Brit. J. Ophthal. (1957) **41**, 93.

DISTENSIBILITY OF THE EYE*

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IN clinical ophthalmology the intra-ocular pressure can rarely be determined directly, and reliance must be placed on measurements of the tension of the coats of the eye. The instruments used for the estimation of ocular tension (tonometers) measure the depth of indentation of the globe produced by a known weight. The depth of indentation depends on several factors, the most important of which are the intra-ocular pressure and the distensibility of the eye. Variations in distensibility can have a large influence on the calibration scales of tonometers and therefore some knowledge of the relationship between changes in volume in the eye and the resultant changes in intra-ocular pressure is necessary.

Schultén (1884), Koster (1895, 1901), Greeves (1913), Ridley (1930), and Clark (1932) investigated such volume-pressure relationships in the eyes of various species and, in spite of some differences in detail, the common feature of all the results of these investigators was that the change in pressure induced by a given change in volume in an eye was not constant but depended on the initial intra-ocular pressure. Smaller changes in pressure resulted from the same change in volume at lower intra-ocular pressures than at higher intra-ocular pressures. Friedenwald (1937) attempted to derive an expression relating the pressure and volume changes which could be applied over a wide range of intra-ocular pressures. In an analysis of the results of Koster, Ridley, and Clark, he claimed that above pressures of 5 mm. Hg a linear relationship existed between the volume increment and the logarithm of the pressure. Accepting this relationship, he formulated an equation:

$$\text{Log}\frac{P}{P_o} = K.\Delta V,$$

where P_o = initial intra-ocular pressure above 5 mm. Hg,
P = final intra-ocular pressure,
ΔV = volume change,
and K is a constant.

The constant K in this formula Friedenwald called the "coefficient of rigidity".

In the course of an investigation into the changes in intra-ocular pressure

* Received for publication November 15, 1956

caused by changes in blood volume within the eye, we obtained results which suggested that the value of K was not constant in the rabbit eye, and the following investigation into the relationship between pressure and volume changes was therefore undertaken.

Method

The experiments consisted essentially in the measurement of intra-ocular pressure before and after the introduction of a known volume of fluid (a 0·9 per cent. solution of sodium chloride) into the eye. As fluid is able to leak from the eye through the normal drainage channels for aqueous humour, it is essential that these measurements be made as rapidly as possible.

Adult rabbits weighing 1·7 to 4·7 kg. were anaesthetized by the intravenous injection of a 25 per cent. solution of urethane in doses of 1·75 g./kg.

Two methods have been employed: the 'manometric' and the 'volumetric'.

(*1*) *Manometric Method.*—Fig. 1 is a diagram of the apparatus. Two needles *N1* and *N2* (15 gauge) were introduced into the anterior chamber of the eye of a rabbit after the application of one drop of 2 per cent. pantocaine into the conjunctival sac. The needle *N1* was connected by rigid polythene tubing (1 mm. internal diameter) to a pressure-measuring device, which consisted of a rubber membrane manometer *M* recording optically on a moving photographic film. A saline reservoir *R* was connected to this system by means of a tap *T*. The needle *N2* was connected directly to a micrometer syringe *S* (Agla) with an adjustable stop which allowed rapid rotation of the micrometer head by a predetermined amount. By this means a known volume of fluid (between 7 and 8μl.) could be introduced rapidly into the eye and associated manometric system.

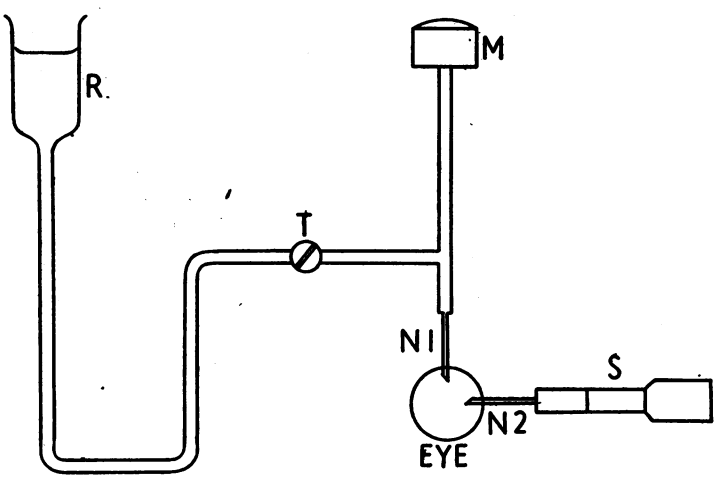

FIG. 1.—Diagram of apparatus for determination of ocular distensibility by manometric method.

M	Rubber membrane manometer	*R*	Saline reservoir
*N*1, *N*2	No. 15 gauge needles	*S*	Micrometer syringe
		T	Tap

The procedure was as follows: the tap *T* was turned to connect the reservoir *R* with the whole system, and the height of the reservoir was adjusted to the initial pressure—usually 5 to 10 cm. saline. The tap was turned to exclude the reservoir and saline was injected from the micrometer syringe. After 5 seconds the micrometer head was turned back to the starting position, and after a further interval of 5 seconds the process was repeated. From three to five injections and withdrawals were made at each pressure level, and the experiment was repeated at ascending pressure steps of 5 or 10 cm. saline up to 50 cm. saline and in similar descending steps to the initial pressure.

The animal was then killed with an overdose of nembutal intravenously and the entire experiment was repeated in the dead animal.

Finally, a calibration of the manometer was recorded on the photographic tracing by connecting the reservoir *R* directly to the manometer and raising *R* in steps of 5 cm. over the range of pressures involved. It was also necessary to determine how much fluid was taken up by the distension of the manometer membrane so that this could be subtracted from the volume injected from the micrometer syringe in order to calculate the volume of fluid which distended the eye. The manometer was therefore connected directly to the micrometer syringe and successive injections of 5μl. saline were made until the movement of the manometer membrane had covered the same range as obtained in the experiments.

Fig. 2 gives an example of a record obtained by this method, showing the changes in intra-ocular pressure following the injection and withdrawal of saline at seven different initial pressures. Using the calibrations of pressure and volume for the manometer, and knowing the total volume injected from the micrometer syringe, the rise of pressure in the eye and the corresponding increase in intra-ocular volume could be calculated.

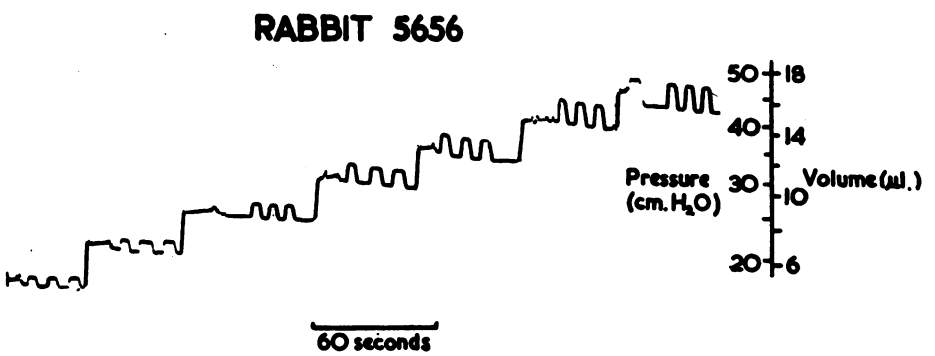

FIG. 2.—Record obtained by manometric method showing variations of intra-ocular pressure after repeated injection and withdrawal of fluid at seven pressure levels. (Pressure tracing line accentuated by re-touching with indian ink.)

(*2*) *Volumetric Method.*—A diagram of the apparatus is shown in Fig. 3 (overleaf). The volume of fluid entering the eye was measured by means of an apparatus which gave a continuous record of the flow of saline through a glass tube. The chief advantage of this method is that the rate of leakage of fluid from the eye is recorded and, if necessary, a correction can be applied for this. The flowmeter consisted of a glass tube *G*, 40 cm. in length, with an internal diameter of 1 mm., having side-pieces *P1* and *P2* at each end. A fine platinum wire *W*, having a resistance of 0·5 ohm/cm. extended through the lumen of the tube and was sealed in at either end and connected as part of a Wheatstone bridge circuit. One sidepiece *P1* of the glass tube was connected to reservoir *R1* which contained mercury, and the other sidepiece *P2* was connected to a second reservoir *R2* containing saline. The tube *G* was then filled, partly with saline and partly with mercury,

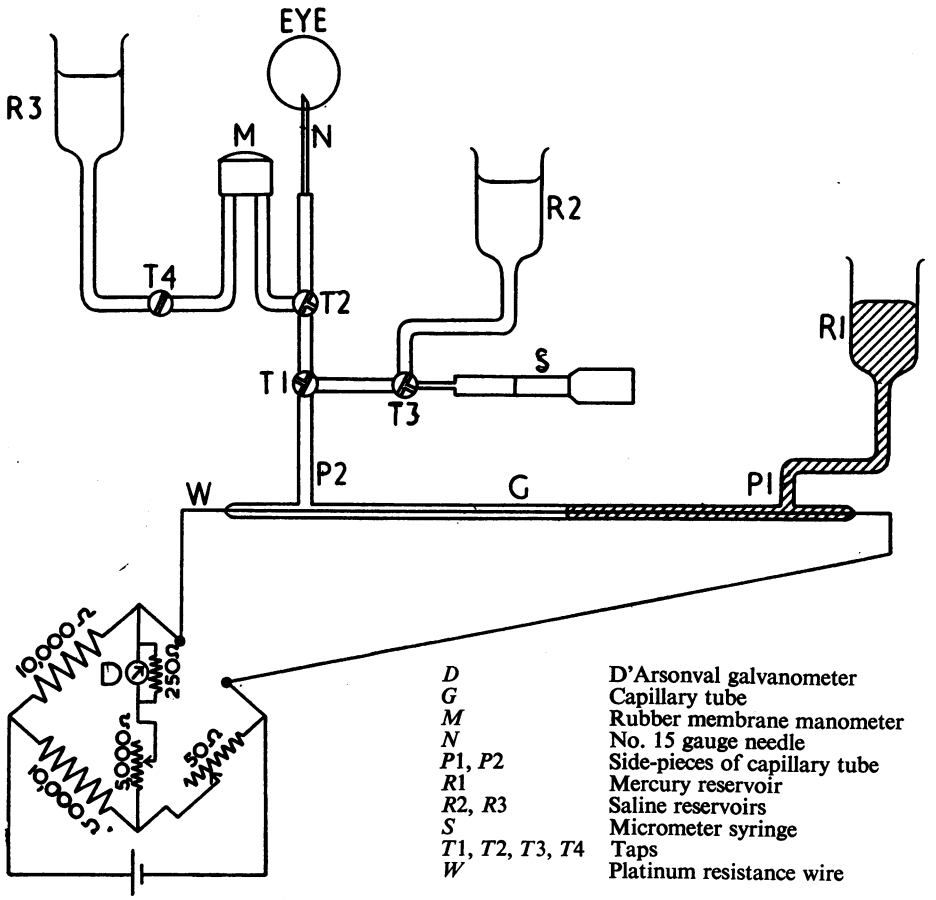

FIG. 3.—Diagram of apparatus for determination of ocular distensibility by volumetric method.

and great care was taken during filling to ensure that air bubbles were excluded. When saline flowed along the tube (from right to left in Fig. 3) the advancing column of mercury decreased the effective resistance of the wire *W*, and this was recorded on a photographic film from the mirror of a D'Arsonval galvanometer *D*.

The sidepiece *P2* was connected *via* the three-way taps *T1* and *T2* to a needle *N*, which was inserted in the anterior chamber of the eye, and also to the three-way tap *T3*, which was in turn connected to the saline reservoir *R2* and a micrometer syringe *S*. By means of a rubber membrane manometer *M*, connected to the anterior chamber *via* the tap *T2*, the intra-ocular pressure was recorded on the same photographic film as the galvanometer deflections. A third reservoir *R3*, filled with saline, could be connected to the system through the tap *T4*.

All connexions were made with polythene tubing and were as short as possible. The rigidity of the system was such that, when the needle *N* was sealed and *R2*, *R3*, *M*, and *S* were excluded from the system (as under the experimental conditions), the pressure could be increased from 0 to 70 cm. saline by raising the reservoir *R1* without any detectable displacement of the boundary between saline and mercury in the tube *G*.

The procedure was as follows:

The needle *N* was inserted into the anterior chamber of the eye of an anaesthetized rabbit with the tap *T2* open to the manometer and the reservoir *R3* set at 25 cm. above the eye and also connected to the manometer *via* the tap *T4*. By using the micrometer syringe *S*, the mercury saline junction was adjusted to a suitable position in the tube, and *T1* was turned to exclude the syringe and *R2* from the system; *R3* was now adjusted to the required pressure and taps *T2* and *T4* were turned to join *R3*, the manometer, and the eye to the tube *G*. *R1* was then raised to give a slow movement of the mercury along the tube. *T2* and *T4* were then turned to exclude the manometer *M* and *R3* from the remainder of the system. After allowing a few seconds for the galvanometer to record the position of the mercury saline junction, the reservoir *R1* was raised rapidly. The resulting influx of saline into the eye caused a movement of mercury along the tube which was recorded on the photographic film from the change in deflection of the galvanometer. *T2* was then opened to the manometer to record the new pressure in the eye. Fig. 4 shows an example of part of a record obtained by this method.

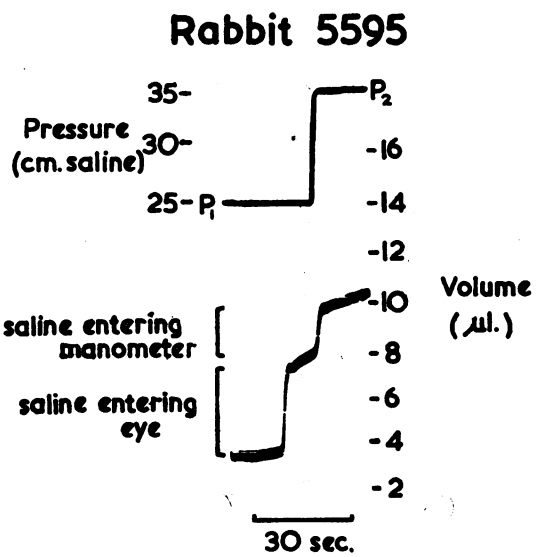

FIG. 4.—Record obtained by volumetric method showing volume of fluid entering eye for rise of intra-ocular pressure of *P*1, to *P*2 cm. saline. (Pressure tracing line accentuated by retouching with indian ink.)

The procedure was repeated at various levels of pressure and again after killing the animal. At the end of each experiment the tracing was calibrated for pressure and volume, using *R3* for the manometer, and the syringe *S* to obtain changes in volume in steps of 5µl. in the flowmeter tube.

Results

Five eyes were studied using the manometric method and five using the volumetric method, but the results from both methods were essentially the same and will be discussed together.

For all ten eyes the increase in intra-ocular pressure for unit volume of fluid injected into the eye became greater as the pressure at which the

measurements were made increased. The results of one experiment are shown in Fig. 5.

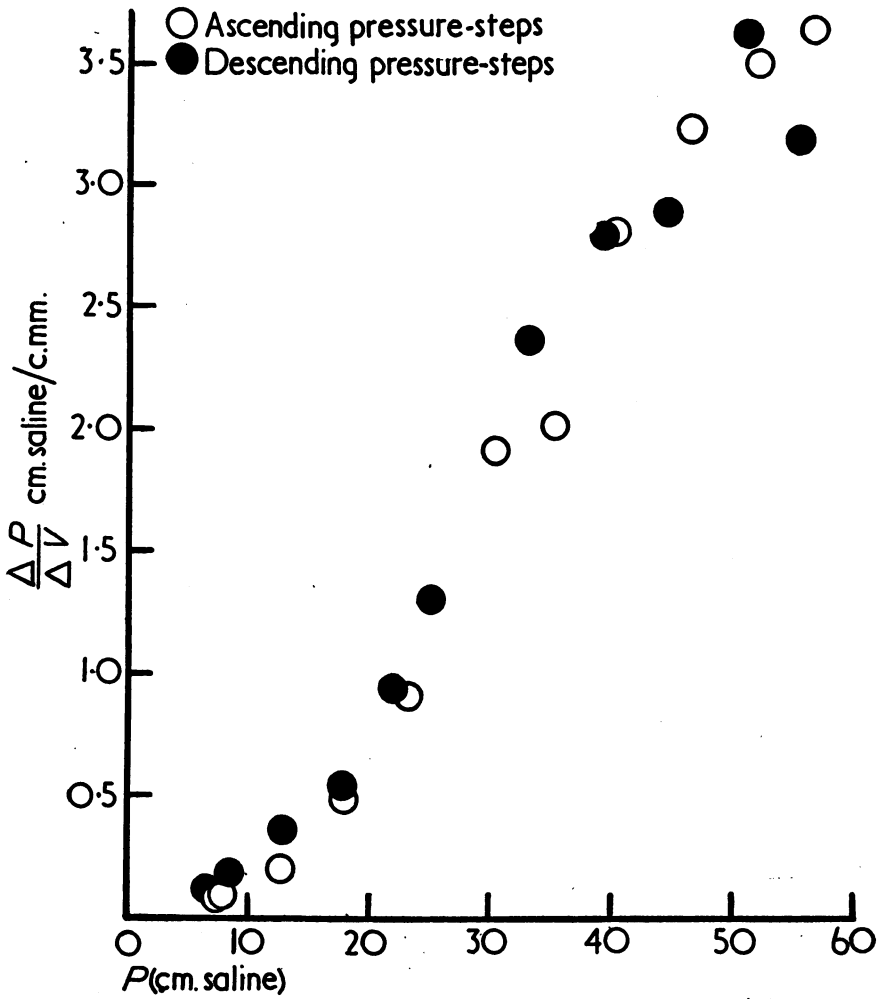

FIG. 5.—Relationship between pressure increment per unit volume injected $\left(\frac{\Delta P}{\Delta V}\right)$ and intraocular pressure (P=mean of initial and final pressures).

The coefficient of rigidity K was calculated at each pressure level from the formula:

$$K=\frac{\log_{10} P-\log_{10} P_o}{\Delta V},$$

where P_o was the initial pressure (cm. saline) and P was the pressure after injection of a volume of fluid, $\Delta V(\mu l.)$.

Fig. 6 (opposite) shows the results of one experiment, and it is seen that

K increased as the pressure at which it was determined increased.

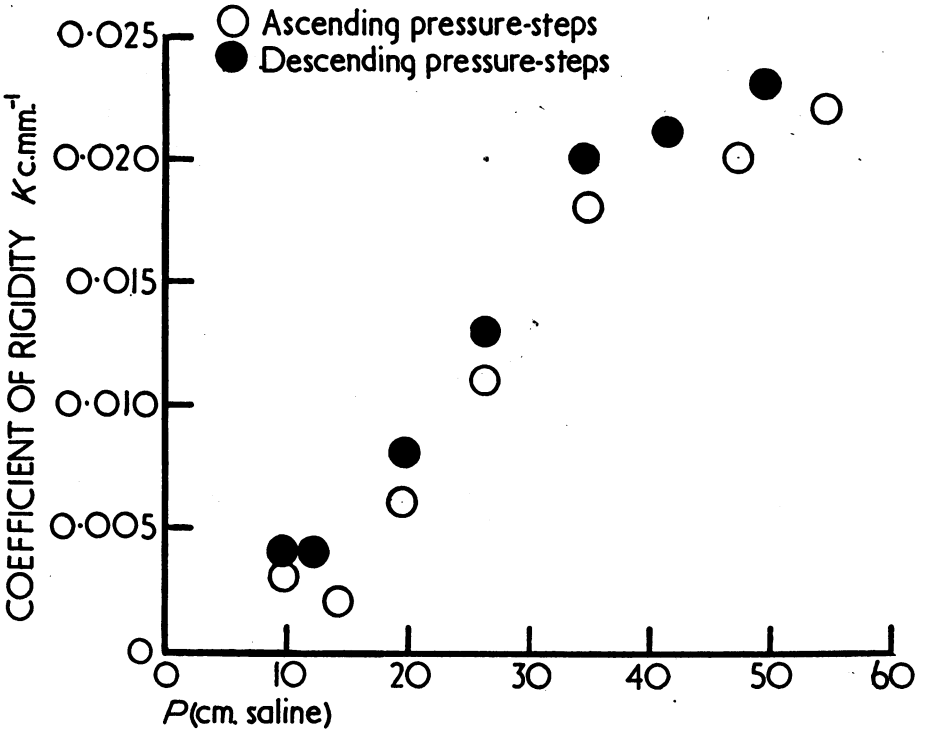

FIG. 6.—Variation of coefficient of rigidity *K* with intra-ocular pressure (*P*=mean of initial and final pressures).

The results for all ten experiments are given in Table I, which shows values for *K* in three pressure ranges, *viz.* 15–25, 30–40, and 45–55 cm. saline; if more than one observation fell within each range, the value of *K* at a pressure nearest to the middle of the range was chosen.

TABLE I
VARIATION OF COEFFICIENT OF RIGIDITY *K* WITH INTRA-OCULAR PRESSURE IN THE LIVING RABBIT EYE

Rabbit No.	Coefficient of Rigidity *K* (c. mm.$^{-1}$)		
	Pressure Range 15–25 cm. Saline	Pressure Range 30–40 cm. Saline	Pressure Range 45–55 cm. Saline
1	0·005	0·010	0·013
2	0·003	0·008	0·011
3	0·006	0·018	0·020
4	0·013	0·019	0·022
5	0·006	0·019	0·023
6	0·011	0·031	0·028
7	0·007	0·010	0·019
8	0·005	0·008	0·015
9	0·003	0·007	0·007
10	0·011	0·023	0·025

The main conclusions to be drawn from these results are as follows:

(1) K increased as the pressure at which it was determined increased.

(2) The variation of K with pressure was greater in some animals than in others.

(3) There was a marked individual variation in the value of K at a given pressure.

Although for the sake of simplicity only three values for K are given for each animal in Table I, between eight and ten determinations at pressure-intervals of approximately 5 cm. saline were made over the range from 10 to 50 cm. saline. From these more detailed results certain additional features were evident:

(*a*) In eight out of ten eyes, determinations of K with descending pressure-steps gave values which were approximately 20 per cent. higher than those obtained with ascending pressure-steps in both living and dead animals.

(*b*) In five out of ten animals, K was approximately 20 per cent. higher in the dead eye than in the living eye at corresponding pressures.

(*c*) Apart from the differences noted in (*b*) the living and dead eyes behaved very similarly.

Discussion

Our experiments show that the rise in intra-ocular pressure which follows the injection of the same volume of fluid increases as the initial pressure rises (Fig. 5), and this finding is in general agreement with the results of previous workers.

In Table II our values for the coefficient of rigidity K are compared with those calculated from the data of other workers. Whilst it is evident that our values for K for the rabbit eye are in general agreement with the results of previous investigations, our finding that K increases as the intra-ocular pressure rises (Fig. 6 and Table I) does not agree with Friedenwald's contention that this coefficient is constant for any individual eye above a pressure of 5 mm. Hg.

TABLE II
COEFFICIENT OF RIGIDITY K FOR THE EYE OF THE RABBIT

Author and Date	K (c.mm.$^{-1}$)	Pressure Range (cm. saline)	No. of Animals	State of Eyes
Present study	0·003–0·028 0·003–0·036	15–55 15–55	10 10	Living Dead *in situ*
Schultén (1884)	0·014–0·028	15–55	5	Enucleated
Koster (1895)	0·005–0·027	15–55	1	Enucleated
Ridley (1930)	0·004–0·010	3–100	6	Dead *in situ*
Grant and Trotter (1955) ..	0·019–0·022 0·012–0·024	Not stated Not stated	1 2	Living Dead *in situ*

Friedenwald (1937) based his calculations mainly on the work of Koster (1895, 1901), Ridley (1930), and Clark (1932), and a critical review of their methods and results reveals the following facts:

(1) Koster's results give values for K which have a wide variation. Consecutive results at pressure intervals of 5 or 10 mm. Hg differ by 50 to 300 per cent., and it is therefore impossible to conclude from them that K remains independent of the intra-ocular pressure.

(2) Ridley briefly described two methods for determining the distensibility of the eye, but it would appear that in neither method was it possible to measure small volume changes accurately, the inaccuracies thus introduced being especially important at higher levels of intra-ocular pressure. Even so, calculations of K from the graphs published by Ridley show some tendency for K to increase as the intra-ocular pressure increases.

(3) Clark used the eyes of the dog, cat, and macaque, and calculations from some of her data show that K tended to increase slightly with the intra-ocular pressure over the range 10 to 50 cm. saline. She did not consider that the rate of loss of fluid from the eye was significant and made no reference to the time taken for each measurement of pressure and volume change. The values of K (dog 0·0015, cat 0·0017, and macaque 0·0041) from her results are low in comparison with our values for the rabbit. This suggests that she overestimated the volume of fluid which distended the eye, because her experimental method may have permitted leakage of a significant amount of fluid through the angle of the anterior chamber. Since the rate of leakage of fluid from the eye is proportional to the intra-ocular pressure, overestimation of the volume of distending fluid would be accentuated at higher pressures. Therefore, the values for K, calculated from Clark's data, are probably too low at higher pressures, and any increase in K with the increase of intra-ocular pressure is partially obscured.

Results for the rabbit eye were also obtained by Schultén (1884), but Friedenwald made comparatively little use of these beyond mentioning that graphical analysis demonstrated an approximately linear relationship between the logarithm of the intra-ocular pressure and the volume increment. However, when K is calculated from Schultén's data, it is found to increase progressively from 0·014 at 17 cm. saline to 0·028 at 48 cm. saline.

It is clear therefore that Friedenwald's assumption that the coefficient of rigidity K is independent of the intra-ocular pressure was based on experimental work, some of which is open to criticism, and that his conclusions therefrom are open to question.

Our results show that the relationship between pressure and volume changes in the eye is complex. This could be due to the fact that the coats of the eye consist of two main layers: the highly vascular choroid, and the almost avascular sclera and cornea. It is conceivable that the choroid could exert a "cushioning" effect in the eye by virtue of its vascularity and connexions with the venous system outside the eye. In the dead eye such an

effect is excluded, and the similarity of the variation of K with intra-ocular pressure in the dead eye and in the living eye makes it very unlikely that the variation found by us is due to the influence of the choroid. On the other hand, the lower values for K in the living eye as compared with the dead eye may be attributable to a "cushioning" effect of the choroid. The sclera does not have a uniform thickness or structure throughout its extent, and Ischreyt (1899) demonstrated that the extensibilities of strips of sclera taken from different meridians of the globe were not the same. Furthermore, it has been observed previously by Ridley (1930) that the maintenance of the high intra-ocular pressure alters the distensibility of the eye; this is the probable explanation of our higher values for K in both living and dead eyes when determined with descending pressure-steps as compared with ascending pressure-steps. In view of the complex physical properties of the sclera, it is not surprising that the relationship between intra-ocular pressure and volume does not conform to a simple law.

This is a question of considerable importance from both the experimental and the clinical point of view, and it is obvious that it merits further exploration.

Summary

(1) Two methods for investigating the relationship between changes in pressure and volume in the rabbit eye are described.

(2) The increase in intra-ocular pressure per unit volume of fluid injected into the eye becomes greater as the intra-ocular pressure increases.

(3) Friedenwald's coefficient of ocular rigidity K was calculated from the data. Contrary to Friedenwald's assertion, this coefficient was not constant, but increased with the intra-ocular pressure in both living and dead eyes.

(4) Measurements of K in dead eyes sometimes gave higher values than in living eyes at corresponding intra-ocular pressures. In the majority of eyes, both living and dead, K was found to be slightly higher after the eye had been subjected to a raised intra-ocular pressure.

(5) It is suggested that the complexity of the relationship between changes in pressure and volume in the eye depends largely on the physical properties of the sclera.

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