SCIENTIFIC REPORT

The effect of changing intraocular pressure on the corneal and scleral curvatures in the fresh porcine eye

B K Pierscionek, M Asejczyk-Widlicka, R A Schachar

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Aim: To measure corneal and scleral radii of curvature in response to intraocular pressure (IOP).

Methods: Using digital photographic profile images of 16 fresh porcine eyes, the curvatures of the cornea and sclera were determined in response to five consecutive incremental 100 µl saline intravitreal injections. IOP was measured and ocular rigidity calculated. Elastic moduli of the cornea and sclera were estimated.

Results: Intraocular pressure and the radius of curvature of the sclera increased linearly with increasing volume. There was no statistical change in corneal curvature. The elasticity of the cornea and sclera was constant during the 15–50 mm Hg increase in IOP. The estimated range of the elastic moduli of the cornea and sclera were, respectively 0.07–0.29 MPa and 0.2 MPa to 0.5 MPa. The scleral rigidity ranged from 0.0017 to 0.0022.

Conclusions: The elastic moduli of the cornea and sclera are independent of IOP. The modulus of elasticity of the sclera is higher than that of the cornea. Elevation of IOP changes the curvature of the sclera but not that of the cornea. Porcine scleral rigidity is similar to human scleral rigidity. Scleral curvature could be a novel method for measuring IOP.

Friedenwald¹ was the first to define scleral rigidity in terms of ocular volume and intraocular pressure (IOP). He realised that the sclera was important in understanding the effects of IOP on the optic nerve, and that the manifestations of glaucoma and the severity of its sequelae may be dependent on scleral rigidity. Recently, a non-linear finite element sensitivity study demonstrated that the stiffness of the sclera was the most important factor for determining the vulnerability of the optic nerve head to increasing IOP.² This study demonstrated that even large strains of neural tissue had less effect on the optic nerve head than the indirect effects of IOP on the sclera.²

The effect of increasing IOP on scleral deformation has not been quantified. As the eyeball is a biological and a curved structure, a sensitive method is required to measure the small deformational changes induced by fluctuations in IOP. This study investigates the change in radii of curvatures of the fresh intact porcine cornea and sclera with IOP. Ocular rigidity is calculated and the ranges of elastic moduli of the cornea and sclera are estimated.

METHODS

Sixteen porcine eyes were obtained from the local abattoir; eyes were collected within 4 h of death and then transported on ice. All eyes were from animals aged 5.5 months. Experiments were completed between 3–6 h postmortem. During the preparation and experiment, samples were kept moist with saline solution. The extraocular muscles and extraneous

fat were carefully removed from each eyeball and each specimen weighed on a digital balance before and after experimentation.

At 20°C, the eyeballs were placed, with their optic axes horizontal, on a specially designed base made of hollow, clear perspex tubing with gradation along the edge, to enable them to be maintained in a secure position during experimentation and to permit unobstructed photography of the whole eye (fig 1). A calibration standard was included in all photographs. Baseline digital photographs (Konica-Minolta, Dimage Z20, 5.0 mega pixel resolution, Konica-Minolta, Tokyo, Japan) were taken and downloaded to a computer (Dell Workstation PWS670, Dell Inc, UK) for analysis. Digital Cartesian co-ordinates were fitted to the profile images of the cornea and sclera using a grid. The points were fitted to an equation for a sphere to obtain the radii for the corneal and scleral profiles separately. The centre of curvature for each section was obtained by an optimisation procedure. An analysis of propagation of errors was done which gave a total error of ± 0.29 mm in the values of corneal and scleral radii.

Baseline IOP was measured with a hand-held corneal applanation tonometer with an accuracy of ± 2 mm Hg (Perkins Mk 2, Clement Clarke International). Five injections of saline were made in 100 µl increments through the optic nerve into the vitreous. After each injection, a photograph was taken, IOP was measured four times, and ocular rigidity was calculated.^{1,3}

The elastic properties of the cornea and sclera were calculated using equations applicable to material properties of thin-walled pressure vessels.³ The assumptions required to treat the eyeball as a thin-walled pressure vessel are that: the cornea and sclera have homogenous material properties, the eye has a spherical and near-spherical shape, thickness of the corneal-scleral shell (t) is less than 1/16th of the mean diameter of the eyeball, and that there is minimal variation in the thickness of the eyeball³ such that changes in volume or pressure do not induce gross distortions of shape. Porcine scleral thickness between the optic nerve and the equator of the eye is relatively constant. However, there are some variations in scleral thickness (up to around 0.6 mm) from the limbus to about 9 mm posterior to it.⁴ The cornea constitutes only 1/8 of the surface area of the eye and the thickness variations are around 18%.⁵ Although these thickness variations are not negated by the assumptions of the thin-walled pressure vessel theory, these were used only to estimate an approximate range of the elastic moduli of the cornea and sclera.

The circumferential stress σ in any direction is given by⁶

$$\sigma = \frac{P \cdot R}{2t}, \quad (2)$$

Abbreviation: IOP, intraocular pressure

Figure 1 Diagrammatic representation of the measurement system.

where

P is the IOP, R is the radius (of the scleral shell) and, t is thickness of the scleral shell (mean wall thickness taken as 0.78 mm⁷).

The volumetric strain

$$\zeta_v = \frac{\delta V}{V}$$

for a thin-walled sphere is⁶

$$\zeta_v = \frac{\delta V}{V} = \frac{3}{E} (\sigma - \nu \cdot \sigma) \quad (3)$$

where ν is Poisson's ratio for the sclera (taken as 0.5 for soft tissues which are incompressible)^{3,6} and E is the elastic modulus.

Substituting equation (2) into (3) gives:

$$\frac{\delta V}{V} = \frac{3PR}{2tE} \cdot (1-\nu) \quad (4)$$

The volume of the eye is

$$V = \frac{4}{3} \pi R_0^3$$

where R_0 is the initial radius of curvature (before fluid injection). Hence,

$$\frac{\delta V}{V} = \frac{\delta V}{\frac{4\pi}{3} R_0^3} = \frac{3 \cdot \delta V}{4\pi R_0^3} \quad (5)$$

Finally, combining equations (4) and (5) gives the following equation for E:

$$E = \frac{2\pi R_0^3 \cdot P \cdot R \cdot (1-\nu)}{t \cdot \delta V} = 3 \cdot (1-\nu) \cdot \frac{\sigma}{\zeta_v} \quad (6)$$

RESULTS

At baseline, the weight of the porcine eye was not predictive of the radius of curvature of the cornea, $R^2 = 0.14$, or of the sclera, $R^2 = 0.04$. The corneal radius of curvature was within 12% of the scleral radius, confirming the approximation to sphericity. With each incremental injection of fluid, IOP and the radius of curvature of the sclera increased linearly ($R^2 = 1$ for both; figs 2 and 3). Scleral rigidity, calculated in accordance with Friedenwald,¹ as the ratio of $\log_e(\text{IOP})$ to the change in volume, ranged from 0.0017 to 0.0022. Elevation of IOP did not significantly change the corneal radius of curvature, $R^2 = 0.10$ (fig 3). For both the cornea and sclera, the calculated circumferential stress increased linearly (fig 4). The estimated ranges of the elastic moduli of the cornea and the sclera were, respectively 0.07–0.29 MPa and 0.2–0.5 MPa. There was no statistically significant difference between the weights of the eyes at the end of the experiment and the original weights plus the total weight of the injected saline ($p = 0.46$). This showed that there were no significant changes in hydration of the tissue or losses of injected fluid.

DISCUSSION

In this study, fresh porcine eyes were used to assess the effects of IOP, measured by applanation tonometry, on the deformation of the cornea and sclera. The effect of using post-mortem tissue to make corneal and scleral measurements has been raised as a potential concern⁷; however, the relevant literature shows that results from enucleated eyes may not deviate significantly from the living eye. Ytteborg⁸ found a slight but non-significant change in scleral rigidity from 8 to 57 h post-mortem. Eisenlohr *et al*⁹ showed that in three of the six human eyes they examined there was no difference in scleral rigidity between living and enucleated eyes.

Ytteborg⁸ demonstrated that although the coefficient of scleral rigidity was slightly higher, when calculated using tonometric values of IOP compared to values obtained from manometric methods, there was little difference in the relationship with change in eye volume. Similarly, Mendelsohn *et al*¹⁰ found that, compared with manometry, applanation tonometry minimally underestimated IOP.

For the estimation of the range of corneal and scleral elastic moduli, this study followed the method of Purslow and Karwatowski,³ and used the thin-walled pressure vessel model.

Figure 2 Mean intra ocular pressure (IOP) plotted against volume of injected fluid.

Figure 3 Mean corneal and scleral radii of curvature plotted against mean intra ocular pressure (IOP).

The values of the corneal and scleral moduli estimated in this study were in the same range as those measured by Kampmeier *et al.*¹¹ and Woo *et al.*¹² Furthermore, consistent with Woo,¹² the present study demonstrates that the elastic modulus of the sclera is approximately twice that of the cornea.

Fresh porcine eyes are fairly spherical, with only a 12% difference in corneal and scleral curvatures. Scleral rigidity in the porcine eye is very close to that found in the human eye.⁴ The cornea does not change curvature; however, scleral curvature, with incremental increases in IOP between 15 mm Hg and 50 mm Hg, increases at the rate of 0.1 mm/mm Hg. Since the circumferential stress of the cornea and sclera increase linearly with incremental increases in IOP, the difference in response is probably related to the much larger variation in scleral thickness than corneal thickness. There is no change in the elastic moduli of the cornea and sclera with an increase in IOP.

The finding that IOP deforms the sclera linearly is consistent with the non-linear finite element sensitivity study, which showed the sclera to be the most sensitive ocular structure in terms of its response to changing IOP.² In view of these findings, clinically measuring the response of the sclera to IOP may be very important in predicting those who are vulnerable for developing primary open-angle glaucoma. Moreover, the linear change in scleral curvature with increasing IOP implies that this could be used as a novel method for assessing IOP.

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Authors' affiliations

B K Pierscionek, M Asejczyk-Widlicka, Department of Biomedical Sciences, University of Ulster, Coleraine, Northern Ireland, UK

Figure 4 Mean stress plotted against the mean volumetric strain ($\delta V/V$) of cornea and sclera. IOP, intraocular pressure.

R A Schachar, Department of Physics, University of Arlington, Arlington, Texas, USA

Correspondence to: B K Pierscionek, Department of Biomedical Sciences, University of Ulster, Coleraine, Northern Ireland BT52 1SA, UK; b.pierscionek@ulster.ac.uk

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