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Corneal shape and astigmatism: with a note on myopia

R A WEALE

From the Department of Clinical Ophthalmology, Institute of Ophthalmology, University of London, Moorfields Eye Hospital, City Road, London EC1V 2PD

SUMMARY The elliptical shape and the physiological astigmatism of the normal neonatal human cornea are attributed to the ellipsoidal shape of the eyeball. This in turn is a feature of ocular development. The analysis is used to examine earlier observations on myopia.

The human eye is said to be spherical, the cornea circular, and corneal astigmatism unexplained.[1] However, careful measurements show that the eyeball is oblate[2,3] and the cornea elliptical.[4] The object of this paper is to try to advance an explanation of these observations.

This analysis asks whether the shape of the young cornea depends on that of the eyeball as a whole. The initial prospect of success is barely encouraging. The neonatal eyeball has a radius of about 8·25 mm, whereas the radius of corneal curvature is nearer 7·4 mm. The disparity increases with age from 10% to some 27% in the adult eye. The fully developed eye therefore has grafted on it, as it were, a refractive bubble of greater curvature than its own, which satisfies well-known optical requirements.

However, heterotropic surface forces—for example, those due to the action of the recti muscles — are transmitted to the cornea via the sclera.[5] The corneal fibrillar organisation (of the adult eye) is not random but polarised, as though the cornea were subject to lines of force, orthogonal to each other and in line with the muscular directions of action, giving rise to an outline reminiscent of a Maltese cross.[6]

Moreover, the cornea barely grows after birth, and it increases its radius of curvature later only by an equivalent of less than 4 D, compensating optically therefore only for some 22% of the postnatal growth (about 6 mm) of the ocular axis. It would seem, therefore, that, approximately up to term, the cornea grows and develops in step with the rest of the eye but resists the effects of ocular growth after birth more and more effectively.

However, in two senses it is deformed already at birth. On average its refraction is slightly aspherical and its shape non-circular. A priori it is improbable that it should develop these characteristics—which are found in many mammals—actively by endogenous forces. Can it do so passively?

Correspondence to Professor R A Weale.

Hypothesis

While various authors agree that the vertical diameter of the globe is the smallest, there is some uncertainty as regards which is the largest. So far only the sagittal diameter has been measured in situ; enucleated material tends to be flaccid, and measurements may depend in part on the resting orientation of the eyeball. In the embryo Scammon and Armstrong[7] found the sagittal diameter to be the largest, while others[3] give its value as intermediate to the other two. Ethnic differences may have a role.[8] It will be shown that the above uncertainty as regards the relative ocular dimensions is immaterial in the present context so long as the vertical diameter is the smallest. The oblate shape of the eyeball is due to embryonic development. Lešer[9] showed that, even at the 5–6 mm stage, the human eye is tubular, a circumstance attributable to ectodermal growth. More recent work[10] concurs with this.

The present postulate is that both corneal ellipticity and physiological (with-the-rule) astigmatism are attributable to the oblate form of the fetal eye, a hypothesis supported inter alia by the observation that the young cornea yields less to stress than does the sclera.[11]

If, then, the corneal dimensions differ in the two principal meridians, are there external forces to account for this? Similarly, if the curvatures differ in the two meridians, are there external forces to achieve this? More especially, if the answer to both questions is yes, are the forces related?

Theory

SHAPE

Let the sagittal, transverse, and vertical diameters of the globe be 2a, 2c, and 2b, in decreasing order. As long as 2b is the smallest, the general conclusions of this analysis are unaffected by the relative magnitudes of the other two. As the scleral thickness is about 1/30 of the above diameters, the tension T can be estimated on the assumption that the eyeball maintains its shape under the influence of the intraocular pressure p. We follow the usual convention, namely that T, measured in a surface per unit length, acts in a direction perpendicularly to the surface. This requires a knowledge of the radius of curvature at the point of action if the surface is curved. An ellipse with principal semiaxes a and b is described by the expression

$$(x/a)^2+(y/b)^2=1 \quad \ldots\ldots \quad (1)$$

The radius of curvature at the point $x=\pm a$, $y=0$ equals b^2/a; similarly, at $x=0$, $y=\pm b$, the value is a^2/b.[12]

Although the tension T is assumed to be constant for the sclera, but may possibly differ for the cornea and almost certainly does so in the lamina cribrosa, these non-uniformities will be assumed to be negligible.

Elementary theory shows that, in any one meridian, $p=T/R$, where R is the radius of curvature at the point under consideration.[13] At the point of intersection of two principal meridians, the respective values being R(1) and R(2), $p=T[1/R(1)+1/R(2)]$. Let the sagittal circumference of the eyeball be described by an ellipse with semiaxes a, b (where 2a is the axial length), and the horizontal circumference by one with semiaxes a, c. Hence the pressures perpendicular to the optic axis are

$$\left.\begin{array}{ll}\text{in the vertical:} & T.b.\,(1/a^2+1/c^2)\\ \text{in the horizontal} & T.c.\,(1/b^2+1/a^2)\end{array}\right\} \quad \ldots\ldots \quad (2)$$

The ratio of the meridional areas perpendicular to them is b/c, so that the ratio G of the forces acting in the vertical and horizontal directions respectively is approximately

$$G=\left(\frac{b}{c}\right)^2\cdot\frac{a^2+c^2}{a^2+b^2} \quad \ldots\ldots \quad (3)$$

This expression demonstrates the validity of the argument regarding 2b being the smallest ocular axis, as mentioned above. Let the numerator and denominator of the second of the two fractions be divided by c^2, and $(a/c)^2$ set equal to X; then

$$G=[1+X]/[1+X/(b/c)^2],$$

which must be smaller than unity irrespectively of the value of X.

Table 1 *Neonatal ocular dimensions and comparison between computed and observed corneal shapes*

Ocular dimensions in mm	*Caucasian*	*Japanese*
a	8·55	8·3
b	8·1	8·0
c	8·4	8·5
G (calculated)	0·963	0·941
G (observed, n=3)	0·94±0·027	

Table 2 *Calculated and observed values for neonatal astigmatism with-the-rule (in dioptres)*

	Caucasian	*Japanese*
Calculated	3·5	5·8
Observed	<4·0	2·2 (average)

The forces stretch the eyeball differently in the two directions perpendicular to the optic axis and, in so far as they are transmitted to the corneal limbus, the pull on the developing cornea in the vertical is smaller than in the horizontal. On the simplest of assumptions it follows that G is approximately equal to the ratio of the vertical and horizontal dimensions of the neonate cornea, as mentioned above. Sets of relevant data are available for Caucasian and Japanese eyes for testing equation 3. The distinction may be material, because there are significant anatomical differences between Mongol and Caucasian eyes.[14] The Caucasian[8] and Japanese[3] data are shown in Table 1 together with the calculated value of G (equation 3) and an estimate of observed values of the corneal shape ratio.

It has to be remembered, however, that the observed value is obtained for instance from photographs, that is, for a fronto-parallel plane, whereas the data are calculated 'in the round'. The ratio of the projections of the vertical and horizontal diameters of the cornea equals b/c, the values for the two populations being 0·964 and 0·941 respectively. These are similar to the calculated figures for G given in Table 1, and justify the mode of comparison of the ratio of the principal corneal dimensions and that of their projections in a fronto-parallel plane.

PHYSIOLOGICAL ASTIGMATISM

Within rather wide limits neonatal astigmatism of the cornea[15,16] is also explicable in terms of the oblate shape of the eyeball. The expression for the radius of curvature of an ellipse shows that the ratio of the two principal radii of curvature R(1) and R(2) at the anterior ocular pole is $(b/c)^2$. Given the expression for astigmatism in terms of the difference between the dioptric powers in the two principal meridians

$$\Delta P = P(1) - P(2) = (\mu - 1).[1/R(1) - 1/R(2)] \approx \{(\mu-1)/P\}.[P(2)/P(1)-1] \quad \ldots\ldots\ldots (4)$$

where R is the mean neonate radius of curvature ($\approx$7·4 mm, see Weale[8]). It is, in effect, equal to 0·5[R(1)+R(2)], but no significant error is introduced by putting $R \approx R(1) \approx R(2)$. With $\mu = 1{\cdot}372$, and values culled from Table 1, those shown in Table 2 are obtained and compared with experimental ones.[16,17]

Half these values are referred to as spherical equivalents.[18] The agreement between theory and experiment is circumscribed. The large theoretical value for Japanese eyes is evidently due to the small value of $(b/c)^2$ (Table 1). Although the excised eyes from which measurements were obtained were fixed prior to measurement, no attempt appears to have been made to establish whether the inherently flaccid tissue was deformed, for example, while it hardened.

Discussion and relevance to myopia

The comparison between observed and calculated values both for corneal shape and physiological astigmatism suggests that, at least in the fetal eye, the relative deformation of the cornea is explicable in terms of tensile forces in the ocular globe. In the adult eye the transmission of such forces seems to be reduced, but this may be less valid for the myopic eye, which incidentally may have a thin sclera. The idea has been advanced[19] that the myopic eye tends to manifest compensatory features: the cornea flattening and, in a manner which was not clear to those authors, the lens too being poised to counteract myopia.

If one disregards corneal astigmatism and recalls that the myopic eye is frequently axially extended, then it is possible to estimate the condition in which the cornea will oppose myopia. Assume that the optic axis of the myopic eye is 2a′ and its diameter 2b′. Then it follows from equation 4 that the difference in refractive power between the myopic and the emmetropic cornea will be approximately

$$\Delta P = \{(\mu-1)/R\}.[(b'/b)^2.(a/a')-1] \quad \ldots\ldots\ldots\ldots (5)$$

where $R \approx 8$ mm; $\Delta P = 0$ when $(b'/b)^2 = a'/a$. Since $a' = a(1+\eta)$ and $b' = (1+\varepsilon)$, where η and ε are small as compared with unity, the transverse diameter need increase by only one half the axial increase. As the elasticity of the cornea resists the bending forces of the globe, the geometrical change may not wholly reflect optical necessity. But it is not hard to see that an extension of the transverse diameter can also act on the lens.

Put at its simplest, owing to zonular tension the focal length f of the lens is proportional to b or f=kb. Thus in the emmetropic eye, f=50 mm, so that 50=11 k, b in emmetropia equalling approximately 11 mm. Therefore f=4·55 b. An increase in b to b′ by only 1 mm in myopia[1] hence leads to a reduction in lenticular power of over 1·5 D, that is, myopia is counteracted. The calculation is invalidated for an ovoid eye, as when a staphyloma develops, but for the majority of simple myopes it offers at least a qualitative explanation of the earlier observations.[19]

The aetiology of myopia is still not understood. However, in so far as axial elongation is involved, this must be the result of the action of some force(s). Ocular inflation could play a part in teenage myopia as it does in the developing eye.[20] It is important to determine to what extent mechanical factors as distinct from growth may be involved at this later age.

In summary, a consideration of the tensile forces acting on the surface of the ocular globe helps our understanding of the development of corneal shape and curvature and may point to a possible modification of some of the processes causing myopia.

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