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IMPRESSION TONOMETRY AND THE EFFECT OF EYE VOLUME VARIATION*

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It is generally accepted that the amount by which an eye can be indented by a given tonometric load will depend on the initial internal pressure and the elastic properties of the cornea and sclera. This paper sets out to show that the amount of indentation will also depend on the initial volume of the eye. In its simplest form, the hypothesis states that, if there are two eyes of differing initial volumes but with equal internal pressures, then for a given tonometric load, the larger eye will be more indentable than the smaller eye.

The present experimental and theoretical work proves this hypothesis for hollow rubber spheres and evaluates the quantitative effect of a given variation in volume on the indentation produced. In the later sections of this paper it is shown how this hypothesis can explain certain anomalies which arise in clinical measurements made by impression tonometers; the relative merits of impression and applanation tonometry are considered.

I. Assumptions and Simplifications

The eye was considered to be a thin-walled elastic envelope enclosing an incompressible fluid. The shape of eyes varies, some being almost spherical, some more like ellipsoids, and some irregular because of ectatic areas. It has been argued that a given increase in volume can be accommodated by the elongated eye becoming more spherical (for example, Koster, 1895; some discrepancies were found, however, between measurements *in vivo* and on the enucleated eye). That this is probably incorrect can be appreciated by anyone who has blown up a toy balloon, particularly of the "sausage" variety; there is no tendency for it to become spherical when the internal volume is increased, but only to enlarge in a geometrically similar pattern. It has therefore been considered justifiable to carry out experiments on hollow spheres and then to apply the results obtained to eyes which may or may not be spherical. The experimental work has, accordingly, been done on two sizes of thin-walled rubber balls.

Because little information is available on the support received by the eye from its surrounding tissue, no account had been taken of it in this investigation. However, if the supporting tissue behaved elastically, the results of the investigation would not be affected; but, if the orbital tissue were abnormally hard, or if the eye were almost in contact with its bony socket, the eye would no longer behave in the assumed fashion.

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II. Elasticity Measurements for Sclera and Rubber

To obtain valid results when experimenting on a model, it is necessary to select a material with elastic properties similar to those of sclera. Measurements of stress and strain were accordingly made on strips of sclera and on strips of rubber to determine whether their behaviour was sufficiently alike.

Throughout the stress range required for the tests, the sclera and the rubber chosen behaved elastically and the values of Young's modulus for the two materials were very nearly equal. The results are given in Fig. 1. It was not possible to measure Poisson's ratio for sclera and the two Poisson's ratios were assumed to be of the same order; any difference can hardly be sufficient to introduce an important error.

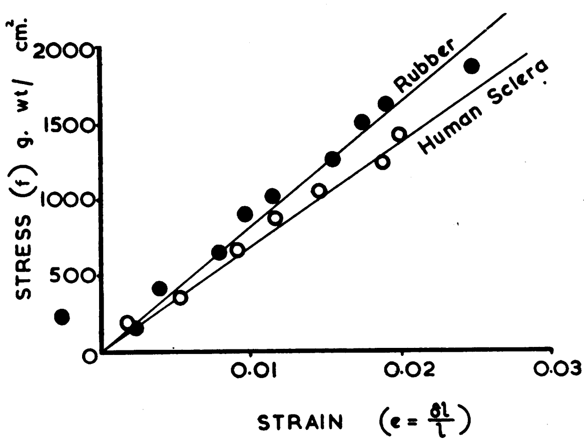

Fig. 1.—Stress-strain curves for rubber and human sclera.

Young's modulus (E) $= \frac{\text{Stress}}{\text{Strain}}$

E (rubber) = 83,000 g. per cm.^{2}
E (sclera) = 70,000 g. per cm.^{2}

For measurements on both rubber and sclera, a parallel-sided test piece was clamped at each end and loaded axially. The strains produced were measured with travelling microscopes by the observation of marks which were a known axial distance apart. Thus any errors arising from slipping in the clamps or any other part of the apparatus were eliminated.

III. Tests on Rubber Model Eyes

As the rubber had been shown to be a suitable material for the models, two hollow rubber spheres were obtained with the following dimensions:

(1) Outside diameter 17·15 cm. Wall thickness 0·269 cm.

(2) Outside diameter 6·04 cm. Wall thickness 0·346 cm.

The results of a series of tests are described in the following sections.

(*a*) *Pressure–Volume Relationships.*—Consider a thin-walled hollow sphere under internal pressure p which undergoes an increase of pressure δp. Let the mean radius of the sphere be r and the wall thickness t. In Fig. 2A (opposite) a sphere is shown cut in half. It is in equilibrium under the action of the skin tension f acting

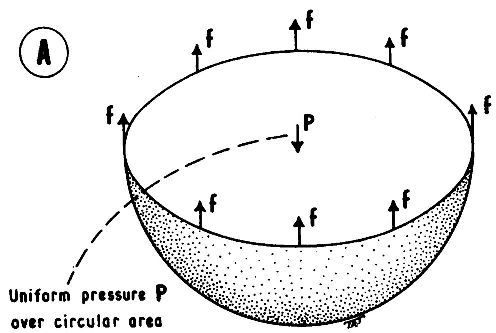

FIG. 2(A).—A hollow sphere cut in half to show equilibrium between skin tension (f) and internal pressure (p) acting over the cross-sectional area πr^2.

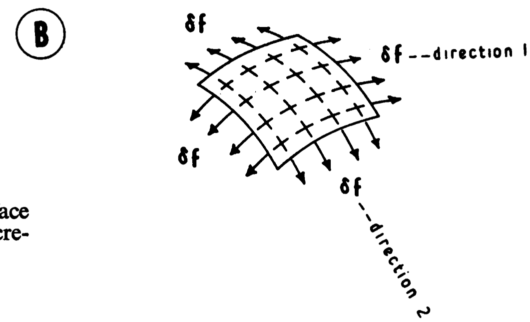

FIG. 2(B).—A small "square" of the surface of the sphere to show directions of increments of stress (δf).

as shown by arrows, and the internal pressure p acting over the cross-sectional area πr^2.

i.e. $$p \,.\, \pi r^2 = 2\pi r \,.\, t \,.\, f.$$

Differentiating,

$$\pi r^2 \,.\, \delta p = 2\pi r \,.\, t \,.\, \delta f.$$

In this expression δf is the increase in skin tension due to an increase of internal pressure δp.

$$\therefore\ \delta f = \frac{r}{2t} \cdot \delta p \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The surface of the sphere is under uniform stress f in all directions. Therefore, if we consider a small piece of the surface as shown in Fig. 2B, the strain in Direction 1 due to stress δf in this direction is e_1,

$$\text{where} \quad e_1 = \frac{\delta f}{E},$$

from the relationship that $\frac{\text{Stress}}{\text{Strain}}$ = Young's modulus (E).

Also, the strain in Direction 1 due to the stress δf in Direction 2 is e_2,

$$\text{where} \quad e_2 = \frac{\delta f}{E} \cdot \frac{1}{m},$$

from the effect of Poisson's ratio, *i.e.* because of tension in Direction 2 there is a contraction in Direction 1.

The resultant strain in Direction 1 is $e_1 + e_2$, and is denoted by e:

$$e = e_1 + e_2 = \frac{\delta f}{E} \cdot \left(1 - \frac{1}{m}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

By substitution for f from Equation (1):

$$e = \frac{\delta pr}{2t} \cdot \frac{1}{E} \cdot \left(1 - \frac{1}{m}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Now, e is the strain around the circumference. But the circumference equals $2\pi r$. Therefore e is also the radial strain.

The initial volume at the original pressure p_o is $\frac{4}{3}\pi r^3$ $(=V_o)$, and the final volume at pressure p is:

$$\frac{4}{3}\pi \cdot \left[r\,(1+e)\right]^3.$$

$$\text{Volume change}\quad \delta V = \frac{4}{3}\pi\, r^3 \left[(1+e)^3 - 1\right]$$

$$= V_o\,[1 + 3e + 3e^2 + e^3 - 1]$$

$$= V_o\,[3e - 3e^2 + e^e].$$

Because e is small, e^2 and e^3 are negligible compared with e,

$$\delta V = V_o \, . \, 3e \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

$$\frac{\delta V}{V_o} = 3e = \text{Volumetric strain.}$$

By substitution from Equation (3):

$$\delta V = \frac{3}{2}\frac{V_o}{E}\left(1 - \frac{1}{m}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (I)$$

where V_o = original volume. E = Young's modulus.
r = mean radius. $\frac{1}{m}$ = Poisson's ratio.
t = wall thickness.

(See, for example, Morley, 1928, where this relationship is derived).

Corresponding dimensions and properties of two spheres of different sizes are to be denoted by the suffixes 1 and 2. From Equation (I), the following ratio is derived:

$$\frac{\delta V_1}{\delta V_2} = \frac{V_1}{V_2} \cdot \frac{r_1}{t_1} \cdot \frac{t_2}{r_2} \cdot \frac{p_1}{p_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (II)$$

(The terms involving E and m and the constant cancel out).

To confirm that this theory was applicable to the spheres used, experiments were carried out to measure the volume change with pressure change.

The apparatus (Fig. 3, opposite) consists of a manometer, made of a burette, connected by thick rubber pressure-tubing to the sphere under test. In this experiment, the indentation rod was not used. The position of the water meniscus in the burette indicated the initial volume and also the mean head of pressure (measured from the centre of the sphere). A change in pressure could be caused by raising or lowering the burette, and this was accompanied by a change in volume so that

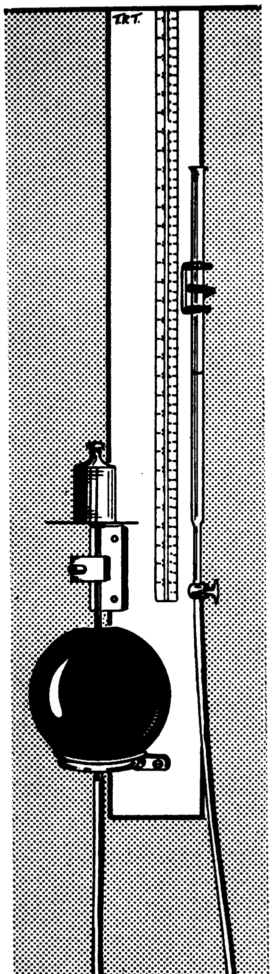

FIG. 3.—Apparatus used for volume–pressure studies. A burette is connected to the sphere under test by thick rubber pressure-tubing; the system is filled entirely with water. Pressure changes are measured from the metre-rule attached to the back-board and volume changes from the markings on the burette. The indentation rod, with platform for weights, slides freely in the mounting block.

the pressure–volume relationship for the sphere was obtained. That the connecting tube did not contribute to this change in volume was checked by sealing the "sphere" end of the rubber tube and then raising the burette to apply a pressure difference of about 150 cm.; the change in volume of the connecting tube was negligible.

The experimental values obtained for the change in volume with change in pressure are given in Fig. 4. Also, it is shown that these results agree with Equation II, so that the theory *is* applicable to the rubber spheres used, and is also, by analogy, applicable to eyes.

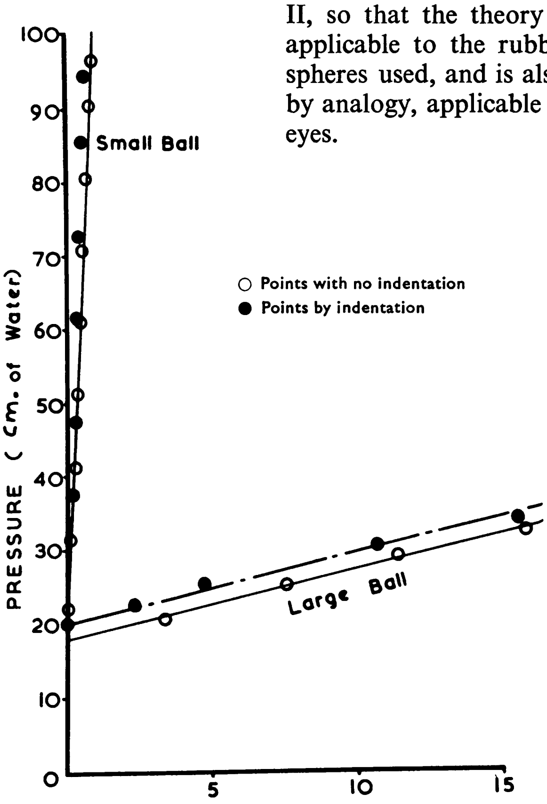

FIG.4.—Pressure changes plotted against volume changes for both large and small balls.

$$\frac{\delta V_1}{\delta p_1} \text{ (large ball)} = 1{\cdot}050 \text{ ml./cm.}$$

$$\frac{\delta V_2}{\delta p_2} \text{ (small ball)} = 0{\cdot}0119 \text{ ml./cm.}$$

$$\frac{\delta V_1/\delta p_1}{\delta V_2/\delta p_2} = 88{\cdot}3$$

Theoretically, from Equation II (by writing $V_1 = 4/3\,\pi\, r_1^3$ and $V_2 = 4/3\pi r_2^3$): $\frac{\delta V_1/\delta p_1}{\delta V_2/\delta p_2} = \frac{r_1^4}{r_2^4} \cdot \frac{t_2}{t_1}$

(*b*) *Pressure–Volume Relationship by Indentation.*—When the volume change is produced by local indentation of the spherical surface, the conditions are no longer exactly those assumed in the previous theory. But it is considered that, provided the indentation is small compared with the size of the sphere, the same pressure–volume relationship will be very nearly correct. Experiments were made to check this assumption with the apparatus shown in Fig. 3. Indentations were produced either by adding weights to the model tonometer (see Fig. 3) or by forcing down a similar rod with a micrometer screw and measuring the indentation produced. After an increment of indentation the pressure was readjusted to its original value and the volume change was obtained from the difference of burette readings. Thus the volume change was measured at constant pressure, but the error involved is small if the increments of indentation are small. Then the original internal volume of liquid in the sphere was restored by a change in the manometer pressure until the burette volume reading had returned to its original position. This gave a measure of δV and δp.

The results are shown in Fig. 4, and it was established that:

$$\delta p = k \,.\, \delta V,$$

and also that:

$$\frac{\delta V_1}{\delta V_2} = \frac{V_1}{V_2} \cdot \frac{r_1}{t_1} \cdot \frac{t_2}{r_2} \cdot \frac{p_1}{p_2} \quad \text{as before.}$$

(*c*) *Indentation–Volume Relationships.*—From the experiments described in (*b*), corresponding values of indentation (*I*) and volume change (δV) had been obtained. When these values were plotted against each other, a non-linear relationship was seen to exist. To discover whether a constant power relationship existed, values of log *I* were plotted against log δV, and Fig. 5 was obtained.

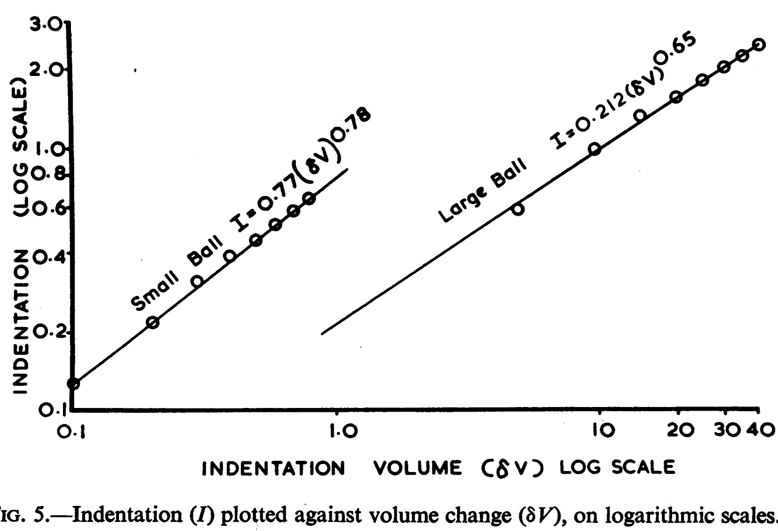

FIG. 5.—Indentation (*I*) plotted against volume change (δV), on logarithmic scales.

It can be seen that a linear logarithmic relationship exists which will be of the form:

$$\log I = n \log \delta V + \log k,$$

giving $$I = k\,(\delta V)^n.$$

The values obtained for k and n for the two spheres gave:

$I_1 = 0{\cdot}212\ (\delta V_1)^{0{\cdot}65}$ for the large sphere.

$I_2 = 0{\cdot}77\ \ (\delta V_2)^{0{\cdot}78}$ for the small sphere.

Dividing these two equations,

$$\frac{I_1}{I_2} = \frac{1}{3{\cdot}63}\frac{(\delta V_1)^{0{\cdot}65}}{(\delta V_2)^{0{\cdot}78}}.$$

Now, the value $\frac{r}{t}$ for each sphere is the ratio of radius to thickness.

Therefore, the ratio $\frac{r_1/t_1}{r_2/t_2}$ is the scale effect between the two spheres used.

By calculation, $\frac{r_1}{t_1} \cdot \frac{t_2}{r_2}$ is found to be 3·65, which is not far from the value of 3·63 in the relationship just obtained; accordingly, as a first approximation, we may write:

$$\frac{I_1}{I_2} = \frac{t_1}{r_1} \cdot \frac{r_2}{t_2}\frac{(\delta V_1)^{0{\cdot}65}}{(\delta V_2)^{0{\cdot}78}}.$$

The scale effect between two eyes of differing volumes will be much less than the exaggerated scale effect used in these tests. Therefore, it seems reasonable to suppose that the index n of δV would not vary much from one eye to another. Also the r/t ratio for an eye is intermediate between the value of r/t for the large and small spheres used in these tests. Hence it is proposed to approximate 0·65 and 0·78 to a value of 0·7 giving

$$\frac{I_1}{I_2} = \frac{t_1}{r_1} \cdot \frac{r_2}{t_2}\left(\frac{\delta V_1}{\delta V_2}\right)^{0.7} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

(Probably the values 0·65 and 0·78 would have been more nearly equal if the r/t ratio for each sphere had been the same).

Before this result is applied to eyes, it is proposed to write t_1', t_2', r_1', r_2', to represent the radii and thicknesses of the indented portion of the eye, namely that of the cornea.

$$\frac{I_1}{I_2} = \frac{t_1'}{r_1'} \cdot \frac{r_2'}{t_2'} \cdot \left(\frac{\delta V_1}{\delta V_2}\right)^{0.7} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3\mathrm{A})$$

From Equation II,

$$\frac{I_1}{I_2} = \frac{r_2'}{t_2'} \cdot \frac{t_1'}{r_1'}\left(\frac{V_1}{V_2} \cdot \frac{r_1}{r_2} \cdot \frac{t_2}{t_1}\frac{\delta p_1}{\delta p_2}\right)^{0.7} \quad . \quad . \quad . \quad . \quad (4)$$

The quantitative effect that differences in eye volume will have on the indentations produced by a given load may now be examined. Although the dimensions of the average eyeball approximate to those of a sphere (Duke-Elder, 1932), it is generally accepted that the larger the eyeball the more ellipsoid, with or without ectatic area, it becomes (Duke-Elder, 1949a, b).

Suppose two eyeballs have the same initial pressure; let one eye be emmetropic with an "average" axial length and one myopic with an abnormally great axial length. Assume the emmetropic eye to be approximately spherical and of mean radius $r_1 = 12$ mm. and the myopic eye to be a prolate spheroid with its major axis $a = 16$ (see Sorsby, Benjamin, Davey, Sheridan, and Tanner, 1957), and its minor axis $b = 13$. By "equivalent volumes", its mean radius, $r_2 = 13{\cdot}94 \simeq 14$ mm.

Also take $t_1 = t_2$. It is assumed that the anterior portions of the eyes are nearly identical so that $r_1' = r_2'$ and $t_1' = t_2'$.

$$\therefore \frac{I_1}{I_2} = \left[\frac{\frac{4}{3}\pi r_1^3}{\frac{4}{3}\pi ab^2} \cdot \frac{r_1}{r_2} \cdot \frac{\delta p_1}{\delta p_2} \right]^{0.7} \quad . \quad . \quad . \quad . \qquad (5)$$

The relationship between δp_1, and δp_2 is now required, and this is given by the condition of equilibrium between the tonometer load and the internal pressure.

As a first approximation we may write:

$$W = (p_o + \delta p)A,$$

where W = tonometric load

p_o = initial internal pressure

δp = rise in pressure due to tonometer

A = *effective* area of contact; this area is greater than the area of the plunger end because the rigidity of the wall of the ball (or eye) spreads the load to some extent. Some preliminary work on tonography has shown that as the indentation deepens slightly the effective area of contact also increases, but only by a small amount which has been ignored in this first approximation.

Then, for two eyes in which p_o is the same, and A the "plunger area" is approximately the same,

$$\delta p_1 \simeq \delta p_2.$$

Continuing with Equation (5), $\frac{I_1}{I_2} = \left[\frac{r_1^3}{ab_2} \cdot \frac{r_1}{r_2}\right]^{0.7}$.

Substituting the appropriate values for r_1, r_2, a, and b,

$$\frac{I_1}{I_2} = \frac{1}{1{\cdot}53}$$

$$I_2 = 1{\cdot}53\, I_1 .$$

For an average emmetropic eye, let indentation $I = 5{\cdot}75$ units with the 7·5 g. weight. On the other hand, the myopic eye, with dimensions assumed and with *the same initial internal pressure*, would be expected to give indentation, I_2, where

$$I_2 = 1{\cdot}53 \times 5{\cdot}75 = 8{\cdot}8 \text{ units.}$$

Observations by Goldmann and Schmidt (1957) indicated $I_2 = 8{\cdot}0$, 8·75, or 9·5 for eyes with refractions of –20 D sph.; their axial lengths would be approximately 32 mm. (see Sorsby and others, 1957), as assumed for purposes of the above calculation. Goldmann and Schmidt's result, explained by low scleral rigidity, gives a very similar answer to the above which has been theoretically derived and has allowed only for differences in intra-ocular volume. In our calculations no account has been taken of variations in thickness of the corneo-scleral envelope or in elasticity of sclera.* The analysis, with its admitted approximations and assumptions, will slightly over-estimate the value of I_2 because as indentation increases so the resistance of the wall of the eye will become more significant.

Clinical Applications

It is now proposed to discuss the possible ophthalmic applications of these physical principles and to show that the inferences drawn are consistent with clinical experience. Mention will be made in the appropriate sections of factors in the biological system of the eye which may affect the conclusions.

In a series of eyes of different volumes but with the same intra-ocular pressure, it would be expected that the larger the eye the lower will *appear* to be the intra-ocular pressure, if it be measured by impression tonometry. Even a pathologically high intra-ocular pressure in a given eye could appear to be within normal limits if the impression tonometer used had been calibrated on a smaller eye. Similar considerations, *mutatis mutandis*, will apply to small eyes. Digital tonometry will suffer from the same defect since it is a form of impression tonometry.

Tonometer Calibration

More consistent results in the calibration of impression tonometers were obtained on enucleated eyes by open-stopcock than by closed-stopcock methods (see discussion of Schiötz's original observations 1905, 1909, and 1911, by Friedenwald, 1954; the latter concludes that variations in scleral rigidity are responsible.) The discrepancy is explicable however, to some extent at least, by the fact that the *relatively* small variations in volume of tested eyeballs are "swamped" in open-stopcock conditions by the large amount of fluid in the system outside these eyeballs, unlike the situation when the stopcock is closed.

Scleral Rigidity

The elasticity of sclera has been investigated by several workers (Weber, 1877; Koster, 1895; Greeves, 1913; Ridley, 1930; Clark, 1932; Friedenwald, 1937; Perkins and Gloster, 1957a, b; and Gloster, Perkins, and Pommier,

* The formula for coefficient of scleral rigidity is unsound because it omits V_0 the original volume, and would be better replaced by Young's modulus and Poisson's ratio (or by a bulk modulus, as implied by Clark, 1932).

1957). Some, at least, of the variation attributed to the elasticity of sclera is likely to have arisen from the statement by Friedenwald (1937): "*We can assume V* (volume of eye) *to be roughly constant*". Data recorded by Sorsby and others (1957) suggest that this assumption is unwarranted, so that variations in volume must replace some of those attributed to scleral rigidity. Clark (1932), however, mentions the importance of volume—"the value for $\frac{dv}{dp}$ would differ from animal to animal owing to differences in eye volume even if the elasticity were the same"—but does not apply the principle to tonometry or the problems of glaucoma. Schiötz (1911) stated that the relationship he found between quantity of fluid injected and increase in pressure did not agree with that of Schultén (1884); this disagreement he attributed to the difference in volume of rabbit and human eyes.

Goldmann (1957a) found a higher scleral rigidity in one −25 D eye than in another of only −20 D. Two explanations not involving scleral rigidity seem possible: the sclera of the −25 D eye may have received support from the walls of its bony orbit; the better explanation is that the more myopic eye had a shorter axial length and a smaller volume than the −20 D eye.

Low-Tension Glaucoma

So-called *low-tension glaucoma* tends to occur in myopic eyes (Duke-Elder, 1949a, b, c); in them, the myopia is presumably axial and therefore, almost certainly, the eyeball has a larger than "normal" volume, so that an impression tonometer would be expected to give an erroneously low reading. The situation may be further complicated by the presence of a flat cornea in axial myopia. The tension of myopic eyes has been shown by applanation tonometry (Goldmann, 1957b) to be usually, in fact, higher than that indicated by impression tonometry, a finding attributed to low scleral rigidity. The very small change in volume, both absolute and relative, produced by applanation (0·44 cu. mm.—Goldmann, 1957c) as opposed to impression (5 cu. mm. or more, depending on intra-ocular pressure: see Goldmann, 1957d) tonometry, must be a very important factor in the discrepancy between readings by these two methods.

Nychthemeral variations in intra-ocular pressure are physiological. A large eye will "react" with a smaller rise in pressure than will a smaller one to the same change in volume. That consideration may be valid in explaining the clinical impression that "low-tension glaucoma" is very slowly progressive and occurs in older people. It assumes that the number of units producing aqueous humour and their rate of production (also its variability) do not vary proportionately from eye to eye with intra-ocular volume—no evidence on that point exists. It has been observed that ocular pulsation produced by the cardiac and respiratory cycles is small or absent in myopic eyes and in eyes with "low-tension glaucoma". Although poor "reactivity" of large eyes, because of their volume, to pulsations of intra-ocular blood vessels may be the explanation, it is quite possible that the "atrophic" state of the choroidal vascular system in myopes is the determining factor.

Since a given ocular refraction can be associated with a range of axial lengths (Sorsby and others, 1957), an "abnormally" large intra-ocular volume need not necessarily imply myopia, nor *vice versa.*

Applanation v. *Impression Tonometry*

In applanation tonometry a "plate" flattens a portion of the eye. Therefore, if the rigidity of the coats of the eye is small, equilibrium is reached when:

$$W = a\,(p + \delta p),$$

where a is again slightly greater than the area of contact of the plate (see notation of Equation 6),

p is initial eye pressure,

and δp is increase in eye pressure due to volume change.

In impression tonometry, a similar relationship will hold, but because of the smaller area of contact, δp will be much larger. It is realized that this expression holds good only for shallow indentations in which skin tension contributes only a small component in the axis of the plunger. This is confirmed by experience with the two methods, for it is found that with the impression method intra-ocular pressure approximately doubles, whereas with applanation, the pressure rises by approximately one-twentieth (Goldmann, 1957a). Also, corneal curvature, within a surprisingly wide range, has a negligible effect on the readings obtained from an applanation tonometer (Schmidt, 1956).

Thus, applanation tonometry is almost a direct measurement of internal pressure, and any errors due to variations in eye volume or scleral rigidity will be within the limits of the pressure increase δp (of the order of 0·75 mm. Hg). Therefore, it is suggested that the anomalous results from impression tonometry due to variations in eye volume as well as any due to those of scleral rigidity can be almost completely eliminated by the use of the applanation method. An example is illustrated in the following Table (data from Goldmann, 1957d):

Tonometry Method	Indentation	Applanation
Volume Change ($mm.^3$)	13	0·44
Initial Pressure (mm. Hg)	16	16·00
Final Pressure (mm. Hg)	38	16·75
Pressure Change (mm. Hg)	22	0·75

Thus the error in indentation tonometry due to the different eye volume will be $\frac{13}{0{\cdot}44} \simeq 30$ times the error incurred in applanation tonometry.

Intracameral Volume

The three compartments of the eye are probably freely intercommunicating, although it might be argued that a sudden rise of intracameral pressure, especially if large, produced by a tonometer, would not immediately be transmitted to the posterior chamber because the iris would be pressed against the iris-lens diaphragm; that might tend to occur especially in eyes predisposed to closed-angle glaucoma and might be expected to produce an even more unrealistically high tonometer (impression) reading than would be expected on the grounds of small intra-ocular volume alone in these eyes. However, even very slight mobility of the iris-lens diaphragm would nullify that effect. François, Rabaey, and Neetens (1956a, b) and François, Rabaey, Neetens, and Evens (1958) have shown that the facility of outflow falls with decreasing depth of anterior chamber. That finding may be explicable by the increasing deformity in the eyeball caused by their method of reducing the depth of the anterior chamber which results in an increasing deformity in the corneal curvature and/or in the channels of outflow.

Hydrophthalmos and Microphthalmos

As a child's eye increases in size to become buphthalmic, impression tonometry will appear to show a fall in ocular tension although, in fact, intra-ocular pressure remains unchanged. Self-limitation of the disease should not, on that evidence, be postulated. However, the increase in size may have two beneficial effects. First, the area of cross-sections of the channels for aqueous outflow may alter with increased size of the globe whereas the rate of aqueous production is unlikely to increase. Secondly, as the eyeball increases in size, it will be able to "accommodate" transient increases in volume with less destructive rise of pressure than in its previous, smaller, state. Furthermore, an impression tonometer would underestimate the tension only if, *ceteris paribus*, the volume of the buphthalmic eye were greater than the presumably adult eye on which the tonometer was originally calibrated.

An eye with an unusually small volume (not necessarily, though usually, hypermetropic) will appear to have a higher than normal tension when it is measured by impression tonometry, even if corneal curvature be not greater than normal. The results of applanation tonometry support that deduction, for they show *lower* pressures than those given by impression methods (Goldmann and Schmidt, 1957: explained on a basis of high scleral rigidity).

Provocative Tests

A false positive water-drinking test may be obtained from a non-glaucomatous small eye, even if the measurements are made by applanation; the impression method would add to the false positives if an arbitrary upper limit were used as an additional criterion of normality irrespective of initial pressure. False negatives can be expected from large but glaucomatous eyes, even with the applanation method. Some of the variance in results from normal eyes must be attributable to the wide range of volumes found in them; other sources of error must, of course, be blood volume, body weight, vascularity of gastric mucosa, etc.

The reaction to darkness and mydriasis of normal and glaucomatous eyes must be affected by intra-ocular volume, even if estimated by applanation. Additional false positive results could arise from the use of an arbitrary upper limit with impression methods as in the water-drinking test above. Foulds (1957) has shown that the reaction to darkness in closed-angle closure glaucoma increases with increase in initial tension. Some of the gradient in his Fig. 2 might be attributable to the effect of increasing (axial) hypermetropia, *i.e.* decrease in volume.

Darkroom outflow (Foulds, 1956) and homatropine outflow (Becker and Thompson, 1958) tests will be relatively little, if at all, affected by variations in volume. That fact may explain (part of) their high sensitivity.

All these considerations are based on the assumption (no evidence exists) that the numbers of units of input, their rate of production of aqueous humour, and their reactions to provocation, do not vary *pari passu* with the size of the eyeball.

Simulated tonography is being investigated. Preliminary results suggest that variations in intra-ocular volume will have much less effect on tonography than on tonometry because P_o, probably, is the only term which will be significantly altered in the usual formula for the calculation of facility of outflow. It is suggested that the difficulty of allowing for initial volume may be overcome by the use of an applanation value for P_o.

Further Discussion

Those who criticize recurrent modifications of the calibration charts accompanying impression tonometers as being, in clinical work, merely confusing receive support from the above physical experiments. A further serious criticism of these re-calibrations is that they entail an unnecessary reassessment of provocative tests, even if only a translation of their values into scale divisions.

It cannot be accepted that a reading of three-scale divisions (with a 5·5-g. weight) is the upper limit of normal, except in certain well-defined conditions of *intra-ocular volume*, corneal curvature, scleral rigidity, and even, perhaps, intracameral volume. It is at present impractical clinically to measure with any degree of accuracy all of these variables, so that applanation tonometry would appear to be a much more accurate method of estimating intra-ocular pressure. Similarly, the validity of the time-honoured practical indication for operation in simple (open-angle) glaucoma, *viz.* continued field loss in spite of medical treatment, is upheld.

It should be emphasized that all the above considerations are based on the *applications* of some entirely *physical* experiments in which some approximations have been used; the detailed picture will be more complex. They agree very well with clinical observations and they provide a more economical hypothesis to explain some aspects of glaucoma. It seems reasonable to suggest, therefore, that variations in scleral rigidity are less important than previously thought. Nevertheless, further work on enucleated eyes and on patients will have to be done to confirm the deductions.

SUMMARY

Experiments on hollow, water-filled rubber spheres have shown that a given change in volume, produced by indentation or other methods, will result in a change in pressure which is an inverse function of the initial volume of the sphere (allowance being made for differing thicknesses of wall). Some quantitative and theoretical aspects of that principle are described. By analogy, it is suggested that eyes which are larger than those on which an impression tonometer was calibrated will give an *apparently* low reading of ocular tension (hence "low tension glaucoma"), whereas the tension will be misleadingly high with smaller eyes. The published observations with the applanation tonometer (which must, *qua* intra-ocular volume, provide a more accurate estimate of intra-ocular pressure) are consistent with that argument; hitherto, variations in scleral rigidity have been held entirely to account for discrepancies between readings obtained by applanation and impression.

Other implications of the thesis, for example in buphthalmos, provocative tests, and open- and closed-stopcock methods of calibrating tonometers are mentioned.

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