ON RECORDING VARIATIONS IN VOLUME BY AIR-TRANSMISSION. A NEW FORM OF VOLUME-RECORDER.

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THE recording of variations in volume of any part of the body has been attained in many ways, which we may conveniently consider as falling into two groups, in the first of which the organ is surrounded by a liquid, and in the second by air. In the first of these groups fall the earlier observations, such as those of Fick, Mosso, and Roy. To Schäfer and Moore is due the credit of first employing air in the transmission of volume-changes, and since then it has been almost universally adopted. The disadvantages in the employment of liquid for transmitting volume-changes are chiefly two. The first lies in the difficulty of ensuring that the pressure in the liquid at the surface of the organ remains constant throughout the whole experiment, and in keeping this pressure low. It is impossible to avoid the first of these two objections when rapid movements have to be recorded. The second great disadvantage entailed in using liquid is due to its great inertia, and it is chiefly from this cause that the older methods of recording have been discarded.

In employing air-transmission for recording variations in volume either a tambour or a piston-recorder has been used as the receiving instrument. But sufficient attention does not seem to have been paid by workers to the great difference entailed by the use of these two instruments. Many experiments with which I was engaged led me to attempt to make an instrument possessing a far greater range than the ordinary forms of piston-recorder obtainable, and the testing of the instrument I finally devised led me to work out many points of detail which are briefly described in the following paper.

To record volume-changes accurately it is clear that the moving parts of the recording instrument must possess as little inertia as possible and must follow volume-changes without setting up changes in pressure. Variations in volume can, of course, also be estimated by recording the variations in pressure set up by the compression or rarefaction of the enclosed air, but in order to deduct with any accuracy the real volume-changes, it is necessary, in each experiment, to calibrate the recording apparatus by writing the variations in pressure set up by injecting known volumes of air into the air-space. A tambour can only be employed in this manner, for the range within which it may be regarded as a volume-recorder is extremely limited. This range varies with each tambour, and depends upon the diameter of the tambour, the thickness and tension of the rubber covering it, and finally with the total volume of air contained within the tambour, connecting tubing, and receiving tambour or oncometer. A tambour is in fact a pressure-recorder rather than a volume-recorder. This is well seen from the following experiment.

A small bottle, of about 150 c.c. capacity, was connected by rubber tubing 5 mm. in internal diameter to a water manometer and to the tambour. This tambour was 30 mm. in diameter and was covered by a rubber membrane 0·2 mm. thick. Successive quantities of water, each 0·5 c.c., were injected into the bottle, and after each injection the pressure in the manometer was read. The successive readings were 8, 16, 32, 50 and 64 mm. of water. Thus the pressure rises quickly to a considerable height.

The same tambour was next covered with very thin rubber (0·04 mm. thick) and the experiment repeated. The pressures then obtained were 5, 10, 14, 18, 22 and 27 mm. of water. These changes of pressure are so considerable that for oncometric experiments in which a moderate range of movement is to be recorded it is very difficult, even impossible, to make the oncometer air-tight. Moreover these relatively high pressures must exert an effect upon the venous outflow.

For these reasons and because it can never give a direct record of volume-changes a tambour should not be used in most oncometer work.

For obtaining a direct record of volume-changes we have, therefore, up to the present, possessed only one instrument, viz. the piston-recorder. The first to make use of the general principle of this recorder was Roy[1] in his various forms of oncograph. A simple form was devised by

[1] Roy. This *Journal*, III. p. 206, 1880.

Schäfer[1] for recording the contractions of the isolated frog's ventricle. In both these instruments a liquid, oil, was used for transmitting the volume-changes, and therefore they possessed the disadvantages already described. The first to invent a piston-recorder registering by air-transmission was Ellis[2], and a little later a modification of this was employed by Johansson and Tigerstedt[3]. The instrument was carefully tested by Hürthle[4], to whom is due the form now commonly employed. The original instrument of Ellis is extremely sensitive, that is, it will respond to very minute volume-variations, but his pattern requires very careful handling. Recently, a more durable form has been described by Lombard and Pillsbury[5], who also have used it for recording minute changes. For experiments of this class there is no other instrument which can be employed.

For very many purposes the piston-recorder works admirably, but it possesses certain disadvantages. The first of these is the junction between the piston and cylinder. In order that the piston may move very freely it must not fit the cylinder too closely. To render it air-tight it is therefore necessary to seal this junction with oil. In a long experiment this requires a good deal of attention, and moreover oil is continually leaking into the lower part of the cylinder, thus introducing an error into the volume-record. Very commonly too oil finds its way into the rubber tubing leading to the oncometer. The oil also damps the instrument, thus leading to the obliteration of many of the finer movements in the record. Recently Hürthle has devised a form in which oil may be dispensed with. The piston is a light vulcanite cup, as in the old pattern, but it works in a metal cylinder which it accurately fits. This is stated to be quite air-tight for all ordinary purposes and one is directed to use no oil. The instrument which I have received is by no means air-tight and is quite valueless for long experiments in which an accurate volume-record is required. One is therefore obliged to use oil and then the friction is considerable, because the fit of the piston in the cylinder is too close. Unless the recorder is quite air-tight the piston tends to move in the direction in which the movement being recorded takes place more quickly.

But the greatest disadvantage of the piston-recorder is its limited

[1] Schäfer. *This Journal*, v. p. 130. 1884.
[2] Ellis. *Ibid.* VII. p. 309. 1886.
[3] Johansson and Tigerstedt. *Skan. Arch. f. Physiol.* I. p. 345. 1889.
[4] Hürthle. *Pflüger's Arch.* LIII. p. 301. 1893.
[5] Lombard and Pillsbury. *Amer. Journ. Physiol.* III. p. 186. 1899.

range. Thus in the latest Hürthle recorder, which is provided with three sizes of piston and cylinder, the greatest available range for the smallest cylinder is 4·5 c.c. For the medium-sized cylinder it is 8 c.c., and for the largest 14 c.c. For such purposes as, for instance, recording volume-changes of the spleen during stimulation of its nerves, in which a diminution of volume amounting to 15 c.c. is often obtained, or in recording the output per beat of the heart these pistons are useless.

The want of an instrument which would record considerable volume-changes and yet remain sensitive led me in the first instance to attempt the manufacture of piston-recorders of large diameter. They proved most unsatisfactory, and after attempting several modifications I had to abandon them. One form which gave moderately good results consisted of a very light cylinder, made of thin celluloid, whose upper end was closed and the lower end sealed by dipping into a water cup. The instrument however possessed too much inertia, and thus the level of the water varied considerably, the water moving rather than the cylinder. To avoid this I used, instead of water, mercury covered with a layer of saturated mercuric chloride solution, the latter in order to reduce the surface tension of the mercury. This gave much better results, but was not altogether satisfactory.

The bellows recorder.

After many further attempts I finally hit upon the idea of making the receiver of the recorder in the shape of a small pair of bellows. This form has proved in many respects of great advantage. The only difficulties experienced in devising them were, in finding a material sufficiently strong, light and flexible, and in making them quite air-tight. These have been overcome by employing peritoneal membrane for the parts where flexibility is required, and by varnishing them with a dilute solution of boiled linseed-oil, which only slightly affects the flexibility.

Fig. 1 gives a picture of one of these recorders.

They are made in the following way. A base of metal, wood, or vulcanite, through the centre of which an inlet tube opens is first made. The base is rectangular, the ratio of the long to the short side being 3 : 2. A rectangle of the same size is then cut from a thin sheet of aluminium, and the centre of this is cut away, leaving only a rim of about 5 to 10 millimetres width. This is then covered with paper which is fixed to it by dilute spirit varnish. This forms the top of the bellows and it is then hinged to the base along one of the shorter sides. For this hinge I have found it best to employ a very thin flexible leather. This is fixed to base and cover by Prout's glue, leaving about 5 mm. of leather between the two[1]. The leather is fixed so that it will lie

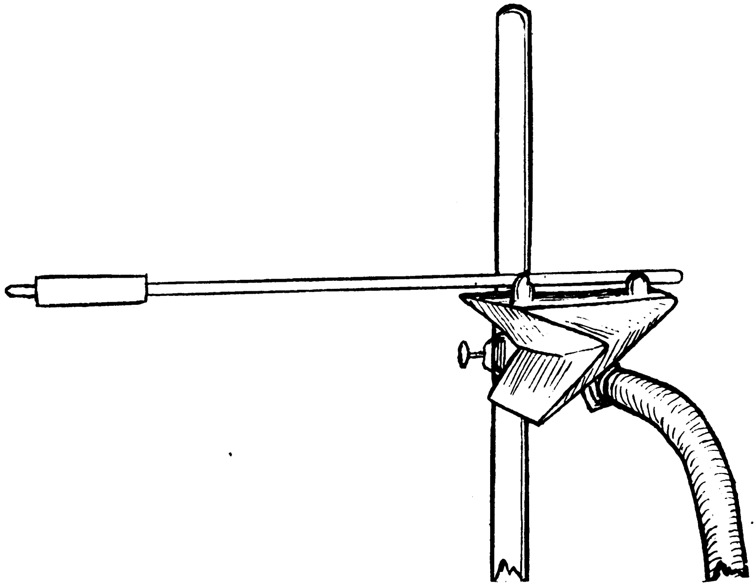

Fig. 1.

entirely within the bellows when finished. A piece of peritoneal membrane free from holes is next chosen and cut roughly into the required shape. I have usually made the sides of such a size that, when the bellows are completely distended, each side is an equilateral triangle, and the face opposite the hinge is thus of the same size as the cover. A piece of thin cardboard of the size of the cover is taken and the peritoneal membrane is folded round this so as to form creases, which enables one more easily to fix it to the cover and base in the proper position. To fix the membrane I have found it best to use dilute spirit varnish. The membrane is first fixed at the end, the sides are then folded over, creased, cut if necessary to the right width and varnished down. If the amount of membrane is not sufficient to cover the whole of the hinge an extra piece is fixed in that position. In using the spirit varnish it is very important that those parts of the

[1] In fixing the leather to the base and cover no cement in the form of a solution can be used, for this soaks into the leather, which thus becomes stiff on drying.

membrane which are to form joints in the bellows should be untouched by the varnish so that they may remain quite flexible. This is especially important at the hinge. When the spirit varnish has thoroughly dried the bellows are folded. The folding should be carried out so that the face opposite the hinge folds inwards to lie between cover and base, whereas the sides are folded outwards (see Fig. 1).

The whole is now coated with a varnish made by diluting boiled linseed oil with three times its volume of xylol. Two or three coats of this are applied at intervals of about half-an-hour. This makes the whole air-tight, but the flexibility still remains. Should the bellows at any time become too stiff all that is necessary is to paint them with xylol, and if they leak a coat of the drying oil varnish will, if they are properly made, at once render them air-tight again. They may be used while still wet if care be taken that the wet surfaces do not touoh one another.

In making large bellows-recorders I find it of advantage to make those parts which do not bend of paper, rather than of peritoneal membrane, because the latter is rather too pliable in large surfaces. All the bending parts must be made of the more flexible peritoneal membrane.

I have given so many of the details of the manufacture of the recorders because it is quite easy to make them for oneself. They are also now being made by the Cambridge Scientific Instrument Company.

Air blown into the bellows lifts the cover which rotates about the hinge, and to record these movements is very simple. No further joint is required—all that is necessary is to attach a writing lever of the necessary length to the cover of the bellows at right angles to the hinge. If it is wished, the cover and writing lever may be counterpoised by a small weight, but this only adds to the inertia, and I therefore usually work without one.

The advantages of this form of recorder are the following:—

(*a*) It is always ready for immediate use and requires no preliminary adjustment.

(*b*) It wears well and is not easily damaged.

(*c*) It is extremely sensitive.

(*d*) It can be made of any capacity, and even with very large ones the weight of the moving parts is minimal.

The last point is, perhaps, its greatest advantage. I have at present in use four different sizes. The smallest is 30 mm. long and 20 mm.

wide and possesses a capacity of 7·5 c.c.; the second is 45 by 30 mm. with a capacity of 25 c.c.; the third is 60 by 40 mm. with a capacity of 67 c.c.; and the largest is 120 × 80 mm. and possesses a capacity of 500 c.c.

The smallest of these recorders is suitable for recording the volume-changes of such organs as the kidney, intestine, or the limb of a small animal, and shows the details of the tracing well. This size is approximately of the same sensitiveness as the smallest piston of the Hürthle recorder. In Fig. 2 is reproduced a tracing yielded by a short length of dog's intestine.

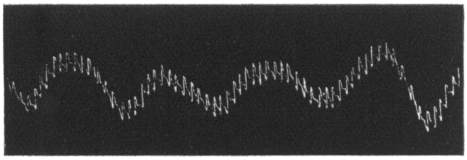

Fig. 2. Volumetric tracing of a loop of dog's intestine. The large waves are due to pendulum movements of the intestine. The small waves are due to the heart-beats. Taken by smallest bellows with magnification 8-fold.

The second size of recorder I have used for cardiometric tracings in cats or rabbits. Fig. 3 gives such a tracing, which illustrates the effect of suprarenal extract upon the output of the cat's heart. It is seen

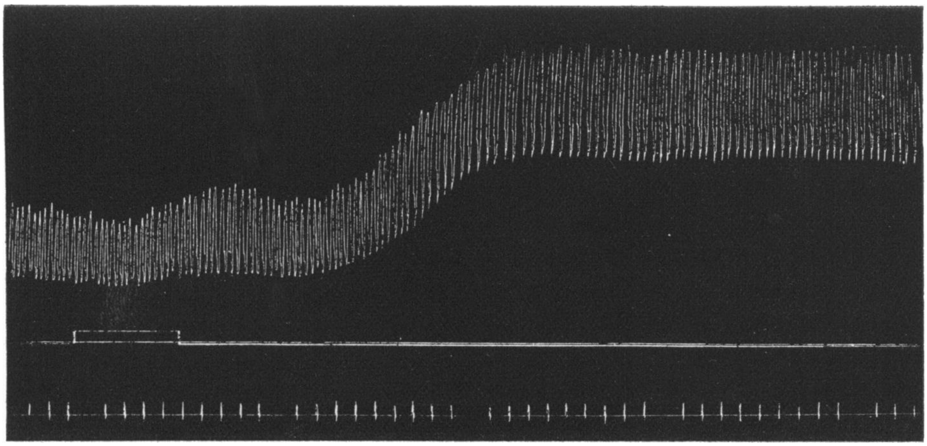

Fig. 3. Cat, anæsthetised with ether. Cardiometric tracing. A downward movement means decrease in volume. At the time indicated by the signal a watery extract from 2 gr. of dried suprarenal was injected. Time record in seconds. Second size of bellows. Magnification 5-fold.

that the output per beat is increased, that the heart becomes considerably distended and at the height of that distension is markedly slower in rate.

I have used the third size of bellows for recording the contractions of the spleen in medium-sized dogs, or for recording the volume-changes of a lobe of the lung. Fig. 4 gives a tracing of the contraction of the spleen of a dog on excitation of one of its nerves. The total contraction

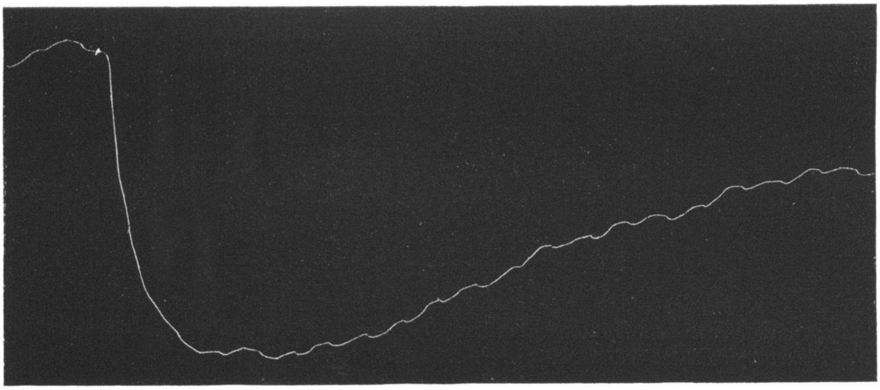

Fig. 4. Medium-sized dog. Ether and morphia. Splenic volume. Contraction on exciting splenic nerve. Total volume-decrease 14 c.c. Third size of bellows. Magnification, 3-fold.

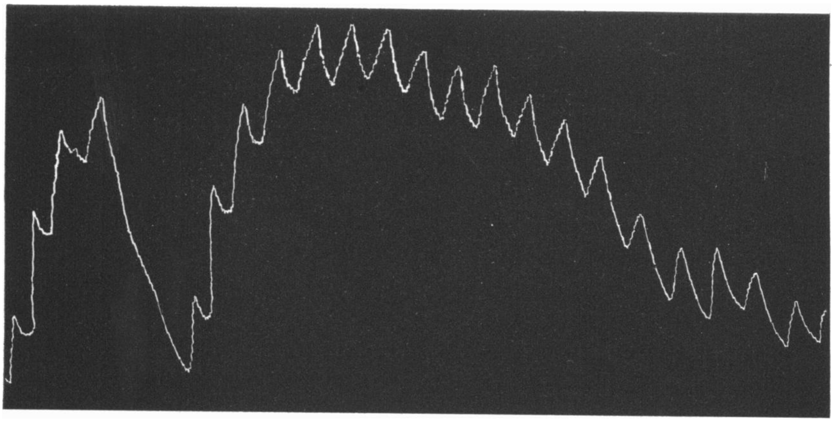

Fig. 5. Same experiment as in Fig. 4, but with smallest bellows. Magnification 6-fold. The total amplitude of the large splenic wave is 2 c.c.

amounted to 14 c.c. In this figure the magnification is very small, and therefore the tracing only shows the splenic waves without any indication of the heart-beats or respiratory waves. For comparison I therefore give Fig. 5, taken from the same animal immediately after the tracing of Fig. 4, but using the smallest bellows. In this the volume-changes due to heart-beat and respiration are very evident.

The largest bellows, I have employed in recording the total air movements in respiration in small animals. Fig. 6 is such a record from an experiment upon a cat. The animal was anæsthetised and

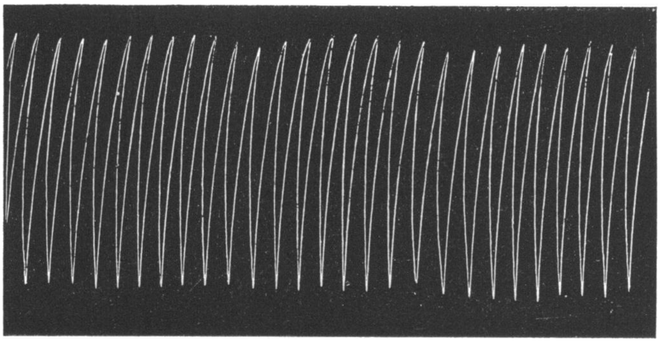

Fig. 6. **Total air-volume movements in respiration of a cat. Inspiration is recorded by a downward movement. Amplitude of movement 90 c.c. Largest bellows. Magnification 2-fold.**

a cannula tied in the trachea. This was connected by a short piece of wide rubber-tubing to a large bottle of 7 litres capacity. From this again a second tube led to the bellows. Inspiration is represented in the tracing by a down-stroke. The extent of the tracing indicates that the air inspired at each respiration amounted to 90 c.c. An interesting feature of the tracing is that it shows variations of amplitude occurring in a regular series. So far as I am aware these waves have never been observed in a respiratory tracing. They are universally present in records obtained by this method and are now being investigated.

The only form of apparatus which in any respect resembles the bellows-recorder is one invented by Gad[1] for recording the inflow and outflow of air in respiration. This instrument, which Gad terms the "Aeroplethysmograph," consists of a hollow wedge made of mica which rotates about one edge as a hinge. The lower edges of the wedge are immersed in water, thus enclosing an air-space into which the animal is made to breathe, a large air-space being interposed between the animal and the recorder.

[1] Gad. *Arch. f. (Anat. u.) Physiol.* p. 181. 1879.

Having found that the recorder gave what were apparently very accurate tracings in many experiments, I next carried out a series of tests with the object both of comparing it with the piston-recorder and of studying the general problem of recording volume-variations by air-transmission. At the outset there were several points involving the bellows only, which had to be examined. The first of these is; is it necessary to counterpoise the cover and writing-lever? It will, of course, be best to avoid the use of a counterpoise if possible and thus reduce the inertia of the moving parts.

The only possible error in working without a counterpoise is that there will always be a positive pressure within the bellows and oncometer during an experiment. This is however of no importance if that pressure be small, and remain constant. I therefore measured it for the four bellows described, and found it to be as follows:—In No 1 (*i.e.* the smallest) it lies between 2 and 3 mm. of water; in No. 2 it is just less than 2 mm.; in No. 3 it is 1 mm.; and in No. 4, 0·5 mm. of water. The pressure is the same for all positions of the cover. In all cases the same writing-lever was employed. It is 240 mm. long and weighs 0·12 gr. It consists of a thin strip of cane 2 mm. wide and 0·22 mm. thick. To its end is gummed a strip of thin writing-paper 20 mm. long and 5 mm. wide. To the end of this is fixed a small bent glass writing-point. The use of the writing-paper gives greater flexibility and enables the writing-point to follow accurately any unevenness of the recording surface. By this writing-lever the magnification with the smallest bellows is 8-fold, *i.e.* the movement of the writing-point is 8 times greater than that of the free edge of the cover of the bellows. This edge, of course, moves more than any other point of the cover.

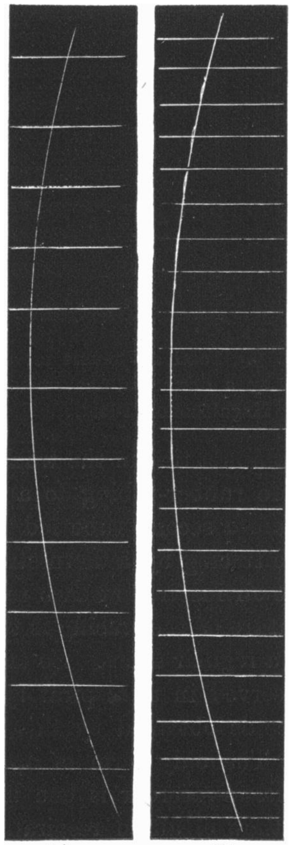

Fig. 7. (Reduced by ½.) Calibration of the first and third sizes of bellows. In (*a*) the volume-increase between two horizontals is 0·5 c.c. (smallest bellows); and in (*b*) it is 2 c.c. (third size of bellows). In both cases the lever was 24 cms. long.

The pressures caused by omitting to counterpoise are in all cases very small, and as they do not vary in different positions, we may conclude that the recorders can quite safely be employed without counterpoising.

The next point tested was whether the recorder gave equal excursions in all positions for equal variations in volume. I found that if the bellows be made so that the sides are in the ratio of 3 : 2, and if the sides be folded as described above, the lever gave very nearly equal increments of movement for equal increments of air injected. This was tested by injecting equal volumes of water into a bottle, the air displaced being carried to the recorder. Examples of the tracings obtained in this manner are given in Fig. 7. In this tracing (*a*) was given by the smallest bellows, the successive horizontal lines indicating differences of 0·5 c.c. of volume. Tracing (*b*) was given by the third size of bellows, and gives differences of 2 c.c. between two successive horizontals. It is seen that the excursions are fairly equal throughout the whole range. A similar tracing yielded by a piston-recorder gives the same result.

In tracing (*a*), the magnification is 8-fold; in tracing (*b*), 4-fold.

Experiments for testing accuracy and sensitiveness.

In the next series of experiments tests were carried out to determine whether the recorder always gave the same excursion on injecting a fixed volume of air, both for different positions of the bellows and on different days. Many such measurements have been made, and they show that the recorder may be completely relied upon in this direction.

The next test was to find how quickly the recorder would respond to known volume-changes. The rapidity at which the recorder can work accurately is largely dependent upon the inertia of its moving parts; but it is also necessary that the connecting tubing should not offer too much resistance to the air-movements. A simple and most accurate test of the manner in which a recorder works consists in observing the air-pressure variations in the recorder, tubing or oncometer. A theoretically perfect recorder should show no measurable variations in pressure. I have tested the accuracy of the recorder in the following manner. A small pump was made to drive a known volume of water in and out of an enclosed space connected to the recorder and to a water-manometer. The pump was driven at varying rates and the movements of the recorder written upon a moving surface. The oscillations of the manometer were read at the same time.

Experimenting in this way it was soon found that irrespective of the recorder two other factors play a most important part. The first is the internal resistance of the air in its movements in the tubing, and the second is the nature of the writing-point. In the case of movements running a slow course, the resistance to the air is of little moment and we may therefore use a long length of tubing of even small diameter (2 to 3 mm.). With quick movements it is essential to employ wide tubing, and further, in order to diminish as far as possible the error due to the fact that the variation travels as a wave along the tube, it is necessary to keep the tube as short as possible. Thus in actual experiments I have found that in taking a cardiometric tracing the tubing leading to the recorder should certainly be not less than 10 mm. in diameter. In respiration experiments it should be 20 or even 30 mm. in diameter.

The second condition is to make sure that the writing point is quite rigid in the vertical direction. Thus the writing-point above described (p. 482), while excellent for small variations and for slow changes, is not suitable for rapid movements of considerable extent. The use of a thin strip of paper does not give it sufficient rigidity in the vertical direction. I have found it best to replace it by a fine writing-point of thin quill such as is used in Hürthle's recorders, or in Verdin's patterns of the Marey tambour.

Having satisfied these conditions we may now return to the experiment the arrangement of which was described above. In the final tests of this kind the tubing leading from the pump to the recorder was 42 cms. long and 10 mm. in internal diameter. In describing the results, for the sake of comparison, similar experiments are given for the piston-recorder and tambour.

(1) With the smallest pattern bellows-recorder the variations in pressure in the manometer, when volume-changes of 1·5 c.c. amplitude were rhythmically produced 80 times per minute, were 1 mm. of water. When the rate was increased to 160 per min. the oscillations were 0·25 mm. (In this case the rate of change was too quick for the manometer to accurately follow the pressure changes.)

(2) With the smallest piston of the Hürthle recorder the variations were 1·5 mm. and 0·5 mm. respectively.

(3) With a tambour 30 mm. in diameter and covered with rubber membrane 0·22 mm. thick the variations were 14 mm. and 4·5 mm. respectively.

In this experiment therefore there is a slight advantage in favour of the bellows over the piston-recorder, and both are far better than a sensitive tambour.

The next two figures (8 and 9) give the result of the test with regard to accuracy in recording the volume-change. The magnification of the record in both cases is five-fold. In tracing (*a*) of the two figures the rate at which the pump was worked was 80 per minute, in (*b*) it

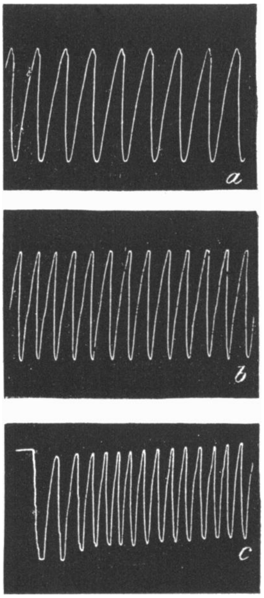

Fig. 8.

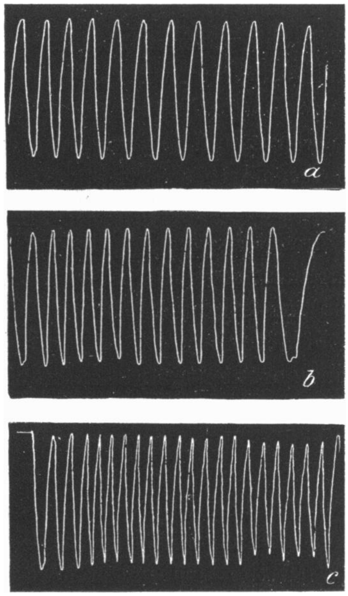

Fig. 9.

was 125 per minute, and in (*c*) 160 per minute. It is seen from the two figures that, with the first two rates, both bellows and piston give accurately all the details of the rhythmic change and there is no alteration in the amplitude of the excursion. With the faster rate both recorders fail to give the complete amplitude, as judged from the first one or two excursions which were recorded while the motor driving the pump was working up to its full speed. There is seen to be very little difference between the behaviour of the two recorders under the conditions of this experiment.

If the two are tested with volume-changes of less extent both follow the movement completely with much faster rates of pumping. Thus with movements 0·5 c.c. in amplitude both gave the full records even when the rate of pumping was increased to 215 per minute. When the rate was increased still further both finally failed, the piston-recorder a little earlier than the bellows-recorder.

A further modification of this mode of testing, which I have employed, consisted in observing the variations in pressure caused by very suddenly driving air into the recorder. This was effected by allowing a weight to suddenly fall upon and compress a wide rubber-tube connected to the manometer and recorder. The volume of the air driven in, in one of these experiments, was 3·2 c.c., and caused an oscillation in the water-manometer of 4 mm. water with the smallest bellows, and of 9·5 mm. with the small piston-recorder.

In addition to testing the accuracy and rapidity with which the two recorders will respond to fairly large volume-changes I have also tested them with respect to sensitiveness, *i.e.* as to how small a change they will accurately record, and whether they will still follow minute changes when the time occupied by the variation is progressively diminished. Perhaps the most searching test of this character is that employed by Marey[1] in testing tambours. This consists in transmitting the vibrations of a tuning-fork to the recorder to be tested. The tuning-fork sets in movement the membrane of a transmitting tambour and these oscillations are transmitted by air to the tambour or recorder. With especially light levers and very sensitive tambours Marey succeeded in recording 250 vibrations per second by this method. With the tambours I had at my command I only succeeded in recording 50 vibrations per second well, the 100 per second record being unsatisfactory. With the smallest bellows-recorder I succeeded in recording 50 vibrations per second easily, and 100 vibrations per second after a few preliminary trials. I reproduce two of these tracings in Fig. 10.

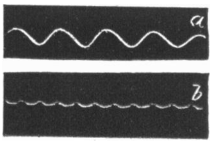

Fig. 10.

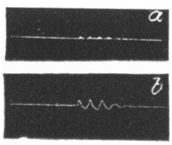

Fig. 11.

Fig. 10. Records of the vibrations of two tuning-forks transmitted from a tambour to the smallest bellows. In *a* the rate of vibration was 50 per sec. In *b* 100 per sec. The drum was rotated by hand.

In my hands the piston-recorder failed completely to respond to the 50 per second vibrations.

[1] Marey. *Travaux de Lab.*, p. 38. 1875.

Another test of sensitiveness to minute changes consists in dropping a small weight from a known height on to a transmitting tambour connected to the recorder. This test was employed by Hürthle[1] in comparing the piston-recorder with a sensitive tambour, and the results are given in his paper upon recording by air-transmission. He allowed a weight of 0·2 gr. to fall 5 mm. upon the central disc of a small tambour. In employing this method I have slightly modified the test in that the weight I used was only 0·105 gr. which fell 5 mm. on to the centre of a thin rubber membrane 0·2 mm. thick stretched across a glass tube 43 mm. in diameter. No disc was fitted to the membrane.

Fig. 11 gives the result of the two experiments, tracing (*a*) is that given by the piston-recorder[2], and tracing (*b*) by the smallest bellows-recorder. In both cases the magnification was eight-fold. The extreme sensitiveness of the bellows is well brought out in this tracing; each impact of a shot is clearly indicated by a very decisive wave and the rebound of the membrane is seen in the parts of the curves below the abscissa line. In other respects the curves speak for themselves.

As a result of these and many other tests of a somewhat similar kind, I conclude that the bellows-recorder is quite reliable as a volume-recorder. In all points of sensitiveness and rapidity of action it compares very favourably with the piston-recorder, which it excels in one direction, viz. that of range. It possesses the further advantage that it can be made of very large capacity without materially increasing the weight of the moving parts, and in these large forms it is quite as accurate as in the smaller. Moreover the weight of the moving parts in the bellows-recorder is considerably less than that of the similar parts in a piston-recorder of the same capacity.

I would especially emphasise the following points, which should be observed in recording volume by air-transmission.

(1) When details of rapid movements are required the tubing leading from transmitter to recorder should be of not less than 10 mm. in diameter, and should be as short as possible.

(2) The more extensive the air-movements the larger should the tubing be. Thus to record the tidal air in respiration in a cat, tubing of 20 mm. diameter should be used.

(3) In recording rapid movements of any amplitude the writing-point should not magnify the movement of the recorder more than five-fold, and the writing-lever must be tested to show that it is really rigid in the direction of the movement.

[1] Hürthle. *Pflüger's Archiv*, LIII. p. 306. 1893.

[2] The piston-recorder has an internal diameter of 19 mm.