Review Articles

Errors in the measurement of cardiac output by thermodilution

Toshiaki Nishikawa MD, Shuji Dohi, MD

Cardiac output (CO) determination by thermodilution, which was introduced by Fegler in 1954, has gained wide acceptance in clinical medicine and animal experiments because it has several advantages over other methods with respect to simplicity, accuracy, reproducibility, repeated measurements at short intervals, and because there is no need for blood withdrawal. However, errors in determination of CO by thermodilution may be introduced by technical factors and the patients' pathological conditions. The current review summarizes these issues and provides our recommendations, based on the medical literature published between 1954–1992. To obtain more reproducible and accurate CO values by thermodilution, one should make several determinations (1) by using 10 ml injectate at room temperature for adults and 0.15 ml · kg^{-1} injectate for infants and children; (2) at evenly spaced intervals of the ventilation cycle; (3) when rapid intravenous fluid administration is discontinued; (4) by observing thermodilution curves so that baseline pulmonary artery temperature drift or the existence of intra- and extracardiac shunts are noticed. Finally, CO determination by thermodilution may be unreliable or impossible in patients with low CO states and tricuspid or pulmonary regurgitation. Since non-invasive CO monitoring has not replaced CO determination by thermodilution, intimate knowledge of this method is crucial for anaesthetists to prevent errors in the management of patients.

La mesure du débit cardiaque par thermodilution introduite par Fegler en 1954 est largement répandue en clinique et en recherche animale grâce à ses nombreux avantages sur les autres méthodes: simplicité, précision, reproductibilité, répétivité à courts intervalles, absence de prélèvement sanguin. Cependant, dans son application il peut facilement s'introduire des erreurs d'origine technique ou pathologique. La présente revue résume ces questions et propose certaines recommandations, basées sur la littérature médicale publiée entre 1954 et 1992. Pour obtenir des mesures fiables et précises du débit cardiaque par thermodilution, il faut répéter les mesures: 1) avec 10 ml d'injectat maintenu à température de la pièce chez le adulte, 0,15 ml · kg^{-1} chez l'enfant; 2) à des moments identiques du cycle respiratoire; 3) après l'arrêt d'une perfusion rapide de liquide intraveineux; 4) en observant les courbes de thermodilution pour pouvoir tenir compte de la dérive de la température initiale de l'artère pulmonaire et de la présence de shunts intra- ou extracardiaques. Finalement, le débit cardiaque par hémodilution peut manquer de fiabilité et peut même devenir impossible à mesurer chez les malades dont le débit est bas ou qui souffrent de régurgitation tricuspidienne ou pulmonaire. Comme le monitorage du débit cardiaque non invasif n'a pas encore remplacé la thermodilution, les anesthésistes doivent posséder une connaissance approfondie de cette méthode pour éviter des erreurs thérapeutiques graves.

Key words
HEART: cardiac output;
MEASUREMENT TECHNIQUES: cardiac output, thermodilution.

From the Department of Anaesthesiology, Institute of Clinical Medicine, University of Tsukuba, Tsukuba City, Ibaraki 305, and the Department of Anaesthesiology, Gifu University School of Medicine, Gifu City, Gifu 500, Japan.

Address correspondence to: Dr. T. Nishikawa, Department of Anaesthesiology, Institute of Clinical Medicine, University of Tsukuba, Tsukuba City, Ibaraki 305, Japan.

Accepted for publication 11th October, 1992.

Contents

- Intra- and extra-cardiac shunts
- Valvular heart diseases
- Paediatric patients
- Electrocautery
- Other pathological conditions

Conclusions

Since cardiac output (CO) measurement by thermodilution was originally introduced by Fegler in anaesthetized dogs in 1954,[1,2] the usefulness of the method has been evaluated by several investigators.[3-16] Swan, Ganz and Forrester *et al.*,[17-19] and Ellis *et al.*[20] made the technique more practicable by development of the balloon-tipped, flow-directed, multiple lumen pulmonary artery (PA) catheter in the 1970's. Since then, this technique has undoubtedly assisted in the management of critically ill adults, infants, and children[21-43] and instrumentation in animal experiments.[44-47]

Accurate knowledge of thermodilution CO measurement is important for anaesthetists and other clinicians engaged in the management of surgical and critically ill patients. The purpose of this review is to discuss the many errors of CO estimation by the thermodilution technique.

Principle of measurement

Thermodilution uses the same principle as other indicator-dilution methods for the measurement of blood flow.[48,49] The injection of a known amount of a cold solution as an indicator into the right atrium through the proximal port of a PA catheter is detected distally by a thermistor located 4 cm from the end of the PA catheter. Although there is some controversy regarding the extravascular distribution of thermal indicator in the pulmonary vascular bed,[50,51] the distance between injection and detection site should be as short as possible to reduce indicator loss due to radial heat exchange.[52] This can be attained by injecting into the right atrium and detection in the PA.[52] The change in temperature of blood in the PA causes a change in the thermistor (Wheatstone bridge) resistance which allows calculation of the area under the thermodilution curve (Figure 1).[48,49,53,54] Cardiac output (CO) is determined from the following equation:

$$CO = V_I\,(T_B - T_I)K_1K_2/\int_0^\infty \Delta T_B(t)dt$$

where V_I is injectate volume; T_B is blood temperature; T_I injectate temperature; K_1 is a density factor which is defined as the specific heat multiplied by the specific gravity of the injectate divided by the product of the specific heat and gravity of blood; K_2 is a compuation constant taking into account the catheter dead space, the heat exchange in transit, and injection rate. The denominator of the equation (the change of blood temperature as a function of time) corresponds to the area under the thermodilution curve.

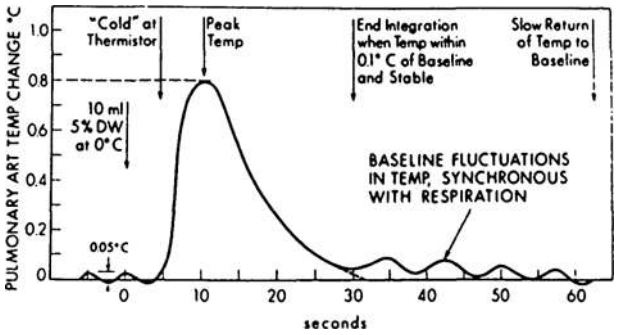

FIGURE 1 Typical thermodilution curve. The peak of the thermodilution curve is 16 times higher than the baseline fluctuations; a good signal-to-noise ratio. Baseline fluctuations may reach 0.1° C. Integration should be continued until the curve returns to within the baseline fluctuations. Reproduced with permission from Weisel RD *et al.*[23]

The thermodilution curve peaks rapidly and then follows an exponential decay, until there is recirculation or delayed cooling from the residual indicator in the PA catheter. To avoid this last portion of recirculation, a cut off point is determined in the thermodilution curve before recirculation occurs (Figure 1).[16,35,55-57]

Factors responsible for erroneous estimation

Thermodilution is a simple, rapid, safe, accurate, and more reproducible method of measuring CO than dye dilution or Fick determinations, particularly at high and low flows (Table I).[5,8,9,14-37,40,47,49,57-69] Thermodilution does not require withdrawal of blood, and can be repeated at short intervals. On the contrary, dye dilution is complex and inaccurate at high and low flows. Fick determination is not suitable in critically ill patients because it requires prolonged steady states.[23] However, several factors may influence the estimation of CO by thermodilution (Table II).

Temperature and volume of injectate

In 1961 Evonuk *et al.*[5] reported a close correlation ($r = 0.96$) between the CO values estimated by dye dilution and thermodilution using injectate at 23–26° C. They suggested that the use of iced injectate as an indicator may have certain disadvantages as it is difficult to maintain and to determine accurately the temperature of the delivered injectate. Also, the iced injectate may affect the heart and other cardiopulmonary haemodynamic variables.[5] However, since Ganz *et al.*[17] reported the first clinical use of 10 ml, iced 5% dextrose in water as an

TABLE I Reproducibility of cardiac output determinations by thermodilution, correlation coefficient between thermodilution and other comparative techniques, and injectate in humans

Author (year)	*Reproducibility* (%)*	*Correlation coefficient*	*Comparative techniques*	*Injectate temperature and volume*
Adults				
Olsson *et al.* (1970)[10]	6.9–7.5	0.98	DD	RT, 10 ml
Enghoff *et al.* (1970)[11]	6.3	N/A	DD, Fick	RT, 10–20 ml
Ganz *et al.* (1971)[17]	4.1	0.96	DD	Iced, 10 ml
Andreen (1974)[22]	4.4	N/A	N/A	RT, 10 ml
Weisel *et al.* (1975)[23]	3.9	0.99	DD	Iced, 10 ml
Berger *et al.* (1976)[25]	3.9	0.99	DD	Iced, 10 ml
Saadjian *et al.* (1976)[35]	N/A	0.98	DD	Iced, 4 ml
Kohanna *et al.* (1977)[37]	8.6	0.90	DD	RT, 10 ml
Stawicki *et al.* (1979)[64]	1.7	0.99	Fick	Iced, 10 ml†
	2.1	0.97	Fick	RT, 10 ml†
	3.6	0.97	Fick	Iced, 10 ml‡
	8.2	0.35	Fick	RT, 10 ml‡
Elkayam *et al.* (1983)[68]	3.1	N/A	N/A	Iced, 10 ml
Pearl *et al.* (1986)[69]	6.1	N/A	N/A	Iced, 10 ml
	6.7	N/A	N/A	RT, 10 ml
Infants and children				
Wyse *et al.* (1975)[30]	8.5	0.93	Fick	RT, 0.14 ml · kg^{-1}
Mathur *et al.* (1976)[31]	8.2	0.90	DD	Iced, 1–3 ml
Venkataraman *et al.* (1976)[34]	N/A	0.85	DD	Iced, 10 ml
Colgan *et al.* (1977)[62]	N/A	0.97	DD	Iced, 2 ml
Freed *et al.* (1978)[63]	5.5	0.91	Fick	Iced, 3ml

DD = dye dilution, RT = room temperature, N/A = not available.
The temperature of iced injectate ranges from 0° C to 5° C.
*Reproducibility is defined as a ratio of standard deviation to mean value of multiple measurements.
†Closed-system automatic injection thermodilution method.
‡Standard open-system manual injection thermodilution method.

TABLE II Factors responsible for erroneous estimation of cardiac output by thermodilution

1	Temperature and volume of injectate[5,17,33,68–76,82]
2	Rewarming injectate[3,17,61,67,84–86]
3	Timing of injection and respiration[75,88,95–104]
4	Speed and mode of injection[105–107]
5	Intravenous fluid administration[108,109]
6	Hypothermia[110–112]
7	Low flow[37,44,53,63,113–117]
8	Catheter dysfunction and position[39,61,118,121–126]
9	Intra- and extra-cardiac shunts[21,59,63,127–132]
10	Valvular heart diseases[10,43,115,135–140]
11	Paediatric patients[29–31,62,63,141–143]
12	Electrocautery[53]
13	Other pathological conditions[22,48,58,81,96,144,145]

injectate in 1971, this has been widely used in adults for more than ten years. Nevertheless, most[68–74] but not all[33,75,76] reports showed that there was no difference in the accuracy or reproducibility when iced or room-temperature injectate was used, and there was no requirement for iced injectate. Elkayam *et al.*[68] reported comparable reproducibility when CO values were estimated by the use of 5 ml, iced injectate, 10 ml, room-temperature injectate, or 10 ml, iced injectate. In critically ill adult patients, Pearl *et al.*[69] recommended the use of 10 ml, iced or room-temperature injectate for CO determinations, because both the 10 ml injectates produced less variability than 3 or 5 ml volumes of injectate.

It is generally assumed that the process of indicator injection does not affect the blood flow being measured when the volume of the injectate is small.[48,54] However, Froněk and Ganz[4] found an increased blood flow in the region of the thermistor with injection. Furthermore, in clinical practice[77–79] and animal experiments[80,81] transient slowing of the heart takes place with alterations in systemic and pulmonary arterial pressures, right atrial pressure, and right ventricular output (pulmonary blood flow) following injection of cold injectate (Figure 2), as Evonuk *et al.*[5] inferred previously. Furthermore, the magnitude of these changes is dependent upon the temperature and volume of cold injectate.[80]

Based on these reports, it is recommended that the volume and temperature of the injectate is selected according to the patient's size and haemodynamic and other conditions. Thus, under most circumstances we should

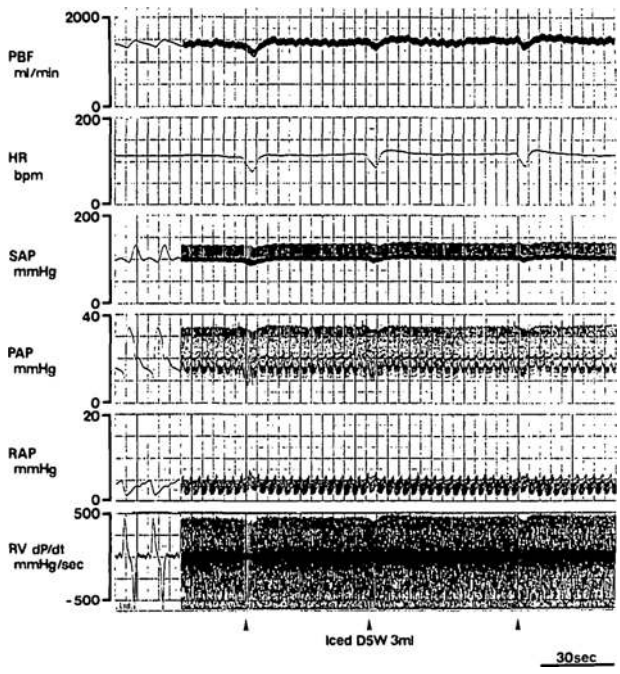

FIGURE 2 Representative polygraph tracings of pulmonary blood flow (PBF), heart rate (HR), systemic arterial pressure (SAP), pulmonary artery pressure (PAP), right atrial pressure (RAP), and right ventricular dP/dt (RV dP/dt) after three injections of 3 ml iced injectate in an anaesthetized dog. Reproduced with permission from Nishikawa T and Dohi S.[81]

use 10 ml injectate at room temperature rather than 10 ml iced injectate in adults.[68,69] Also, with respect to the maintenance of temperature, room-temperature injectate seems to be superior to iced injectate.[72,74] When it is important to prevent volume overload in patients with pulmonary oedema secondary to congestive heart failure, or renal failure, the use of 5 ml injectate volumes is justified.[68,69] For infants and children, approximately 0.15 ml · kg^{-1} of injectate is recommended.[30,31,63] Moreover, a single calibrated syringe designed to deliver a known and constant volume of injectate is preferable to disposable plastic syringes.[82] Also, uniform cooling of the injectate[83] is essential to make an accurate estimate of CO.

Rewarming injectate

Errors in measurement may be introduced by rewarming the injectate from handling before its injection[84] and by heat transfer during passage through the catheter.[17,67,85,86] Since the temperature of iced injectate in a 10 ml syringe held in a warm hand at 36° C will increase 1° C every 13 sec, this could result in overestimation of CO by 2.86% for each ° C of rewarming. Also, indicator loss during passage of iced injectate through the PA catheter can overestimate the CO values. It is assumed that 17% of the potential signal is lost before a 10 ml bolus of injectate at 0° C leaves the catheter and a correction factor of 0.83 is used[61] in the thermodilution equation to correct for this loss of thermal indicator. The factor is unique for each catheter computer system.[49]

Hence, the injectate temperature should be monitored at the point of entry into the circulation,[48,87] and the use of a calculated correction factor[3,32,85] should help to increase the accuracy of CO determinations. In this respect, room temperature injectate seems to be superior to iced injectate. Room temperature injectate does not require cooling of the syringe before use and less "negative heat" is lost during its passage through the injection catheter.

Timing of injection and respiration

Fluctuation of the baseline temperature in the PA with respiration (0.01–0.1° C)[18,23,24,88–91] represents physiological "noise" (Figure 1),[17] and may make accurate assessment of the area of the thermodilution curve impossible.[89] Although the mechanism of production of these thermal variations has not been fully elucidated, the direction of the temperature changes may depend on the humidity and temperature of inspired gas,[91] the composite of changes in flow as well as blood temperature changes in the superior and the inferior venae cavae during the respiratory cycle[90] and/or reflex effects of respiration on the circulatory system.[90] Some animal experiments show that the baseline temperature in the PA at expiration increases during spontaneous breathing, whereas it decreases during intermittent positive pressure ventilation (IPPV).[88,90,91] Therefore, CO will be underestimated during spontaneous breathing and overestimated during IPPV in the face of large variations in PA temperature when end expiration is used to time indicator injection.[88] However, most CO computers alleviate the possibility of respiratory-associated baseline drift by electronically averaging the blood temperature for a short time before the injection of indicator.[88,92]

Right ventricular output may vary due to cyclic alterations in venous return and right ventricular afterload during IPPV[93,94] or Kussmaul breathing.[75] The variation of flow was found to increase as inflation pressure increased in dogs.[95] Most human and animal data[75,88,96–102] have demonstrated that timing of injections with the respiratory cycle enhances the reproducibility of CO values, although two reports[103,104] showed no need for timing the injections during IPPV or high-frequency jet ventilation. We recommend that at least two to four determinations are made at evenly spaced intervals of the ventilation cycle (e.g., at end-inspiration,[96] midinspiration,[98,100] or end-expiration[99,100]) during IPPV.[95–101]

Speed and mode of injection

Although an injection time of up to four seconds may be accepted when the injectate volume is 5 or 10 ml, CO values are unreliable due to poor quality of the thermodilution curves if the injection time is too long.[105] The use of an automatic injector has been recommended.[35,106] However, small variations in injection time, injectate flow rate, and consistency of injection may occur during automatic injection with a gas powered injector, which may show no improvement over the manual method in injection reproducibility or CO values when the manual injection is made by an experienced operator. The overall consistency of injection (uniformity of upstroke in pressure, steadiness of pressure, and injectate flow rate) may be more important than the speed of injection.[107]

Intravenous fluid administration

Rapid peripheral intravenous infusion of 90–220 ml fluid at room temperature prior to the measurement may result in underestimation of CO in adults after cardiopulmonary bypass.[108] This is attributed to the temperature change caused by the infusion augmenting the area of the thermodilution curve area (Figure 3). In contrast, CO values will be overestimated if the injection is made just after the plateau temperature in mixed venous blood by the peripheral intravenous infusion has been reached (Figure 3). These observations indicate that rapid infusion of fluid either should be maintained at a constant rate or discontinued for at least 30 sec before CO measurement.[108] In addition, the infusion of fluids through the introducer side-port extension should be discontinued during CO determinations.[109]

Hypothermia

A close correlation (r = 0.96) has been noted between CO values measured by thermodilution using 5 ml iced injectate and with an electromagnetic flowmeter in hypothermic (20–35° C) anaesthetized dogs.[110] In hypothermic (32.7° C) patients undergoing cardiac surgery, CO values measured by thermodilution using 10 ml iced injectate correlated well with those using 10 ml (r = 0.951) or 5 ml (r = 0.925) injectate at room temperature (19–25° C), suggesting that there is no requirement for iced injectate even during hypothermia.[111]

The PA temperature decreased after cardiopulmonary bypass when systemic cooling and rewarming are performed during cardiopulmonary bypass. Recently, these alterations in PA temperature have been shown to cause substantial underestimation of CO measured by thermodilution.[112] Since the baseline PA temperature drift is readily detected by examination of the thermodilution curves, incorrect data can be avoided by accepting only thermodilution curves that begin and end on a stable baseline.[112]

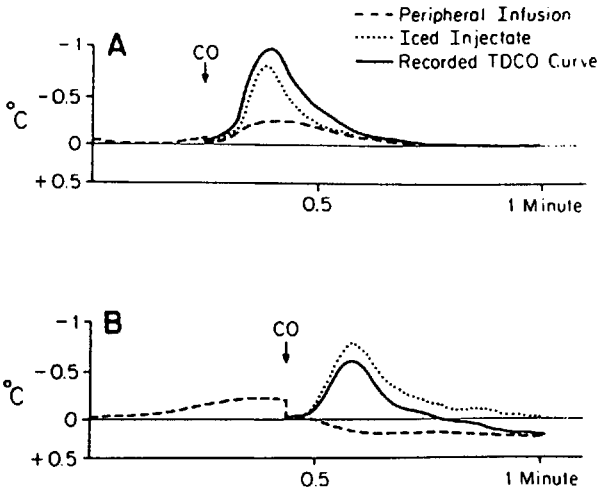

FIGURE 3 Diagramatic representation of effects of peripheral volume infusion on the temperature curve. Peripheral volume infusion was started at time = 0. CO = start of cardiac output measurement (followed by iced saline injection). (A) Temperature change caused by peripheral volume infusion augments measured change following iced saline injection. (B) Temperature change caused by volume infusion decreases measured change after iced saline injection (notice effect of "rezeroing" referenced baseline temperature at CO). Reproduced with permission from Wetzel RC and Latson TW.[108]

Low flow

Although the accuracy of thermodilution CO values has been noted at low CO of less than 1 to 2 $L \cdot min^{-1}$ in *in vitro*[113,114] or *in vivo* studies of paediatric[63] and adult[115] patients, or animals,[113,116] appearance of the thermal curve is delayed and its decay is prolonged in low CO states. Recirculation of indicator may occur before the computed analysis is completed, and loss of thermal indicator may be considerable. These sources of error may contribute to the variable CO values obtained during low CO states.[53] The potential error is likely to be large in adult patients,[37,117] although these patients are candidates for frequent CO determinations. Thermodilution overestimates CO in this situation probably due to excessive heat exchange secondary to slow passage of injectate.[44,117] Clinical errors can be reduced by observing the thermodilution curve and changes in clinical variables.[53] Under certain circumstances, methods other than thermodilution may be preferable when accurate determination of CO is necessary in patients with low CO states.[117]

Catheter dysfunction and position

Relatively common causes of PA catheter dysfunction include thrombus formation around the catheter[118] and occlusion of the proximal lumen.[119] The CO value is pro-

gressively underestimated as the size of catheter thrombus increases, which is due to overestimation of thermodilution curve area by prolonged rewarming of the thermistor.[118] When the proximal lumen opening of the PA catheter is obstructed because of improper perfusion, the catheter should be removed and replaced. However, CO measurements can also be obtained by injection of cold injectate through a central venous catheter inserted into the lower portion of the superior vena cava,[119] or through a right ventricular port of the PA catheter that was originally designed for pacemaker introduction or fluid administration.[120] There are three reports in which using the proximal port within the introducer sheath resulted in overestimation of CO because the thermal indicator refluxed within the introducer and failed to mix adequately with venous blood flow.[121-123] If this problem occurs, the sheath should be withdrawn slightly to allow a more usable length of catheter.[122,123]

When the thermistor of the PA catheter is located in the non-dependent lung or in the non-dependent zone during thoracotomy or during application of positive end-expiratory pressure, the injectate may be warmed less on the side of the thoracotomy,[124] and a different rate of thermal dissipation in the pulmonary circulation occurs around vessels in the non-dependent zone.[125] However, animal experiments have shown that the measurement of CO is not influenced by catheter position.[124-126] Similarly, no differences were demonstrated between CO values obtained with the catheter in a central or in a peripheral position in the PA.[39,61,124]

Intra- and extra-cardiac shunts

Recirculation occurs early and is seen on the downslope of the thermodilution curve in a patient with left-to-right intracardiac shunt, so that the exponential downslope of the thermodilution curve is interrupted. The shunt ratio may be calculated by obtaining the ratio of the area under the entire thermodilution curve to the area under the first portion of the curve which is measured by extrapolation of the first-pass curve to the baseline before the early recirculation (Figure 4).[127,128] The values measured by this method correlate well with those obtained with the Fick technique ($r = 0.89$),[127] and are fairly reproducible (7.9%).[128] Likewise, thermal dilution can be used to measure the outputs of the left and right ventricles separately in infants and children with atrial septal defects and with transposition of the great arteries.[21] The ratio of pulmonary:systemic flow calculated by this method correlates well with that obtained by the Fick method ($r = 0.91$). Thus, thermodilution provides a simple, rapid, and accurate method for determining the magnitude of left-to-right intracardiac shunts, provided that there is opportunity for the indicator to mix adequately in the main

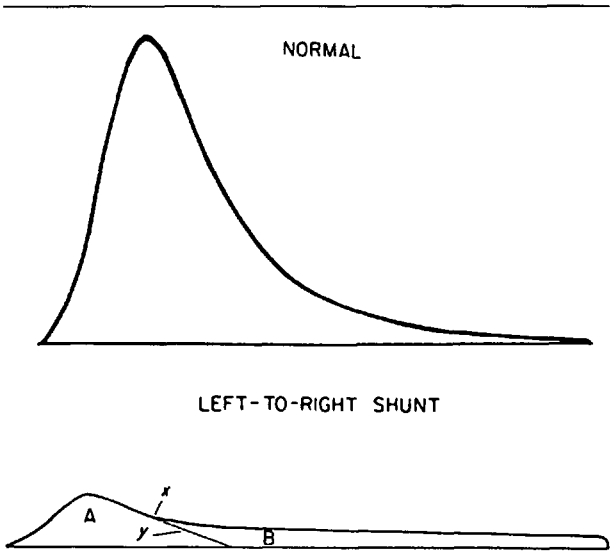

FIGURE 4 Schematic representation showing the method for calculating the ratio of left-to-right intracardiac shunt. Top panel, an example of a normal thermodilution curve demonstrating an exponential downslope. Bottom panel, a thermodilution curve obtained in a patient with an atrial septal defect (a left-to-right shunt). X marks the point of deflection in the usual exponential downslope of the thermodilution curve, due to early recirculation of cold indicator through the atrial septal defect. The exponential portion of the downslope, proximal to point x, was transposed to a log amplitude versus time scale, resulting in a linear series of points that was then extrapolated to the baseline. This point along the baseline was then transposed on to the original thermodilution curve and connected to point x, resulting in line y. A is the area under the first portion of the thermodilution curve, whereas B is the area under the terminal portion of the thermodilution curve. Shunt ratio is calculated by obtaining the ratio of the area under the entire thermodilution curve (A + B) to the first portion of the thermodilution curve (A). Reproduced with permission from Morady F *et al.*[127]

blood stream before shunting occurs.[129-131] The CO measurement with this technique may suggest the existence of left-to-right shunting, which resulted in falsely high CO values in a patient with congestive heart failure.[132] However, this method cannot be used when there is an additional shunt at the ductus level or in the presence of a right-to-left shunt.[128] The existence of a left-to-right shunt may be missed unless the thermodilution curve is displayed.[53] Furthermore, when the shunt flow is high, recirculation may not be seen on the thermodilution curve and the computed CO may be similar to systemic rather than pulmonary blood flow.[133]

In the presence of a right-to-left shunt, some of the indicator bypasses the thermistor to reach the left-side of the heart, and this results in overestimation of CO.[63] To calculate the shunt fractions in the right-to-left shunts, the forward triangle method (Figure 5) has been shown to be useful, in an animal experiment, since this method

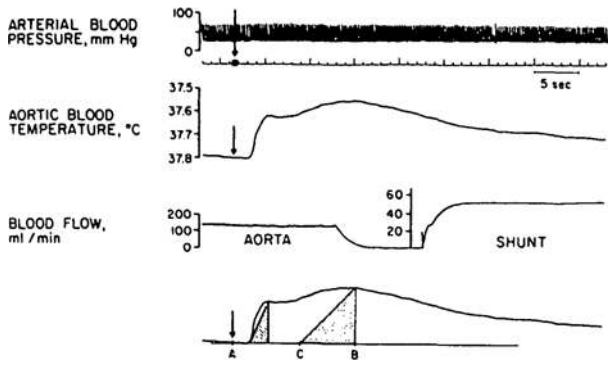

FIGURE 5 The forward triangle method for obtaining the shunt fraction of right-to-left intracardiac shunt. This diagram shows a thermodilution curve with arterial blood pressure, and blood flow through the aorta and the shunt during right-to-left shunt, when injection was performed in the right atrium, at the time marked by the arrow. The lower part of the figure shows the triangle used for the estimation of shunt ratio. The proportion of right-to-left shunt may be obtained by calculating the shunt triangle (left, the first peak from injection) in per cent of the sum of the shunt triangle and the triangle of the primary curve (right, the second peak from injection). To obtain the build-up time (BC) for the primary curve, the time between injection and peak concentration (AB) is measured and BC = fx AB, where the factor for the relation between build-up time and injection to peak concentration time (f) is calculated from data without shunting. Reproduced with permission from Hedvall G *et al.*[59]

provides the closest representation of true values and does not need oxygen-enriched inspiratory air as in the blood gas method.[59] In this method the proportion of injectate passing through the shunt is obtained by the ratio of the shunt triangle (left) to the sum of both triangles.[59, 134] In addition, the absolute blood flow through the shunt may be calculated by using the fraction of shunt and the total left ventricular output, if the latter can be estimated from a thermodilution curve after injection in the left atrium.[59]

Valvular heart diseases

There is one report of pulmonary valve insufficiency caused by surgical valvectomy that did not affect the measurement of CO in dogs, although the magnitude of the peak temperature change and the downslope of the thermodilution curve decreased because the indicator mixed with a larger volume of blood and the transit time of indicator was prolonged.[135] However, accurate determination of the area under the thermodilution curve is impossible when pulmonary regurgitation is associated with a low CO.[135]

Cardiac output determination by thermodilution was reported to be impossible or unreliable in patients with tricuspid regurgitation.[10,43,136] A recent animal investigation[137] has demonstrated that CO values estimated by thermodilution correlated well with pulmonary blood flow measured by an electromagnetic flowmeter in dogs with tricuspid regurgitation, and suggests that thermodilution CO determination may be more accurate than previously assumed, particularly in low CO states. However, in clinical settings, CO determination using the Fick method appears to be superior to the thermodilution technique in the presence of tricuspid regurgitation.[10,43,136]

Aortic or mitral regurgitation may render the indicator dilution technique inaccurate.[115,138-140] Distortion of the dye dilution curves by coronary recirculation in patients with severe aortic or mitral regurgitation[138] may be alleviated by sampling dye in the right heart.[139,140] However, a recent investigation failed to demonstrate any disparity between thermodilution and Fick measurements, and suggested that thermodilution was preferred to dye dilution in patients with aortic or mitral regurgitation.[115]

In summary, the Fick method should be selected for accurate determination of CO in patients with pulmonary or tricuspid regurgitation. In the presence of aortic or mitral regurgitation, CO measurement by thermodilution can be used as reliably as Fick method.

Paediatric patients

There is an excellent correlation (r = 0.91–0.97) between CO by thermodilution using 1–3 ml iced injectate or injectate at room temperature with values obtained by using the Fick technique or dye dilution in infants and children.[30,31,62,63,141] Withdrawal of blood into the injection lumen of the catheter before injection may lead to overestimation of CO because of the heat gain by small volumes of cold injectate during passage through the catheter.[142] Thus, for accurate measurement of CO by thermodilution in infants and children, pre-aspiration of blood should be avoided,[142] and the catheter lumen should be filled with fluid at the temperature of the injectate.[142] Also, a factor[60,142,143] which corrects for the loss of thermal indicator during passage of the injectate through the intravascular portion of the injectate catheter, should be used.

Electrocautery

Pulmonary artery baseline temperature is affected by the electrical noise created by electrocautery. Determinations should not be made while electrocautery is applied.[53]

Other pathological conditions

Candidates for frequent CO determinations include patients with pulmonary oedema and/or respiratory failure, hypoxia, metabolic acidosis, myocardial ischaemia, acute blood loss, or endotoxaemia. Although it has been suggested that considerable loss of cold indicator might occur in oedematous lungs, resulting in overestimation of CO,[48]

an animal model of dextran infusion- or oleic acid-induced pulmonary oedema[58,96,144] has demonstrated that variability of PA temperature did not affect the reliability of CO determinations. We have observed excellent agreement between CO values estimated by thermodilution and by electromagnetic flowmeter in anaesthetized dogs with pulmonary oedema,[81] myocardial ischaemia,[81] hypoxic hypoxia,[145] metabolic acidosis[145] and endotoxaemia.

The CO computer calculates using factors for the specific heat and density of blood at a haemotocrit of 42%.[22] Thus, alteration in haematocrit is presumed to change the specific gravity and specific heat of blood. However, in massive bleeding, a density factor remains unchanged and it is unnecessary to correct for different values of haematocrit within reasonable limits.[22] The product of specific heat and density of blood decreases from 0.9336 to 0.9196 if haematocrit decreases from 42% to 30%,[146] which results in an error of only 1% in the estimation of CO.[22]

Conclusions

Recent developments in non-invasive CO monitoring have not replaced CO determination by thermodilution. Knowledge of the errors inherent in thermodilution measurement is essential for the anaesthetists and other clinicians engaged in the management of critically ill patients. The erroneous estimation of CO may lead to inappropriate management and adverse outcomes.

References

1 *Fegler G.* Measurement of cardiac output in anaesthetized animals by a thermo-dilution method. Quarterly Journal of Experimental Physiology 1954; 39: 153–64.

2 *Fegler G.* The reliability of the thermodilution method for determination of the cardiac output and the blood flow in central veins. Quarterly Journal of Experimental Physiology 1957; 42: 254–66.

3 *Goodyer AVN, Huvos A, Eckhardt WF, Ostberg RH.* Thermal dilution curves in the intact animal. Circ Res 1959; 7: 432–41.

4 *Froněk A, Ganz V.* Measurement of flow in single blood vessels including cardiac output by local thermodilution. Circ Res 1960; 8: 175–82.

5 *Evonuk E, Imig CJ, Greenfield W, Eckstein JW.* Cardiac output measured by thermal dilution of room temperature injectate. J Appl Physiol 1961; 16: 271–5.

6 *Pávek K, Boska D, Selecký FV.* Measurement of cardiac output by thermodilution with constant rate injection of indicator. Circ Res 1964; 15: 311–9.

7 *Lüthy E, Galletti PM.* In vivo evaluation of the thermodilution technique for measuring cardiac output. Helv Physiol Acta 1966; 24: 15–23.

8 *Branthwaite MA, Bradley RD.* Measurement of cardiac output by thermal dilution in man. J Appl Physiol 1968; 24: 434–8.

9 *Solomon HA, San Marco MA, Ellis RJ, Lillehei CW.* Cardiac output determination: superiority of thermal dilution. Surg Forum 1969; 20: 28–30.

10 *Olsson B, Pool J, Vandermoten P, Varnauskas E, Wassén R.* Validity and reproducibility of determination of cardiac output by thermodilution in man. Cardiology 1970; 55: 136–48.

11 *Enghoff E, Michaëlsson M, Pavek K, Sjögren S.* A comparison between the thermal dilution method and the direct Fick and the dye dilution methods for cardiac output measurements in man. Acta Societatis Medicorum Upsaliensis 1970; 75: 157–70.

12 *Lin Y-C, Dawson CA, Nadel ER, Horvath SM.* Reliability of cardiac output measured by thermodilution method in small animals. Comp Biochem Physiol 1970; 34: 245–50.

13 *Sanmarco ME, Philips CM, Marquez LA, Hall C, Davila JC.* Measurement of cardiac output by thermal dilution. Am J Cardiol 1971; 28: 54–8.

14 *Silove ED, Cantez T, Wells BG.* Thermodilution measurement of left and right ventricular outputs. Cardiovasc Res 1971; 5: 174–7.

15 *Hanwell A, Linzell JL.* Validation of the thermodilution technique for the estimation of cardiac output in the rat. Comp Biochem Physiol 1972; 41A: 647–57.

16 *Wilson EM, Ranieri AJ Jr, Updike OL, Dammann JF Jr.* An evaluation of thermal dilution for obtaining serial measurements of cardiac output. Med Biol Eng Comput 1972; 10: 179–91.

17 *Ganz W, Donoso R, Marcus HS, Forrester JS, Swan HJC.* A new technique for measurement of cardiac output by thermodilution in man. Am J Cardiol 1971; 27: 392–6.

18 *Ganz W, Swan HJC.* Measurement of blood flow by thermodilution. Am J Cardiol 1972; 29: 241–6.

19 *Forrester JS, Ganz W, Diamond G, McHugh T, Chonette DW, Swan HJC.* Thermodilution cardiac output determination with a single flow-directed catheter. Am Heart J 1972; 83: 306–11.

20 *Ellis RJ, Gold J, Rees JR, Lillehei CW.* Computerized monitoring of cardiac output by thermal dilution. JAMA 1972; 220: 507–11.

21 *Silove ED, Tynan MJ, Simcha AJ.* Thermal dilution measurement of pulmonary and systemic blood flow in secundum atrial septal defect, and transposition of great arteries with intact interventricular septum. Br Heart J 1972; 34: 1142–6.

22 *Andreen M.* Computerized measurement of cardiac output by thermodilution: methodological aspects. Acta Anaesthesiol Scand 1974; 18: 297–305.

23 *Weisel RD, Vito L, Dennis RC, Berger RL, Hechtman*

HB. Clinical applications of thermodilution cardiac output determinations. Am J Surg 1975; 129: 449–54.

24 *Weisel RD, Berger RL, Hechtman HB.* Measurement of cardiac output by thermodilution. N Engl J Med 1975; 292: 682–4.

25 *Berger RL, Weisel RD, Vito L, Dennis RC, Hechtman HB.* Cardiac output measurement by thermodilution during cardiac operations. Ann Thorac Surg 1976; 21: 43–7.

26 *Swan HJC, Ganz W.* Use of balloon flotation catheters in critically ill patients. Surg Clin North Am 1975; 55: 501–20.

27 *Tietjen GW, Gump FE, Kinney JM.* Cardiac output determinations in surgical patients. Surg Clin North Am 1975; 55: 521–9.

28 *Hodges M, Downs JB, Mitchell LA.* Thermodilution and Fick cardiac index determinations following cardiac surgery. Crit Care Med 1975; 3: 182–4.

29 *Alfieri O, Agosti J, Subramanian S.* Thermodilution cardiac output measurement in infants and small children following intracardiac surgery. J Pediatr Surg 1975; 10: 649–55.

30 *Wyse SD, Pfitzner J, Rees A, Lincoln JCR, Branthwaite MA.* Measurement of cardiac output by thermal dilution in infants and children. Thorax 1975; 30: 262–5.

31 *Mathur M, Harris EA, Yarrow S, Barratt-Boyes BG.* Measurement of cardiac output by thermodilution in infants and children after open-heart operations. J Thorac Cardiovasc Surg 1976; 72: 221–5.

32 *Callaghan ML, Weintraub WH, Coran AG.* Assessment of thermodilution cardiac output in small subjects. J Pediatr Surg 1976; 11: 629–33.

33 *Buchbinder N, Ganz W.* Hemodynamic monitoring: invasive techniques. Anesthesiology 1976; 45: 146–55.

34 *Venkataraman K, DeGuzman MF, Hafeezkhan A, Haywood LJ.* Cardiac output measurement: a comparison of direct Fick, dye dilution and thermodilution methods in stable and acutely ill patients. J Natl Med Assoc 1976; 68: 281–4.

35 *Saadjian A, Quercy JE, Torresani J.* Cardiac output measurement by thermodilution. Methodologic problems. Med Prog Technol 1976; 3: 161–7.

36 *Weil MH.* Measurement of cardiac output (Editorial). Crit Care Med 1977; 5: 117–9.

37 *Kohanna FH, Cunningham JN Jr.* Monitoring of cardiac output by thermodilution after open-heart surgery. J Thorac Cardiovasc Surg 1977; 73: 451–7.

38 *Aikawa N, Martyn JAJ, Burke JF.* Pulmonary artery catheterization and thermodilution cardiac output determination in the management of critically burned patients. Am J Surg 1978; 135: 811–7.

39 *Hoel BL.* Some aspects of the clinical use of thermodilution in measuring cardiac output. Scand J Clin Lab Invest 1978; 38: 383–8.

40 *Fischer AP, Benis AM, Jurado RA, Seely E, Teirstein P, Litwak RS.* Analysis of errors in measurement of cardiac output by simultaneous dye and thermal dilution in cardithoracic surgical patients. Cardiovasc Res 1978; 12: 190–9.

41 *Forrester JS, Diamond GA, Swan HJC.* Correlative classification of clinical and hemodynamic function after acute myocardial infarction. Am J Cardiol 1977; 39: 137–45.

42 *Connors AF Jr, McCaffree DR, Gray BA.* Evaluation of right-heart catheterization in the critically ill patient without acute myocardial infarction. N Engl J Med 1983; 308: 263–7.

43 *Sharkey SW.* Beyond the wedge: clinical physiology and the Swan-Ganz catheter. Am J Med 1987; 83: 111–22.

44 *Warren DJ, Ledingham JGG.* Cardiac output in the conscious rabbit: an analysis of the thermodilution technique. J Appl Physiol 1974; 36: 246–51.

45 *Merjavy JP, Hahn JW, Barner HB.* Comparison of thermodilution cardiac output and electromagnetic flowmeter. Surg Forum 1974; 25: 145–7.

46 *Hendriks FFA, Schipperheyn JJ, Quanjer PH.* Thermal dilution measurement of cardiac output in dogs using an analog computer. Basic Res Cardiol 1978; 73: 459–68.

47 *Levine BA, Sirinek KR.* Cardiac output determination by thermodilution technique: the method of choice in low flow states. Proc Soc Exp Biol Med 1981; 167: 279–83.

48 *Hosie KF.* Thermal-dilution technics. Circ Res 1962; 5: 491–504.

49 *Levett JM, Replogle RL.* Thermodilution cardiac output: a critical analysis and review of the literature. J Surg Res 1979; 27: 392–404.

50 *Arfors K-E, Malmberg P, Pavek K.* Conservation of thermal indicator in lung circulation. Cardiovasc Res 1971; 5: 530–4.

51 *Vliers ACAP, Oeseburg B, Visser KR, Zijlstra WG.* Choice of detection site for the determination of cardiac output by thermal dilution: the injection-thermistor-catheter. Cardiovasc Res 1973; 7: 133–8.

52 *Vliers ACAP, Visser KR, Zijlstra WG.* Analysis of indicator distribution in the determination of cardiac output by thermal dilution. Cardiovasc Res 1973; 7: 125–32.

53 *Nadeau S, Noble WH.* Limitations of cardiac output measurements by thermodilution. Can Anaesth Soc J 1986; 33: 780–4.

54 *Zierler KL.* Theoretical basis of indicator-dilution methods for measuring flow and volume. Circ Res 1962; 5: 393–407.

55 *Phillips CM, Davila JC, Sanmarco ME.* Measurement of cardiac output by thermal dilution II. A new computer for rapid convenient determinations. Medical Research in Engineering 1970; 9: 25–9.

56 *Olsson SB, Wassén R, Varnauskas ED, Wallman H.* A simple analogue computer for cardiac output determination by thermodilution. Cardiovasc Res 1972; 6: 303–8.

57 *Korner PI, Hilder RG.* Measurement of cardiac output

and regional blood flow by thermodilution. Clin Exp Pharmacol Physiol 1974; Suppl 1: 47–66.

58 *Kay JC, Noble WH.* A comparison of thermal and dye dilution methods of determining cardiac output. Can Anaesth Soc J 1973; 20: 347–56.

59 *Hedvall G, Kjellmer I, Olsson T.* An experimental evaluation of the thermodilution method for determination of cardiac output and of intracardiac right-to-left shunts. Scand J Clin Lab Invest 1973; 31: 61–8.

60 *Meisner H, Hagl S, Heimisch W, et al.* Evaluation of the thermodilution method for measurement of cardiac output after open-heart surgery. Ann Thorac Surg 1974; 18: 504–15.

61 *Sørensen MB, Bille-Brahe NE, Engell HC.* Cardiac output measurement by thermal dilution: Reproducibility and comparison with the dye-dilution technique. Ann Surg 1976; 183: 67–72.

62 *Colgan FJ, Stewart S.* An assessment of cardiac output by thermodilution in infants and children following cardiac surgery. Crit Care Med 1977; 5: 220–5.

63 *Freed MD, Keane JF.* Cardiac output measured by thermodilution in infants and children. J Pediatr 1978; 92: 39–42.

64 *Stawicki JJ, Holford FD, Michelson EL, Josephson ME.* Multiple cardiac output measurements in man. Evaluation of a new closed-system thermodilution method. Chest 1979; 76: 193–7.

65 *Pelletier C.* Cardiac output measurement by thermodilution. Can J Surg 1979; 22: 347–50.

66 *Rogers MC, Nugent SK, Pickard LR, Roland J-M, Shermeta DW.* Experimental evaluation of 2F transthoracic thermodilution cardiac outputs in small animals. Crit Care Med 1979; 7: 171–3.

67 *Runciman WB, Ilsley AH, Roberts JG.* Thermodilution cardiac output – a system error. Anaesth Intensive Care 1981; 9: 135–9.

68 *Elkayam U, Berkley R, Azen S, Weber L, Geva B, Henry WL.* Cardiac output by thermodilution technique. Effect of injectate's volume and temperature on accuracy and reproducibility in the critically ill patient. Chest 1983; 84: 418–22.

69 *Pearl RG, Rosenthal MH, Nielson L, Ashton JPA, Brown BW Jr.* Effect of injectate volume and temperature on thermodilution cardiac output determination. Anesthesiology 1986; 64: 798–801.

70 *Bilfinger TV, Lin C-Y, Anagnostopoulos CE.* In vitro determination of accuracy of cardiac output measurements by thermal dilution. J Surg Res 1982; 33: 409–14.

71 *Stetz CW, Miller RG, Kelly GE, Raffin TA.* Reliability of the thermodilution method in the determination of cardiac output in clinical practice. Am Rev Respir Dis 1982; 126: 1001–4.

72 *Shellock FG, Riedinger MS.* Reproducibility and accuracy of using room-temperature vs. ice-temperature injectate for thermodilution cardiac output determination. Heart Lung 1983; 12: 175–6.

73 *Vennix CV, Nelson DH, Pierpont GL.* Thermodilution cardiac output in critically ill patients: comparison of room-temperature and iced injectate. Heart Lung 1984; 13: 574–8.

74 *Nelson LD, Anderson HB.* Patient selection for iced versus room temperature injectate for thermodilution cardiac output determinations. Crit Care Med 1985; 13: 182–4.

75 *Runciman WB, Ilsley AH, Roberts JG.* An evaluation of thermodilution cardiac output measurement using the Swan-Ganz catheter. Anaesth Intensive Care 1981; 9: 208–20.

76 *Woog RH, McWilliam DB.* A comparison of methods of cardiac output measurement. Anesth Intensive Care 1983; 11: 141–6.

77 *Nishikawa T, Dohi S.* Slowing of heart rate during cardiac output measurement by thermodilution. Anesthesiology 1982; 57: 538–9.

78 *Harris AP, Miller CF, Beattie C, Rosenfeld GI, Rogers MC.* The slowing of sinus rhythm during thermodilution cardiac output determination and the effect of altering injectate temperature. Anesthesiology 1985; 63: 540–1.

79 *Nishikawa T, Dohi S.* Hemodynamic status susceptible to slowing of heart rate during thermodilution cardiac output determination in anesthetized patients. Crit Care Med 1990; 18: 841–4.

80 *Nishikawa T, Namiki A.* Mechanism for slowing of heart rate and associated changes in pulmonary circulation elicited by cold injectate during thermodilution cardiac output determination in dogs. Anesthesiology 1988; 68: 221–5.

81 *Nishikawa T, Dohi S.* Haemodynamic changes associated with thermodilution cardiac output determination during myocardial ischaemia or pulmonary oedema in dogs. Acta Anaesthesio Scand 1992; 36: 679–83.

82 *Reininger EJ, Troy BL.* Error in thermodilution cardiac output measurement caused by variation in syringe volume. Cathet Cardiovasc Diagn 1976; 2: 415–7.

83 *Hammermeister KE, VanDamme J.* A simple, new system for maintaining measured quantities of saline cold and sterile for thermodilution cardiac output measurement. Cathet Cardiovasc Diagn 1979; 5: 95–9.

84 *Powner DJ.* Thermodilution technic for cardiac output (Correspondence). N Engl J Med 1975; 293: 1210–1.

85 *Meisner H, Glanert S, Steckmeier B, et al.* Indicator loss during injection in the thermodilution system. Res Exp Med 1973; 159: 183–96.

86 *Kim ME, Lin YC.* Determination of catheter wall heat transfer in cardiac output measurement by thermodilution. Clin Exp Pharmacol Physiol 1980; 7: 383–9.

87 *Singh R, Ranieri AJ Jr, Vest HR Jr, Bowers DL, Dammann JF Jr.* Simultaneous determinations of cardiac out-

put by thermal dilution, fiberoptic and dye-dilution methods. Am J Cardiol 1970; 25: 579–87.

88 *Woods M, Scott RN, Harken AH.* Practical considerations for the use of a pulmonary artery thermistor catheter. Surgery 1976; 79: 469–75.

89 *Wessel HU, Paul MH, James GW, Grahn AR.* Limitations of thermal dilution curves for cardiac output determinations. J Appl Physiol 1971; 30: 643–52.

90 *Afonso S, Herrick JF, Youmans WB, Rowe GG, Crumpton CW.* Temperature variations in the venous system of dogs. Am J Physiol 1962; 203: 278–82.

91 *Wessel HU, James GW, Paul MH.* Effects of respiration and circulation on central blood temperature of the dog. Am J Physiol 1966; 211: 1403–12.

92 *Riedinger MS, Shellock FG.* Technical aspects of the thermodilution method for measuring cardiac output. Heart Lung 1984; 13: 215–21.

93 *Guyton AC.* Regulation of cardiac output. N Engl J Med 1967; 277: 805–12.

94 *Whittenberger JL, McGregor M, Berglund E, Borst HG.* Influence of state of inflation of the lung on pulmonary vascular resistance. J Appl Physiol 1960; 15: 878–82.

95 *Snyder JV, Powner DJ.* Effects of mechanical ventilation on the measurement of cardiac output by thermodilution. Crit Care Med 1982; 10: 677–82.

96 *Armengol J, Man GCW, Balsys AJ, Wells AL.* Effects of the respiratory cycle on cardiac output measurements: reproducibility of data enhanced by timing the thermodilution injections in dogs. Crit Care Med 1981; 9: 852–4.

97 *Jansen JRC, Schreuder JJ, Bogaard JM, Van Rooyen W, Versprille A.* Thermodilution technique for measurement of cardiac output during artificial ventilation. J Appl Physiol 1981; 50: 584–91.

98 *Tajiri J, Katsuya H, Okamoto K, Urata K, Sato T.* The effects of the respiratory cycle by mechanical ventilation on cardiac output measured using the thermodilution method. Jpn Circ J 1984; 48: 328–30.

99 *Stevens JH, Raffin TA, Mihm FG, Rosenthal MH, Stetz CW.* Thermodilution cardiac output measurement. Effects of the respiratory cycle on its reproducibility. JAMA 1985; 253: 2240–2.

100 *Okamoto K, Komatsu T, Kumar V, et al.* Effects of intermittent positive-pressure ventilation on cardiac output measurements by thermodilution. Crit Care Med 1986; 14: 977–80.

101 *Versprille A.* Thermodilution in mechanically ventilated patients (Editorial). Intensive Care Med 1984; 10: 213–5.

102 *Jansen JRC, Versprille A.* Improvement of cardiac output estimation by the thermodilution method during mechanical ventilation. Intensive Care Med 1986; 12: 71–9.

103 *Sherry KM, Feneck RO, Normandale J.* Thermodilution cardiac output measurements during conventional and high-frequency ventilation. J Cardiothorac Vasc Anesth 1988; 2: 320–5.

104 *Thrush DN, Varlotta D.* Thermodilution cardiac output: comparison between automated and manual injection of indicator. J Cardiothorac Vasc Anesth 1992; 6: 17–9.

105 *Enghoff E, Sjögren S.* Thermal dilution for measurement of cardiac output in the pulmonary artery in man in relation to choice of indicator volume and injection time. Ups J Med Sci 1973; 78: 33–7.

106 *Dizon CT, Gezari WA, Barash PG, Crittenden JF.* Hand held thermodilution cardiac output injector. Crit Care Med 1977; 5: 210–2.

107 *Nelson LD, Houtchens BA.* Automatic vs manual injections for thermodilution cardiac output determinations. Crit Care Med 1982; 10: 190–2.

108 *Wetzel RC, Latson TW.* Major errors in thermodilution cardiac output measurement during rapid volume infusion. Anesthesiology 1985; 62: 684–7.

109 *Shellock FG, Riedinger MS.* Hemodynamic measurement errors caused by catheter introducers (Correspondence). Cathet Cardiovasc Diagn 1982; 8: 319.

110 *Merrick SH, Hessel EA II, Dillard DH.* Determination of cardiac output by thermodilution during hypothermia. Am J Cardiol 1980; 46: 419–22.

111 *Shellock FG, Riedinger MS, Bateman TM, Gray RJ.* Thermodilution cardiac output determination in hypothermic postcardiac surgery patients: room vs ice temperature injectate. Crit Care Med 1983; 11: 668–70.

112 *Bazaral MG, Petre J, Novoa R.* Errors in thermodilution cardiac output measurements caused by rapid pulmonary artery temperature decreases after cardiopulmonary bypass. Anesthesiology 1992; 77: 31–7.

113 *Moodie DS, Feldt RH, Kaye MP, Strelow DA, van der Hagen LJ.* Measurement of cardiac output by thermodilution: development of accurate measurements at flows applicable to the pediatric patient. J Surg Res 1978; 25: 305–11.

114 *Norris SL, King EG, Grace M, Weir B.* Thermodilution cardiac output – an in vitro model of low flow states. Crit Care Med 1986; 14: 57–9.

115 *Hillis LD, Firth BG, Winniford MD.* Analysis of factors affecting the variability of Fick versus indicator dilution measurements of cardiac output. Am J Cardiol 1985; 56: 764–8.

116 *While SW, McRitchie RJ, Porges WL.* A comparison between thermodilution, electromagnetic and Doppler methods for cardiac output measurement in the rabbit. Clin Exp Pharmacol Physiol 1974; 1: 175–82.

117 *van Grondelle A, Ditchey RV, Groves BM, Wagner WW Jr, Reeves JT.* Thermodilution method overestimates low cardiac output in humans. Am J Physiol 1983; 245: H690–2.

118 *Bjoraker DG, Ketcham TR.* Catheter thrombus artifactually decreases thermodilution cardiac output measurements. Anesth Analg 1983; 62: 1031–4.

119 *Martin C. Saux P, Auffray JP, Fulachier V, Setbon F, Gouin F.* Thermodilution cardiac output measurements by injection in pulmonary artery vs CVP catheter. Crit Care Med 1983; 11: 460–1.

120 *Pesola GR, Carlon GC.* Thermodilution cardiac output: proximal lumen versus right ventricular port. Crit Care Med 1991; 19: 563–5.

121 *Bearss MG, Yonutas DN, Allen WT.* A complication with thermodilution cardiac output in centrally-placed pulmonary artery catheters (Correspondence). Chest 1982; 81: 527.

122 *Curley J, Harte F, Sheikh F.* Erroneous cardiac output determination due to pulmonary artery catheter proximal port dysfunction (Correspondence). Anesthesiology 1986; 64: 662.

123 *Stoller JK, Herbst TJ, Hurford W, Rie MA.* Spuriously high cardiac output from injecting thermal indicator through an ensheathed port. Crit Care Med 1986; 14: 1064–5.

124 *Landais A, Morin JP, Roche A, Cornec C, Sansoy N.* Measurement of cardiac output by the thermodilution method during left thoracotomy in the lateral position in the dog. Acta Anaesthesiol Scand 1990; 34: 158–61.

125 *Hasan FM, Malanga A, Corrao WM, Braman SS.* Effect of catheter position on thermodilution cardiac output during continuous positive-pressure ventilation. Crit Care Med 1984; 12: 387–90.

126 *Boucek C, Klain M, Obuchowski N, Molner R.* Pulmonary artery catheter monitoring during single-lung ventilation in dogs. J Clin Monit 1992; 8: 209–15.

127 *Morady F, Brundage BH, Gelberg HJ.* Rapid method for determination of shunt ratio using a thermodilution technique. Am Heart J 1983; 106: 369–73.

128 *Hedvall G.* The applicability of the thermodilution method for determination of pulmonary blood flow and pulmonary vascular resistance in infants and children with ventricular septal defects. Scand J Clin Lab Invest 1978; 38: 581–5.

129 *Jögi P, Werner O.* Left-to-right shunt assessed by thermodilution during surgery for congenital heart disease. Scand J Thorac Cardiovasc Surg 1987; 21: 203–6.

130 *Burchman CA, Lappas DG.* Thermodilution cardiac output provides unanticipated intraoperative diagnosis (Correspondence). J Cardiothorac Vasc Anesth 1988; 4: 584–5.

131 *McGuirk SM, Welker FH, Muir WW, Hull BL.* Thermodilution curves for diagnosis of ventricular septal defect in cattle. J Am Vet Med Assoc 1984; 184: 1141–5.

132 *Kahan F, Profeta J, Thys D.* High cardiac output measurements in a patient with congestive heart failure. J Cardiothorac Vasc Anesth 1987; 3: 234–6.

133 *Pearl RG, Siegel LC.* Thermodilution cardiac output measurement with a large left-to-right shunt. J Clin Monit 1991; 7: 146–53.

134 *Swan HJC, Zapata-Diaz J, Wood EH.* Dye dilution curves in cyanotic congenital heart disease. Circulation 1953; 8: 70–81.

135 *Beyer J, Lamberti JJ, Replogle RL.* Validity of thermodilution cardiac output determination: experimental studies with and without pulmonary insufficiency. J Surg Res 1976; 21: 313–7.

136 *Ohteki H, Nagara H, Wada J, Inoue Y, Kimata S.* Measurement of cardiac output by thermodilution and Fick methods in man – problems in case of tricuspid regurgitation. Kokyu to Junkan 1981; 29: 433–7.

137 *Kashtan HI, Maitland A, Salerno TA, Lichtenstein SV, Byrick RJ.* Effects of tricuspid regurgitation on thermodilution cardiac output: studies in an animal model. Can J Anaesth 1987; 34: 246–51.

138 *Rahimtoola SH, Swan HJC.* Calculation of cardiac output from indicator-dilution curves in the presence of mitral regurgitation. Circulation 1965; 31: 711–8.

139 *Samet P, Bernstein WH, Castillo C.* Validity of indicator-dilution determinations of cardiac output in patients with mitral regurgitation. Circulation 1966; 33: 410–6.

140 *Samet P, Castillo C, Bernstein WH.* Validity of indicator-dilution determination of cardiac output by in patients with aortic regurgitation. Circulation 1966; 34: 609–10.

141 *Alfieri O, Subramanian S.* Cardiac output determination in infants and small children after open intracardiac operations. Ann Thorac Surg 1975; 19: 322–6.

142 *Maruschak GF, Potter AM, Schauble JF, Rogers MC.* Overestimation of pediatric cardiac output by thermal indicator loss. Circulation 1982; 65: 380–3.

143 *Baskoff JD, Maruschak GF.* Correction factor for thermodilution determination of cardiac output in children. Crit Care Med 1981; 9: 870–2.

144 *Pavek K, Lindquist O, Arfors K-E.* Validity of thermodilution method for measurement of cardiac output in pulmonary oedema. Cardiovasc Res 1973; 7: 419–22.

145 *Nishikawa T, Dohi S.* Haemodynamic changes associated with thermodilution cardiac output determination during metabolic acidosis or hypoxic hypoxia in dogs. Eur J Anaesthesiol (in press).

146 *Mendlowitz M.* The specific heat of human blood. Science 1948; 107: 97–8.