THE BRITISH JOURNAL OF OPHTHALMOLOGY

MAY, 1920

COMMUNICATIONS

TONOMETRY

BY

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A PREVIOUS article by the present writer, on "Tonometry," which was published in the *Archiv für Augenheilk.*, Vol. LXVIII., Part 1, p. 77, is already some years old. Although during these years I have never quite ceased to occupy myself with the tonometer, I have not until the last three or four years been able to turn my full attention to a close investigation of the subject. My aim is partly to improve the instrument, if possible, partly to extend our knowledge of the mode of action of the tonometer, and partly to check and correct the curves, the construction of which I based on not more than eight enucleated eyes.

With regard to the last problem, a highly esteemed colleague, Mr. Priestley Smith, of Birmingham, has forestalled me. In his treatise "On the Limitations of the Tonometer,"* he published the results of a series of very minute tonometric and manometric measurements of dead eyes *in situ*, showing that my measurements of enucleated eyes gave undoubtedly too low values, evidently because the bulb and cornea became more rigid after enucleation than they are in their natural surroundings in the orbit. I will discuss these measurements later, but will merely remark here that I did not consider the values which I found at that time to be final.

In other respects I fully agree with Mr. Priestley Smith in every one of his statements concerning the tonometer and its application. As pointed out by him, his conclusions on the whole bear out my own. I understood his article to be, to use his own words, "not an attack on the Schiötz tonometer, but rather a defence."

Immediately after the appearance of my tonometer the objection was put forward from various quarters that the weight had to be

* *Ophthalmic Review*, 1915, p. 65.

FIG. 1.

unscrewed from the plunger when another weight was needed. My esteemed colleague, now deceased, Dr. Marple, of New York, made several statements on this point. After working at the problem for a considerable time, I have now constructed a new model (Fig. 1) in which the plungers and weight form one piece, which may be put into the cylinder from above. If a heavier weight is needed, another weight may be placed on top of the first one. The new

model has not yet been fully tested by experiment, and I do not know whether it will prove as reliable with regard to its measurements as the original. I hope that it will be obtainable before long at Jacobsen's Elektriske Verksted, Christiania, for comparison with the old one.

In my experiments I employed, besides eyes, a small hollow metal cylinder or drum of 14 mm. diameter. It is closed above by a thin rubber membrane, below by a tap, by means of which its connection with the manometer may be opened or closed. As a manometer I used an irrigator hung on a stand or wall; it can be raised by 5 or 10 cm. at a time.

The Plunger

During my experiments I became aware of the extraordinary influence of the shape of the lower end of the plunger on the extent of the deflections of the pointer. In my tonometer the lower end of the plunger is concave, and the radius of curvature is the same as that of the concave surface of the base, viz., 15 mm. For technical reasons the question was raised whether the lower end of the plunger should be made flat. I found, however, that with a flat plunger the deflections were considerably greater than with a concave plunger under the same pressure, and a still greater difference was found with a convex plunger. I may state, further, that with one "flat" plunger the difference was relatively slight, while with another it was considerable; I found that the former was in reality slightly concave, and the latter, perhaps, a trifle convex.

TABLE I
Weight 5.5 gm.
Deflections of the pointer in mm.

Pressure H ₂ O.	Concave Plunger.		Convex Plunger.	
	Open.	Closed.	Open.	Closed.
5 cm.		11 mm.		19.3 mm.
10 "		7.5 "		16 "
20 "	14 mm.	4.3 "		11.5 "
30 "	6 "	3 "	15.2 mm.	8.5 "
40 "	3.5 "	1.7 "	10.7 "	6.3 "
50 "	2.3 "	1 "	7.5 "	5 "
60 "	1.5 "	0.4 "	6 "	4.2 "
70 "	<1 "	0 "	4.9 "	3.5 "
80 "	0.3 "		4 "	3 "
90 "	0 "		3.2 "	2.3 "
100 "			2.6 "	2 "
110 "			2 + "	1.6 "
120 "			1.6 "	1.05 "

Table 1 shows the deflections obtained under weight of 5.5

grammes, with a concave and a very convex plunger respectively, the drum being covered with a double rubber membrane, each layer of which was 0.133 mm. thick.

It will be seen that under the lower pressures the deflections given by the two plungers differ by as much as 8 mm. Under higher pressures the difference decreases, but while zero was reached with a water pressure of 80-90 cm. in the one case, a deflection of 16 mm. still occurred even at a water pressure of 120 cm. in the other, and the zero was still far off, for pressure-increments of 10 cm. here would soon be represented by quite minimum variations in the deflections.

The influence of the shape of the plunger-end came as a complete surprise to me, but it may be explained in the following way :

When a concave plunger rests on a correspondingly curved membrane, and the upward pressure against the small area of membrane which is in contact with the plunger equals the weight of the plunger, the plunger is counter-balanced—assuming that the membrane itself exercises no resistance. Thus the plunger with its adjuncts weighs 5.5 grm., and its end has a diameter of 3 mm., giving an area of nearly 7 sq. mm. This area of 7 sq. mm. bears a weight of 5.5 grm., or approximately 0.8 grm. per sq. mm. It must, therefore, be balanced by an upward pressure of 0.8 grm. per sq. mm., or 80 grm. per sq. cm., i.e., by a water-column of 80 cm. This is fairly accordant with the experiments (Table 1 concave plunger, communication with drum open). In like manner a plunger having an end-surface of only 1 sq. mm. and the same weight as before, would require an upward pressure of 5.5 grm. against this area as a counterbalance, i.e., a water column of 550 cm.

When the plunger presses the membrane downwards, it carries down not only the small portion with which it is in contact, but more or less of the surrounding membrane also. These together form the supporting area for the plunger. The plunger comes to rest when the upward pressure against this area equals the downward pressure, i.e., the weight of the plunger.

We can find the extent of the supporting area (A) by dividing the weight of the plunger by the water-pressure per sq. mm. which is found to counterbalance it. For example, the concave plunger, when giving a deflection of 6 mm. (Table 1) was balanced by an upward water-pressure of 0.3 grm. per sq. mm.; whereas the convex plunger, when giving the same deflection, was balanced by a water-pressure of 0.6 grm. per sq. mm. The supporting areas in the two cases are then as follows :

$$\text{For the concave plunger } A = \frac{5.5}{0.3} = 18.3 \text{ sq. mm.}$$

$$\text{For the convex plunger } A = \frac{5.5}{0.6} = 9.2 \text{ sq. mm.}$$

We see then that, with the *same weight* in each case, the concave plunger depresses a larger area of the membrane than does the convex plunger; which is the same as saying that it rests on a larger supporting area and consequently requires less upward pressure per sq. mm. to support it. We see also that with the *same water-pressure per sq. mm.* in each case, the convex plunger makes a deeper impression in the membrane than does the concave, in order to produce the same supporting area; for example, with a water-pressure of 30 cm. the convex plunger deflects the pointer 15.2 mm., whereas the concave plunger deflects it only 6 mm., the supporting area being in each case 18.3 sq. mm.

According to what is stated above, I am inclined to think that the concave plunger is the best because, with high pressures, it gives variations of deflection that are sufficiently distinguishable right down to zero. The flat plunger is undesirable because a slight error either towards convexity or concavity causes perceptible variation in the deflections. In the case of the convex plunger the deflections are strongly influenced by slight variation in the degree of curvature. It is true that with the convex plunger, since it acts on a wider range of manometer-pressures, the heavier weights might, perhaps, be avoided, but the small and decreasing intervals in the deflections in the case of high pressures would, I think, endanger the exactitude of the results. In any case, whatever shape be adopted, it is clear that the deflections given by different tonometers will not be comparable if the plungers are differently shaped.

The Weight of the Tonometer

The weight of the tonometer is represented by two distinct parts acting independently. The one consists of the cylinder with its cup-shaped base, together with the loop carrying the flat strip and the graduated arc. This part of the tonometer, as used at present, weighs 10.1 grm. The other part consists of the plunger with its loose weight together with the pointer. The weight of this part varies with the loose weight employed: it is 5.5, 7.5, 10, or 15 grms. respectively.

The weight of the cylinder part of the instrument is of no importance as long as there is free connection between the testing drum described above (or the eye) and the manometer; with a given water-pressure the same deflection of the pointer is obtained whether the graduated arc be loaded with a weight of 10, 20, or 30 grms. It is otherwise when the communication between the drum (or the eye) and the manometer is closed. In that case the weight of the cylinder part is of the utmost importance because of the rise of pressure occurring in the drum (or eye) when the tonometer is placed upon it (see Table II).

TABLE II
Water pressure at beginning of experiment.
Deflections of the pointer in mm.

Weights attached to graduated arc.	0 cm.	20 cm.	40 cm.	60 cm.
0 grammes	18 mm.	5.5 mm.	2.1 mm.	1 mm.
10 "	11 "	3.5 "	1.5 "	0.8 "
20 "	6.5 "	2 "	0.9 "	0.4 "
30 "	2.5 "	1.3 "	0.5 "	0 "
40 "	1 "	0.3 "	0 "	—
50 "	0.5 "	0 "	—	—
60 "	0 "	—	—	—

At the commencement of the experiment the water-pressure is 0 (column 1), i.e., the fluid in the manometer is level with the rubber membrane. Then the connection is shut off and the tonometer with the 5.5 grm. weight on the plunger is placed on the membrane; the pointer is deflected 18 mm. Now weights are placed on the graduated arc and the increasing weight causes decreasing deflection exactly as when the connection is open and the manometer is raised. With a weight of 60 grm. on the arc the pointer moves past the zero line. The pressure in the drum is now due to the weight of the tonometer proper, viz., 15.5 grm. plus the added weight of 60 grm. totalling 75.5 grm. This weight rests on the lower surfaces of the base and plunger, an area of about 84 sq. mm., The pressure below the membrane, therefore, in order to counter-balance the loaded tonometer must be $75/84$ or 0.9 grm. per sq. mm., a value corresponding exactly with the pressure giving nil deflection in Table 1, viz., 90 cm.

It will be seen that when the initial water-pressure is 20 cm. (column 2), and the communication is shut off, zero is reached when the arc is loaded with 50 grm. With an initial pressure of 40 cm. it is reached with a load of 40 grm., and with an initial pressure of 60 it is reached with a load of rather less than 30 grm. In the first of these cases, when the pointer stands at 0, the loaded tonometer has a weight of 65.5 grm., and rests on an area of about 84 sq. mm. This will produce inside the drum a pressure of $65.5/84=0.75$ grm. per sq. mm., i.e., a water-column of 75 cm. If the initial pressure of 20 cm. H_2O is added the total amounts to 95 cm. H_2O .

In the same way we find in the two last cases (column 3 and 4) respectively 106 cm. H_2O and 114 cm. H_2O . The last value especially is much too high, but this experiment does not claim to be very exact and the value given must be considered as approximate, the purpose of the experiment being chiefly a demonstration of the action of

the instrument and of the importance of the weight of the tonometer.

The influence of the weight of the tonometer is most clearly seen when one works with the communication between manometer and drum alternately open and closed. The following deflections were obtained when working with a weight of 5.5 gm. on the plunger and a thin rubber membrane (0.133 m.m.) on the drum.

TABLE III
Deflections in mm.

Pressure H ₂ O.			Open.	Shut.
5 cm.	...	...	—	14 mm.
10 "	...	...	—	10 "
20 "	...	...	16.5 mm.	5.8 "
30 "	...	...	8 "	3.4 "
40 "	...	...	4.3 "	2 "
50 "	...	...	2.55 "	1.1 "
60 "	...	...	1.5 "	0.75 "
70 "	...	...	0.8 "	0.1 "
80 "	...	...	0.3 "	0 "
90 "	...	...	0	(The membrane is considerably inflated.)

¹ I would ask those readers who are interested in the tonometer to work out graphs according to the values given in the tables; many facts will then appear more clearly than from a mere study of the tables.

If the tonometer is placed on the drum while the latter is in open connection with the manometer, and the water pressure stands at a height of 30 cm., the pointer will show a deflection of 8 mm. Now let the tonometer be removed and a little later let the connection with the manometer be closed. The pressure in the drum will be the same as before; it will still correspond with a water-column of 30 cm.; but when the tonometer is once more placed on the membrane the deflection is only 3.4 mm., an amount which, when the connection is open, corresponds with a water-column of 45 cm. The increase in pressure can only be due to the weight of the tonometer.

If graphs are worked out according to the values given in Table III, for the open and the closed drum respectively, it will be seen that the difference between them at the lowest pressure amounts to nearly 17 cm., decreasing at higher pressures to about 12 cm. at zero, i.e., when the pointer stands at the first line, or when no deflection is obtained. At a water pressure of 73 cm. the tonometer still gives a deflection of 0.6 mm., but when, after the removal of the tonometer, the connection with the drum is closed, and the tonometer replaced on the membrane, the pointer stands at zero.

While the tonometer rests on the membrane the water pressure in the drum apparatus has risen to 85 cm., i.e., the pressure which brings the pointer to zero when the communication is open.

In the case before us, where the plunger in both circumstances is pushed completely up, it is only the cylinder part of the tonometer which causes the difference in pressure between the open and the closed cylinder. The cylinder part weighs 10 gm. and rests on a supporting area of 76 sq. mm., viz., the whole surface of the tonometer, 84 sq. mm., minus the under surface of the plunger, 7 sq. mm., or, as the whole is a fraction larger, 8 sq. mm. Every square millimetre therefore bears a pressure of $10/76$ or 0.13 gm. The pressure of the cylinder part of the instrument will produce a corresponding pressure inside the drum of 0.13 gm. per sq. mm., or 13 gm. per sq. cm., which corresponds to a rise of the manometer of 13 cm.; this agrees approximately with the value found, viz., 12 cm. The zero point is not easily determined by means of a rubber membrane.

At lower pressures complications arise with regard to what is due to the weight of the plunger part, and what to the cylinder part. At all events the difference must be dependent on the weight of the whole tonometer (15.5 gm. in our case), which rests on the supporting area of 84 sq. mm.; each square mm. is subject therefore to a pressure of $(15.5/84)$ 0.185 gm., causing in its turn, an equal increase of pressure in the cylinder, and corresponding to a rise of the manometer of 18.5 cm., which is fairly concordant with the difference of 17 cm., found between the curves.

In my paper "Tonometrie" (*Archiv f. Augenheilk.*, Vol. LXII, Part iv, 1909, p. 319), I pointed out this difference between the graphs of the open and the closed eye, but the values given there for the difference were much too high, especially for the higher weights at low pressures; thus for 5.5 gm. it was 20 cm., for 7.5 gm., 26 cm.; for 10 gm. 31.5 cm.; and for 15 gm., 43 cm., while the correct values, according to computation, should be respectively 19 cm., 21 cm., 24 cm. and 30 cm.

According to my latest measurements, taken as recommended by Priestley Smith, the difference between graphs of the open and the closed eye is much less, at least for the weight of 5.5 gm., viz., at low pressures 1.55 cm. and at zero only 10.5 cm.

I used to imagine the probable existence of an invariable proportion between the graphs of the open and the closed eye, and also that the graphs might be checked and corrected thereby. A series of experiments recently finished, however, proves clearly that no such invariable proportion is to be found.

The extent of the deflections, and with them the shape and the conditions of the graphs, are dependent on two factors, apart of course from variations in the parts of the tonometer itself, viz.,

(1) the nature of the walls in the vessel (the eye) and (2) the nature of the membrane supporting the tonometer. The following experiments illustrate this statement :

In order to have always the same membrane, I employed in all my experiments a small metal drum having a volume of 1·4 cc., covered by a rubber membrane 0·133 mm. in thickness. In the present experiments, instead of connecting the drum directly with the rubber tube of the manometer, I interposed a glass bulb having a volume of a little more than 250 cc. This bulb was immediately continuous with the drum, on the one hand, and was connected by a glass tube and tap with the rubber tube of the manometer, on the other.

The method was as follows.—After raising the manometer to the height required, the tap of the drum was closed. The tonometer was then placed on the membrane and in the supports belonging to the apparatus (see Fig. 1), in such a way as to keep it immovable during the experiment. The deflection of the pointer was noted. Then the tap on the manometer side of the glass bulb was closed, and the tap between the drum and the glass bulb was opened. When the small volume of 1·4 c.c. was thus connected with the large volume of 250 cc., there was practically no variation in the deflection of the pointer; at the very lowest pressures the index made a very slight movement of 1 mm. at the outside, and even this was usually only obtained by a slight shaking or tapping of the table. At pressures of 50 cm. and upwards, no movement on the part of the pointer was discernible, as is seen from Table IV. Identical results were obtained with a weight of 15 grm.

TABLE IV

Pressure H ₂ O.	Drum closed.	Drum + Bulb closed.	All open.
5 cm.	14·6 mm.	15·5 mm.	—
10 „	10·2 „	10·7 „	—
20 „	5·5 „	5·8 „	17·5 mm.
30 „	3·4 „	3·55 „	7·7 „
40 „	2·2 „	2·3 „	4·2 „
50 „	1·6 „	1·6 „	2·8 „
60 „	1·1 „	1·1 „	1·85 „
70 „	0·6 „	0·6 „	1·2 „
80 „	0·3 „	0·3 „	0·7 „
90 „	0 „	0 „	0·4 „

The membrane is over-distended.

In the next experiment the glass bulb was replaced by a thin sausage-shaped rubber bag 10 cm. long, 1·5 cm. in diameter, and with a volume of about 17 c.c. In the same order as before, the tap of the drum was closed, the tonometer was placed on the

membrane and the deflection was noted. Then the tap between the rubber bag and the manometer was closed, and the tap between the drum and the rubber bag was opened. *At this moment the pointer was deflected and gave the same deflection as when there was open connection with the manometer.* Frequently it was necessary to tap the table slightly in order to obtain the last fraction of a millimetre. Even at a pressure of 40 cm. the rubber bag was over-distended, and it should be noted that with an open connection and a water pressure of 40 cm. which the walls could no longer withstand, the deflections were considerably wider than with a pressure of 30 cm.

The rubber bag was then swathed in strips of gauze. The water pressure could now be increased up to 70 cm., but at this point parts of the bag were over-distended and the same phenomenon occurred; the tonometer registered a lower pressure than the manometer. With water-pressure under 70 cm., and with open communication between drum and rubber bag, the deflections were always the same as with open communication with the manometer.

A piece of a rubber glove was then tied round the bag in the whole of its length. The deflection now did not quite reach the full value given by the open drum, but it was still considerable, as will be seen from Table V.

Finally, a rubber tube 11 cm. in length, 7.5 mm. in diameter, and about 2.5 c.c. in volume was inserted in the place of the rubber bag. The deflections were considerably nearer to those obtained with the closed drum. Table V. shows the deflections obtained respectively with the various elastic-walled vessels.

TABLE V
Deflections in mm.

Pressure H ₂ O.	Drum open.	Drum + Bag closed.	Drum + Bag swathed, closed.	Drum + Tube closed.	Drum only closed.
5	—	—	—	18.7	15.2
10	—	—	—	13.5	10.8
20	18.5	18.5	15	7.1	5.8
30	8	8	7	4.1	3.7
40	4.2	4.3	3.8	2.5	2.2
50	2.5	2.5	—	1.6	1.4
60	1.6	1.6	—	1.1	1 +
70	1.1	over-distended.	—	0.75	0.7

(To be concluded.)