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# THE DENSITY FLOWMETER, A DIRECT METHOD FOR THE MEASUREMENT OF THE RATE OF BLOOD FLOW

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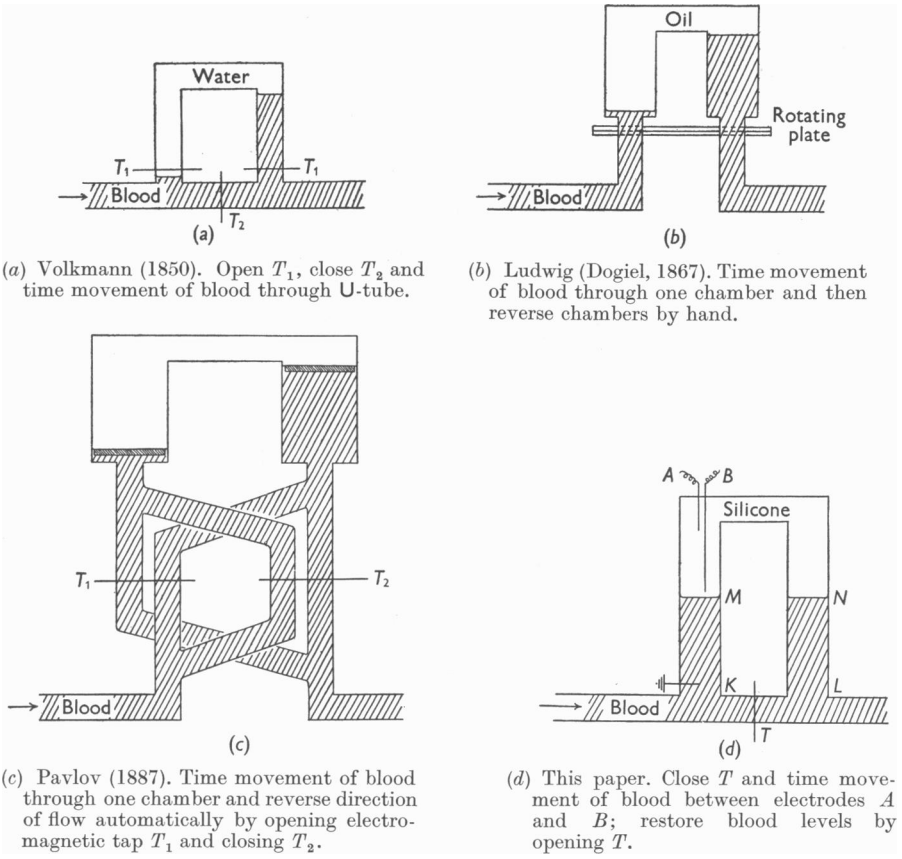
Of the many methods available for measuring the rate of blood flow, few rely upon a *direct* measurement of volume and time. Volkmann (1850) (Fig. 1*a*) measured the rate of arterial blood flow directly under conditions approximating to physiological, and his apparatus was modified and improved by Ludwig who incorporated a reversible oil-chamber (Dogiel, 1867) (Fig. 1*b*). In 1887 Pavlov made Ludwig's stromuhr automatic by providing electromagnetic taps to change the direction of flow in the two bulbs (Fig. 1*c*), using the Y inlet and outlet tubes devised by Stolnikow (1886). Since then many modifications of this principle of measuring rate of flow have been published. These modifications have been of two kinds, involving either the mechanical apparatus used for closing or opening the four tubes (Fig. 1*c*), or the detection device which operates it, e.g. floating contact-maker (Pavlov, 1887), change of electrical resistance (from oil to mercury) or change of opacity detected by photo-cells (Lu & Melville, 1950). The apparatus has, however, remained bulky and inconvenient.

The method to be described was designed to make direct measurements of the rate of blood flow in an artery. It involves an application of Volkmann's principle which is mechanically simpler than Ludwig or Pavlov's method, or any more recent modification thereof.

## METHOD

Fig. 1*d* illustrates the principle used. Blood flows continuously through the apparatus. The upper portions of the two chambers are filled with a fluid which is lighter than and immiscible with blood, and which has an electrical resistance much greater than that of blood. The cycle of operation begins with closure of the electromagnetic tap $T$, when the blood which previously flowed directly from $K$ to $L$ is diverted around the upper portion of the apparatus. The meniscus ($M$) between the blood and the inert fluid above it begins to rise,

and the time taken for this meniscus to travel between the ends of electrodes *B* and *A* is recorded. This is the time for a known volume of blood to pass through the apparatus. As the meniscus *M* rises, meniscus *N* falls, and because of the difference in specific gravity of the two fluids a small (physiologically insignificant) pressure difference develops across *KL*. When meniscus *M*




(*a*) Volkmann (1850). Open $T_1$, close $T_2$ and time movement of blood through U-tube.

(*b*) Ludwig (Dogiel, 1867). Time movement of blood through one chamber and then reverse chambers by hand.

(*c*) Pavlov (1887). Time movement of blood through one chamber and reverse direction of flow automatically by opening electromagnetic tap $T_1$ and closing $T_2$.

(*d*) This paper. Close $T$ and time movement of blood between electrodes *A* and *B*; restore blood levels by opening $T$.

**Fig. 1. Principle of operation of direct-recording flowmeters.**

reaches electrode *A* the electromagnetic tap is released and because of the pressure difference meniscus *M* falls below electrode *B*, ready for the next cycle to begin. It will be seen that only one tube has to be opened and closed, as compared with four in Pavlov's and subsequent applications of Volkmann's principle.

*Details of construction*

The overall dimensions of the flowmeter are 8·5 cm wide, 7 cm deep and 17·5 cm high. The Perspex chambers and Portex and rubber tubing of which the apparatus is composed are assembled on a duraluminium panel, to which they are attached by two plugs on the back of the

electrode chamber and a clip around the return chamber (Figs. 2 and 3). They are easily removed for cleaning. The lower plug which supports the electrode chamber penetrates the wall and constitutes the earth connexion. The electromagnet which operates the tap, and the main electrical socket and all wiring points are enclosed behind the panel (Fig. 3). The whole flowmeter is supported from a single horizontal rod, and one 7-core flexible cable carries the electrical leads.

Consideration of Fig. 1*d* explains at once certain features of the design. The connecting tubes are as wide as possible to minimize pressure loss across the meter; they are short in order to keep the volume of the apparatus small. The distance *AB* is such that instrumental error (arising from the pulsation of the meniscus *M*) is negligible. The quantity of blood in the return chamber *NL* at

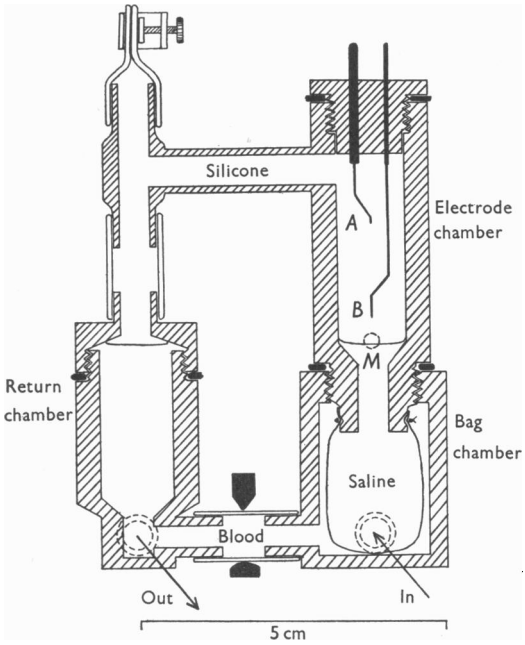



Fig. 2. Sectional view of flowmeter. The chambers are made of Perspex, the washers from Portex sheet, the connecting tubes of rubber and the electrodes of silver wire. The bag is moulded from rubber solution on a former.

the beginning of the cycle of operation is larger than that contained between the electrodes *AB* so that there is no chance of the inert fluid entering the blood stream. A small economy in height is also made by expanding the lower parts of the two chambers as shown in Figs. 2 and 3.

The volume of blood contained between electrodes *A* and *B* in this form of the instrument was 1·5 ml., and it was used successfully for recording flows of 2–50 ml./min. The upper limit is determined in part by the temporal resolution of the recording instrument, which is discussed later, and the lower limit by the danger of producing vasotonins when a large measuring chamber is used with very slow rates of flow. For larger volumes of flow, larger measuring chambers have been constructed. The inside of the measuring chamber and the electrodes must be polished and clean, so that the meniscus rises smoothly.

In our first experiments xylene was used as the 'inert fluid'; this has a sp.gr. 0·8, low viscosity and is immiscible with water. It was feared that it would be too toxic, but in practice it never appeared to mix with the blood. Experiments ran for hours at a time without any undesirable effects on the animal, but the xylene slowly softened the Perspex and connecting tubes. It was

therefore abandoned in favour of Silicone DC 200/0·65 cs, sp.gr. 0·75, viscosity 0·49 cP at 25° C, b.p. 99·5° C made by Midland Silicones Ltd. This fluid is colourless and has a very low electrical conductivity; it does not affect the Perspex or plastic and rubber connecting tubes, it forms a well-defined meniscus with blood and is non-toxic.

With both xylene and Silicone DC 200/0·65 cs, there was a tendency for the blood to form fibrin threads on the electrodes, in spite of the use of a large amount of heparin. Although the apparatus would sometimes work satisfactorily for more than an hour at a time, on other occasions it soon

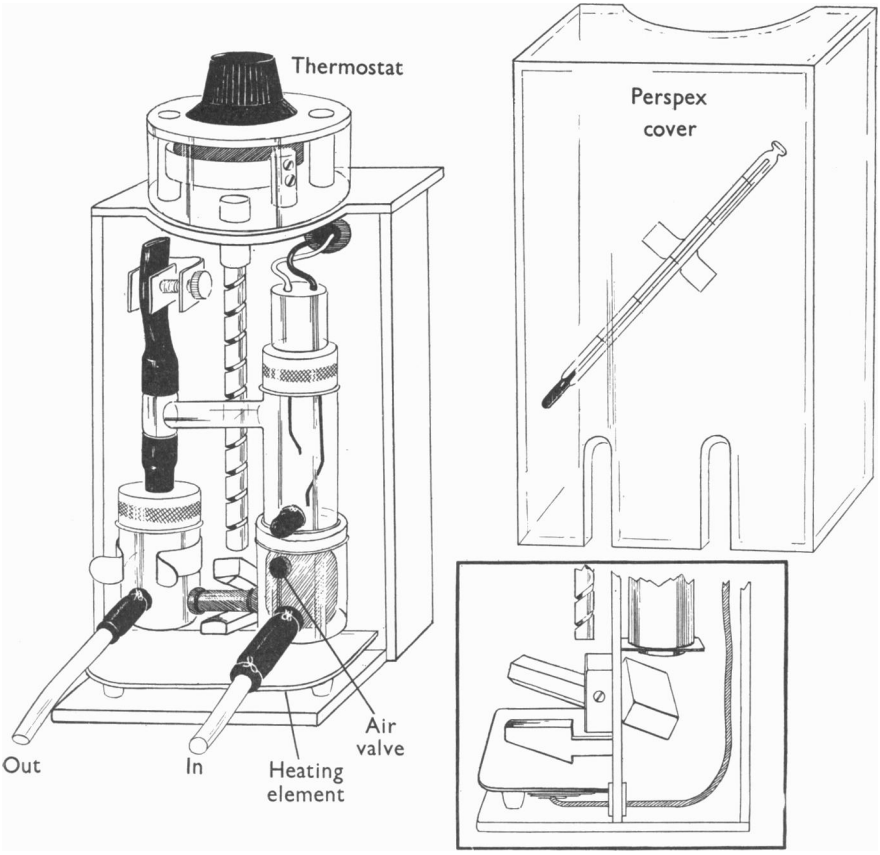



Fig. 3. The assembled flowmeter and Perspex cover. The insert shows the detail of the electromagnetic tap when the side of the instrument has been removed.

became quite unreliable, as the lower electrode was effectively lengthened by a thread of fibrin. This problem was not solved until blood was prevented from coming into contact with the electrodes by the interposition of a thin rubber bag filled with saline (Fig. 2). The bags are cast from rubber solution on a Perspex former and are made as thin as possible and of such a shape as to offer negligible resistance when distorted.

The electromagnetic tap consists of a brass bar, one end of which is wedge-shaped so that it can compress the rubber tube between *K* and *L* (Fig. 1*d*) against a cylindrical anvil. It is pivoted at its centre on the duraluminium panel (Fig. 3). A block of soft iron is attached to the other end of this bar and is pulled upwards by two 200 Ω relay coils supplied from the 40 V power-supply which operates the control unit. The control unit was designed so that the electrode current (5 μA)

was only applied for a short time. The circuit is shown in Fig. 4 and the operation cycle in Table 1. The only point which requires further comment is that while the meniscus $M$ is falling its position is tested automatically at intervals regulated by the value of the condenser across the relay coils $R_s$. This relay opens, and, if the meniscus $M$ (Fig. 1*d*) has not yet fallen below $B$, closes again for a further interval. The measuring part-cycle is thus prevented from starting until the meniscus has fallen below $B$. And on the other hand, the frequency of this test can be adjusted so that the least possible time is wasted on the (useless) return part of the cycle.

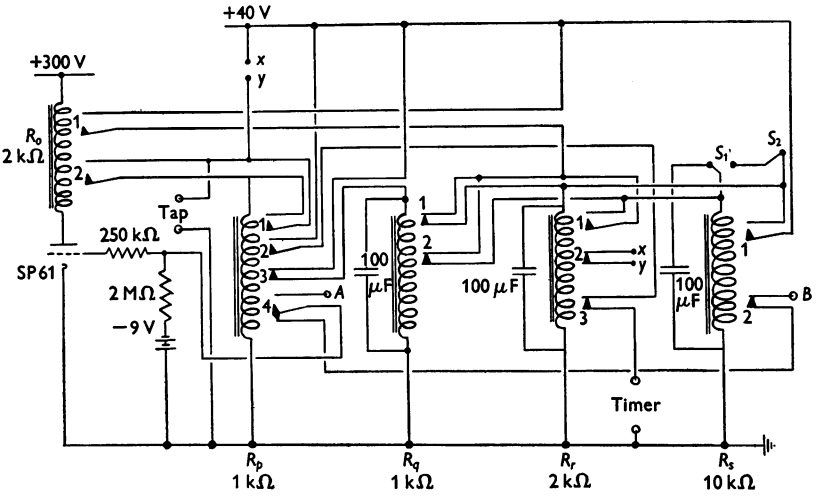



Fig. 4. Circuit diagram of the control unit. Relay contacts are shown in the position occupied when current is not flowing. The principle of operation is explained in Table 1.

TABLE 1. Operation cycle for flowmeter

Initial state: upper electrode $A$; lower electrode $B$; $S_1$, $S_2$ as drawn; blood level below $B$ and, since tap is closed, rising.

| Blood | $R_0$ | Tube grid to | $R_p$ | $R_q$ | $R_r$ | $R_s$ | Tap | Timer |
|---|---|---|---|---|---|---|---|---|
| Below $B$ | Off | $B$ | Off | On | Off | Off | Closed | Off |
| At $B$ | On | $B$–$A$ ($R_p$4) | On | On | Off | Off | Closed | On ($R_p$2) |
| | Off | $A$ | On ($R_p$1) | Off (condenser discharged) | Off | Off | Closed | On |
| At $A$ | On | $A$ | On | Off | On ($R_0$1) ($R_q$1) | On ($R_0$1) ($R_q$2) | | |
| | Off | Open ($R_s$2) | Off ($R_r$2) | On ($R_p$3) | On ($R_s$1) | On (100 μF × 10 kΩ) | Open ($R_r$2) | Off ($R_r$3, later $R_p$2) |
| Below $A$ | On | $B$ ($R_s$2) | Off ($R_r$2) | On ($R_p$3) | On (100 μF × 2 kΩ) | Off | Open | Off |

Under these conditions $R_s$ closes again by $R_0$1, $R_r$1 and its condenser is recharged. This cycle will then repeat until the blood falls below $B$ and $R_r$ is able to open; the tap will then close and blood begin to rise again.

*Note.* (1) The current (about 5 μA) will only flow through either electrode for a fraction of a second, closure of $R_0$ at once resulting in electrode contact being broken. (2) If $S_1$ is moved over, the cycle will stop with the tap open, when $R_s$ is held on ($R_s$1). Push-button interruption of this circuit at $S_2$ will then allow one complete cycle only.

The time interval measured by the instrument can be recorded in a number of ways. We have so far used two methods which are fairly simple and readily available. Gaddum's drop-timer (Gaddum & Kwiatkowski, 1938) gives a visual record on a smoked-drum, which is easily calibrated. When the measurement of the absolute rate of blood flow was required simultaneously at more than one point in the circulation over a number of hours, it was found better to use another method. A synchronous motor was geared down so that it made and broke a pair of contacts ten times per second. The pulses thus generated were used to actuate four post-office electromagnetic counters each connected to a separate flowmeter during the recording part of the cycle. The interval was then read off to the nearest tenth second.

Heat loss was prevented by enclosing the apparatus within a Perspex cover which slips vertically over it (Fig. 3). A small heating element, arranged beneath the two chambers and covered by a thin sheet of mica was controlled by a thermostat. In order to keep the differential temperature as low as possible a constant current was maintained through the heating element. The current was increased by the thermostat circuit when the temperature in the apparatus fell. Variation in laboratory temperatures was sufficiently large to warrant the provision of a fairly wide range of heat dissipation from the element (30 Ω). This was achieved by supplying the element from alternative transformer tappings of 12–30 V in 3 V steps. With this system there was little danger of the blood in immediate contact with the Perspex walls of the chambers being at any time raised to an excessive temperature.

To prepare the meter for use, saline, dextran or blood is run into the lower part. The bag is filled with saline and the upper part is filled with silicone; the levels of the menisci are then adjusted to their operating positions. The quantity of saline in the bag can be altered by introducing a fine syringe needle through the rubber nipple at the bottom and front of the electrode chamber (Fig. 3). The electrode assembly is then screwed into position and air bubbles are removed through the valve provided.

### *Performance*

By using different sizes of measuring chamber, rates of blood flow have been recorded from 1 to 500 ml./min. The range could presumably be extended much further. The pressure drop across the meter naturally varies with the velocity of blood flow and with the viscosity; it also increases during the measuring part-cycle owing to the difference in specific gravity of blood and of the inert fluid in the meter. This component did not exceed 1·5 mm Hg, and the maximum total pressure loss using a mean rate of blood flow of 50 ml./min did not exceed 3–4 mm Hg. The duration of the useless recovery part-cycle is not more than a few seconds. Variation in outflow temperature has not been more than $\pm 0{\cdot}5°$ C and is usually much less.

The quantity of blood required to fill the apparatus is not large; it varies with the size of the measuring chamber, which in turn is dependent on the largest volume flow required to be measured and the temporal discrimination of the recording apparatus. For a meter which will comfortably handle 45 ml./min, with an inter-electrode volume between *A* and *B* of 1·5 ml. and (in this instance) a minimum measuring time of 2·0 sec, the blood volume required to fill the apparatus is between 4 and 5 ml. with an adequate safety margin. To this must be added the volume needed to fill the tubes connecting the apparatus to the artery, which may vary according to the experimental conditions.

The accuracy of the meter has been checked by pumping saline through it from a pulsatile pump at rates of from 1 to 50 ml./min; the effluent was collected in a measuring cylinder over a known period of time. The absolute accuracy of the meter under these conditions was better than $\pm 4\%$. Part of this variation was undoubtedly due to the apparatus used for recording the time interval, and this could certainly be improved should it be required. Two other sources of variation may be mentioned. First, the meniscus may change shape as it passes up the measuring chamber. This change may be reduced by cleaning and polishing the measuring chamber. Secondly, if the heart rate is slow and the rate of flow rapid, there may be an apparent variation in recorded rate of flow because the pulsations of the meniscus strike the two electrodes at different phases of the cardiac cycle. It is difficult to detect this phenomenon when the time taken for the meniscus to pass between the electrodes is greater than 2 sec (i.e. six heart-beats at a rate of 180 per min). This consideration determines the inter-electrode volume and is a useful guide to the maximum rate of flow which can be accurately measured with a given type of time-measuring instrument.

It is convenient to have a concise name for a flowmeter. In order to recall the principle on which the recovery part-cycle depends, we propose the name density flowmeter.

## DISCUSSION

This method of measuring the volume of blood flow involves section of the vessel, and clotting must be prevented in the meter, by heparin for example. The apparatus gives no indication of the instantaneous rate of flow during the cardiac cycle, but intermittently measures the time for a predetermined volume of blood to flow through it. For most purposes this is all that is required. The chief virtue of the method is that it measures rate of blood flow by direct observations on volume and time. It is therefore unaffected by changes in viscosity, backflow and other variables. All the other methods of measuring the rate of arterial blood flow in present-day use rely on indirect observations, of differential pressure (by venturimeter, pitot tube, orifice-meter or rotameter), by measuring the movement of a bubble or the change of e.m.f. in a magnetic field. While some of these methods have the advantage that they continuously measure instantaneous flow, few have been adequately checked against a direct method *in vivo*, and none can yet give an absolute measurement of volume flow. On the contrary the Volkmann (1850) flow-meter, and its many modifications by Ludwig (Dogiel, 1867), Stolnikow (1886), Pavlov (1887), Montgomery & Lipscomb (1929), Hemingway (1931), Bennett & Still (1933), Montgomery, Moore & McGuinness (1934) and Lu & Melville (1950) do give a direct measurement of volume flow. The effect of the new application of Volkmann's principle described in this paper will be seen to be

a reduction in the number of tubes to be opened and closed from four to one. The apparatus thus becomes mechanically simpler, smaller and more reliable, and it has been a practical proposition to use several simultaneously in the same animal.

SUMMARY

An apparatus is described which intermittently measures the time for a fixed volume of blood to flow through it.

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