Improvement on Automatic Bubble Flowmeter

NAGATAKA YAGO, SHIGERU OHASHI

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The automatic bubble flowmeter with vacuum tubes which has been used so far is apt to be unreliable. In view of this, we have completed a reliable, easy-to-operate, automatic bubble flowmeter in which vacuum tubes are replaced by transistors. It has a U-shape glass tube and a time ordinator, which enables flow velocity to be recorded on smoked paper.

It was impossible with the old bubble flowmeter with simple U-shape glass tube to determine flow volume above 250 cc/min. The new flowmeter tube is fitted with a bypass joining the necks which enables the total flow volume to be determined from the partial volume passing through the U-tube. By this method flow volume can now be determined up to 1250 cc/min. In addition this paper includes a report on determinations of cardiac output, coronary blood flow and femoral blood flow in animals, which were carried out with the new flowmeter.

A bubble flowmeter was first used by Soskin (1) to determine blood flow in a dog's hindlimb vein. Later it was used by Dumke (2) to measure cerebral blood flow, and by Eckenhoff (3) to determine coronary blood flow. Various improvements have since been made by many researchers, while all the fundamental problems involved seem to have been thoroughly studied by Brunner (4). Automation of this flowmeter was then designed and effected separately by Selkurt (5), Sokalchuk (6), Winder (7) in the United States, and by Baumgartner (8), Braun (9), Friedburg (10) in Germany. All of them made use of photoelectric cells and seem to have attained an appreciable measure of stability. However, an apparatus made by us along similar lines was electrically rather unstable and much skill and special care were necessary in manipulating it. Its greatest defect was in that the internal resistances of its photoelectric cells and other vacuum tubes were so high that change in photoelectric current produced by the difference between bubble and blood in light transmission and electric current in the whole circuit were quite small (several μA). In our improved flowmeter in which photo- and other transistors are used, change in photoelectric current is 50 to 60 times as large and it can function with remarkable stability.

The tube for taking measurements in the bubble flowmeter is made of glass or synthetic resin with an internal diameter of 3–5 mm. Hydrodynamics require a minimum limit of 3 mm, while a maximum of 5 mm is required because, above it, error becomes too great. It is consequently all but impossible to determine flow volume above 250 cc/min with this type of flowmeter (8) and in this respect it is considered inferior to the rotameter or electromagnetic flowmeter. In our new flowmeter a bypass is connected to the U-shape glass tube, and by measuring the partial flow through it total flow volume can be estimated. By this means it is now possible to determine flow volume as high as 1250 cc/min.
Using this apparatus we determined blood flow in a rabbit's femoral artery, dog's femoral and coronary artery, and cardiac output in a dog’s heart-lung preparation.

ARRANGEMENT OF APPARATUS

A. Principle of how the apparatus functions:
The bubble flowmeter is an apparatus to determine flow velocity by measuring time for a bubble to pass a distance between two points in a tube which represent a certain given volume. There are various improved types. In our present method a bubble is introduced at the first point and then caught photoelectrically at the second point. At the same time the next bubble is introduced.

B. Wiring of the amplifier:
In all hitherto used automatic bubble flowmeters vacuum tubes are placed in the circuit of the amplifier. They require a high potential of 200–350 volts to operate. Internal resistance of photoelectric cells are very high and owing to this, change in current due to photoelectric difference between a bubble and blood cannot be higher than 1.5–2 $\mu$A. Consequently, it is necessary to use high amplification in operating the relay, which in turn permits irrelevant signals to be caught as well, making the readings inconsistent. Also change in the electric source potential has a considerable effect on the readings so that inconsistency is increased. To improve these defects, an amplifier as shown in Fig. 1 is devised, in which all vacuum tubes are replaced by transistors. As a result, the charge of the collector come down to 20 volts, the effect of the change in electric source potential is reduced, dark current (transmission through blood) of the phototransistor ranged between 50–150 $\mu$A (varying in different transistors), and the photoelectric change signalling the pass of the bubble is 30–100 $\mu$A. Before the first transistor a diode is so placed to pick up only positive changes and exclude negative changes with the object of eliminating effects due to the size of a bubble and flow velocity reduction. The first and second transistors (multivibrator circuit) act to transform the current into rectangular current and to divide the relay into different time of 0.25, 0.5 and 0.75 sec.

C. Pump and recording mechanism:

For the introduction of a bubble, the same device as that of Braun et al. (9) is used. As

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Fig. 1. Electronic circuit of amplifier catching the bubble photoelectrically, and sending signal to time ordinator and bubble introducer.  
MCP 71: phototransistor. 2SB71, 2SB76, 2SB130; transistor.  
si-1, si-2, si-3: silicon diode.  
D-1, D-2, D-3: gelmanium diode.  
To-Air-Pump plug leads to bubble introducer. To-Recetcoil and To-Syn-Motor wire lead to time ordinator.  

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for the removal of a bubble, intense study is being made to find an adequate method. With our present apparatus the second point is connected to the introduction pump through a valve and bubbles are rotated in circulation as in Baumgartner's method. For simultaneously recording the speed of a bubble on smoked paper, a time ordinator is used. Unlike that of Braun et al. (9), this time ordinator rises at constant rates of 8.6 mm/sec. and 4.3 mm/sec. When a bubble passes the second point, it is caught photoelectrically and the time ordinator drops. After a certain very short time lag, the ordinator rises again and the same process is repeated. The sum of the elevation and the time lag of the ordinator represents the time it takes for the bubble to pass between the two points. Flow volume is computed from this time.

D. Glass tube for taking measurements

Soskin (1) used a U-shape glass tube and Dumke (2) a spiral-shape one. Brunner (4) investigated in detail the relation between the shape of the tube and flow resistance. Our experiences show that, whether the shape of the tube is spiral, helical or rectangular, when the whole of the tube is not on one plane, a bubble moves faster than blood flow in the ascending part and slower in the descending part and thus does not accurately indicate exact flow velocity. Consequently, the simplest U-shape on a horizontal plane is considered best.

The internal diameter of the tube is limited hydrodynamically a range of 3–5 mm and it is important that the curvature not be too small. Owing to this limitation it is impossible to determine with the old-type flowmeter the volume above 250 cc/min. at most. In view of this, we make a tube fitted with a bypass as shown in Fig. 2 in the first attempt at a liquid flowmeter. The bypass-fitted U-tube has an internal diameter of 4.5 mm, the same as that of the old simple U-tube. In the new type the branching part is the most important aspect and experiments with various angles of branching show that a range of 30°–45° gives satisfactory results and 30° the best. Also tests are performed with differing diameters of the bypass, and it is found that when bypasses of 4 mm, 5 mm and 6 mm are used, a linear relation as shown in Fig. 5 is obtained between flow volume in the U-shape tube and the total flow volume in the range from a minimum 180 cc/min. to a maximum of 1250 cc/min.

**Experimental Results**

A. Assessment of difference between actual and measured flow volume:

![Fig. 2. Diagram of new bubble flowmeter tube with bypass enabling the total flow volume to be computed from U-tube flow volume. PH.T.: phototransistor
L: light transistor
B.I.: bubble introducer.](image)

It is desirable in assessing the difference to consider separately the error of the measuring part and the fidelity of the recording part. For all practical purposes, however, it is the error as a whole that is important. So we allow heparinized blood to flow through the measuring tube at a constant speed, accurately measure the volume which flow out in a minute, and compare it with the value computed from the elevation of the time ordinator recorded on the smoked paper. Since the ascending limit of the time ordinator is 130 mm, it takes 15 seconds to attain the limit at a speed of 8.6 mm/sec. or 30 seconds at a speed of 4.3 mm/sec. Therefore, as to the minimum measurable flow volume, it can be said that when the time for the bubble to pass between the two points is longer than 15 or 30 seconds, that is to say, when the flow volume per minute is less than 4 or 2 times the volume between the two points, determination is difficult. As for the maximum measurable value, it is desirable, considering the time lag of the time ordinator, that the time to pass the distance be 1.5 seconds, or flow volume per second be smaller than 40 times the volume between the two points.

a) Measuring with a tube with an internal diameter of 3 mm and capacity of 1 cc:

The results of measurements are shown in

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Fig. 3. The measuring error is below ±5% within a range of 5 cc/min. and 35 cc/min. From the same figure it appears that above 25 cc/min. there may be an overestimation, but even if so, the error is below ±5% and therefore need not be taken seriously. The correlation coefficient between actual and computed value is 0.990.

b) Measuring with a tube having an internal diameter of 4.5 mm and capacity of 5 cc:

The results of assessment are shown in Fig. 4. With this tube determination is possible within a range between a maximum of 220 cc/min. and a minimum of 25 cc/min. with an error below ±5%. The correlation coefficient is 0.995.

c) Measuring with a tube with a bypass:

i) When branching angle is 30° and internal diameter of the bypass tube is 4 mm:

The results of assessment are shown in Fig. 5. Determination is possible between 180 cc/min. and 700 cc/min. Denoting the whole flow volume with a y and that through the U-shape measuring tube with an x, the relation is expressed by the formula $y = 3.17x + 87.2$. The determination error is below ±5% and the correlation coefficient 0.993.

ii) When branching angle is 30° and internal diameter of the bypass tube is 5 mm:

Determination is possible within a range from 300 cc/min. to 950 cc/min. with an error of ±5%. Denoting the total volume with a y and that through the U-shape tube with an x, the relation is expressed by the formula $y = 5.05x + 146.5$. The correlation coefficient is 0.992.

iii) When branching angle is 30° and internal diameter of the bypass tube is 6 mm:

Fig. 4. The relationship between measured flow volume (vertical axis) and value computed from the elevation of the time ordinator (horizontal axis) in the case of a measuring tube with an internal diameter of 4.5 mm and capacity of 5 cc.

Fig. 5. The relation between total flow volume (vertical axis) and U-tube flow volume computed from the elevation of the time ordinator (horizontal axis) in the case of a measuring tube with a bypass with a branching angle of 30° and an internal diameter of 4 mm. The straight line shows the regression line.
Determination is possible between 500 cc/min. and 1300 cc/min. with an error of ±5%. When the total flow volume is a x and that through the U-shape tube is a y, the relation is expressed by the formula \( y = 11.28x + 195.3 \). The correlation coefficient is 0.987. But when the flow volume is greater than 1300 cc/min., the flow volume through the U-shape tube cannot be the index of the total volume.

B. Experimental cases using our new flowmeter:

a) Measuring rabbit’s femoral blood flow:

Determination of blood flow was made by drawing blood from rabbit’s left carotid artery and passing it through our new flowmeter (with a tube having an internal diameter of 3 mm and capacity of 1 cc) into the left femoral artery. Acetylcholine 20\( \gamma \) and theophylline-ethylenediamine 2.5 mg were injected into an artery cannula for 10 seconds. The results are shown in Fig. 6.

b) Measuring dog’s coronary and femoral blood flow:

To determine the coronary blood flow, blood from the femoral artery was passed through the flowmeter (internal diameter 4.5 mm, capacity 5 cc) into the left coronary artery orifice by means of a cannula. To determine the femoral blood flow, blood was drawn from the proximal end of the left femoral artery by means of a cannula and passed through the flowmeter (internal diameter 4.5 mm, capacity 5 cc) into the distal end of it. The effect of 2\( \gamma \) of adrenaline on the coronary blood flow is shown in Fig. 7, and that of acetylcholine 2\( \gamma \) and histamine 2\( \gamma \) on femoral

Fig. 6. Blood flow responses in the hind leg of the rabbit following intra-arterial injection of acetylcholine (20\( \gamma \)) and theophylline ethylenediamine (5 mg) in the case of a measuring tube of internal diameter of 3 mm and capacity of 1 cc.

F. B. F. stands for femoral blood flow. Horizontal axis shows time in minutes.

The left figure shows the effect of acetylcholine, and the right that of theophylline ethylenediamine.

Fig. 7. Blood flow response in the coronary artery of the dog following intra-arterial injection of adrenaline (2\( \gamma \))

Vertical axis indicates respiration, systemic blood pressure in mm Hg, perfusion pressure in mm Hg: coronary blood flow recorded with the new flowmeter (inter. dia. 4.5mm, cap. 5 cc). Horizontal axis indicates time in minutes.
blood flow in Fig. 8.

c) Measuring cardiac output of a dog's heart-lung preparation:

The heart-lung preparation was made by Krayer's (11) and by Hashimoto's (12) method. The flowmeter (angle of bypass 30°, internal diameter 4 mm) was placed between the resistance and the venous reservoir. Fig. 9 represents the effect of 2γ of adrenaline on a normal heart (right atrial pressure 20–30 mm H₂O) and on an failing heart (right atrial pressure 90–100mm H₂O).

**DISCUSSION AND CONCLUSION**

In an improvement on the hitherto conventional automatic flowmeter on which

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**Fig. 8.** Blood flow responses in the hind leg of the dog following intra-arterial injections of acetylcholine (2γ) and histamine (2γ).

Vertical axis indicates systemic blood pressure in mmHg, perfusion pressure in mmHg, femoral blood flow recorded with the new flowmeter (inter. dia 4.5 mm, cap. 5 cc). Horizontal axis shows time in 30 second intervals. The left side shows the effect of acetylcholine (2γ), and the right that of histamine (2γ).

**Fig. 9.** Effect of adrenaline (2γ) on cardiac output and right atrial pressure in dog's heart lung preparation. (in the case of a measuring tube with bypass, branching angle 30°, inter. dia of bypass 4 mm). The left figure shows the effect on a normal functioned heart (R.A.P. 20–30 mmH₂O) and the right figure the effect on a failing heart (R.A.P. 90–100 mmH₂O). Vertical axis indicates blood pressure in mmHg, right atrial pressure in mmH₂O, cardiac output recorded with the new flowmeter. Horizontal axis indicates time in 30 second intervals (left) and minute intervals (right).
used vacuum tubes in the amplifying circuit and signalling mechanism, we devised a new flowmeter having transistors in place of vacuum tube and a time ordinator similar to that of Braun et al., which enables various determined values to be recorded simultaneously on smoked paper. It also has a bypass connected to the measuring U-shape tube and the total flow volume can be computed from the partial flow through the U-tube. With these devices the new flowmeter can measure flow volume up to 1250 cc/min, which is impossible with the old one. In the old flowmeter the effect of blood viscosity and pulse pressure on flow volume was considered almost negligible (8), but in the new flowmeter with bypass these are theoretically considered to have an appreciable effect and experiments with water and liquid of specific viscosity 4 actually revealed a remarkable difference. For this reason heparinized blood was used in the present calibration.

When this new flowmeter is used for a long time, consideration must be given to the likelihood of a difference appearing between the beginning and end of experiments due to viscosity change. But when determination does not take longer than ten minutes as in the present experiments, there is no need to take this into consideration.

As for the relation between viscosity and flow volume in this flowmeter, further investigation is being carried out by us.

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