# Continuous Cardiac Output Determination by Thermodeprivation

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A modified thermodilution catheter (KATS catheter) capable of monitoring continuous cardiac output by thermodeprivation and preserving its conventional function was devised.

The KATS catheter has a thermistor incorporated closer to the tip of the catheter in addition to the usual thermistor used for conventional thermodilution. This additional thermistor is heated by a constant electric current but is capable of measuring its own temperature. The degree of heat deprivation is detected as the cooling of the thermistor, which is proportionally larger with larger blood velocity. Since blood flow is not the only source of heat deprivation, the actual formula was empirically derived by performing in vitro studies.

Cardiac output can be determined by assuming the cross sectional area of the pulmonary artery is stationary. Calibration can be derived from a cardiac output measurement by the usual thermodilution method with the same catheter.

The KATS catheter readings correlated significantly with conventional thermodilution values and electromagnetic flowmeter readings in anesthetized dogs. Continuous cardiac output measurement by the KATS catheter appears to be a promising technique. (Key words: Cardiac output, Continuous measurement, Thermodilution, Thermodeprivation)

(Miyasaka K, Volgyesi G, Katayama M, et al.: Continuous cardiac output determination by thermodeprivation. J Anesth 5: 205–212, 1991)

Cardiac output measurement by thermodilution played an important role in critical care since its introduction[1–4]. However the frequent use of injectate can cause problems such as fluid overload, hypothermia or bacterial contamination[5]. The frequency of measurements is thus limited by the patient's condition, especially in pediatric patients or in patients with cardiac failure. Paradoxically, the need for frequent measurement is usually greater in those patients who do not have the reserve to allow for such frequency.

We have modified the conventional thermodilution catheter and made continuous monitoring of cardiac output by thermodeprivation possible without frequent use of injectate. This catheter was named the KATS catheter; Continuous Arterial Thermodeprivation System.

## Principle

Figure 1 illustrates a schematic diagram of the KATS catheter. The catheter does not appear to be very much different from the conventional four-lumen thermodilution catheter. It has a PA port, a CVP port, a balloon and their corresponding lumens and

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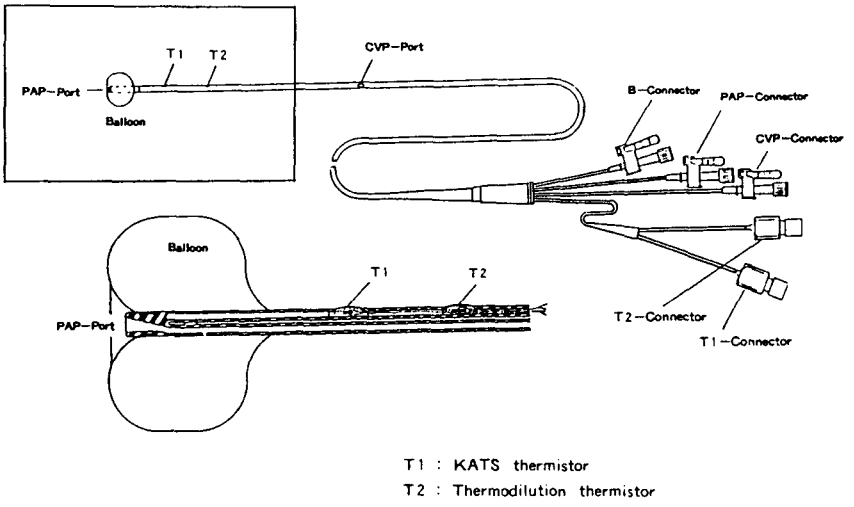


**Fig. 1.** Schematic diagram of KATS catheter.

stopcocks. However, there are two electric connectors instead of the usual one.

In addition to the usual thermistor (T2) used in conventional thermodilution, another thermistor, the KATS thermistor (T1) is incorporated closer to the tip of the catheter. This additional thermistor (T1) is heated by a constant electric current. The heating and measurement of the thermistor's temperature forms the basis for continuous monitoring. Since the thermistor is heated by constant electric current, heat deprivation, which is detected as the cooling of the thermistor, is proportionally larger with larger blood velocity[6].

Cardiac output (C.O.) can be determined from the cross sectional area of the pulmonary artery (S) and blood velocity in the pulmonary artery (v) by the following formula[6].

$$C.O. = S \times v \quad (1)$$

If we can measure "v" continuously, the cardiac output obtained from this formula will be continuous, since the the diameter of any given patient's pulmonary artery can be considered stationary. In practice, "S" could be derived from a one-point cardiac output measurement by the usual thermodilution method.

When the KATS thermistor (T1) is heated by a constant electric current I, the blood velocity is given by formula (2)[7,8]. Blood velocity "v" is proportional to heat production of T1 which is the numerator "I squared times T1 thermistor's resistance Rt" and is inversely proportional to the T1 thermistor's temperature "$T_{T1}$" referenced to blood temperature "Tb". Here, $K_0$ is an empirical constant.

$$v = (I^2 \times Rt)/K_0 \times (T_{T1} - Tb) \quad (2)$$

Rt, which is the resistance of the KATS thermistor (T1) is obtained by measuring "V1" which is the voltage across the KATS thermistor. This is because the electric current applied to T1 is fixed to I.

$$Rt = V1/I \quad (3)$$

Determination of Rt in turn, determines the KATS thermistor temperature "$T_{T1}$". Blood temperature "Tb", which is used for reference, is calculated from voltage across the thermodilution thermistor "V2". To summarize, measurement of V1 and V2, which once again are the voltages across the KATS thermistor (T1) and the T2 thermistor respectively, should determine all other parameters in this formula.

The thermodeprivation formula (2) assumes that blood flow is the only source of heat deprivation. However, heat is lost to surrounding structures in other ways and the actual formula should include these factors. The final formula was empirically derived by

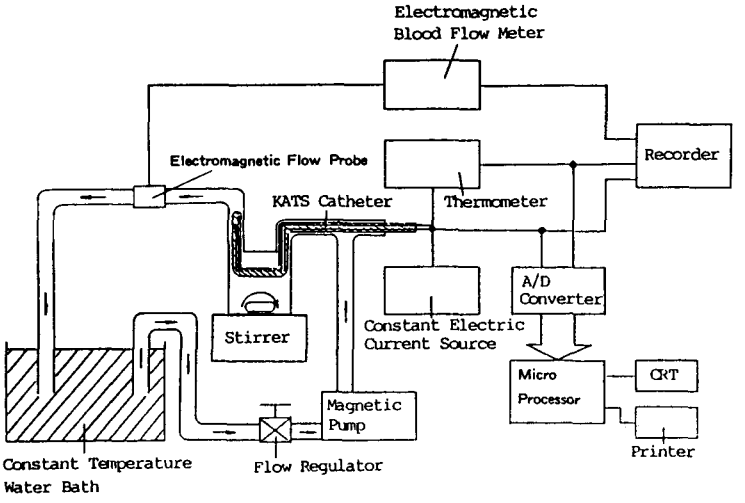


**Fig. 2.** Schematic diagram of in vitro water bath system.

performing in vitro studies.

## Materials and Methods

A four lumen 5Fr. KATS catheter was made. The KATS thermistor (T1) was placed 1.0 cm from the tip and 1.0 cm away from the T2 thermistor. T1 has a resistance of 1k ohm at 37°C. A constant current I of 10.0 mA was applied to T1. The two voltages of V1 and V2 were measured continuously. These signals were transformed into digital signals with the use of a 12-bit A to D converter (OKI 80304). Blood velocity was calculated continuously using an 8-bit microprocessor (OKI-IF 800) at a sampling speed of 40 msec and a processing time of 1600 msec. Ten pieces of data were averaged and displayed on the CRT every 2 seconds. The performance of this catheter was evaluated both in vitro and in vivo.

*a) In vitro experiment*

The relationship between thermistor temperature and blood velocity was compared in an in vitro water bath system as is shown in figure 2. The temperatures of the normal saline solutions were changed from 30°C to 45°C. The fluid velocity was changed from 0 to 60 $cm \cdot sec^{-1}$ in a 10 mm or 20 mm diameter PVC tube (0 to 2.8 or 0 to 11.2 $l \cdot min^{-1}$). The fluid velocity was measured by an electromagnetic flowmeter (Nihon Kohden, Tokyo).

*b) In vivo experiment*

Figure 3 shows a schematic diagram of an animal experiment. 5Fr. KATS catheters were inserted into the right jugular veins of 10 mongrel dogs (body weight, 8.5 kg – 15.4 kg) under general anesthesia. The trachea was intubated after induction of anesthesia by thiopental and muscle relaxation by pancuronium bromide. Intermittent positive pressure ventilation was started and maintained to give normal blood-gas values throughout the experiment. A Newport E-100 (NMI, Newport Beach, CA) ventilator with a heated humidifier incorporated coaxial breathing circuit was used.

5Fr. conventional thermodilution catheters (American Edwards, CA) were inserted into the femoral veins. The positioning of the catheter tips in the main pulmonary artery were confirmed by the pulmonary artery pressure waveform and by fluoroscopy. After comparisón of the two catheters on single injection thermodilution, the conventional thermodilution catheters were withdrawn from the main pulmonary arteries. A left thoracotomy was performed, and an electromagnetic flow probe was attached to the main pulmonary artery after calibration.

Cardiac output determination by single injection thermodilution was repeated three

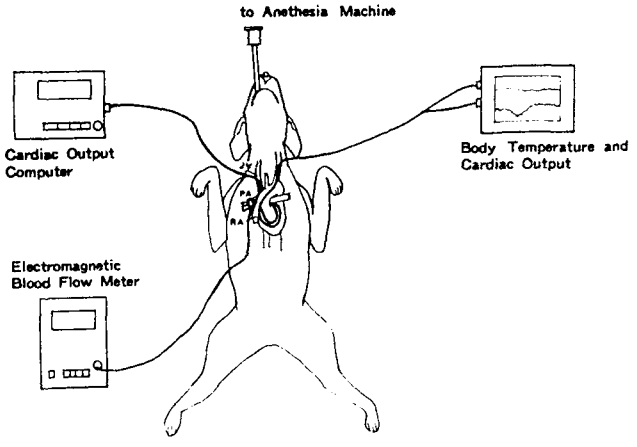


**Fig. 3.** Schematic diagram of animal experiment.

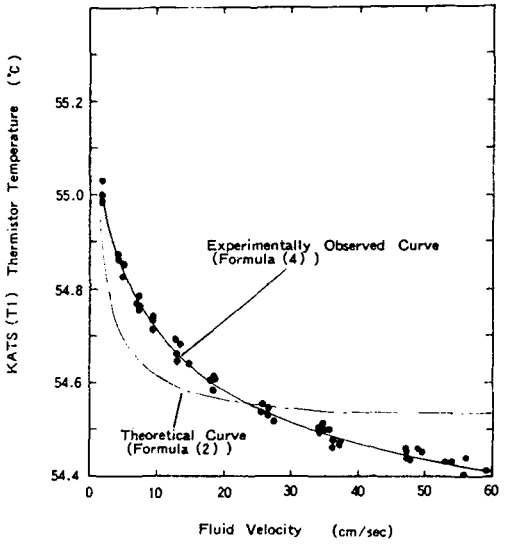


**Fig. 4.** Results of in vitro experiment; fluid velocity vs thermistor (T1) temperature.

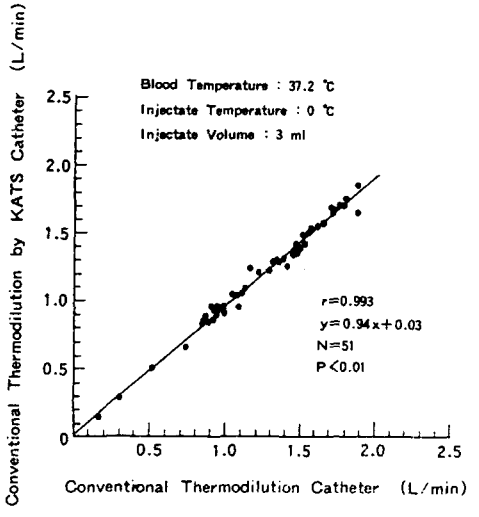


**Fig. 5.** The comparison of single injection thermodilution cardiac output by the KATS catheter and conventional thermodilution catheter.

times after the thoracotomy was closed and the average value of the two closest data was regarded as the cardiac output at that time. 5 ml of cold (0°C) normal saline was used as an injectate. The value obtained was used to calibrate the KATS catheter.

Continuous readings from the KATS catheter were recorded and compared to the continuous recordings of the electromagnetic flow probe. Single injections for regular thermodilution cardiac output determinations were repeated intermittently for comparison.

Rapid intravenous fluid infusion or high concentration halothane inhalation was used to manipulate cardiac output. The position of the catheter was checked frequently by fluoroscopy in addition to pressure waveform monitoring.

Animals were autopsied at the end of the experiment to check catheter position, clot formation and blood vessel injuries.

## Results

*a) In vitro experiment*

The relationship between fluid velocity

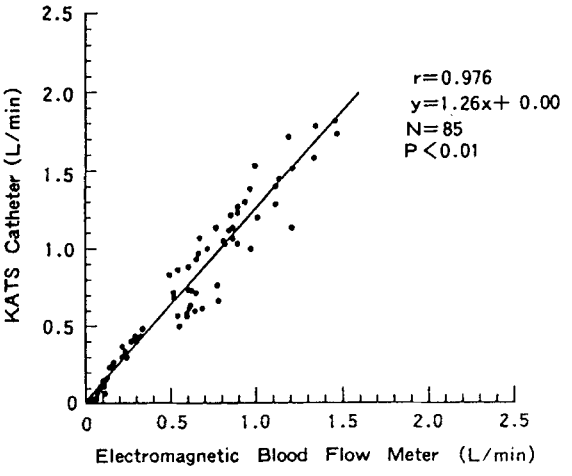


**Fig. 6.** Continuous cardiac output as measured by the KATS catheter on the Y-axis and by the electromagnetic flowmeter on the X-axis.

and T1 temperature is shown in figure 4. A total of 130 points were calculated with the least square method for the best curve fitting to find hyperbolic or logarithmic relationship.

Formula (2) was transformed into a general hyperbolic formula.

$$Tt = a/v + b \qquad (2')$$

where Tt is the KATS thermistor temperature (°C)

v is fluid velocity (cm/sec)

"a" and "b" are empirical constants

The least square method revealed "a" to be a constant of 0.894°C × cm/sec and "b" to be a constant of 54.52°C with an r value of 0.874

A logarithmic formula was made in general form as is shown in formula (4) and calculated also.

$$\log(Tt) = a' \times \log(v) + b' \qquad (4)$$

where Tt is the KATS thermistor temperature (°C)

v is fluid velocity (°C × cm/sec)

"a'" and "b'" are empirical constants.

The constants "a'" and "b'" derived from this curve by the least square method revealed "a'" to be $-2.95 \times 10^{-3}$ and "b'" to be 4.0086 with an r value of 0.997.

The experimentally determined curve was more closely related to a logarithmic curve than to the expected hyperbolic relationship. Formula (2) was then replaced by formula (4) and the constant a' was used for actual in vivo continuous cardiac output measurement. However the constant b' was adjusted in individual cases by performing single injection thermodilution.

*b) In vivo experiment*

Figure 5 shows the comparison of single injection thermodilution cardiac output by the KATS catheter and conventional thermodilution catheter. There is a significant linearity between the two methods.

Figure 6 shows the cardiac output measured by the KATS catheter on the Y-axis and the values by the electromagnetic flowmeter on the X-axis. There is a significant linearity between the two methods.

Figure 7 shows the KATS catheter output on the Y-axis and the thermodilution values on the X-axis. The linearity between the two is again significant.

Figure 8 shows the reliability of the KATS catheter readings for two and a half hours in one of the dog experiments. Ringer's lactate was infused after observing stable readings for about an hour. The changes in cardiac output readings in response to infusion and its interruption were well followed by the KATS catheter method. Halothane was administered briefly and the decrease and recovery of cardiac output were observed. The animal developed cardiac arrest during the second administration of halothane. Cardiac output values by the three separate meth-

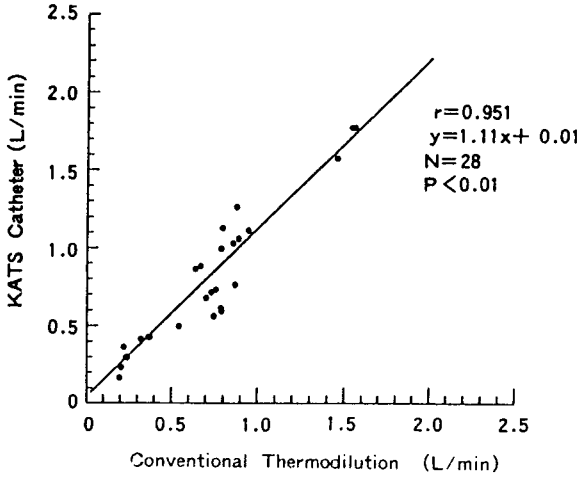


**Fig. 7.** Continuous cardiac output as measured by the KATS catheter on the Y-axis and conventional thermodilution catheter values on the X-axis.

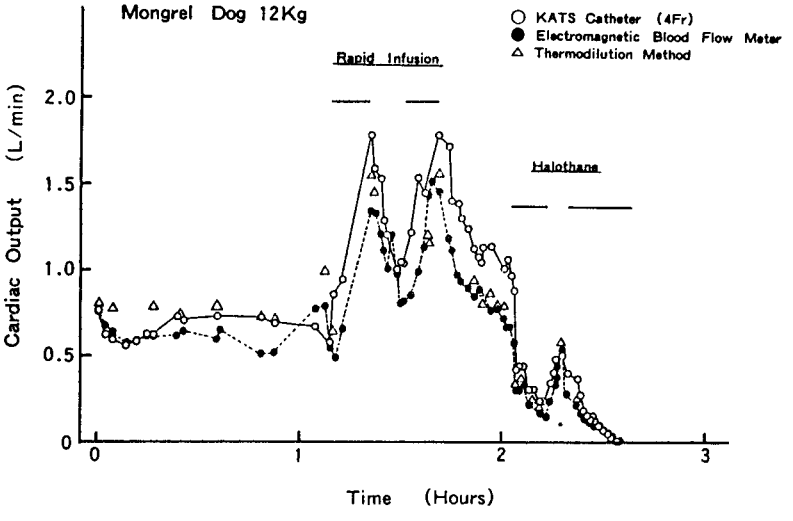


**Fig. 8.** The reliability of the KATS catheter readings for two and a half hours in one of the dog experiments. The cardiac output values by the three independent methods are shown on the Y-axis, and the time in hours is shown on the X-axis. Open circles show the KATS catheter values, filled circles the electromagnetic flowmeter values, and triangles the thermodilution method.

ods increase and decrease in accord, tracking each other closely. The readings were especially close to each other below 0.5 $l \cdot min^{-1}$. The discrepancy was relatively larger in the higher fluid velocity ranges.

The autopsy results showed no clotting formation or vessel wall injuries of the main pulmonary arteries.

## Discussion

Although the thermodilution principle to measure cardiac output is not new, it was only after Swan et al's work that this became a clinically feasible technique[1,8,9]. Since then, it has been investigated extensively. Although their technique was extremely use-

ful, it provided only intermittent data and was not adequate in the management of patients with unstable hemodynamic conditions. In addition, the frequent use of injectate can cause fluid overload in patients with marginal cardiovascular function. The cold temperature of the injectate can result in hypothermia in newborns and infants. All of these complications can be avoided with the KATS catheter since it needs only occasional calibration using conventional thermodilution function of the same catheter.

Various attempts have been made in the past to determine continuous cardiac output directly with limited success[10,11]. Most methods employed heating ofthe blood and detection of the temperature change at the downstream thermistor[12]. To make this method sensitive enough, it became mandatory to increase the heating supply. Philip et al reported that they required 4W of energy to give measurable signals[5]. In contrast, our method of thermodeprivation requires only 100 mW to obtain a fluid velocity measurement and causes only a small increase in thermistor temperature. This is extremely important when considering for clinical applications.

The thermodeprivation method assumes that blood flow is the only source of thermistor cooling. However, heat loss occurs from other factors including direct transmission of heat to surrounding catheter materials. Also, if the resistance of the KATS thermistor (T1) is fixed, applying a fixed current should produce a fixed energy. However, the resistance of the T1 thermistor varies depending on the thermistor temperature. Thus the energy produced by the T1 thermistor varies even under the same electric current. These factors made in vitro determination of the actual formula necessary.

As is shown in figure 4 and formula (4), the actual curve was logarithmic (formula (4)) rather than hyperbolic (formula (2)). The actual cardiac output measurement in dogs by the KATS catheter was performed with the logarithmic formula (4). There was an excellent relationship between values from the electromagnetic flowmeter and the thermodilution method. The discrepancy of the three different methods became larger in the high fluid velocity range with current catheter design. This indicates that there is a need for further evaluation of the in vivo formula. Cardiac output is derived from velocity based on the assumption that pulmonary artery diameter is relatively constant. Thus factors influencing pulmonary artery diameter should also be studied.

The catheter size we made is 5 French. This size should allow measurement even in infants. A larger size KATS catheter for adult use is being tested at the present time. The functions of conventional thermodilution catheters such as pressure measurement, blood sampling, blood temperature monitoring, as well as intermittent cardiac output measurement by conventional thermodilution are fully preserved.

Determination of the characteristics of the T1 thermistor is of vital importance since the heating and measurement of the additional thermistor (T1) forms the basis of this method. The lowest possible thermistor temperature and relatively low voltage range for easier measurement were desirable. The T1 thermistor's resistance of 1K ohm at 37°C was chosen to obtain maximum fluid velocity sensitivity without the application of a large electric current and without producing a high thermistor temperature. Although it is theoretically possible to further decrease the current, a 10 mA electric current is the minimum level of stable current we can easily apply for this purpose at the present time. Since $W = Rt \times I^2$ where W is the wattage of the T1 thermistor and I is fixed, a bigger Rt (resistance) is advantageous because the thermistor's resistance changes are used to detect blood flow velocity. However Rt should not be too high to minimize increases in thermistor temperature. The T1 thermistor was placed distal to the T2 thermistor. The KATS thermistor (T1) was placed 1.0 cm from the tip and 1.0 cm away from the T2 thermistor in the 5Fr. KATS catheter. This location was chosen to obtain the maximum distance between the two thermistors in the main pulmonary artery of infants to

avoid any heating effect of the T1 thermistor on the T2 thermistor. This effect was measured at less than 0.3°C in the current design, but is compensated for in the calculation of cardiac output.

Heating of the T1 thermistor may be of some concern. Theoretically the catheter surface temperature is highest when blood flow is completely stopped. Although it is possible that part of the T1 thermistor itself may become 55°C, the increase in the catheter surface temperature was negligible because of heat transmission in all directions and was never more than 2.0°C higher than the surrounding blood temperature. Since the catheter material has a softening point of 80°C, even maximal heating would not cause deformation of the catheter of blood[13]. Conventional functioning of the T2 thermistor was not affected by having T1 heated and no untoward effects were observed. A clinical trial is currently being undertaken.

In summary, a modified thermodilution catheter capable of monitoring continuous cardiac output by thermodeprivation and preserving its conventional function was devised and tested in dogs. The KATS catheter readings correlated significantly with thermodilution values and electromagnetic flowmeter readings.

Continuous cardiac output measurement by the KATS catheter appears to be a promising technique for both experimental and clinical medicine.

(Received Jan. 10, 1991, accepted for publication Jan. 23, 1991)

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