THE CORNEA IN POLARISED LIGHT*

(Preliminary Communication)

BY

A. STANWORTH

MANCHESTER

THE elasticity of the cornea and sclera has aroused some interest in relationship to the regulation of the intra-ocular pressure (see Duke-Elder, 1938), but the technique of photo-elastic analysis, well known to engineers as a method of studying stresses, does not seem to have been used. On account of its transparency, the cornea is an attractive medium for such studies, especially in relation to the effects of a rise in intra-ocular pressure, and it is the purpose of this paper to describe the possibilities of the method.

THE PRINCIPLES OF PHOTO-ELASTICITY

It is not intended to describe fully the theoretical basis of the method, but merely to provide a brief summary of the relevant facts.

When the velocity of any wave-train of light is the same in all directions through a substance, the latter is said to be isotropic. Many crystalline and most organic substances are, however, anisotropic; that is, the velocity of a light-wave in them is not the same in all directions, and the substance has more than one refractive index. These substances are said to be doubly refracting, or to exhibit birefringence, and light passing through them is split, in general, into an ordinary and an extra-ordinary ray, which are plane-polarised in mutually perpendicular directions. The two wave-fronts travel at different speeds and therefore emerge with one retarded behind the other, producing a phase-difference between them.

In general a substance may be birefringent as a result of three different mechanisms:—

1. Crystalline ("eigen") birefringence, which is due to a regular arrangement of the molecules of the substance.
2. Form birefringence, due to a regular orientation of particles which, though larger than molecules, are smaller than the wave-length of light.
3. Birefringence occurring as a result of stress.

In engineering-stress analysis, a model of the structure to be studied is made in some suitable transparent material, for example celluloid, and the stresses are applied to the model, which is then

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examined in polarised light, the change in birefringence at any point being a measure of the stress at that point. For the cornea no such model is necessary, because this structure can be examined directly.

Photo-elastic materials vary greatly in their sensitivity to stresses, but can be compared by means of the stress-optical co-efficient, which is given by the following formulae, adapted from Frocht (1941) :—

1. Retardation per unit thickness=Stress-optical co-efficient $\times$ twice the shearing stress applied.

2. For a strip under simple tension, Stress-optical co-efficient in brewsters=

$$\frac{\text{Retardation} \times \text{Width of strip in cm.}}{\text{Tension applied in dynes}} \times 10^{13}$$

GRAPH. 1.

PRESENT INVESTIGATIONS

Cleanly-cut strips of cornea 1.5 mm. wide, with a small length of attached sclera at each end, were obtained from fresh cats' eyes by means of a double knife. The unstretched length was measured, and the sclera then clamped in two artery forceps. These were fixed to two pillars, the distance between which could be altered by means of a double screw, so that the cornea was elongated but its centre-point remained stationary. The distance between the tips of the forceps was measured to 0.1 mm. by means of a fine pointer moving over a scale observed through a magnifying glass.

The retardation produced by the cornea was measured at the stationary point by the method of Goranson and Adams (1933); in this way a change in retardation of $0.1 \mu\mu$ could theoretically be measured, and even in biological tissues it is not difficult to measure a retardation with an accuracy of $3 \mu\mu$.

The change in birefringence with the length is shown in Graph 1, which is the average of seven strips of cornea. It will be seen that elongation of the strip produces a very rapid increase in the birefringence.

In order to calculate the stress-optical coefficient from these results, it is necessary to relate the increase in length to the applied stress. This was done by means of the autographic load-extension recorder described by Cliff (1933), Graph 2 being the curve obtained for the corneal strip described above with a rate

GRAPH. 2.

of loading of 125 gm. per minute. It will be seen that the curve forms a straight line only for relatively large loads of more than about 100 gm., producing an elongation of more than 13 per cent. For this range Young's Modulus is approximately 1.7×10^6 dynes per sq. mm., a figure of the same order as that given by Schelske (1864). The stress-optical coefficient should be calculated only for this range, but unfortunately it is not possible to obtain accurate measurements of the retardation for this degree of elongation. The nearest approach that can be made is to take the range around an elongation of 11 per cent., when Young's Modulus is about 1.45×10^6 dynes per sq. mm. For this range the stress-optical coefficient can be calculated, according to the formulae given above, to be approximately 1,800 brewsters. The table gives the value of this constant for some common photo-elastic materials, and it will be seen that the value for the cornea is relatively large.

TABLE OF STRESS-OPTICAL COEFFICIENTS
for light of wave-length 5461 Å. (Carleton 1934.)

Bakelite	...	...	...	...	...	46.4	
Celluloid	...	...	...	...	...	12.8	
Glass (plate)	...	...	...	...	...	2.7	
Rubber (soft)	...	...	...	...	...	2,000	(approx.)
Rubber (hard)	...	...	...	...	...	106	

The range of stress over which this constant applies is well above that of the normal or even the glaucomatous eye. The stress-strain curve in Graph 2 is not sufficiently accurate for calculation of Young's Modulus over the physiological range, but it is obvious that the extensibility over the earlier part of the curve is very much greater, and the modulus therefore very much smaller, than over the higher range of applied stress. In fact Clark (1932), from observations on the increase in volume of the intact eye with increasing intra-ocular pressure, gives a value of the modulus of only about 5×10^4 dynes per sq. mm.; and since the rate of increase of birefringence with length is almost as great in the physiological as in the upper range, it would be expected that the stress-optical coefficient for the physiological range would be even larger than the value given above.

DISCUSSION

It is not possible to compare these results directly with those that would be expected in the whole eye. In the corneal strip, the increase in birefringence is produced mainly by the elongation of the lamellae running directly between the fixed ends, as those running in other directions will not be pulled upon to the same extent. In the whole eye, however, the lamellae remain curved and the applied stress is not a linear one. Nevertheless,

the corneal lamellae must increase in length as the eye enlarges with a rise in intra-ocular pressure, and for lamellae running in any one direction this would be expected to produce a change in birefringence of the same order as that given above. Assuming that the eye approximates to a sphere, and that the extensibilities of the cornea and sclera are identical, the elongation produced in such lamellae can be calculated from the graph given

GRAPH. 3.

by Ridley (1930) for the increase in the volume of the eye with a rise in intra-ocular pressure, and hence the latter can be plotted in place of the elongation in Graph 1. The hypothetical relationship thus obtained between the birefringence and the intra-ocular pressure is shown in Graph 3.

It will be seen that at physiological pressures there should be a fairly rapid increase in such birefringence with a rise in intra-ocular pressure. This change in birefringence may thus provide the basis for a method of measuring changes in intra-ocular pressure by purely optical means, but this can only be realised if a way can be found of isolating, either in whole or in part, the change in birefringence of lamellae running only in one direction, and experiments are now in progress to explore this possibility.

From Graph 3 it would appear that any such method would have its greatest sensitivity for a range of intra-ocular pressure on the low side of normal, where a change in retardation of 3 m μ corresponds on the graph to a change in intra-ocular pressure of about $\frac{1}{4}$ mm. Hg; but the exact sensitivity to be expected can scarcely be deduced from the graph owing to the large number of assumptions involved in its derivation. In fact the cornea is probably more extensible than the sclera (Schelske, 1864), and also has a different curvature, both of which factors will probably tend to increase the sensitivity by increasing the changes in lamellar length and the shearing stresses within the cornea, especially at the periphery. On the other hand, failure to isolate completely the birefringence due to lamellae running only in one direction would decrease the magnitude of any observed change in birefringence, though it may be possible to balance this by increasing the length of the pathway taken in the cornea by the light used. It is hoped that a fuller discussion of these factors, together with the experimental results, will be published later.

One further use of data regarding stress-birefringence and the stress-strain relationship is in the study of molecular structure (Schmidt, 1938; Treloar, 1947), and this too will be discussed in a further publication.

Summary

The principles of photo-elasticity are described, and the stress-optical coefficient of strips of cornea determined. The value obtained shows that the birefringence of the corneal lamellae changes rapidly with elongation of the strips, and hence also with the intra-ocular pressure. The possible use of this as a basis for a purely optical method of measuring changes in the intra-ocular pressure, and as a method of studying the molecular structure of the cornea, is described.

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