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VOLUME CHANGES IN INDENTATION TONOMETRY*†

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APPLANATION tonometry is now regarded as the most accurate clinical method of measuring ocular tension, and is rapidly replacing indentation tonometry. Nevertheless, the latter method is still widely used, particularly for tonography, tonometry during operative procedures, examination of children under anaesthesia, and for measuring diurnal variations in tension. The purpose of the present study was to determine the optimum configuration of an indentation tonometer, with particular reference to the volume of indentation caused by the tonometer.

The Schiøtz tonometer is a typical and well-known example of an indentation tonometer. The plunger of the tonometer which indents the cornea also acts on a lever which has an indicator pointing to a calibrated scale. Although the scale readings can be calibrated in terms of intra-ocular pressure when the eye is connected to a manometer (open stopcock readings), it is found that the original pressure (P_o) in the intact eye increases as the indentation tonometer comes to rest on the cornea. This increased tension during tonometry (P_t) could be used to deduce the original pressure if all the factors contributing to the raising of tension were taken into account.

Friedenwald (1947) introduced a nomogram correlating scale readings (R), P_o, and P_t with two other factors, namely the volume of indentation (V_c), and a constant (K) which he called scleral rigidity. In 1954 his work was incorporated in the Decennial Report by the Committee on Standardization of Tonometers of which he was Chairman. He correlated the scale readings (R) of the Schiøtz tonometer with P_o, using a closed stopcock method. This method, previously used by Schiøtz himself at the turn of the century, consisted of cannulating the eye through the optic nerve, measuring the intra-ocular pressure manometrically, closing the connexion between the eye and the rest of the system as close to the eye as possible, and calibrating the scale readings after the instrument had rested on the eye. For the correlation of the scale readings with the V_c and P_t values, it was necessary to use an open stopcock experiment. Here, as the tonometer comes to rest on the cornea, fluid is allowed to escape into the manometer system, the volume change being measured. Finally, ocular rigidity was determined by correlating the rise in intra-ocular pressure produced by the introduction of known volumes of fluid.

These techniques enabled Friedenwald to derive the pressure rigidity nomogram and the following equation:

$$\text{Log } P_o = \text{Log } P_t - KV_c$$

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The coefficient of scleral rigidity is always less than unity; the mean value in 500 normal eyes measured by Friedenwald was 0·0215. On examining the above equation, it is obvious that if the factor KV_c is reduced to zero, log P_o is equal to log P_t, and consequently the P_t calibration, which can be derived with a fair degree of accuracy experimentally, can be used to obtain a value for P_o.

K is an attribute of the eye, but if the volume of indentation (V_c) is reduced to a minimum, the factor KV_c becomes smaller and P_t becomes more nearly equal to P_o.

With this argument in mind, this work was aimed at studying the configuration of the Schiøtz type of indentation tonometer in relation to V_c.

Methods

Enucleated human eyes which had been stored in liquid paraffin at 4°C. for a period of not more than one month were used. The swelling of the cornea which takes place under these conditions was reduced by bathing the cornea on both surfaces with a solution of 6 per cent. dextran. The experiments were conducted when the corneal thickness reached 0·5 to 0·65 mm. The anterior segment of the eye was mounted in a chamber (Fig. 1) so that the external surface of the cornea was exposed, and the inner surface bathed with isotonic saline, which exerted a pressure on the posterior corneal surface equal to the height of the fluid in a reservoir connected to the chamber. The pressure could be varied by changing the height of the reservoir. A graduated glass pipette containing a small air bubble was placed between the chamber and the reservoir and acted as an indicator of the volume of saline displaced from the eye to the reservoir. The system also included a 3-way tap and a syringe, used for positioning the air bubble at the zero mark before each reading. Footplates, plungers, or both were gently lowered to rest on the cornea, using two guide rings to ensure correct application of the instrument. Three readings were taken at each pressure.

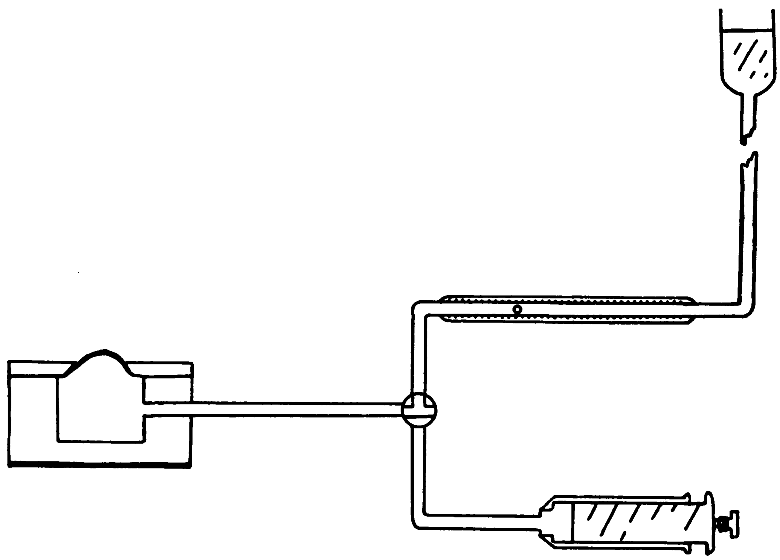

FIG. 1.—Diagram of apparatus.

During the study of the deformation of the cornea by the plunger, moulds of the plunger on the cornea were taken in a fashion similar to contact-lens fitting techniques. Alginate dental impression compound was poured onto the undisturbed cornea and a mould was obtained. This mould produced a negative cast which was liable to shrink and disintegrate and was therefore transferred within 10 minutes into a permanent stone mould. When the stone mould was hard, it was ground down with fine corrosives until the central section of the mould was reached from both sides, and a profile of the cornea less than 1 mm. thick was thereby obtained. Similar casts were produced from eyes on which a plunger was resting.

Results

(A) Footplate and Plunger

The ordinary Schiøtz tonometer was first examined with various plunger weights, 5·5, 7·5, and 10 g. The effects on the volume of displacement at various intra-ocular pressures are seen in Table I and Fig. 2.

TABLE I
EFFECT ON VOLUME OF INDENTATION (µL.) OF DIFFERENT PLUNGER WEIGHTS USING A COMPLETE SCHIØTZ TONOMETER

P_t (cm. saline)	Weight of Plunger (g.)		
	5·5	7·5	10·0
10	152	Over 180	Over 180
20	69	84	169
30	31	40	102
40	19	26	38
50	13	18	25

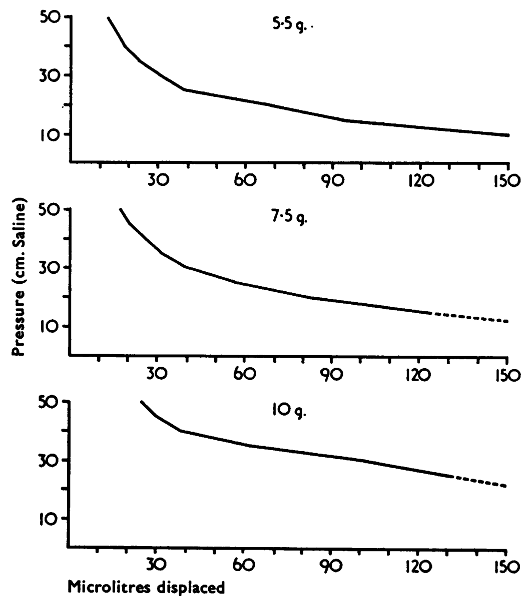

FIG. 2.—Effect on V_c of different plunger weights, using a complete Schiøtz tonometer.

The greater the weight of the plunger of a tonometer resting on an eye with a given intra-ocular pressure, the greater is the volume of fluid displaced. It is equally obvious that, with a given plunger weight, V_c is greater in an eye with a low intra-ocular pressure than in one with a higher pressure.

The next step was to analyse separately the effects on volume displacement of changing the configuration of the footplate and plunger.

(B) Footplate

The footplate of the Schiøtz tonometer has the following physical characteristics, as laid down in 1954 by the Committee on Standardization of Tonometers:

Weight of footplate and scale lever (without handle)	12·5 g.
Diameter of footplate	10·0 mm.
Radius of curvature of footplate	15·0 mm.
Shape of footplate	Spherical concave.

A series of footplates was constructed with variations in each of the above characteristics, and the effect on volume displacement was recorded.

(*1*) *Changes in Weight*.—Three footplates were constructed having a normal shape and radius of curvature but varying in weight. The weights tested were 7·5, 10·0, and 12·5 g. No plunger was used. The findings are shown in Table II and Fig. 3.

These results follow a similar pattern to those found with the tonometer as a whole. The important finding is the great reduction in V_c values when a light-weight footplate is used.

TABLE II

EFFECT ON VOLUME OF INDENTATION (μL.) OF VARIATION IN WEIGHT OF FOOTPLATE

P_t (cm. saline)	Weight of Footplate (g.)		
	7·5	10·0	12·5
10	14	26	73
20	6	9	24
30	3	5	11
40	2	3·5	6
50	1·5	2	4

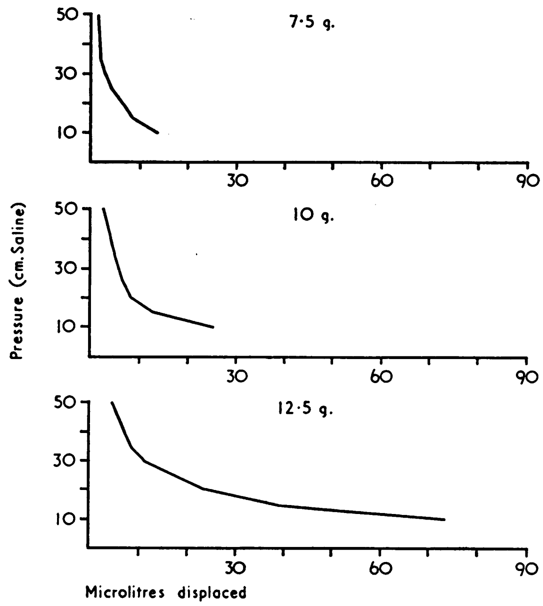

FIG. 3.—Effect on V_c of different footplate weights.

(2) *Changes in Diameter.*—Keeping other characteristics constant, three footplates with diameters of 8, 10, and 12 mm. were tested. The results, shown in Table III and Fig. 4, indicate that there is little difference between the 10- and 12-mm. footplates, but that with the 8-mm. footplate the volume change is high. Perhaps foot-

TABLE III

EFFECT ON VOLUME OF INDENTATION (μL.) OF VARIATION IN FOOTPLATE DIAMETER

P_t (cm. saline)	Diameter of Footplate (mm.)		
	8	10	12
10	145	73	70
20	32	18	20
30	12	10	11
40	7	6	6
50	5	4	4

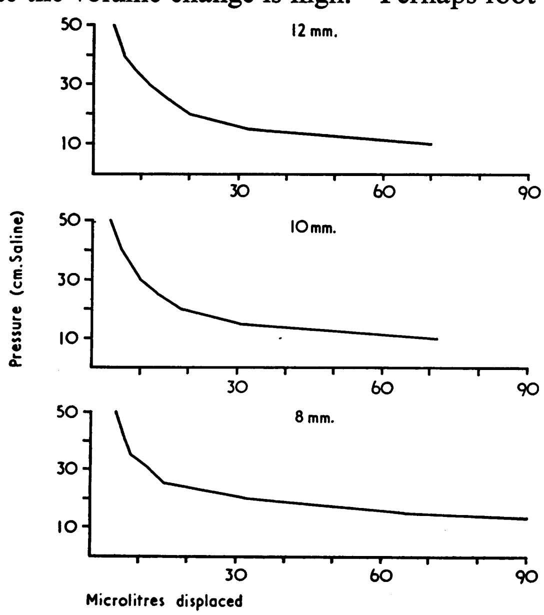

FIG. 4.—Effect on V_c of different footplate diameters.

plates with small diameters act more as plungers than as supporting devices, and in turn indent the cornea. The difference between these footplates is most marked in the lower ranges of intra-ocular pressure, where the area of contact between the cornea and the footplate is greatest.

(*3*) *Changes in Curvature*.—Four footplates were constructed, each with a different radius of curvature; three had concave ends with radii of 15, 12, and 8 mm., while in the fourth footplate the curvature was infinitely large, *i.e.* the end was flat. The volumes of fluid displaced by these footplates are shown in Table IV and Fig. 5.

TABLE IV
EFFECT ON VOLUME OF INDENTATION (μL.) OF VARIATION IN FOOTPLATE CURVATURE

P_t (cm. saline)	Radius of Curvature (mm.)			
	8	12	15	Flat
10	56	67	73	117
20	15	17	18	40
30	7	9	11	21
40	5	6	6	13
50	3	4	4	1

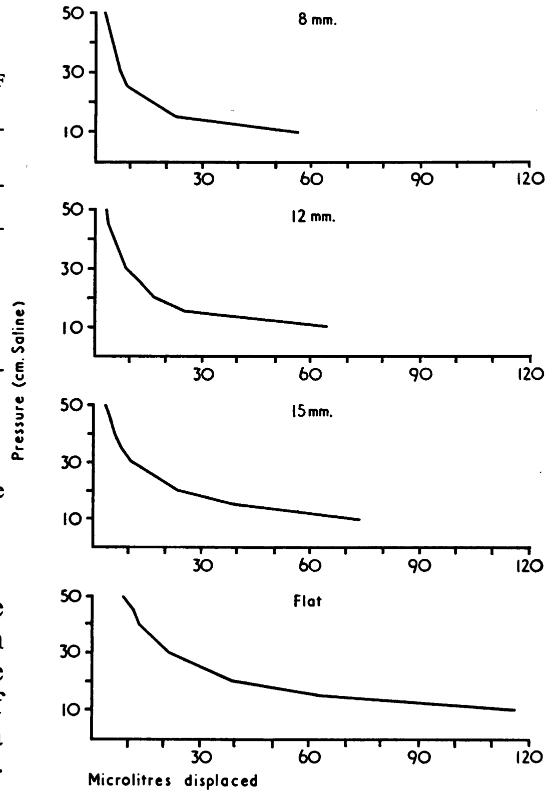

FIG. 5.—Effect on V_c of different footplate curvatures.

The conventional 15-mm. footplate displaced a larger volume of fluid from the eye than the other two concave footplates with a shorter radius of curvature. The footplate with a radius of curvature of 8 mm. displaced the smallest amount of fluid, while the flat footplate produced the greatest displacement. The difference was most noticeable in the eyes with low intra-ocular pressures. The footplate which conformed with the anterior corneal curvature (average radius 7·8 mm.) displaced the least amount of fluid, while the flatter footplates displaced a greater volume as the radius of curvature increased. Kronfeld (1954) tested footplates with radii of curvature from 14 to 16 mm., and found that such a variation did not alter the performance of the instrument.

(*4*) *Changes in Shape*.—We have seen that altering the curvature of the footplate alters the volume of indentation. Maurice (1958) described a tonometer with a hollow conical footplate with which he found the volume of displacement to be very small. The apical angle of the cone he used was 120°.

Three cones were constructed with apical angles of 102°, 106°, and 112°. The angles chosen were designed to produce tangents to a sphere with a radius of 7·8 mm.; the chords joining the two tangents were 11, 10, and 9 mm. long respectively (Fig. 6).

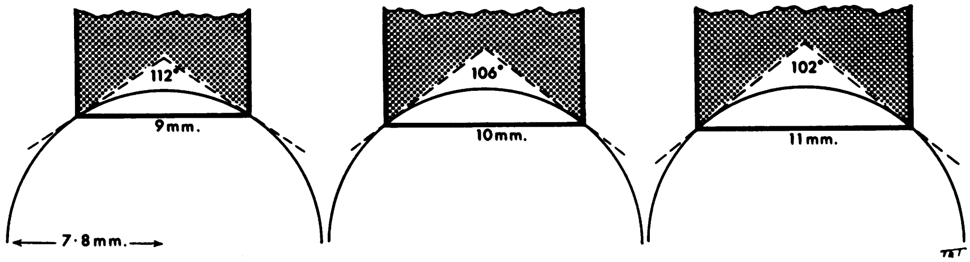

FIG. 6.—Conical footplates.

In other words, cones were used of which the base, when fitting an average cornea, subtended approximately the angle chosen. Maurice's cone with an apical angle of 120° would cut a chord approximately 8 mm. long when resting on an average cornea. Results with 10-g. footplates only are shown in Table V (opposite), as lighter weights showed similar changes but smaller volumes of indentation (Fig. 7).

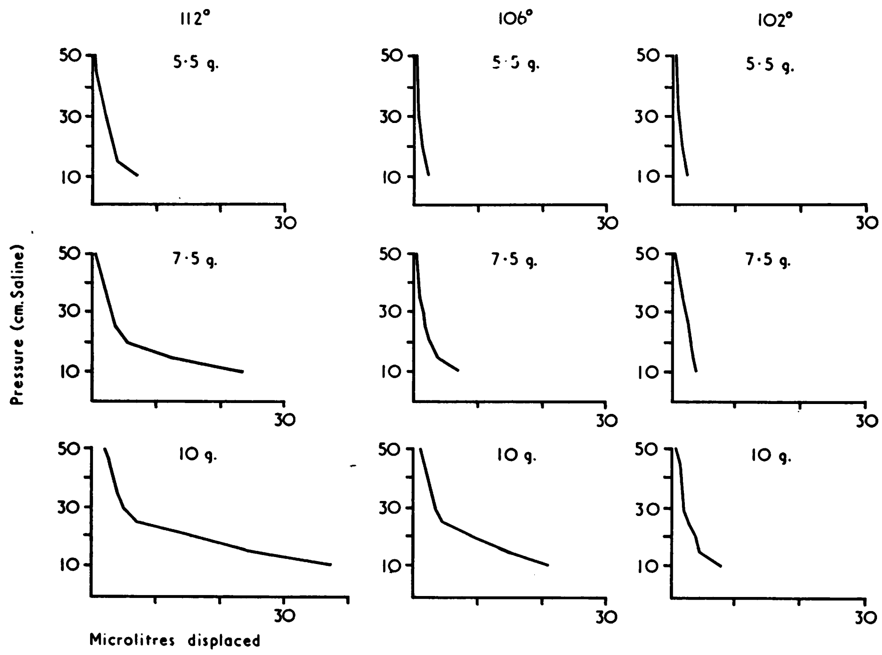

FIG. 7.—Effect on V_c of conical footplates of different curvatures and weights.

The results show that the smaller the apical angle, and at the same time the greater the diameter of the base of the cone, the less is the volume of displacement. The footplate with a conical end having a diameter of 11 mm. at its base and an apical angle of 102° displaced the smallest volume of all the footplates tested. It seems that a cone with a wide base can exert its weight at the limbus and deform the cornea less (especially at low intra-ocular pressures) than a cone with a large apical angle and narrow base which exerts its deforming force mainly on the cornea, the distortion of which is largely responsible for the V_c values.

TABLE V

EFFECT ON VOLUME OF INDENTATION (μL.) OF APICAL ANGLE OF 10-G. CONICAL FOOTPLATE

P_t (cm. saline)	Apical Angle of Cone		
	102°	106°	112°
10	8	21	31
20	4	15	25
30	2	4	5
40	2	2	3
50	1	2	2

TABLE VI

EFFECT ON VOLUME OF INDENTATION (μL.) OF DIAMETER OF 10-G. RING FOOTPLATE

P_t (cm. saline)	Diameter of Ring (mm.)	
	8	10
10	68	26
20	21	7
30	7	3
40	3	2
50	2	2

Two more footplates were constructed from wire 0·8 mm. in thickness; the wire was made into rings with an external diameter of 8 and 10 mm. respectively. Their effect on volume of indentation is represented in Table VI and Fig. 8. Only values for 10-g. tonometers are shown in Table VI, which shows that the ring 10 mm. in diameter caused a smaller amount of fluid to leave the eye than the ring with a diameter of 8 mm. However, considering comparable cones and rings, *i.e.* the 10-mm. ring footplate with the 106° conical footplate, the results are similar.

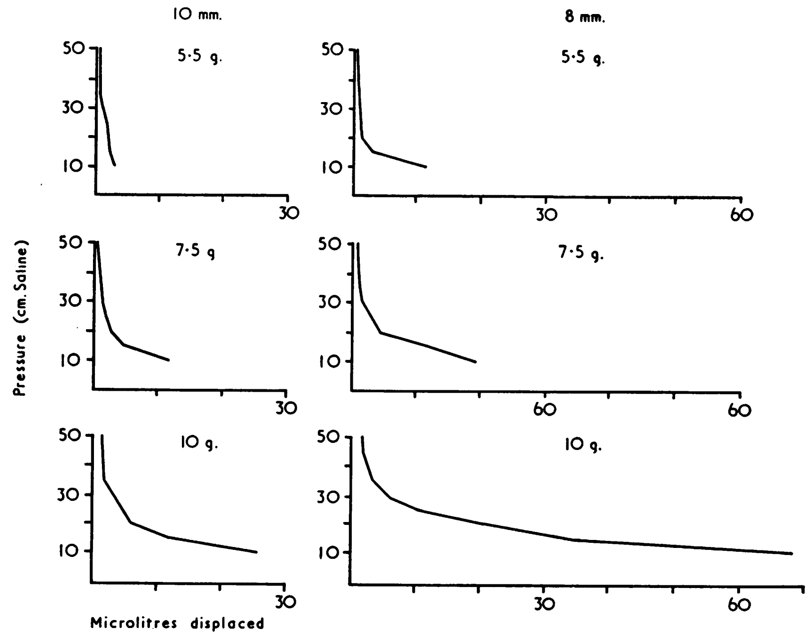

FIG. 8.—Effect on V_c of ring footplates of different sizes and weights.

It is very probable that the support of the clamps of the chamber holding the eye contributes to the rigidity of the limbus, and it would not be surprising if these cones and ring footplates were found to behave differently on the intact eye. For reasons given below in the Discussion, these footplates are not practicable in use, but their effect on such a preparation gives us the relative values of V_c with alteration of the shape of the footplate.

(C) Plunger

(*1*) *Changes in Weight.*—It would not be correct to deduce the effect of the plunger on volume of indentation by subtracting the results obtained from the footplate alone from those of the plunger and footplate together, as the footplate of the present Schiøtz tonometer modifies the corneal contour during tonometry. The effect of the plunger alone on the undisturbed cornea was therefore investigated. Three plungers with the specification laid down by the Committee on Standardization of Tonometers were tested; the weights were 5·5, 7·5, and 10 g. The effect on the volume of indentation of varying the weight of the plunger is shown in Table VII and Fig. 9.

TABLE VII
EFFECT ON VOLUME OF INDENTATION (µL.) OF VARIATIONS IN WEIGHT OF PLUNGER

P_t (cm. saline)	Weight of Plunger (g.)		
	5·5	7·5	10·0
10	32	81	141
20	14	31	45
30	7	12	20
40	5	8	14
50	2	5	7

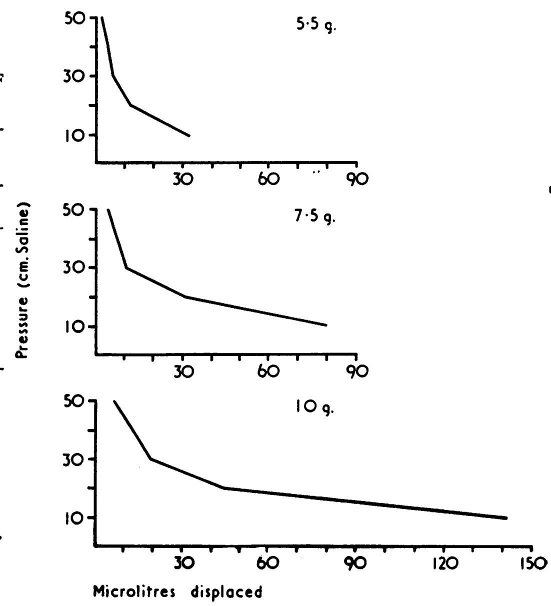

FIG. 9.—Effect on V_c of plunger weight.

The results follow the general pattern found with the footplates. The greater the weight, the larger is the volume of indentation, and, similarly, the lower the intraocular pressure and consequently the resistance of the eye, the higher are the V_c values. The other noticeable effect is the relative action of the footplate weight versus the plunger weight on V_c: we find that the plunger is displacing a larger volume of fluid from the eye than a footplate of comparable weight.

(*2*) *Changes in Plunger Protrusion.*—The initial protrusion of the plunger from the end of the footplate was measured while the instrument was not on the eye; the degree of protrusion was then varied and the effect on V_c values found. Fourteen indentation tonometers were first examined, and their initial plunger protrusion, measured with a micrometer while the tonometer was held vertically, was found to vary by about 215 per cent., the smallest protrusion encountered being 1·42 mm. and the largest 3·15 mm. However, when these instruments were tested on the 16-mm. block, they all recorded zero on the tonometer scale. In other words, the plunger moved a distance of about

3·14 mm. in one of the tonometers tested with whatever load it was carrying, before resting on the block, and registering zero on the scale.

Does this have an effect on V_c? To answer this question, a light-weight tonometer was constructed with the usual specification but with a footplate weighing only 6 g. and a plunger weighing only 4 g. A small guard-ring weighing 20 mg. was incorporated on the plunger; this guard prevented the plunger from protruding more than 0·5, 0·25, or 0 mm. from the level of the lower end of the footplate when the instrument was not resting on the cornea. The volume of displacement of such a tonometer weighing about 10 g. is shown in Table VIII and Fig. 10.

TABLE VIII

EFFECT ON VOLUME OF INDENTATION (µL.) OF VARIATIONS IN PLUNGER PROTRUSION WITH TONOMETER WEIGHING 10 G.

P_t (cm. saline)	Plunger Protrusion (mm.)		
	0	0·25	0·5
10	33	37	45
20	18	18	23
30	9	11	16
40	5	9	11
50	3	4	8

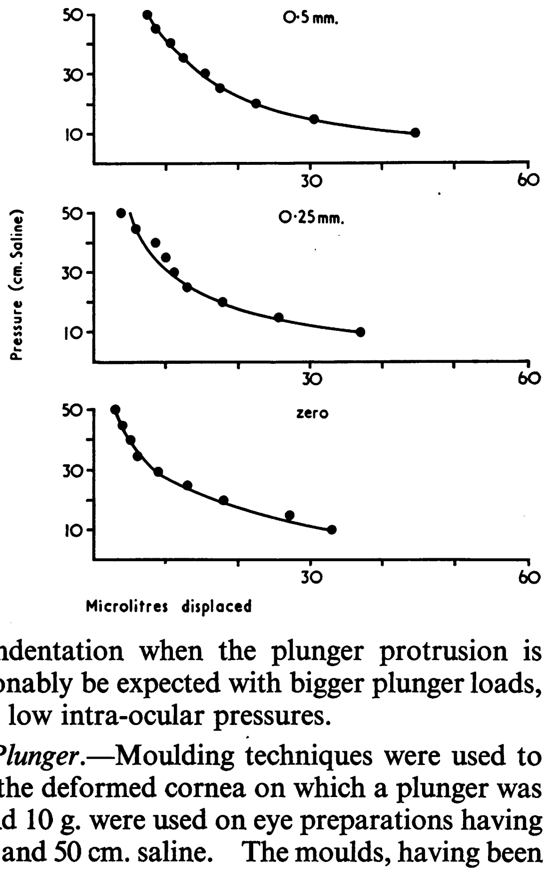

FIG. 10.—Effect on V_c of plunger protrusion.

The results indicate an increased indentation when the plunger protrusion is increased; a larger discrepancy can reasonably be expected with bigger plunger loads, and the difference is more marked with low intra-ocular pressures.

(3) *Corneal Configuration under the Plunger.*—Moulding techniques were used to obtain a profile of the configuration of the deformed cornea on which a plunger was resting. Plunger weights of 5·5, 7·5, and 10 g. were used on eye preparations having an intra-ocular pressure of 10 cm. saline and 50 cm. saline. The moulds, having been ground to a wafer-thin profile, were projected on a graph and drawn (Fig. 11, overleaf).

The increasing deformation of the cornea with increasing weight and also the greater effect of the tonometer at lower pressures than at higher pressures can be seen from Fig. 11. This illustrates very well why hyperbolic formulae were obtained by Schiøtz when he was calibrating his instrument. He found that the scale readings and intra-ocular pressures correlated linearly only between 3 and 10; hence his recommendations to use the lightest weight with low pressures and to change the plunger load with increasing intra-ocular pressure. In other words, the plunger load giving the smallest indentation and still capable of recording a pressure reading between these scale

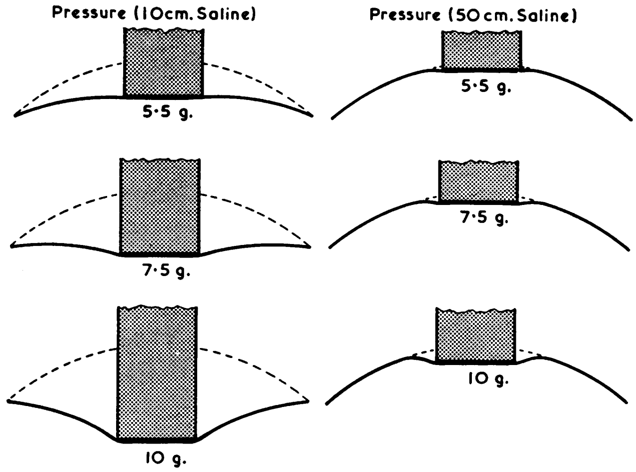

FIG. 11.—Profile of corneal indentation made by plungers of different weights.

limits will have P_t values more nearly approaching P_o values, because V_c is at a minimum under these conditions.

To visualize the corneal deformation under a tonometer, it was necessary to construct a Schiøtz-like indentation tonometer from transparent plastics. It had the usual specifications, except that the top part of the footplate was flat in order that photographs could be obtained. Three plunger loads weighing 5·5, 7·5, and 10 g. were used in conjunction with the footplate. The intra-ocular pressures of the eye so tested varied from 10 to 50 cm. saline. The photographs taken at the highest and lowest pressures are presented in Fig. 12 *a-f* (opposite).

An area can be seen surrounding the plunger where the footplate is separated from the cornea by a gap filled with fluid. The periphery of this gap is where contact takes place between the cornea and the footplate. This moat-like area increases with plunger weight, and also with reduction in intra-ocular pressure.

Discussion

These results suggest some ways in which indentation tonometers could be modified to reduce volume displacement. Firstly, the footplate weight could be reduced. The weight of the footplate is the major factor contributing to V_c as far as this portion of the tonometer is concerned. A reduction of one-fifth of the weight of the footplate will reduce the volume displaced by the footplate by about one-half, and a reduction of two-fifths will reduce the volume displaced by about two-thirds. This could perhaps be achieved by using lighter material or by reducing the thickness of the footplate cylinder or some other components of the footplate structure.

Very little could be achieved by modifying the present footplate diameter, but the experiments show an increase in the volume of fluid displaced when the footplate diameter is smaller than the corneal diameter. This is probably due to concentration of the weight over a small area so that the whole footplate starts to indent the cornea like a plunger.

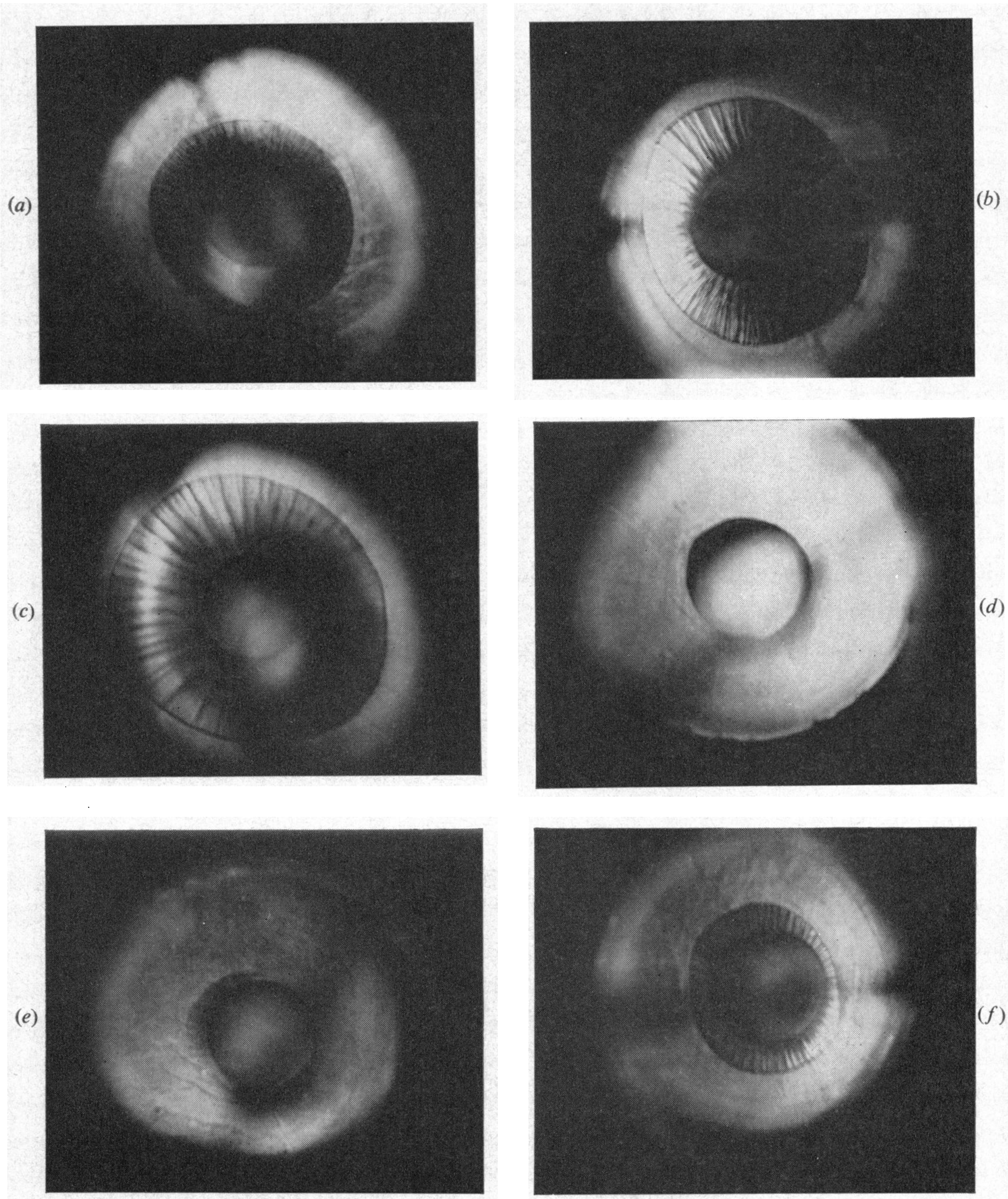
(a) (b) (c) (d) (e) (f)

FIG. 12.—Corneal deformation seen through transparent tonometer.

The question of footplate curvature is very interesting. It was found that the footplate which conformed to the configuration of the corneal curvature displaced a smaller volume of fluid than those which did not, including the flat footplate. It seems that the volume of fluid displaced is directly related to the degree of corneal deformation. The footplate, apart from providing a guide for the moving plunger and a support for the recording lever, is essentially a reference point from which the amount of indentation produced by the lower end of the plunger is measured; therefore this reference structure should alter the cornea minimally, or not at all, and it seems reasonable to suggest that the footplate should fit the cornea rather than the cornea the footplate. The radius of curvature of the footplate must not be less than the greatest radius of curvature of the cornea likely to be encountered, *e.g.* in buphthalmic eyes, in which tonometry is an important diagnostic procedure. Nevertheless, corneal curvatures greater than 11 mm. in radius are very infrequently encountered, and therefore some reduction in the present radius of 15 mm. would be desirable.

Friedenwald (1954) was surprised to find high scleral rigidities in eyes with buphthalmos. He was expecting to find a low scleral rigidity in such eyes, because according to Grant (1951) the same volume of indentation induces a greater stress on the ocular coats of a small eye than on those of a large eye. Friedenwald's observations showed the ocular rigidity of buphthalmic eyes to be, on the average, double that in the normal ambulatory adult, and he suggested that this might be caused by a deficiency in the elastic fibres of the sclera or by these eyes' being stretched beyond their elastic limit.

This present study suggests another reason. When a buphthalmic eye with a large radius of curvature is examined using a tonometer in which the radius of curvature approaches that of such an eye, the volume of fluid displaced is less. In other words, as the footplate descends on the cornea, a larger area of the buphthalmic eye supports its weight and less deformation is required for it to conform to the curvature of the footplate. In an eye with a smaller radius of curvature, the area of contact between the footplate and the cornea as the tonometer comes to rest on the eye is limited to the area round the plunger, and the cornea is deformed progressively from the centre to the periphery to conform to the curvature of the footplate; as it does so, a greater amount of deformation takes place and more fluid is displaced. Although no buphthalmic eyes were tested, it is possible that such eyes may appear to have a lower ocular rigidity if the tonometer has a footplate with a larger radius of curvature than the normal 15 mm., thus artificially increasing the difference of curvature between the two surfaces.

As far as the cone-shaped footplate is concerned, the footplate with the largest base indented the cornea least. Considering the ring footplate with a comparable diameter, *i.e.* the 10-mm. ring and 106° cone, the V_c values are comparable. The force applied by the footplate, which is largely a function of the weight, when exerted at the periphery of the cornea in such an eye preparation can be resolved into two vectors, one (represented in Fig. 13 as R) acting radially towards the centre of the globe and the other acting tangentially (T). As the force F moves towards the centre of the cornea, the radial force increases in magnitude and the tangential force decreases to a negligible amount. The radial vector is counteracted by the intra-ocular pressure and the rigidity of the corneal fibres, which are disposed at right angles to the force; centrally their resistance is small, but at the limbus the vector T transmits some of the force to the ocular coat. The clamping system used in these experiments may also contribute to the extra rigidity of the sclera, and the results may not be valid for the performance of a tonometer on the intact living eye.

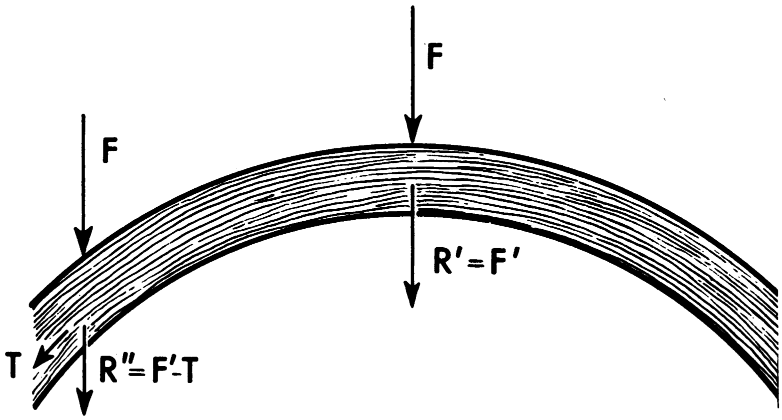

FIG. 13.—Resolution of vector forces on different segments of the cornea.

The advantages of the cone-shaped footplate and also those of the ring footplate are offset by the loss of the footplate's major function, *viz.* as a reference point from which the degree of protrusion of the plunger is measured. If a cone-shaped footplate or a ring footplate is used, the point of first contact of the plunger with the cornea no longer has a fixed relationship to the footplate and will vary from one eye to another, depending on the radius of curvature of the cornea.

The weight of the plunger has a relatively greater effect on V_c than the weight of the footplate, as the weight of the latter is distributed over a larger area. The concentration of the weight in the plunger, acting at a place where the resistance to indentation is mainly due to the intra-ocular pressures, is exactly what indentation tonometry is aiming at. It would, however, be ideal to use the smallest amount of indentation which would still give a measurable movement. This may be achieved by reducing the diameter of the plunger, but this increases the danger of trauma to the cornea. Another method of decreasing V_c would be to reduce the weight of the plunger and amplify the movement electronically.

Schiøtz, in calibrating his instrument, found a hyperbolic formula to correlate pressure and scale readings. The correlation was approximately linear between scale readings of 3 and 10 units. As readings beyond 10 are not accurate, it is not necessary to have a plunger protrusion greater than 0·5 mm. Even if the full scale of 20 units is retained there is little justification in increasing plunger protrusion to more than 1 mm. from the level of the footplate. This is the problem that should be considered by manufacturers and calibration centres and an attempt should be made to reduce the large variations found. Many Schiøtz-type tonometers have on the footplate a small screw which fastens the cylinder of the footplate to the recording system in such a way that the plunger will lift the lever to the zero mark when the instrument is resting on the test block. When the reading is not zero, the screw is unfastened, the recording section is rotated on the thread of the footplate cylinder until the pointer is at zero, and the screw is fastened again. This causes the variation in plunger protrusion mentioned above. Schiøtz (1920) recommended "bending the pointer a little beyond or a little within the zero line while the tonometer rests on the model, *i.e.* test block". His recommendations have unfortunately been ignored.

The transparent tonometer and the moulding technique permitted a three-dimensional model to be made of what is likely to take place during indentation tonometry.

Not only is the deformation of the cornea excessive with a large weight acting on an eye with a low intra-ocular pressure, but also the reading is incorrect, as the reference plane of the footplate, which is supposed to be at the same level as the cornea, is raised above its correct position. We must therefore admit that we have no way of reading ocular tensions lower than 7 mm. Hg with a Schiøtz tonometer, and that even higher tensions are only approximations. If it is desired to read lower tensions with the Schiøtz tonometer some plunger loads weighing less than 5·5 g. must be designed and calibrated.

Another feature was noticed through the transparent tonometer. When, with the instrument resting on the eye, the pressure was altered by moving the reservoir, the area of the "moat", *i.e.* the space where there is no contact between cornea and footplate, decreased when the pressure was raised and increased when it was lowered. The saline trapped in the moat when the pressure was raised escaped up the shaft of the footplate cylinder and came down again when the pressure was lowered. Occasionally a small air bubble appeared: this is likely to be a source of error, and the footplate and plunger should be kept dry and clean to minimize friction as much as possible.

Summary

Some of the physical characteristics of the Schiøtz-type indentation tonometer have been examined. Possible ways of reducing the volume of indentation are discussed and the following suggestions are made to improve certain features of such tonometers.

The weight of the plunger should be reduced when possible (depending on intra-ocular pressure).

The weight of the footplate should certainly be decreased.

The radius of curvature of the footplate should be decreased, and made to conform as closely as possible with the curvature of the cornea on which it is to rest.

The protrusion of the plunger should be limited to 0·5 mm. from the level of the end of the footplate.

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* Alginate—Produced by S. S. White Dental Manufacturing Co. Ltd., 126 Portland Street, London, W.1., England.