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Evaluation of the Continuous Thermal Dilution Technique for Measurement of Coronary Blood Flow

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ABSTRACT

A continuous thermodilution technique has been used in a flow model. It has been difficult to determine the exact flow, but alterations of the flow have been reliably determined.

For in vivo measurement the catheter is inserted into the vein of the actual organ. The indicator is injected against the bloodstream with a constant speed. The temperature of the indicator and the fall of blood temperature during the injection of indicator are measured with thermistors located at the catheter.

The inability to measure the exact flow was mainly due to three factors; it turned out to be difficult to obtain the total and uniform mixing between the "blood" of the flow model and the indicator. Heat leakage occurs within the catheter as well as to ambient structures. The Wheatstone bridge was found not to be suitable, and a new type of instrument for determination of changes of resistance in the thermistors was used.

INTRODUCTION

The continuous thermodilution technique for measurement of regional blood flow presented by Ganz et al and others (3,7) has been tested in a flow model. Most methods for measurement of blood flow are based on the indicator technique. Exceptions are electromagnetic flow meters and flow meters based on the Dopler effect. In order to use these it is, however, necessary to dissect the actual vessel. The traditional dye dilution methods are not convenient for measurement of coronary blood flow, as the myocardium is supplied through two arteries, and the venous drainage is variable. The left ventricle is, however, mainly supplied from the left coronary artery and drained via the coronary sinus. This fact has been used in studies of myocardial metabolism by Ericsson (1) and for determination of myocardial blood flow by inert gases by Rau (6). The continuous thermodilution technique has recently been evaluated in clinical studies (5).

METHODS

A specially designed catheter, CCS-7 U-90 B, (Wilton Webster laboratories, P.O. Box 237, Altadena, California, 91001, USA) was used in this study. The thermodilution technique for measurement of coronary sinus blood flow differs from that used for measurement of cardiac output by Ganz (2). The injection of indicator is made against the blood stream and it is injected at a constant speed until the temperature of the mixture of blood and indicator has reached a steady state. The catheter is inserted into the vessel and the indicator is injected obliquely against the blood flow (Fig. 1). Isotonic saline or isotonic glucose were used as indicators. The indicator is injected through the catheter at a constant speed. The catheter has two thermistors; one measures the indicator temperature and the other measures the temperature of the blood-indicator mixture. To calculate the blood flow in the vessel it is necessary to know the rate of injection of the indicator, the specific heat of the indicator and the specific heat of the blood.

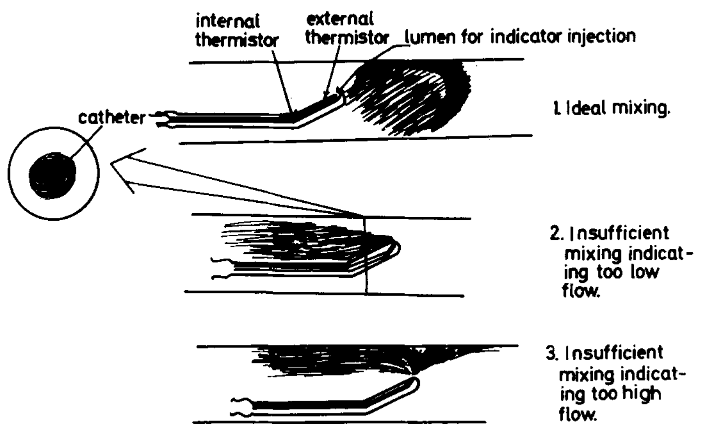


Fig. 1. Different patterns of mixing between blood and indicator. The positions of the thermistors on the catheter are marked.

As no heat is gained or lost by the system, the heat taken up by the indicator equals the heat lost by the blood.

Let F_B and F_I be the flows of the blood and indicator respectively in ml/min, S_B and S_I the densities in g/cm^3, and C_B and C_I the specific heats in $cal/g/^oC$ and finally T_B and T_I the temperatures in ^oC of blood and indicator respectively. T_M is the temperature of mixed blood and indicator during indicator infusion.

If heat lost equals heat gained:

$$F_B \times S_B \times C_B \times (T_B - T_M) = F_I \times S_I \times C_I \ (T_M - T_I)$$

Which can also be expressed as:

$$F_B = F_I \times \frac{S_I \times C_I}{S_B \times C_B} \times \frac{T_B - T_I}{T_B - T_M} = 1 \text{ ml/min}$$

$\frac{S_I \times C_I}{S_B \times C_B}$ is constant if the same indicator is used, namely 1.08 for isotonic glucose and 1.19 for isotonic saline mixed with blood.

Test in a flow model

In order to check the technique, in vitro tests were made in a flow model with a constant flow of a fluid of fixed temperature in tubes of different diameters. The heat loss to ambient air was minimized by isolation of the tubes.

Mixing defects were studied with a thermocamera connected to a computer for registration of changes of temperature at a rate of 4 pictures/second. Thickness of the wall in the model vessel was about 0.2 mm.

RESULTS

In fig. 1 different patterns of mixing between fluid and indicator are presented. Three different patterns are possible. In fig. 1:1 the mixing is complete without the indicator spreading too far upstream. In fig. 1:2 the mixing is incomplete and the dilution thermistor is cooled too much, leading to an underestimation of the flow. In fig. 1:3 the indicator is partially brought past the thermistor without cooling it, leading to an overestimation of the flow. As can be seen in fig. 2 the temperature distribution was not uniform before the infusion. The temperature is lower in the zone around the dilution thermistor, where the flow of fluid is lower and the fluid is thus cooled through the thin tube wall. After starting the infusion a new temperature equilibrium was reached in less than 5 seconds. The thermocamera reveals greater ununiformity and the lowest temperature is registered in the middle of the area examined where the dilution thermistor is situated, and consequently the flow will be underestimated.

The effect of different rates of indicator infusion was also studied with the thermocamera (fig. 2). An infusion rate of 48 ml/min gives a more even heat distribution than one of 20 ml/min.

In order to check heat leakage within the catheter, it was placed in a reservoir containing 10 litres of water with a temperature of 37°C. The indicator temperature was 22.6°C thus $T_B - T_I$ is 14.4°C.

The temperature change of the dilution thermistor indicates that $T_B - T_M = 1.3^{\circ}$C. This investigation was made in a reservoir with stagnant water.

The influence on the dilution thermistor is probably not greater than 0.2°C, which is the difference in temperature change between the dilution thermistor in a catheter where the indicator passes and a catheter without flow of indicator (Table 1).

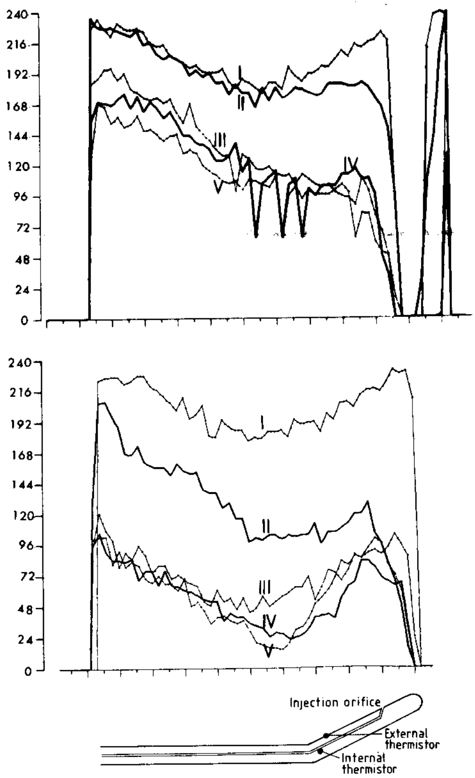


Fig. 2. Mixing defects during measurement of flow. The position of the catheter in relation to the thermistor is marked. The tip of the catheter was isolated, which gives the steep dip in the right part of the curves. The x-axis represents the length of the tube. The y-axis is graded in counts representing the temperature. Curve 1 represents the heat distribution at the start of indicator infusion. The time interval between the curves is 2 seconds in both figures. The conditions are, in A, flow of fluid 188 ml/min, infusion rate of indicator 30 ml/min, temp scale 25 counts = 0.4 $^{\circ}$C, in B, flow of fluid 188 ml/min, infusion rate of indicator 48 ml/min, temp scale 25 counts = 0.4 $^{\circ}$C.

Table 1. Measurement of flow with two catheters in a tube with a diameter of 10 mm. D $T_B - T_M$ is the difference of change of temperature between the two dilution thermistors.

Calculated flow ml/min		
None indicator catheter	Indicator catheter	Delta $T_B - T_M$ $^{\circ}$C
247	200	0.19
167	128	0.30
84	52	0.28

The results of the measurements made in the flow model are presented in in Fig 3. The infusion speeds and the diameters of the tubes were changed in order to get an idea of appropriate infusion speeds during different conditions. The flow obtained by the thermodilution technique does not always correspond to the real flow. Furthermore the values obtained during different conditions do not always agree with each other. The different curves are, however, parallel at least up to a flow of 250 ml/min. Thus, calculated alterations of flow are in accordance with real changes if the flow does not exceed 250 ml/min and the rate of injection of indicator is 40-50 ml/min.

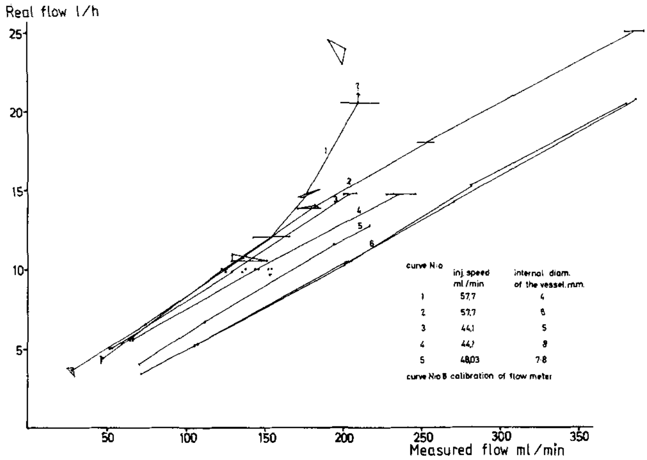


Fig. 3. Measurements in the flow model.

DISCUSSION

The main sources of error using this method should be: Insufficient mixing of fluid and indicator, heat leakage within the catheter as well as to the surrounding tissues, finally inadequate technical equipment. Both insufficient mixing and heat leakage will be revealed in the form of an incorrect change of resistance in the dilution thermistor, i.e. a false value for $T_B - T_M$.

Mixing between fluid and indicator is influenced by the position of the catheter in the tube and by the ratio of the speed of indicator flow to the speed of flow in the tube. The tip of the catheter is closed and both the aperture for indicator fluid and the dilution thermistor are placed on the concave side of the slightly bent catheter in order to prevent any of these from touching the wall of the tube. The flow of indicator is directed obliquely towards the fluid flow in order to produce turbulence and to prevent the indicator from spreading too far upstream, thereby cooling more tissues causing a greater leakage of heat.

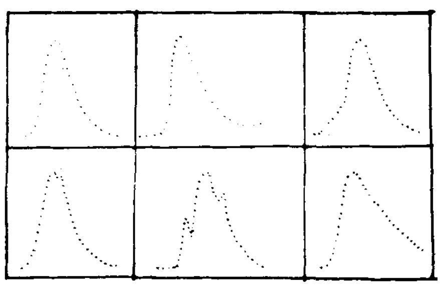
The rate of indicator infusion is of great importance. According to Ganz et al indicator infusion flow of at least 35 ml/min is necessary up to a blood flow of 300 ml/min. The diameter of the distal aperture for indicator infusion is of great importance, as the speed of indicator in cm/sec compared with the speed of blood flow in the coronary sinus will determine the pattern of mixing. Small changes of this diameter will influence the speed, due to the fact that a small change in the diameter will cause a great change of the opening area. The best infusion volume might vary somewhat between different catheters.

The rate of flow in the coronary sinus is important for the mixing of blood and indicator. The flow rate has been estimated from the blood flow and diameter of the coronary sinus presented by Ganz (3). The mean flow in the coronay sinus is reported to be about 122 ml/min and the diameter to vary between 6-15 mm. This means that the rate of flow in the coronary sinus at least varies between 1 - 10 cm/sec.

Heat leakage within the catheter is an obvious source of error. The cooling of the dilution thermistor is presumably rather constant, and thus calculation of changes of flow should not be influenced to a great extent. Heat leakage to surrounding areas takes place. During in vitro experiments with isolated tubes a steady state is achieved in less than 5 seconds. In in-vivo measurements it takes about 15 seconds before the temperature of the dilution thermistor is stable. Presumably this time is needed to cool surrounding tissues. By the continuous thermodilution technique a large indicator flow is used and the heat leakage does not essentially influence the measurement.

Flow determination might be disturbed if the aperture for indicator fluid or the dilution thermistor touches the wall of the tube. As previously mentioned this should be prevented by the position of these on the catheter. Hornych et al (4),who used a single injection thermodilution technique for the measurement of renal blood flow, have reported that the form of the thermodilution curve after a single injection gives information about the position of the catheter (Fig. 4).

This indicates the importance of making a single injection before a measurement with the continuous method in order to check the position of the catheter and the external thermistor.



Upper row 1, 2, 3 and lower row 4, 5 and 6.

Fig. 4. Thermodilutioncurve after a single injection.

1. Ideal position of the catheter.
2. Baseline drift.
3. Deformation of the ascending part of the curve due to heat leakage within the catheter.

4-5. Inhomogenous mixing between blood and indicator due to the injection of indicator into one or more segmental veins.

6. Deformation of the descending part of the curve due to contact between the dilution thermistor and the vessel wall. From Hornych et al (4).

In previous studies of the thermodilution technique the changes of resistance in the thermistors have been measured with a Wheatstone bridge with fixed calibration resistances. For flow determinations a resistance of

1000 Ohm has been used as a reference, and it has been postulated that there is a linear relation between the change of tension over the bridge and change in the resistance of the thermistor. The approximation that the relation is rectilinear might influence the measurement to a certain extent especially if the resistance 1000 Ohm is used as a reference for the calculation of changes of resistance of both thermistors. This will lead to an underestimation of changes of resistance in the indicator thermistor and to an overestimation of changes of resistance in the dilution thermistor.

In order to avoid these problems a "thermistor amplifier" was used in which a constant current will pass through the thermistor (Fig. 5). In this way changes of resistance of the thermistor will always be proportional to changes of tension. However, the "thermistor amplifier" has also got a constant resistance, which must be calibrated.

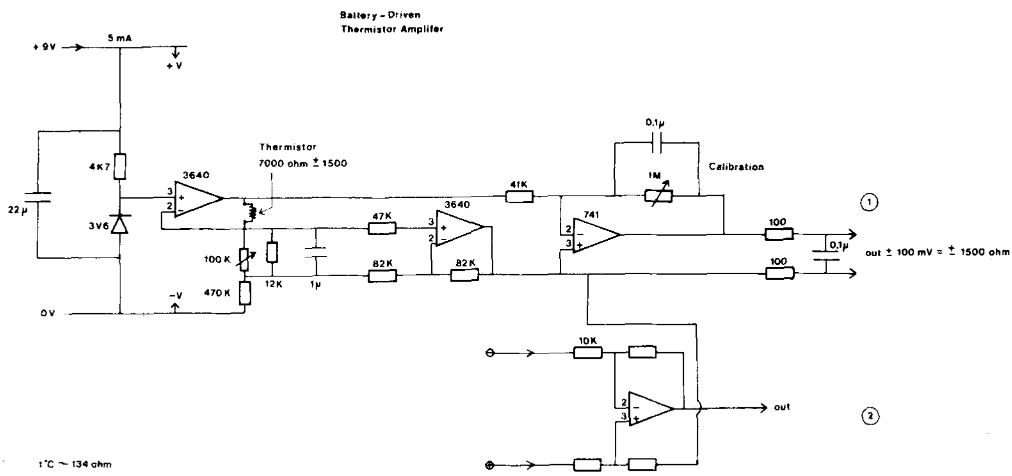


Fig. 5. The thermistor amplifier.

For practical reasons infusion volumes somewhat greater than 35 ml/min were used. The results indicate that the changes of flow agree very well with the real flow changes in tubes with a greater diameter than 4 mm. The smaller the tube is the more will the calculated value differ from the real flow. The results from measurements in tubes of 4 mm in diameter will give a line which is relatively parallel with the others up to a flow of about 220 ml/min. The necessary infusion volume of indicator is thus somewhat greater than reported by Ganz et al (3).

In fig. 6 line x represents measurements in a tube of 8 mm and line y represents measurements in a tube of 6 mm in diameter. The speed of infusion is 44.1 and 57 ml/min respectively. In spite of these almost identical conditions line x agrees much better with true flow than line y, probably because of a more careful positioning of the catheter in the first case. In this case the tube was bent as to follow the bend of the catheter. In the second case this was not done and the bend was probably too sharp when the catheter was placed in the vein. This probably caused the indicator flow to be directed towards the tube wall, leading to a mixing defect according to fig. 1:2 and to an underestimation of the flow. The overestimation of $T_B - T_M$ which represents the difference between real and calculated flow is presented in the figure. For line x the overestimation is constantly $0.6^{\circ}C$. The temperature deviation is greater for line y at a lower flow than at a higher one. The error as a percentage of total $T_B - T_M$ is also somewhat greater at a low flow. This might be explained by the formation of a zone of colder fluid between the tube wall and the tip of the catheter at a low flow.

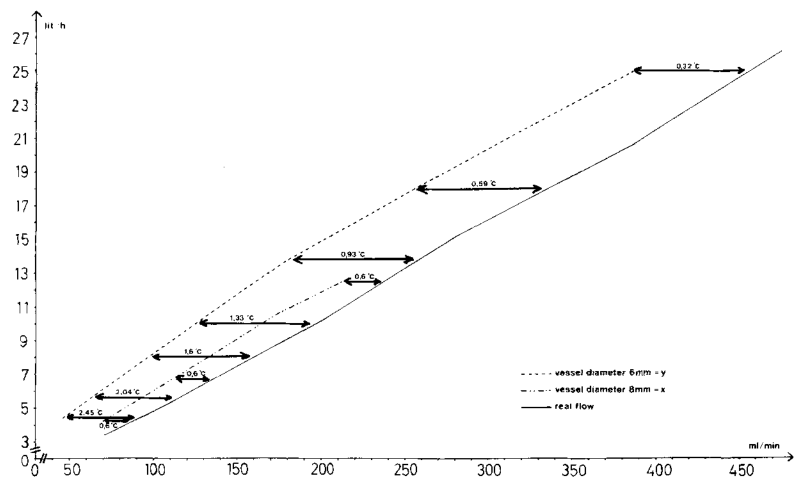


Fig. 6. Two of the curves from fig 3. The temperatures mark the deviation of $T_B - T_M$, which gives the difference between calculated and real flow.

The heat leakage within the catheter will also be more pronounced at a small flow. An increasing distance between the aperture for indicator infusion and the dilution thermistor would decrease the overestimation of $T_B - T_M$ caused by incomplete mixing. The importance of this was investigated by using two thermistors, one with the ordinary position (thermistor 1) and one placed on another catheter which was positioned about three centimeters further downstream, (thermistor 2).

The results are presented in fig. 7. The changes of temperature were smaller in thermistor 2. This means that the values obtained on thermistor 2 were smaller than those obtained on thermistor 1 which agreed better with the real flow. The smaller change in temperature on thermistor 2 is explained either because it was placed on a catheter which was not used for infusion and thus not exposed to temperature leakage from indicator fluid, or because the blood and indicator were more completely mixed at that level. The results presented indicate that even with this technique using two catheters at different levels it is not possible to measure true values and consequently the technique is not essentially improved if the dilution thermistor is moved some centimeters further downstream.

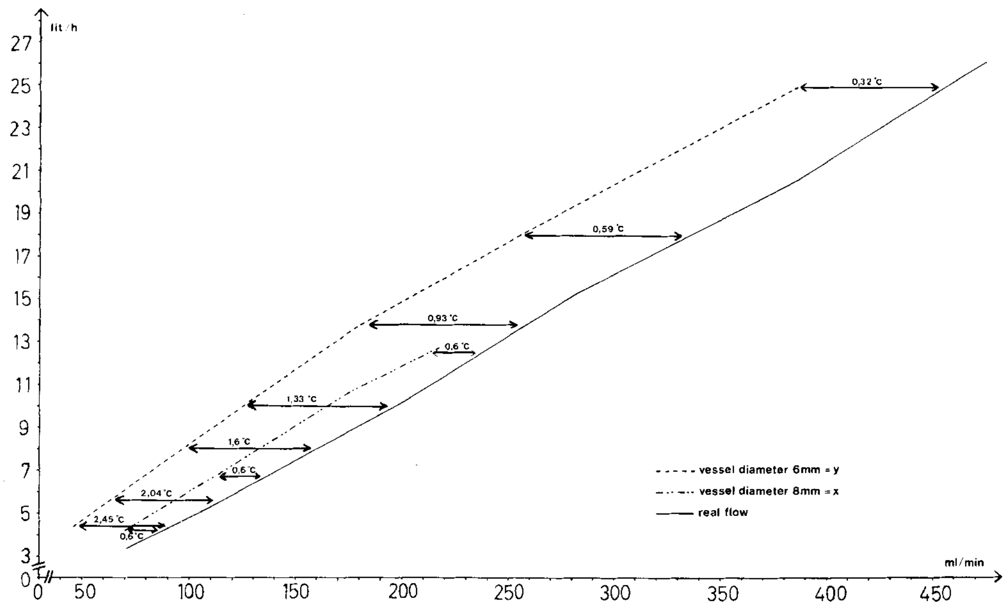


Fig. 7. The flow measured with two catheters. Catheter 2 is placed 3 cm further downstream compared to catheter 1. The flow is measured in two tubes of different calibre. F_1 are flows registered with the original thermistor and F_2 are flows registered with the "downstream" thermistor.

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