Measurement of Venous Flow by Continuous Thermodilution and its Application to Measurement of Mammary Blood Flow in the Goat

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With the Technical Assistance of Ivan R. Fleet

Fegler showed in 1957 that the thermodilution method of measuring cardiac output\(^1\) could be used also to measure the blood flow in the central veins of dogs.\(^2\) Small quantities (0.4 to 1.0 ml) of saline at room temperature were rapidly injected through a three-holed needle into the vein, and the brief fall in temperature was recorded photographically from a thermocouple located 7 to 15 cm downstream. The blood flow was calculated from the concentration-time curve of the injected indicator ("cold"), the blood temperature and the temperature and volume of saline injected.

The method was readily adapted to measure the venous flow from the udder of conscious goats, and with it were made the first direct measurements of mammary blood flow in conscious animals. These results agreed well with indirect estimates of blood flow calculated on the Fick principle from the transfer of plasma precursors into milk.\(^3\)\(^-\)\(^5\)

To ease the placement of the thermocouple and injection needles, and to reduce the chances of loss of indicator by heat exchange with the tissues, one mammary vein was exteriorized permanently as a skin covered loop, and was thus surrounded by air. Advantages of the method were chiefly that the injection and recording needles could be inserted and removed repeatedly for many months without disturbing the animal and without seriously damaging the exteriorized vessel, and since there was no recirculation of indicator and each response lasted about 5 sec, measurements could be made frequently. However, calculation of the flow from the area under each response was tedious and time consuming, and, although mean flow was fairly constant at a given stage of lactation (coefficient of variation 10\%)\(^6\), single estimates could vary by as much as 50%, which may have been caused by extraneous factors influencing central venous pressure in the conscious animal.

Modifications have been adopted to overcome these difficulties. Blood temperature is now recorded continuously on paper with a needle thermistor whilst saline is injected at a constant rate for 20 to 60 sec. The immediate measurement of the fall in blood temperature allows the flow to be calculated at once and the continuous record makes assessment of mean flow much easier. The validity of a constant rate infusion thermodilution method has been established in models in two laboratories,\(^6\)\(^-\)\(^7\) but not checked in vivo although Pávek, Boska and Selecký\(^7\) showed that cardiac output can be measured by injecting cold saline for 6 to 10 sec into the right atrium and recording the fall of temperature in the pulmonary artery.

The purpose of the present paper is to report that the technique has been further checked in vivo by three methods: 1) comparison with the single rapid injection technique, 2) comparison with mammary flow estimated on the Fick principle and 3) cannulation of the vessel and collection of blood in a measuring cylinder. The short continuous injection method has an additional advantage...
for mammary blood flow measurement in goats, which may apply also to other organs with a multiple venous drainage. The exteriorized vein is only one of the two main veins draining each half of the udder and it is in continuity with another vein of equal size, which may either carry venous blood away from the udder or carry nonmammary blood into the exteriorized vein. A simple method of manually occluding this other vein has been described, which either diverts all mammary venous blood into the exteriorized vessel or prevents contamination with nonmammary blood. With the new method the results of this test, which are essential in any work where mammary venous blood is needed, can be assessed immediately and new data are presented of mammary venous flow determined in this way.

**Methods**

**ANIMALS**

Six female Saanen goats, aged two to eight years in their first to seventh lactations were used over a period of two years. They had been surgically prepared previously for the single injection thermodilution method. Under cyclopropane or halothane anesthesia one caudal superficial epigastric (subcutaneous abdominal or milk) vein and one carotid artery were exteriorized as skin covered loops 9 cm long, and the two glands forming the udder were separated to divide vessels crossing between them. In two animals the glands were separated permanently by skin; in four others regrowth of ligated blood vessels was prevented by oversewing with the median suspensory ligament. The experiments were done either in the animal's own pen or on the milking stand. The animals were accustomed to the procedure and experiments. Local anesthesia was used for arterial puncture.

Five acute experiments were also done, using goats anesthetized with chloralose (50 mg/kg) and urethane (500 mg/kg) given iv. One was a female goat and four were castrated males, in which blood flow in an exteriorized external jugular vein was measured; in two males the loop had been prepared some weeks before the experiment.

**ANATOMY**

Each half of the udder (two glands in the cow, one in the goat and sheep) has only one main artery but two main veins (fig. 1). One vein (the external pudic) accompanies the artery through the inguinal canal and is the only drainage in the virgin animal. The other, which is an extension of the external pudic running through the gland cranially, has valves directing blood towards the external pudic. With advancing age and parity these valves become incompetent and then, in the standing position, the flow reverses so that most or all of the mammary venous blood may leave via this vein (caudal superficial epigastric, subcutaneous abdominal or milk vein). Moreover nonmammary blood may flow down the pudic instead of up and mix with the mammary venous blood. Therefore the blood in each milk vein, which is easy to sample and has always been assumed to be mammary venous blood may have originated either from part of one gland (goats in first lactation), or from the whole of the gland or from the gland and the neighbouring tissues (abdominal wall and pelvic tissue) in some old animals. Similarly the external pudic vein may contain blood from the whole, or part of one mammary gland, or may not contain mammary blood at all. When the animal lies down the milk vein is occluded and then all the blood leaves via the external pudic vein. In goats of the large dairy breeds in their second lactation or beyond, it is usual for most of the blood to be leaving via the milk vein when the animal stands and as the valves are usually incompetent it is possible to ensure this by clamping the external pudic vein. Mechanical snare ultimate cause thrombosis.
but the vein can be occluded manually by squeezing just in front of the external pudic artery which is easily palpated (fig. 1).

PROCEDURES AND APPARATUS

The injection and thermistor needles were inserted and held in place in the loop with rubber straps as shown in figure 1. A second needle thermistor monitored the temperature of the injectate near the injection needle.

It is important that the rate of injection and temperature of the saline should not vary during injection. This was accomplished by injecting, with an accurately machined stainless steel piston driven by a velodyne motor, saline from a three-liter reservoir at equilibrium with room temperature (14 to 20°C). In long term chronic experiments the injected saline, which was sterile and pyrogen free, was displaced from the reservoir by saline (containing the antiseptic, thiomersalate) injected into a thin walled rubber bag within the reservoir.

Blood and saline temperatures were measured with thermistors, of 2 kohms resistance (at 20°C), mounted at the tips of hypodermic needles 3 to 4 cm long, 1 mm outside diameter (Grant Instruments, Toft, Cambridge) and each forming one arm of two separate Wheatstone bridge circuits powered by Mallory Hg cells. Decade resistance boxes forming the variable arms of the bridges were calibrated in terms of temperature, using thermometers calibrated at the National Physical Laboratory and Beckman thermometers. The thermistors were shunted (1.0 to 1.3 kohms) to make the resistance changes linear over the range 0 to 40°C. The bridges were balanced at the start of recording and the off balance responses recorded on a 2-channel 1 mv potentiometric recorder (Texas Instruments). Sensitivity was altered by varying the bridge voltage, making sure, from the manufacturers information, that the power dissipated did not appreciably heat the thermistors. This was confirmed by checking that the resistance was not altered in flowing water.

CALCULATION OF RESULTS AND MODEL TESTS

With the single injection method of measuring flow, either in a single vessel or for total cardiac output, the effect of the injection is usually ignored in calculating the results because the volume injected and the time taken to inject are both small in relation to the flow being measured and the passage time of the indicator. However, this is not the case with a continuous injection of indicator so that the effect of the injection on the flow must be considered.

The theoretical situation may be considered for any indicator injected continuously. The indicator, of concentration \( C_i \), is injected at rate \( V_i \), into the blood stream flowing at rate \( V_b \). Downstream and after mixing, let the flow rate of the mixture equal \( V_m \), and its indicator concentration \( C_m \). If no indicator is lost from the circulation \( C_i V_i = C_m V_m \). For thermodilution (T.D.), where the indicator is cooler than the blood, (fig. 2)

\[ C_m = \text{blood temp minus mixture temp } (T_f) \]  
\[ C_i = \text{blood temp minus injectate temp } (T_i) \]

Two different situations may be envisaged:

1. The injectate may displace an equal volume of blood and therefore the blood flow will be reduced by the amount of the injectate flow, and will equal the mixture flow.

\[ \therefore V_b = V_m = V_i \frac{C_i}{C_m} \]

Substituting from 1 and 2 for T.D.,

\[ \text{blood flow} = V_i \frac{T_f}{T_i} \]

(3)

(2) The blood flow may not be reduced by the injectate flow and therefore the flow of the mixture will be measured.

\[ \therefore V_b = V_m - V_i = V_i \left( \frac{C_i - C_m}{C_i} \right) \]

From equations 1 and 2 for T.D.,

\[ \text{blood flow} = V_i \left( \frac{T_f}{T_i} - 1 \right) \]

(4)

The ideal injectate is cooled, autologous blood, but this is somewhat impractical. If saline is used, allowance must be made for the different specific gravity and specific heat of the blood, which varies with the hematocrit, and saline (for factors see Fegler1, 2 and Fronek and Ganz9).

Models mimicking the exteriorized vein were
set up with saline or water at 37 to 40°C flowing steadily at up to 1.0 liter/min (from a constant level reservoir 15 to 20 cm above) through a curved silicone rubber tube of 8 mm internal diameter (11 mm O.D.) and with the tips of the injection and thermistor needles 10 cm apart. It was found that the flow was usually increased by the injectate but seldom by the full amount infused. If the flow was controlled by a resistance (screw clip) upstream the increase of flow during infusion was 0.65 \( V_i \) to 0.87 \( V_i \) at flows below 500 ml/min and 0.15 \( V_i \) to 0.5 \( V_i \) at flows between 500 and 1000 ml/min. With the controlling resistance downstream there was no increase in flow at high rates and only 0.17 \( V_i \) to 0.3 \( V_i \) at flows below 600 ml/min. With screw clips above and below the point of injection the flow was increased at all rates of flow by 0.35 \( V_i \) to 1.0 \( V_i \). Changes in fluid pressure were very small (ca. a few mm H\(_2\)O).

Under all conditions the estimation of flow by T.D. fluid pressure were very small (ca. a few mm H\(_2\)O). Below the point of injection the flow was increased very detectably, and changes of venous blood pressure did not change detectably. arterial pressure and heart rate did not change detectably, and changes of venous blood pressure did not change detectably.

For details see Methods. Crosses indicate injectate flows of 5 to 27 ml/min; circles, 46 ml/min. Calculated regression and 95% confidence limits.

The most satisfactory arrangement for vessel size and flows encountered in this work was an injection with the tip blocked and three radially-placed holes each 250 \( \mu \)m diameter 1 to 2 mm from the tip, which directed the injectate across the stream (fig. 1). A needle with five or six holes, each of 44 \( \mu \)m diameter was also tested but gave no better results. It was less convenient since it required a much greater pressure for injection and became blocked more easily. A practical solution both in vitro and in vivo was to use injectate at room temperature and to use an infusion rate above 10 to 20 ml/min but sufficient to produce a fall in blood temperature of 1 to 2 C. If \( T_i \) is 20 C and \( T \) is 1 C then the difference in calculated flow between equations 3 and 4 is only 5%.

### CHEMICAL METHODS

Samples of arterial and mammary venous blood for the Fick measurements were taken before the measurement of blood flow to avoid blood dilution with the saline. Glucose was measured in 1.0 ml of whole blood by the glucose oxidase method and later by the toluidine method of Hultman; the two methods gave identical values, when used on the same sample of blood. Volatile fatty acids were measured in 10 ml of whole blood by steam distillation. Since the arteriovenous difference is exclusively due to acetate the results are expressed in terms of this acid. Blood gases were measured in the manometric apparatus of Van Slyke. Since milk fat concentration varies during a single milking, milk for analysis was collected during the experiment and, in addition, aliquots of milk secreted for three days before the experiment were combined. For lactose estimations milk proteins were precipitated by adding 9 ml of Grimbleby’s reagent, diluted 80 times, to 1.0 ml of milk; the supernatant was diluted 1:100 and lactose then estimated by the phenol method of Marier and Boulet. Milk fat was estimated gravimetrically after extraction with ethanol, ether, and petroleum ether.

### Results

**EFFECTS OF THE CONTINUOUS INJECTION METHOD ON VENOUS FLOW**

The external pudic vein lies at about the level of the right atrium but the milk vein is 15 to 40 cm below, depending on the pendulousness of the udder and of the abdomen, and is therefore permanently distended. During the injection of saline, temperature about 20 C, at rate of 50 ml/min, into the milk vein of mature goats, weighing 50 to 90 kg, arterial pressure and heart rate did not change detectably, and changes of venous blood pres-
sure in the loop were negligible. The injection of this quantity of saline at room temperature reduced blood temperature in the milk vein by 1 to 7 °C depending on the blood flow. There was some recirculation of saline as shown by the observation that after about 1 min the mammary venous blood upstream from the injection site was cooled by 0.05 to 0.1 °C. This could be determined after the injection had stopped (fig. 2). Although normal fluctuations in blood temperature in this superficial vein might exceed 0.05 to 0.1 °C, this was a further reason for regulating the rate of saline injection to produce a fall in blood temperature of only 1 to 3 °C.

It was considered most probable that the method measures the flow of blood plus saline in vivo \( V_b = V_m - V_i \). This was observed directly in anesthetized animals with a T cannula in the vein (fig. 1), but only with certainty at low blood flows because at higher flows the spontaneous fluctuations in blood flow were as large as \( V_i \). The results were calculated therefore by equation 4. Nevertheless it seemed possible on theoretical grounds that, as with the model, the injectate might reduce the blood flow slightly or that the effects might vary. In the conscious animal very low \( V_i \) (5 to 10 ml/min) did not measure flows accurately above 200 ml/min. This was because, with the needles found to be most practical, the jets of saline had insufficient energy to produce good mixing. However for flows of 200 to 1000 ml/min the calculated flow was independent of \( V_i \) in the range 20 to 50 ml/min.

**Accuracy of the Method in Vivo**

During a constant injection of cool saline in vivo, blood temperature downstream fell promptly but showed fluctuations (fig. 4). Moving the tips of the thermistor and injection needles in the blood stream during injection produced little change in temperature showing that mixing was adequate. Therefore these larger variations in blood temperature during injection undoubtedly reflect changes in flow. Measurement of venous pressure in the loop showed that flow was affected temporarily by any factors influencing central venous pressure. The most obvious in the conscious animal were respiration, fidgeting, snorting, coughing, and particularly bleating. The effects of such influences could be recognized at once on the record of blood temperature during the injection of cool saline so that it was much easier than with the single injection method to

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**Figure 4**

Tracings of original recordings of blood temperature in the milk vein during continuous thermodilution showing the three possible effects of manual occlusion of the external pudic vein. See figure 1 for anatomy. A. Clamping vein decreases milk vein flow. B. Clamping vein increases milk vein flow. C. Clamping vein has no effect but clamping artery reduces flow.
estimate a mean fall in temperature for the calculation of mean flow during the period of the saline injection.

The method was compared with the single injection method on eight occasions in five goats with an exteriorized milk vein. On each day three estimates with the continuous injection were preceded and followed by three or four measurements by single injections of saline at the same temperature. The mean values for each method given in Table 1 show that the two methods do not differ significantly.

The method was also checked by the measurement of blood flow by direct bleeding in six anesthetized goats, including one female with a milk vein loop and five castrated males with jugular vein loops, which were the same size as milk vein loops (three prepared at the time of the experiment and two some weeks before). The animals were heparinized and a T cannula inserted in the vein distal to the exteriorized portion, with two vertical tubes attached to the side arm, one for monitoring venous pressure and the second for allowing blood to flow out during measurement. To measure flow the vein was clamped distal to the cannula and blood collected at the same venous pressure as existed previously (Fig. 1). The results are shown in Figure 5. The solid circles represent data obtained in acutely made loops and are not entirely satisfactory, because, with the use of heparin, blood tended to collect between the vein and skin and caused partial occlusion. The two points which are off the line were recorded in an acutely prepared jugular vein loop with a competent valve in it; this may have interfered with mixing. Valves are not always found in the milk vein loops and, in older animals, are always completely incompetent. Excluding these two points, the overall accuracy is ±14%, the calculated slope is 45°, and the correlation coefficient is 0.98. The open circles are data obtained in chronically prepared loops; they agree with the directly measured flow to within ±5% and may be taken as an indication of the accuracy to be expected in conscious animals.

It should be noted also that the continuous injection method was as accurate at low flows as at high, which is in contrast to the single injection method in veins of this size.

**TABLE 1**

Comparison of Single and Continuous Injection Methods of Measuring Venous Blood Flow in the Exteriorized Caudal Superficial Epigastric (Milk) Vein in Conscious Goats

<table>
<thead>
<tr>
<th>Goat no.</th>
<th>Blood flow measured by</th>
<th>Ratio, continuous injection</th>
<th>Ratio, single injection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Blood flow measured by</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Single injection</td>
<td>Continuous injection</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>542 ml/min</td>
<td>560 ml/min</td>
<td>1.03</td>
</tr>
<tr>
<td>2</td>
<td>256 ml/min</td>
<td>255 ml/min</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>432 ml/min</td>
<td>407 ml/min</td>
<td>0.95</td>
</tr>
<tr>
<td>4</td>
<td>275 ml/min</td>
<td>245 ml/min</td>
<td>0.95</td>
</tr>
<tr>
<td>5</td>
<td>200 ml/min</td>
<td>200 ml/min</td>
<td>1.00</td>
</tr>
<tr>
<td>6</td>
<td>365 ml/min</td>
<td>370 ml/min</td>
<td>1.01</td>
</tr>
<tr>
<td>7</td>
<td>272 ml/min</td>
<td>297 ml/min</td>
<td>1.09</td>
</tr>
<tr>
<td>8</td>
<td>1020 ml/min</td>
<td>978 ml/min</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Comparison of venous flow measured in milk vein or jugular loops of anesthetized goats by continuous thermodilution (T.D.) with flow measured with a cannula distal to vein loop, at the existing venous pressure. Filled circles apply to loops prepared during experiment; open circles to loops made some weeks before.
vein, while in some, blood from the abdominal wall and perineum may flow down the external pudic vein into the milk vein as well (see Anatomy section and fig. 1). For long term experiments it was found possible to occlude temporarily the external pudic veins at each sampling to ensure that only mammary venous blood flowed in milk veins and the effect of this could be assessed by observing the changes (if any) of blood flow in the milk vein. The continuous injection method makes this much easier because changes in flow are seen at once on the recorder during the experiment. Figure 4 shows examples of increased flow, i.e., some blood previously leaving via the external pudic vein has been diverted into the milk vein, and of decreased flow, i.e., nonmammary blood coming down the external pudic vein has been prevented from mixing with mammary blood in the milk vein. The procedure of manual compression of the external pudic vein (fig. 1) had no detectable effect on heart rate, or arterial pressure. The venous pressure in the milk vein was increased slightly if more mammary blood was diverted into it and decreased if nonmammary blood from the external pudic vein was diverted from it.

In figure 6 the effects of this manual clamping procedure are shown for four goats at different stages of pregnancy and lactation. On each occasion the flow of blood in the exteriorized milk vein was measured both with and without the external pudic vein being clamped manually. In all four goats, at the end of pregnancy, clamping the external pudic vein reduced the flow of blood in the milk vein, showing that it carried a considerable admixture of nonmammary blood at this time. This situation was temporarily reversed near term due to the great increase in mammary blood flow that occurred a few days before parturition. Thereafter goats Alice (four years old) and Jill (eight years old) always had nonmammary blood in the milk vein, whereas in Balham (six years old) and Julie (two years old, first lactation) the milk vein normally carried only part of the mammary venous outflow. The fall in true mammary blood flow at the end of lactation is

![Graph](http://circres.ahajournals.org/issue/S18/1/6/0751.pdf)
clearly shown when goats Alice, Julie and Balham were dried up by stopping regular milking.

MEASUREMENT OF MAMMARY BLOOD FLOW ON THE FICK PRINCIPLE

For many years mammary blood flow has been estimated by means of the Fick principle from the concentration of a substance in milk divided by the arteriovenous difference of the blood precursor and expressed as the number of volumes of blood or plasma that would have to flow through the mammary gland to account for the formation of one volume of milk. Although Linzell found that this ratio of blood flow to milk yield increases greatly at very low milk yields, over the greater part of lactation it is in the range of 400 to 650:1. The combination of recent isotopic studies with older arteriovenous difference measurements means that the main precursors of the major milk constituents are known. It is therefore possible to apply the Fick principle to several constituents simultaneously and, of course, the ratio of milk yield to blood flow should be the same in each instance. This has been done in the present work and the results compared with the ratio measured directly from the milk yield and blood flow measured by continuous T. D. There are valid reasons for assuming that, in undisturbed animals, the precursors are transferred quantitatively to the milk and that tissue pools of intermediates are not altering. Linzell found that since the magnitude of mammary lymph flow is similar to that of the rate of milk secretion, it follows that 2% or less of Ca and glucose removed from the blood go to lymph rather than into milk. It is well known that milk secretion is continuous and, like blood flow, ordinarily does not vary much from hour to hour or day to day.

The continuous T. D. method has been used over a period of two years in six goats. The mean blood flow during active lactation was 43.5 ± 1.7 (SE) ml/100 g tissue/min; and the milk yield 0.09 ± 0.004 ml/100 g tissue/min. The ratio of these means is 483:1, and the mean of the ratio measured on 30 occasions was 493 ± 15.

The ratio may be calculated by means of the Fick principle as follows. The mean concentrations in milk were lactose 4.6 ± 0.4, fat 4.3 ± 0.7 (3.76 fatty acids, 0.54 glycerol) and total nitrogen 0.46 ± 0.09 g/100 ml, and the corresponding mean arteriovenous differences were glucose 14.4 ± 0.9, acetate 5.7 ± 0.4, triglycerides 6.7 ± 0.3, and amino acid nitrogen 1.04 ± 0.08 mg/100 ml of blood. The ratio of blood flow to milk yield may be calculated directly for N as 460/1.04 = 442. Blood glucose gives rise to nearly all the lactose in milk (360 g forms 342 g lactose and therefore 4600 mg of lactose requires 4840 mg of glucose) and about half the glycerol of milk fat (270 mg) and 25 ± 6% of the glucose taken up by the tissue is oxidized. The ratio is therefore 4840 + 270/14.4 - 3.6 = 474. The main precursors of milk fatty acids are blood acetate and triglycerides; 47 ± 6% of the acetate is oxidized leaving 3.0 mg/100 ml for synthesis, which could form 1.77 mg fatty acids. Of the triglyceride arteriovenous difference 6.0 mg/100 ml are fatty acids. Therefore the ratio of blood flow to milk yield for fatty acids may be calculated as 3760/1.77 + 6.0 = 483. This calculation is less certain because some of the triglyceride may be oxidized and some fatty acids are formed from β hydroxybutyrate.

Thus the mean ratios of blood flow to milk yield, as measured by continuous T. D. and by Fick principle agree within 5%. This confirms the accuracy of the new method in vivo and indicates that the milk vein is capable of carrying most of the mammary flow when the animal is standing; it suggests also that the infusion of cool saline for a short time during T. D. measurements does not seriously alter mammary flow.

**Discussion**

The general validity of Fegler's thermodilution method is now well established and it is in use for measuring cardiac output in a number of laboratories. Although Fegler also showed that it could be used for measuring flow in single vessels, it has been used less frequently for this purpose, and in only
two studies has a continuous injection been used.\textsuperscript{6, 7} The present results confirm that the continuous injection method gives figures similar to the single injection technique in models and in vivo. They also show that the mammary flows observed in conscious animals are in reasonable agreement with the mean flow calculated on the Fick principle using milk precursors. However the figures in figure 5 appear to be the first check of the method in vivo, by the actual collection of blood in a graduated cylinder.

The situation of the milk vein in the female goat is ideally suited to this method. The vessel is large, accessible, and, when exteriorized in a skin loop, free of branches. The injection and thermistor needles can be placed accurately and held in midstream, and the thermistor can be placed sufficiently far downstream for mixing to occur. Pávek et al.\textsuperscript{7} found that for tubes of 5 to 13 mm in diameter the ideal distance for this was 5 to 25 cm. The animal is of such a size that the injection of saline, in quantities sufficient to produce an easily measured fall in temperature, has negligible effects on the general circulation and the venous flow from the organ. Another reason for the success of the method may be that the blood vessel and injectate tubing are thermally insulated by air so that the temperature of the injectate, immediately before it unites with the blood, is known. Warming of the injectate before it mixes with the blood is a problem in deeply situated vessels. The continuous injection method has the great advantage over single rapid injections that one can calculate the result immediately, and that it is more accurate at the low flow rates encountered in nonlactating animals, in which, in spite of low blood flows, the vessel remains large and distended because it is below heart level so that blood velocity is much reduced.

However, the main advantage of the continuous injection method in the present work is that one can assess immediately the proportion of the total mammary venous flow that is being measured by observing the effect of manual compression of the external pudic vein on the blood flow in the milk vein. This matter is of crucial importance in any study where pure mammary venous blood must be sampled, such as in metabolic and isotopic studies and in blood flow measurement by the Fick principle. It has been recognised for many years by dairy scientists that in cows and goats there is a complete circle of large veins forming a shunt between the cranial and caudal venae cavae (fig. 1). The point in the circuit where the two flows diverge is in the region of the udder and the physiological significance of small variations in its position were not appreciated until the mechanics of this dual venous drainage were pointed out.\textsuperscript{4, 8} Rasmussen,\textsuperscript{20, 21} has recently confirmed the findings in both cows and goats by observing the concentration of antipyrine in the blood in the two veins after injecting antipyrine into the teat.

It is obvious that if the milk vein is sampled the external pudic must be occluded (easy manually in most goats, but can be very difficult in some cows) or alternatively a catheter may be passed from the milk vein through the udder into the external pudic and the milk vein occluded during sampling. This is difficult in some old cows and goats because the veins are very tortuous. Permanent ligation of the external pudic is not successful because the animal occludes the milk vein when it lies down and collateral venous channels develop quickly.\textsuperscript{4} It might seem that manual compression of the external pudic vein is an imprecise procedure and liable to have other physiological effects, such as stimulation of the external spermatic nerve lying in front of the vein or compression of the external pudic artery just behind, either of which might alter mammary blood flow. However, the pressure needed to occlude the vein is much less than is required to occlude the artery, and it is useful to determine this with each animal by deliberately squeezing the artery and observing the milk vein flow which very quickly falls to zero (fig. 4). Furthermore, the finding that the results are so repeatable over long periods for a given animal (fig. 6) suggests that neither the artery nor the nerve is being affected by the squeezing.
Summary

The thermodilution method of Fegler, previously used as a single injection technique to measure the flow in one of the main veins draining the mammary gland of goats, has been adapted to a continuous injection technique. Saline at room temperature is injected at rates of 10 to 50 ml/min for 20 to 60 sec and the blood flow is calculated directly from the fall in blood temperature downstream. The method has been checked in vivo by cannulation of the vessel and shown to be as accurate as the single injection technique and the measurement of mammary flow on the Fick principle. It is particularly valuable for determining rapidly the proportion of the mammary venous flow leaving by each of the two main veins.

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References

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