difference in refraction between the two principal meridians), Ferree and Rand inferred the power and length of the eye, considering that eyes with small degrees of peripheral astigmatism were likely to be longer and less powerful, and vice versa for eyes with higher degrees of peripheral astigmatism.

While others since them involved in peripheral refraction have been vague about eye shape, e.g. is it the retinal shape or an overall shape of the eye, Ferree and Rand[11] seemed to have in mind the shape of the retina: "Attention may be called to the following points: the possibility of determining roughly the conformation of the retina and the shape of the posterior half of the eyeball" (pages 937-938).

Rempt et al.[13] investigated peripheral refraction in 442 young adults undergoing pilot training out to 60º along the horizontal visual field using retinoscopy. They described five patterns of peripheral refraction (types I to V), shown in stylistic pattern in figure 7. There is a progression in pattern from type I, which is the same as type B identified by Ferree et al., to type II, type IV and type V, in which both horizontal meridian and vertical meridian refractions move in the myopic direction. Type III is an asymmetric pattern similar to Ferree et al.'s type C. The frequency of the patterns was related to the central refraction with 91/141 myopes having the type I pattern, 135/217 emmetropes and 61/84 hyperopes having the type IV pattern, and 17/34 cases of type V occurring for hyperopes.

The findings of Rempt et al.[13] regarding the way in which peripheral refraction patterns change with central refraction have been supported and elaborated by numerous studies. Since this time, results have been shown as the mean refraction combined with a measure, or measures, of astigmatism. A summary of findings along the horizontal visual field is as follows:

1. There is considerable intersubject variation within members of the same group (eg within emmetropes), as occurs for the higher order aberrations.
2. Several studies have found emmetropic groups to have a weak relative peripheral myopia[14-17] although some have found a weak tendency in the hypermetropic direction

on one or both sides of the visual field.[18] Myopic groups show relative peripheral hyperopia,[14-19] which to some extent increases with increase in myopia,[15] and hypermetropic groups show relative peripheral myopia.[18, 20] As noted by Charman and Radhakrishnan,[3] there is a tendency for the peripheral refractions of the different refraction groups to converge as field angles get larger and this will occur for the axial expansion model eye of Figure 3.[21, 22]

3. Some subjects shift from a relative peripheral myopic pattern to a relative peripheral hyperopic pattern at large angles eg > 45°.[23]
4. Peripheral astigmatism decreases with increase in myopia;[15] possibly because of small numbers this has not been noted in many studies.
5. The turning point (minimum or maximum) of mean refraction or of regular (J_{180} or 90/°180°) astigmatism is usually a few degrees into the temporal visual field[24-26] and decreases slowly with increase in myopia.[15] This is usually attributed to the angle alpha, the angle between the visual axis and the best fit optical axis at the nodal point; Atchison et al.,[15] but not Dunne et al.,[26] found a significant relationship between the turning point of astigmatism and angle alpha.
6. The oblique component of astigmatism (J_{45} or 45/°135° astigmatism), which was not investigated in most studies before 1981, is much smaller in the periphery than the J_{180} component and is linearly related to peripheral angle.[15]
7. Effects of age[17, 20] and ethnicity are small.[16]
8. The effects of accommodation are unclear: Walker and Mutti[27] found a hyperopic shift in relative peripheral hyperopia upon accommodation. Calver el al.,[28] Davies and Mallen[29] found no effect of accommodation on relative peripheral refraction for either emmetropic or myopic groups, and Whatham et al.[30] found a myopic shift in relative peripheral

refraction in a group of myopic children (eg 0.74D and 0.59D at 40° temporal and nasal fields, respectively, with nearly 3D increase in accommodation demand).

9. Manipulating refractive correction in the form of refractive surgery,[31] orthokeratology,[32-34] special contact lenses[35] and special spectacle lenses[36] has considerable and largely predictable effects on peripheral refraction.

Studies of peripheral refraction have been restricted mainly to the horizontal visual field, while some two dimensional studies have only gone to small angles, e.g. 20-25° degrees from fixation.[37, 38] Atchison et al.[15] measured along the vertical visual field to ±35° from fixation in a subset of 43 of their 116 subjects and found different patterns than along the horizontal visual field. For emmetropes the relative peripheral myopia was greater along the vertical than along the horizontal visual field. With increase in myopia, there was little change in relative peripheral refraction. These findings have since been supported.[17, 19] Atchison et al. found that the regular astigmatism was similar in vertical and horizontal fields, apart from a change in sign. In the vertical visual field the turning point of regular astigmatism was ≈ (–) 3° in the inferior field, without any dependence on central refraction. The oblique astigmatism changed at three times the rate with increasing angle along the vertical field than along the horizontal field, and this was attributed to angle alpha along the horizontal visual field.

Without any changes in the optics of the eye apart from the shape and position of the retinal surface, all models of retinal stretching predict, to various degrees, the trend of increasing relative peripheral hyperopia along the horizontal visual field with increase in myopia (Figure 5), but only the global stretching model comes close to predicting the relative lack of change of relative peripheral refraction along the vertical visual field.

Atchison[39] modelled peripheral optics according to biometric measurements in 121 emmetropic and myopic young adults. The models showed increase in corneal curvature, increase in vitreous length, and change in retinal shape with increase in myopia. The retinal vertex radii of curvature and the retinal asphericities in XZ and YZ sections were given by

R_{xv} (mm) = –12.91 – 0.094*SR*

Q_x = +0.27 + 0.0026*SR*

R_{yv} (mm) = –12.72 + 0.004*SR*

Q_y = +0.25 + 0.0017*SR*

where *SR* is the spectacle refraction[5] [see Measurements of retinal shape]. The modelling predicted relative peripheral myopia in emmetropic eyes in both horizontal and vertical visual fields. Along the horizontal visual field, the modelling predicted slight increases in relative peripheral hyperopia with increase in myopia that were less than those of the experimental results of Atchison et al.[20] Along the vertical visual field, the modelling predicted little change in refraction, compared with the relative peripheral myopia of the experimental results for a range of refractions (Figure 8).

Relative peripheral refraction and progression of myopia

Hoogerheide et al.[40] followed the refraction of 214 trainee pilots over an unspecified time interval ("during the following years"), most of whom were in the Rempt et al.[13] study. The emmetropes and hyperopes who developed myopia were disproportionately represented by those with the type I refractive profile. The proportions of each type that went on to develop myopia were 17/36 of type I (47%), 3/43 type II (7%), 3/14 type III (21%), 3/112 (3%) type IV, and 0/9 (0%) type V. Stone and Flitcroft[41] and Wallman and Winawer[1] drew attention to this work, beginning a period of interest that peripheral optics might influence development of myopia either through the peripheral refraction pattern or through the retinal shape.

Mutti et al.[14] measured peripheral refraction at 30° in the nasal visual field in 820 children aged between 5 to 15 years. Following Ferree et al., they described ocular shapes on the basis of relative peripheral refraction at this position. Relative peripheral hyperopia of +0.80 ± 1.29D was measured in myopic children and interpreted as indicating prolate eye shapes. Relative peripheral myopia of –0.41 ± 0.75D was measured in emmetropic children and interpreted as indicating near spherical or oblate eye shapes, and relative peripheral myopia of –1.09 ± 1.02D was measured for hyperopic children and interpreted as indicating oblate shapes. These inferences of shape based on peripheral refraction have appeared in many papers since.

Mutti's group has followed its cohort for a decade. Mutti et al.[42] reported rapid changes in relative peripheral refraction in the hyperopic direction before the onset of myopia, although as noted by Charman and Radhakrishnan[3] progression towards myopia began before relative peripheral refraction became markedly hypermetropic. In their latest paper Mutti et al.[43] were less enthusiastic, reporting that relative peripheral hyperopia had little consistent influence on the risk of myopia onset, with a mean annual progresion of myopia of only −0.024D per diopter of relative peripheral hyperopia.

Sng et al.[44] performed a one year longitudinal study on central and peripheral refraction along the horizontal visual field at ±15° and ±30° in Chinese Singaporean children aged 7 ± 3 years. At baseline, the peripheral refraction patterns in children who became or did not become myopic were similar. The children who were myopic at baseline or who became myopic had relative peripheral hyperopia at the follow up, while children who did not become myopic retained relative peripheral myopia. Shifts in spherical equivalent refraction after 1 year in the 'became myopic group' were −1.51 ± 0.63D at centre and −1.08 ± 0.70D and −1.06 ± 0.64D at temporal and nasal 30º visual field, respectively. These results indicate that relative peripheral hyperopia might not be an essential factor in development of myopia.

Studies with rhesus monkeys by Earl Smith's group provide compelling evidence for the role of peripheral retina in the development of myopia.[45-49] Smith and colleagues suggested that, for the monkey model, there are similarities in the ocular shape changes that occur due to form deprivation and imposed refractive blur, perhaps indicating a common mechanism relating these different visual interventions.[47] However, the recent findings mentioned above lead to the view, that in humans, the peripheral refraction pattern is largely a consequence of, rather than a determinant of central refraction. It remains possible that the retinal shape, possibly through biomechanical factors, might be a determinant for the development of myopia.[50-52]

Measurements of eye shape

Eye shape can be investigated by imaging techniques such as X-rays and computerized tomography,[53-55] ultrasonography[56, 57] and magnetic resonance imaging.[5, 58-65] The results from several studies of eye shape are given in Table 1. The mean increases in axial length with increase in myopia for adult eyes are 0.33 mm/D and 0.35 mm/D according to Deller et al.[53] and Atchison et al.[61] which are in good agreement with studies of axial length in adults using other methods. Eye shape in these studies was mainly a comparison of one or both of height H and width of the eye W with the length L. The dimensions were not measured consistently across studies, for example some studies used the outer eye while others used the inner retina, but this does not affect the rate at which dimensions change with alteration in refraction. The results are expressed in different ways, but apart from Cheng et al.[59] the studies found greater increase in length than in height and/or width with increase in myopia. Deller[53] found changes in *L*, *H*, *W* with changes in refraction in the approximate ratio 2: 1: 1, while Atchison et al.[61] obtained the ratio 3:2:1 (in the midst of considerable intersubject variation). Two studies found no significant differences between eye shapes in emmetropia and hyperopia, but hyperopia was small in one study[53] and its range was not specified in the other.[54]

Some studies referred to the eye shape in terms of ellipsoids, using prolate and oblate to describe the situation where the ratio *L*/*H* (and/or *L*/*W*) is greater than and less than one, respectively,[62-64] while Zhou et al[54] used the terms “long oval-shaped” and “cross oval-shaped” and Moriyama et al.[63] used the terms “cylindrical” and “barrel”. Ishii et al.[65] considered that the use of a single metric was insufficient to describe eye shape and proposed the use of “elliptic Fourier” descriptors. Two of these, “width expansion” and “posterior length” terms, were strongly correlated with the *L/H* ratio and seemed to give useful information, although it is doubtful that these are any more suitable than providing the lengths.

Atchison et al. considered that approximately a quarter of their myopes fitted each of the global and axial expansion models, described in Figure 3, exclusively. When considering height the proportions shifted slightly in favour of the global expansion model (30% vs. 26%), and while considering width the proportions shifted in favour of the axial expansion model (18% vs. 47%).

Measurements of retinal shape

Retinal shape can be determined by the methods mentioned in the previous section, e.g. magnetic resonance imaging.[5, 58, 66] It can be determined also by indirect optical methods that are based on peripheral refraction[22, 67, 68] and partial coherence interferometry.[69-73] Results using these techniques are summarised in Table 1.

Following their magnetic resonance imaging study of eye shape,[61] Atchison et al.[5] analysed posterior retinal shapes as asymmetric, decentred and tilted ellipsoids. An example of this analysis is given in Figure 9. The mean ellipsoid of emmetropes had an oblate retinal shape with the dimensions R_z =10.04 ± 0.49mm, R_x =11.40 ± 0.47mm, R_y =11.18 ± 0.50mm,). With increase in myopia, the retinas became less oblate with more elongation in length (0.16mm/D) than in height (0.09mm/D) and width (0.04mm/D), the latter not being significantly different from zero, but few myopes had retinal shapes that were prolate. There was significant increase in vertex curvature c_{xv} with myopia (0.64m^{-1}/D) along the horizontal plane, but not along the vertical plane. Fitting equations were:

c_{xv} (mm^{-1}) = –77.639 + 0.636SR

Q_x = +0.279 + 0.028SR

c_{yv} (mm^{-1}) = –78.691 – 0.019SR

Q_y = +0.258 + 0.018SR

where SR is the spectacle refraction. Also of note is that the mean retinal ellipsoid was tilted by 11.5° degrees about the vertical axis towards the nose, the retina vertex was decentred relative to the visual axis by x = –2.28 + 0.055SR (to the nasal side) and there was a space, or "anterior segment", from the anterior cornea to the front of the retinal ellipsoids of approx 3.0 mm that was not affected by refraction.

Dunne[67] developed an algorithm to determine retinal shape. Model eyes were generated, using a method devised by Bennett[74] and modified by Royston et al.,[75] comprising a corneal surface, two lens surfaces and the retina, using measurements of corneal curvature, lens thickness, anterior chamber depth, vitreous depth, and peripheral refraction. In this method, the curvatures of the lens surfaces are selected so that the ratio of the surface curvatures matches those of the lens in the Gullstrand-Emsley model eye. Dunne determined theoretical peripheral refractions at each field angle using sagittal and tangential ray-tracing. The corneal surface was treated as an ellipse and its asphericity was adjusted so that the calculated peripheral astigmatism matched the measured peripheral astigmatism at any field angle. The retinal curvature was altered until the theoretical sagittal refraction matched the measured sagittal refraction. When this procedure was completed for a number of positions, the retinal shape was estimated by fitting an ellipse. Testing with model eyes gave good results.

Logan et al.[68] used Dunne's method to estimate retinal shape in the transverse axial section for white and Chinese isomyopes and anisomyopes. Their measure was the ratio of the transverse chord diameter of the retina, at the maximum angles tested, to the axial length. This was found to be smaller in the more myopic eye of anisomyopes, and become smaller as myopia increased in the Chinese eyes only. Reduction in the ratio was interpreted as a more prolate shape of the retina, but this parameter requires further investigation.

Partial coherence interferometry compares the optical path lengths of two beams, one of which is reflected from the cornea and the other which travels into the eye and is reflected at one of the surfaces. Because the source (diode laser or super luminescent diode) has a wide bandwidth of wavelengths compared with a laser, and consequentially a short coherence length, a strong interference signal occurs only when the optical path lengths are similar rather than when optical path lengths differ by multiples of wavelengths. One commercial instrument, the Carl Zeiss IOLMaster, provides only the total axial length (anterior chamber depth is provided by an optical method), while the newer Haag-Streit Lenstar provides internal lengths also. The IOLMaster uses a single index within the eye (1.3549), but Haag-Streit does not indicate what is used for the Lenstar.

Schmid[69-71] developed his own partial coherence interferometer. He measured corneal to retinal lengths both axially and in the periphery at a maximum of 20° from fixation and gave a measure of retinal steepness by subtracting the central length from the peripheral length (relative peripheral eye length, *RPEL*). Because of the small angles used, this is probably a measure of foveal radius of curvature and surface tilt. RPEL was more negative ("steeper") for myopic than for emmetropic and hypermetropic children,[69, 70] and myopic shifts over 2 years correlated significantly with RPEL at 20° nasal field (steeper retinas giving more myopic shift).[71]

Mallen and Kashyap[72] used the IOLMaster with an external attachment containing a beam splitter, goniometer and a Maltese cross target that allowed the measurements of peripheral eye lengths. Figure 10 shows measurements with this type of system. This method could be extended to giving estimates of vertex radius of curvature and asphericity.

As it has been applied to determining retinal shape, partial coherence interferometry suffers from optical distortions. Firstly, little account has been taken of the different refractive indices in the eye's media; as mentioned earlier the IOLMaster uses a constant refractive index to convert from optical path lengths to distances, and it is not clear what procedure is used by the Haag-Streit Lenstar. Secondly, no allowance has been made for deviation of beams inside the eye.

A theoretical investigation of the partial coherence interferometry technique indicated that it can give reasonably accurate results for retinal shape.[73] An improved method would make allowance for deviation of beams inside the eye using other biometric parameters (e.g. corneal topography, internal distances, lens surfaces from Scheimpflug photography or phakometry and lens gradient index from magnetic resonance imaging) and should be verified by a direct technique such as magnetic resonance imaging. Figure 11 shows the conversion of the off-axis length measurements of Figure 10 to retinal shapes using a simple eye model. The match between the partial coherence method and MRI is excellent apart from at the temporal retina for which the partial coherence technique overestimates the steepness of the retina and more sophisticated modelling is required.

If measuring retinal shape is considered to be important and potentially diagnostic concerning the value of treatment for myopia, it will be useful to validate methods such as Dunne's method and partial coherence interferometry, as these provide cheaper and quicker alternatives to magnetic resonance imaging.

Conclusions

This paper has shown how eye and retinal shapes may be described in terms of conicoids, and in it we have described an axis and section reference system for determining shapes. We have described how patterns of retinal expansion during the development of myopia contribute to changing patterns of peripheral refraction, and how the pre-existing retinal shape might be a contributor to the development of myopia. We have described techniques, both direct and indirect, for determining eye and retinal shape, and results using these techniques.

To conclude this review, we make the following points:

1. Eye shape and retinal shape are not the same; as an example an eye shape may be described as prolate because the length is longer than the width and/or height, but the corresponding retinal shape might be oblate.
2. Merely describing an eye shape as being prolate or oblate is insufficient without some understanding of the parameters contributing to this; in myopia a prolate eye shape is likely to involve a steepening retina near the posterior pole with a flattening (or a reduction in steeping) away from the pole.
3. In the recent literature, eye and/or retinal shape have been inferred from peripheral refraction, and to a lesser extent, vice versa. Given that both the eye's optics and the retinal shape contribute to the peripheral refraction, and the large variation found in the latter, this inference should be made cautiously.
4. For further work on retinal shape using cheaper alternatives to magnetic resonance techniques, determining the validity of the techniques is essential.

Acknowledgements

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Figures and Captions

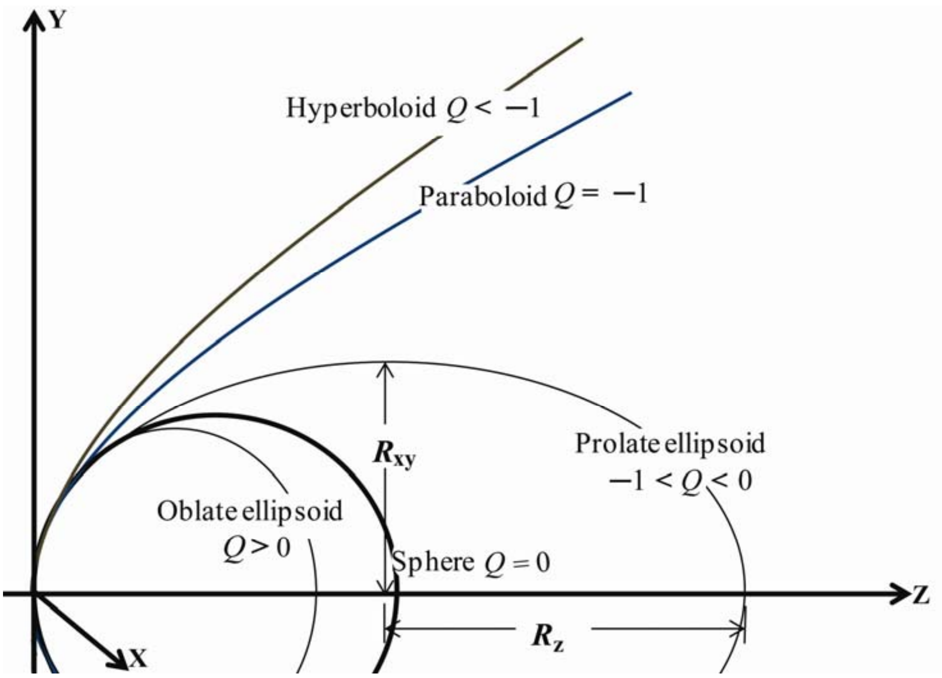

Figure 1: A family of conicoids, all with the same vertex curvature R_v. Semi-axis lengths R_{xy} and R_z are shown for the prolate ellipsoid.

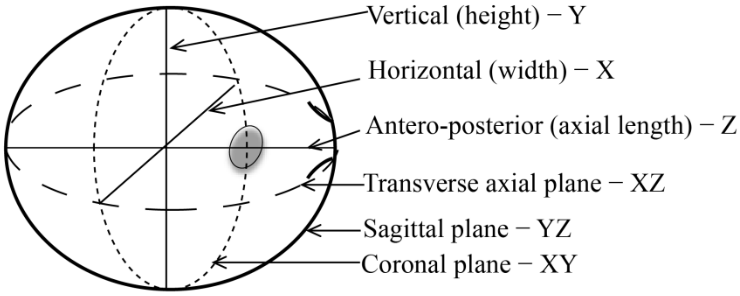

Figure 2: Scanning sections and axes of the eye. The sagittal section (solid line) is a vertical section containing the visual axis, the transverse axial section (dashed line) is a horizontal section containing the visual axis, and the coronal section (dotted line) is a vertical section perpendicular to the visual axis.

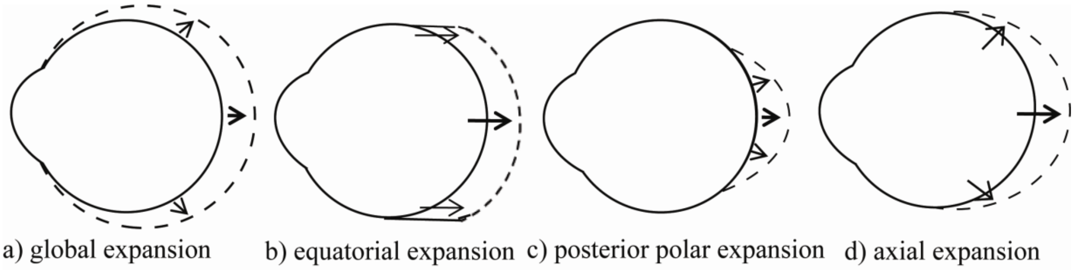

Figure 3: Models of retinal stretching in myopia: a) global b) equatorial c) posterior polar and d) axial expansion. The solid circles represent the shape of the retina of an emmetropic eye, the dashed shapes represent the myopic retinas, and the arrows indicate the regions of stretching. The first three models were presented by Strang et al.[6]

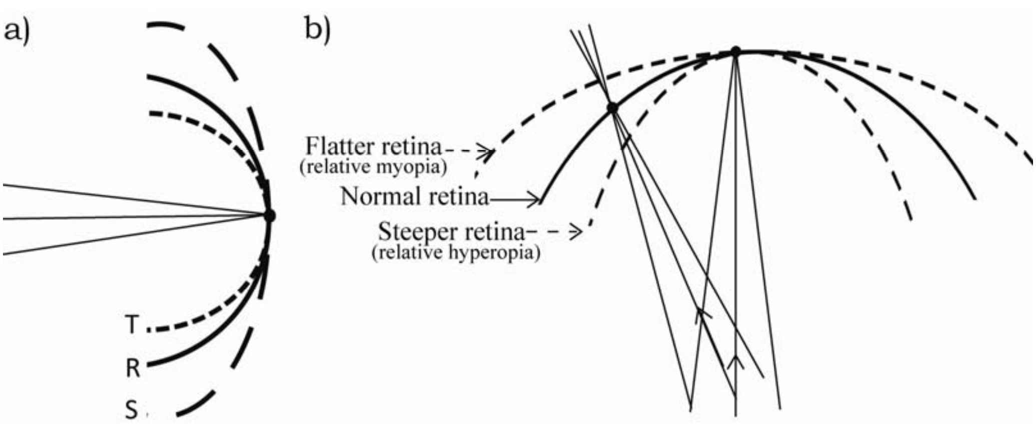

Figure 4: a) Formation of tangential (T-dotted line) and sagittal (S-dashed line) images either side of retina (R-bold line). b) Formation of the mean of the image shells, and its location relative to the retina for three different retinal shapes. Should the shape of the retina influence growth, this will be on the basis of summation of signals across the retina, not merely at a single position.

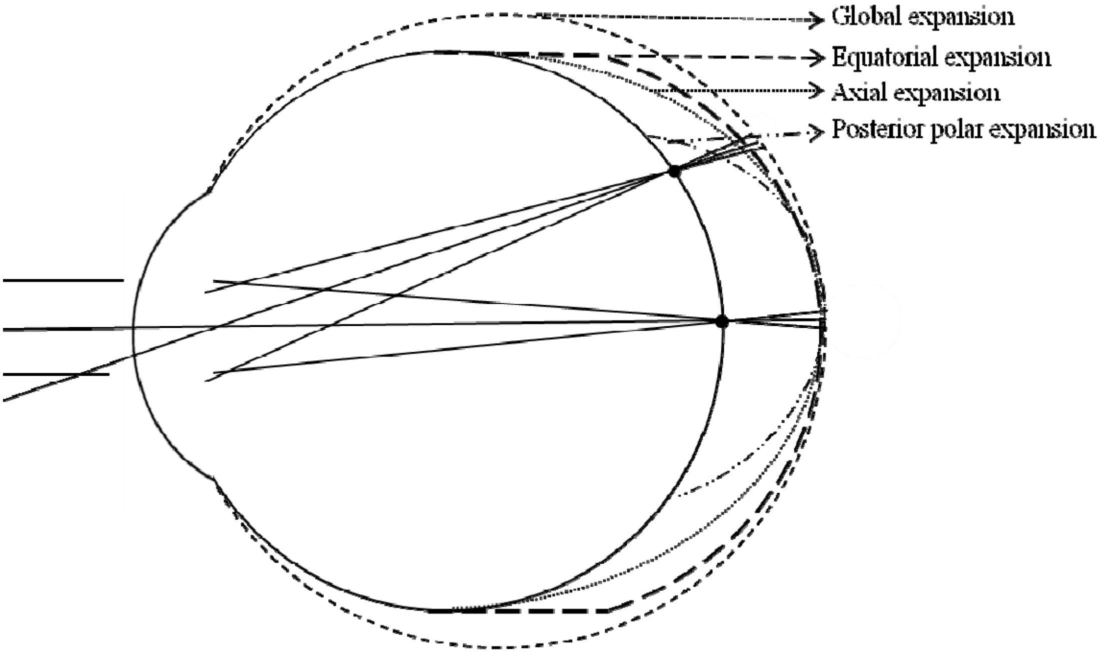

Figure 5: Positions of images relative to the myopic retina for the global, equatorial, posterior pole, and axial expansion models. It is assumed that the retinal surfaces remain spherical in the elongated regions for the first three models, while the surface for the axial expansion model is a prolate ellipsoid.

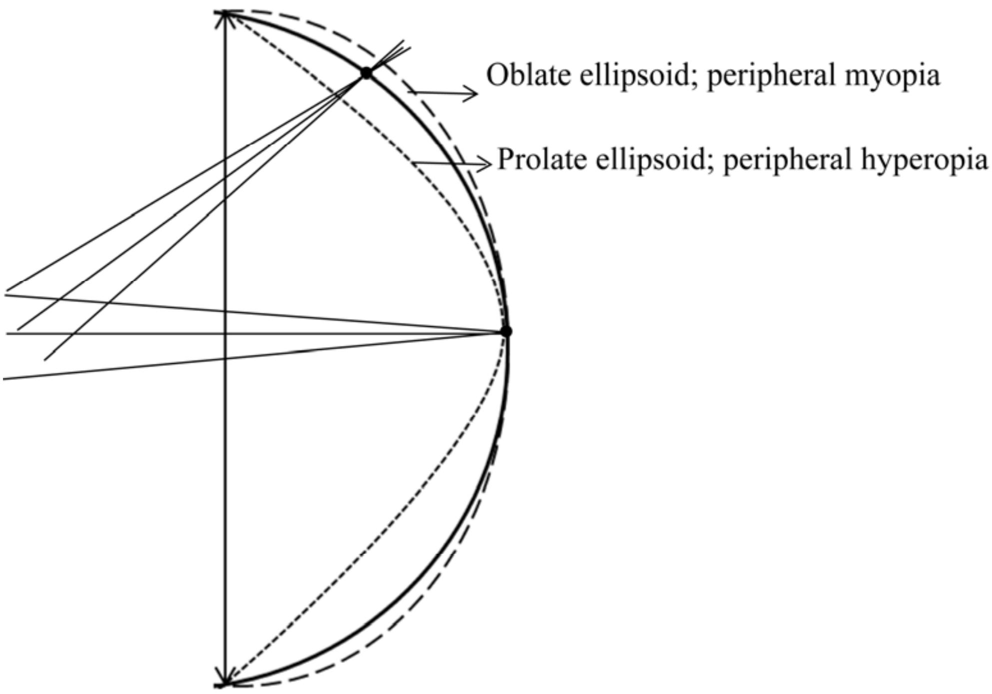

Figure 6: Effect of different shaped ellipsoids with constant equatorial diameter on peripheral refraction.

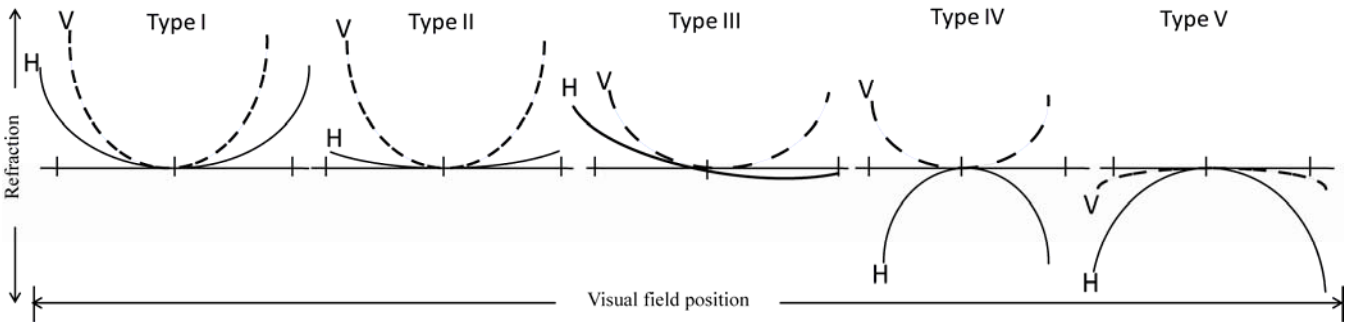

Figure 7: Five types (I- V) of skiagrams (peripheral refraction plots) described by Rempt et al.[13]. Types I, III and IV are similar to types B, C, and A, respectively, identified by Ferree et al. The curves are shown as parabolas, but real plots are seldom as regular.

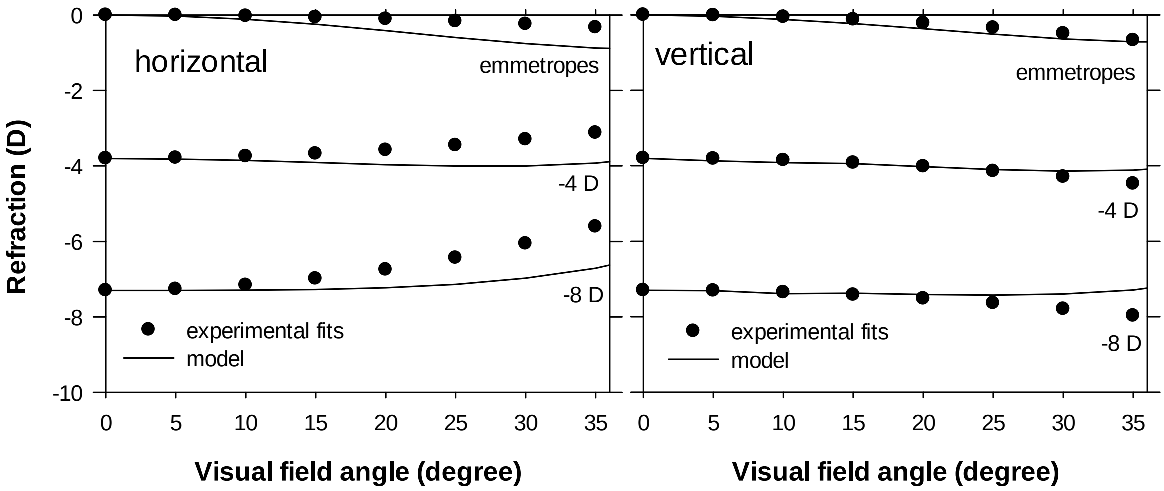

Figure 8: Mean refraction in a) horizontal and b) vertical visual fields, as a function of angle for measured data fits[15] and theoretical data[39] for emmetropia, 4.00D myopia and 8.00D myopia.

For the experimental results, quadratic fitting coefficients are used and asymmetry about the fixation point is ignored. The quadratic fitting co-efficient is given by H –0.000206x – 0.000270, V –0.000551, where x is central refraction in dioptres, with units of D/degrees^2.

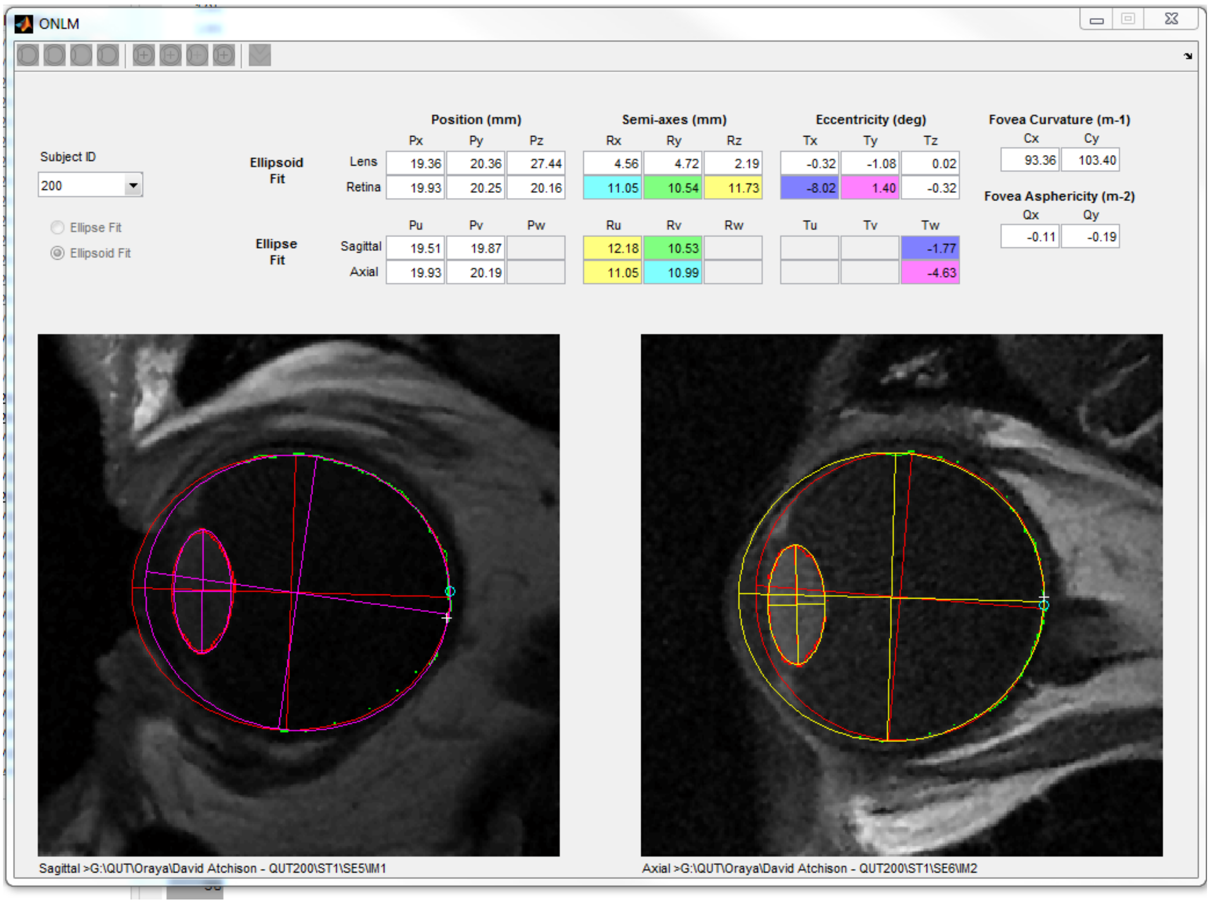

Figure 9: Processing of sagittal (left) and transverse axial magnetic resonance images for one subject with a –2.50 D refraction. Note that this subject has negative retinal asphericities, unlike most participants in the Atchison et al.[5] study.

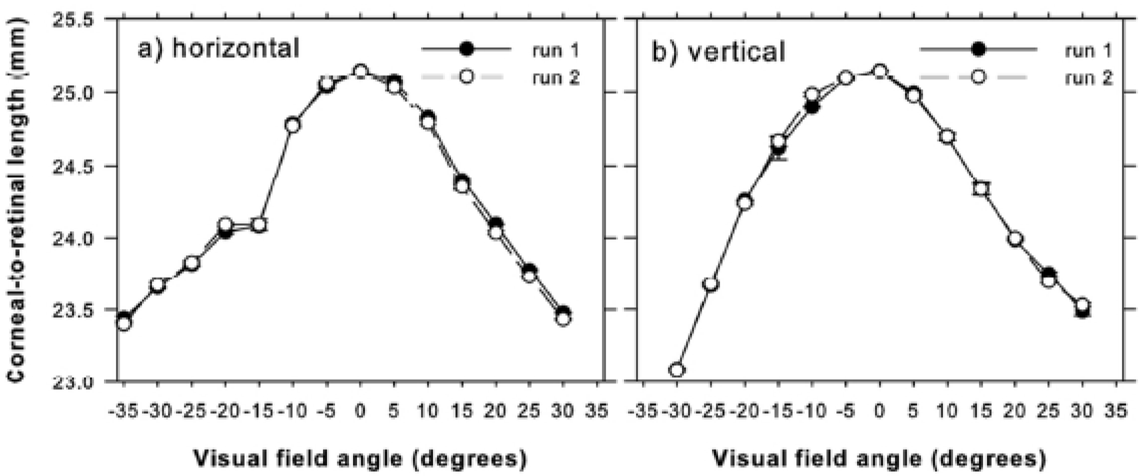

Figure 10: Off-axis length measurements for one participant using partial coherence interferometry (Haag-Streit Lenstar) along the horizontal a) and vertical b) visual fields. Results are shown for two runs and error bar show intra-run standard deviations of 5 measurements.

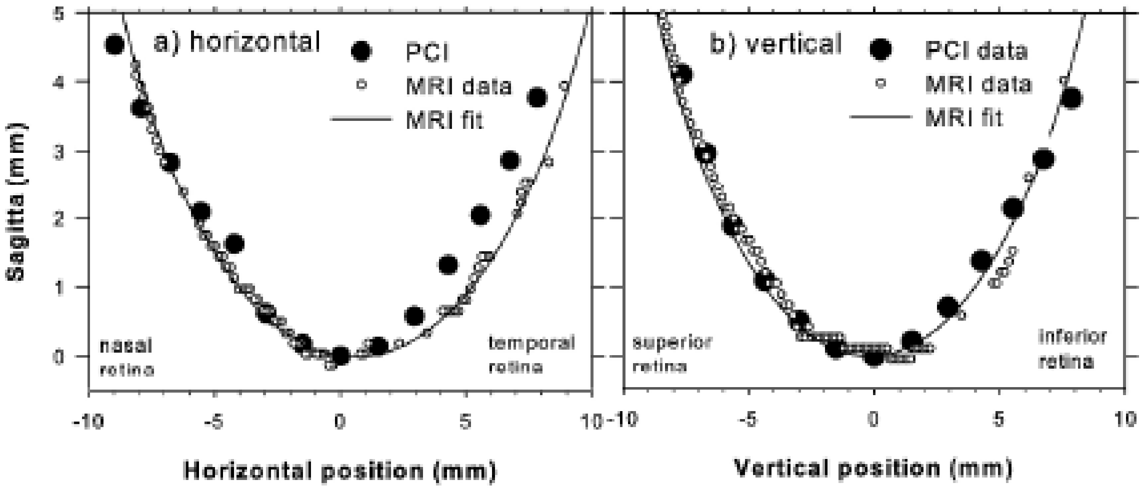

Figure 11: Horizontal and vertical retinal contours corresponding to the off-axis length measurements in Figure 10. The retinal contours have been determined using the Gullstrand-Emsley model eye, ignoring refraction at the lens, altering its length to match that of the participant's eye, assuming normal incidence of light at the cornea, and using the lengths for the first runs. For comparison, MRI data and MRI conic fitting are included.

Table 1. Summary of studies of eye shape and retinal shape

Authors	Technique	Procedure	Subjects	Results	Comments about distances *
Deller et al. [53] #	Radiography from X-rays – subjective responses	Slit beam transversed the eye perpendicular to the dimension measured. Exposure marked on film	11 Hyp, 19 E, 15 My adults	E : similar L, H, W; Hyp similar L, H, W As My↑, increase in L, H, W in approx ratio 2:1:1	
Vohra & Good [56] #	B-scan ultrasonography	Transverse axial	100 eyes/50 patients classified by axial length. Most high My	ΔL:ΔW > 3	
Fledelius & Goldschmidt[57] #	B-scan ultrasonography	Transverse axial	61 eyes/31 unilateral and bilateral high My > 50 years	"Regular" and "irregular" shapes Mean L/W 1.07 – range 0.92 to 1.36 Irregular shaped eyes had highest My and high L/W	
Zhou et al.[54] #	Computerized X-Ray tomography	Transverse axial section	33 Hyp, 76 E, 141 My (255 eyes/131 adults)	L/W for My > L/W for E , Hyp L/W ↑ as My↑	Not clear. L measured through optic nerve
Song et al.[55] #	Computerized X-Ray tomography	Transverse axial and coronal sections	406 eyes/354 children < 20 years	Emmetropes similar L, H, W Myopia AL > H, W	L from posterior cornea
Cheng et al.[59] #	Magnetic resonance imaging	Eye coil, transverse axial and coronal sections	8 Hyp, 6 E, 7 My	W > L, H Little change in shape with refraction	Outer dimensions
Chen et al.[58] $	Magnetic resonance imaging	Eye coil, transverse axial and coronal sections	3 Hyp, 4 E, 4 My	Posterior retina more prolate in shape for My than E and Hyp in transverse axial section	
Miller et al.[60] #	Magnetic resonance imaging	Transverse axial section	9 Hyp, 32 E, 37 My	As My↑, ΔL > ΔW	
Atchison et al.[61] #	Magnetic resonance imaging	Eye coil, transverse axial and sagittal sections	22 E, 66 My young adults	As My↑, increase in L, H, W in approx ratio 3: 2: 1	
Atchison et al.[5] $	Magnetic resonance imaging	Per Atchison et al. 2004 Retina shape determined from posterior 240°. 3D shapes obtained from sections, with rotations, decentration and asymmetry	Per Atchison et al. 2004	As My↑, increase in L, H, W of posterior retina in approx ratio 3: 2: 1 Oblate shape retinas in most eyes, but less so as My↑ Steepening of vertex curvature in transverse axial section, but not sagittal section	

Singh et al.[62] #	Magnetic resonance imaging	Head coil 3D images determined from 2D transverse axial slices Ocular shape described qualitatively by colour coding	7 young adults with a range of refractions	Considerable variations in eye shape between subjects of similar refractive errors	Outer dimensions
Moriyama et al.[63] #	Magnetic resonance imaging	Head coil Section not stated 3D images determined from series of 2D slices	20 E, 8 unilateral high myopes, 36 bilateral high myopes	Posterior staphyloma in several high myopic subjects Some had exaggerated posterior retinal oblate shapes (termed "barrel") and others had pronounced prolate shapes (termed "cylindrical")	Outer dimensions
Lim et al.[64] #	Magnetic resonance imaging	Head coil 3D images determined from series of 2D transverse axial slices	134 eyes/67 6 year old Singaporean Chinese boys	For non-My, as refraction less hyperopic: L↑, H↑, W↑ (unadjusted for height) For My, as My↑: L↑ but no change H, W (unadjusted for height) Conclusion: My eyes axially elongated	Outer dimensions
Ishii et al.[65] #	Magnetic resonance imaging	Head coil 3D images determined from 2D transverse axial slices Analysis of horizontal section Shape given by "Elliptic Fourier" descriptors	105 children, 1 month to 19 years old	"width expansion" term PC1 strongly positively correlated with "oblateness" given by 1 –L/(2*W) and also with spherical equivalent refraction "posterior length term" PC2 negatively correlated with oblateness Summary: Hard to made firm conclusion with regards eye shape and refraction as confounding effect of age	L measured from post corneal
Gilmartin et al.[66] #$	Magnetic resonance imaging	Head coil 3D images Determined semi-distances from visual axis at 17.%, 52.5% and 72.50% of axial length	31 E, 35 My young adults	Most retinas have oblate shapes, but less so for My than for E At half axial length, (H for My)/(H for E) = 1.02 and (W for My)/(W for E) = 1.01 Above results suggest predominately axial expansion in both horizontal and vertical meridians	
Logan et al[68] $	Dunne's approach [67]	Transverse axial section Peripheral refraction to ±35° Transverse chord diameter *TCD* (width at maximum angles) compared with *L*	56 isometropes and anisomyopes (> 2 D), white and Taiwanese-Chinese	*TCD*/*L* smaller in the more My eye *TCD*/*L*↓ as My↑ in Chinese eyes only Smaller *TCD*/*L* interpreted as more prolate shape	
Schmid[69, 70] $	Partial coherence interferometry	Retinal steepness based on comparing lengths along different meridians to ±20°. *RPEL* = peripheral *L* – central *L,* steeper as more negative	23 Hyp, 23 E, 17 My 7-15 years	RPEL steeper in My than E, Hyp RPEL significantly related to refractive error group at 15° nasal and superior visual fields	
Schmid [71] $	Partial coherence	Retinal steepness per Schmid 2003a,b	140 7-11 year children, 92	Myopic shifts over 2 years correlated	

	interferometry		available at 2 year follow-up	significantly with RPEL at 20° nasal field (steeper retinas give more myopic shift)
Mallen & Kashyap[72] $	Partial coherence interferometry	Modification of commercial instrument, horizontal and vertical fields to ±40°	One emmetrope and two myopes	Retinal asymmetry Evidence of temporal-nasal retinal asymmetry
Atchison & Charman[73] $	Partial coherence interference	Theoretical		In model eyes, reasonably accurate measure of retinal contour when incident beam normal to cornea without taking into account light bending within eye.

Most technical details omitted. It is understood that L for Myp > L for E > L for H, as is found for all relevant studies and this is not covered

*Information included if length is not anterior cornea to inner retina or height and width are not measured between inner retinas

eye shape; $ retinal shape

E - emmetropes, My - myopes, Hyp – hyperopes; L - length, H - height, W - width; ↑ increases; ↓ decreases