Brief Review

Limitations of cardiac output measurements by thermodilution

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Cardiac output (CO) can be determined using pulmonary artery catheters and thermodilution techniques. The purpose of this paper is to describe the thermodilution principle and to consider factors and pathology which may invalidate the CO determination.

Thermodilution technique

The injection of a known amount of indicator (a cool solution) into the right atrium through the proximal port of a pulmonary artery catheter (PAC) is detected distally by a thermistor located 4 cm from the end of the PAC.[1] The change in temperature of blood in pulmonary artery causes a change in the thermistor Wheatstone bridge resistance which allows a computer to calculate the area under the thermodilution curve (Figure (a)). This and the volume of injectate allow computation of CO.[2] The shape of the thermodilution curve is similar to dye dilution curves except thermodilution recirculation is small (about four per cent of the peak of the curve).[3] The thermodilution curve peaks rapidly and then follows an exponential decay, until there is recirculation or delayed cooling from the residual indicator in the PAC.[4] This last portion of the curve should not be used in determining the area under the curve.

Cardiac output is determined from the following equation[2]

$$CO = V_I (T_B - Ti)K_1K_2/\Delta T_B(t)dt$$

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

Many methods have been used to determine the integral of the temperature change to avoid including recirculation. These methods determine a cut off point in the curve before recirculation occurs.[2] Phillips[3] used a cut off point of 12 per cent of the peak. Wessel[5] used a cut off from 70 to 30 per cent of the peak. Others chose 80 per cent of the peak to 40 per cent of the peak by multiplying by a constant.[2] These techniques will vary in accuracy depending on the shape of the curve.

Technical errors

Errors in measuring CO by thermodilution may be introduced by inaccuracies in any of the variables in equation #1. First is the injectate temperature (Ti). Iced solutions provide a better signal to noise ratio. But some cold could be lost (i) to the catheter wall,[6] or (ii) by rewarming the syringe from handling before injection (probably not significant if the time of handling is less than 30 seconds[7] – for each degree of rewarming an overestimation of CO of 2.9 per cent results[8] and a 10 ml syringe held in a warm hand will increase temperature 1°C every 13 seconds).[9]

These problems can be avoided if the injectate temperature is monitored at the point of entry into

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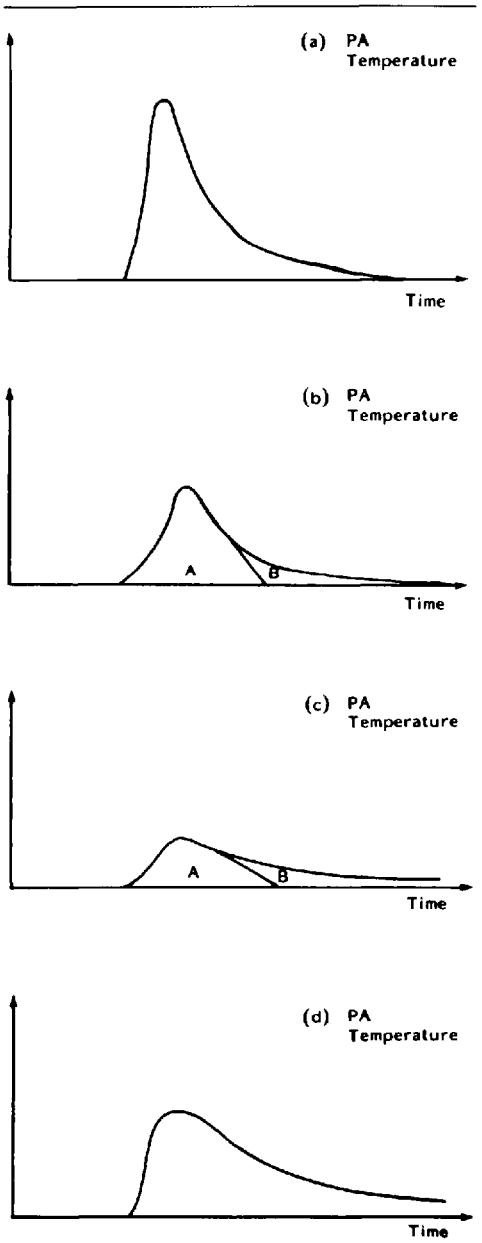

FIGURE Cardiac output thermodilution curves in four settings: the x axis representing time and the y axis representing decreasing pulmonary artery temperature. (a) normal, (b) a small VSD, (c) a large VSD (the area A in both cases represents the pulmonary blood flow minus the shunt blood and the area B the shunt), and (d) pulmonary insufficiency.

the circulation.[5] On the other hand, room temperature injectates necessitate large volumes (10 ml) of indicator to achieve a sufficient concentration at the site of the thermistor.[5] Room temperature injectates do not require cooling of the syringe before utilization, which is required with the cold injectate (usually an hour to cool from room temperature to zero degrees).[2] There is less catheter wall heat exchange and no significant hand warming of the room temperature injectate versus the iced injectate.[2] Since room temperature injectate is more practical and as accurate as iced injectate, room temperature injectate is clinically used, except during significant hypothermia ($T°_B$ 29–30° C).[10] If the temperature probe measuring injectate temperature is not sensing room temperature (e.g., sitting in warm equipment or near a cold bag of blood), CO using room temperature injectate will be in error (underestimated if the reference temperature is higher than room temperature).[11] For certain computer models (e.g., Edwards) the computer constant must be adjusted depending on the injectate temperature or the measured CO will not be accurate.

Secondly the *volume of injectate* is imporant. The larger the volume used, the better the signal–noise ratio, especially with room temperature injectates. A 10 ml volume of injectate is commonly used. If the injectate volume is less than expected (e.g., 9 ml instead of 10 ml) the calculated CO will be falsely high[12] (the area under the curve is smaller).

Thirdly the *timing of injection* has to be considered. With respiration, there is a variation in the baseline pulmonary artery (PA) temperature (T_B). This variation is usually not a problem during quiet breathing as opposed to the pattern in respiratory distress.[2] Obviously the best thermodilution CO will be made during apnoea but this is impractical. The thermal content of the superior vena cava (SVC), inferior vena cava (IVC) and blood is different during the various phases of respiration. Since the ratio of venous return from SVC and IVC is changed by respiration, it will also alter the PA temperature. Depending on when the injection is made different CO will result.[13]

The change in T_B with respiration also depends on the temperature, humidity and flow rate of inspired air. At the end of expiration, the PA temperature decreases in mechanically ventilated patients (heated and humidified gases) but increases

in spontaneously breathing patients.[7] Therefore for mechanically ventilated patients, T_B is already reduced at end expiration. This means the difference from injectate temperature is less, the area under the curve is underestimated, and CO is overestimated. In spontaneously breathing patients, determination of CO by thermodilution at end expiration, will underestimate the CO.[7]

These considerations apply to curves analysed by hand or by digital computer, but not to the commercial computers since all of them average a baseline PA temperature. By averaging the baseline, accuracy is not improved, but reproducibility is.[5] When the injection was synchronized to the same point in the ventilatory cycle, CO values varied by up to 6.7 per cent.[7] When the injections were out of phase by half the respiratory cycle, the variations were as large as 14 per cent. Woods suggests these variations can be minimized by always injecting at the same point in the respiratory cycle.[7]

The pulmonary artery baseline temperature can also be modified by rapid infusions of other fluids. If iced solutions are rapidly infused at the same time as the cool indicator is injected, a greater decrease in the PA temperature results, increasing the area under the curve and underestimating CO.[14] The greater the difference of temperature between the intravenous infusion and the blood (baseline PA temperature), the greater is the difference between the control CO and measured CO. On the other hand, if the infusion of the solution preceeds the injectate of the indicator by about 20 seconds, this causes a cooling of baseline PA temperature. Therefore the injected indicator does not produce as much change in temperature and the area under the curve is decreased, falsely increasing CO. Rapid volume infusions should therefore be maintained at the same rate or should be discontinued at least 30 seconds prior to the CO measured by thermodilution.[14]

Another factor that will affect pulmonary artery baseline temperature is the electrical noise created by cautery. Thermodilution CO should not be determined while cautery is applied.

The duration of injection, a variable included in the computation constant K_2, does not influence the K_2 value as long as the indicator is injected over 2 to 4 sec. If there is a longer injection rate, the recirculation may affect the shape of the curve.[5]

Intervals of 20–90 sec are suggested as adequate times between injections, because recirculation (although minimal for thermodilution) occurs 5 to 35 sec after the injection.[2]

A change in haematocrit will cause a change of specific gravity and heat of blood, but K_1 remains virtually unchanged. A decrease of haematocrit from 52 to 30 per cent will correlate respectively with a K_1 of 1.13 and 1.07, causing a negligable effect on the CO determination (about one per cent).[5] When the pulmonary artery catheter is in a wedged position[5,15] or has a clot over the thermistor,[16] the thermal curve has a delayed appearance time, a lower peak height, and a prolonged decay. Curves of this type are difficult to analyse and may create error. Bjoraker[16] found a small decrease in calculated CO when a clot surrounded the thermistor.

When using a commercial computer for thermodilution CO, an average of three measurements are recommended.[6] Even with three measurements previous studies indicate there must be more than a 12–15 per cent change in CO before it can be considered clinically significant.

Accuracy in pathologic conditions

To be accurate, measurements of CO by thermodilution must meet these conditions: no loss of indicator between the point of introduction and sensing and absence of recirculation.

Since there is recirculation in the presence of left to right shunts, the exponential downslope of the thermodilution curve will be interrupted by a deflection, corresponding to recirculation via the shunt. The larger the shunt, the earlier will be the interruption by recirculation[17] (Figure (b, c)). In unidirectional left to right shunt, the extrapolation of the first part of the downslope of the curve will represent the pulmonary blood flow minus the shunt blood (Figure (b), area A). The total area under the curve will represent the total pulmonary blood flow including shunt. This represents the right sided CO and will overestimate the left sided forward CO. The ratio of the total area of the curve (A + B) to the area of the first portion of the curve (A) should be an index of the pulmonary blood flow to systemic blood flow ratio.[17] If the thermodilution curve is not displayed we may miss the fact that a left to right shunt exists. With many computers the cut off point may exceed area A and so lead to an inaccurate cardiac output calculation. When a patent ductus

arteriosus is present, the thermistor should be located distal to the shunt; to allow adequate mixing and include the shunt fraction.[17]

In presence of a right to left shunt, some of the indicator reaches the aorta without passing the thermistor. This gives spuriously high values for CO.[18]

In cases of pulmonary valve insufficiency, the shape of the thermodilution curve is changed, the indicator is mixed with a larger volume of blood and the transit time of indicator is prolonged – resulting in a smaller peak and slower return to baseline (Figure (d)).[19] Thermodilution curves are prolonged with pulmonary insufficiency, but CO is measured accurately using thermodilution since the areas under the curves before and after pulmonary insufficiency are the same.[19] However, there will be times when pulmonary insufficiency is associated with such a low CO that accurate determination of the area under the curve is not possible. In this setting CO may be over- or underestimated. The display of a low peak and prolonged thermodilution curve may indicate cardiac output determinations are not accurate.

In tricuspid regurgitation, measurement of CO by thermodilution in 16 patients was not accurate when compared with the Fick method.[20] Thermodilution both under- and overestimated CO by the Fick principle.

In low CO states, the appearance time of the thermal curve is delayed and the decay is prolonged. This creates a potential for error because (a) the recirculation of indicator before the computed analysis is complete, and (b) loss of thermal indicator may become significant. These sources of error may explain the divergent thermodilution CO results found at low CO. Norris *et al.*[21] found *in vitro* thermodilution CO accurate below 1 $L \cdot min^{-1}$. Freed *et al.*[18] accurately measured thermodilution outputs as low as 1.4 $L \cdot min^{-1}$ in paediatric patients. In adults Hillis *et al.*[22] observed a good correlation between Fick and thermodilution values at outputs less than 2 $L \cdot min^{-1}$. Moodie *et al.*[23] found at CO less than 2 $L \cdot min^{-1}$ thermodilution was not accurate in paediatric patients when compared to the Fick method. However, they assumed an oxygen consumption rather than measuring it.

Patients with extremely low CO are likely to be the ones who depend the most upon accurate invasive haemodynamic monitoring. Unfortunately the potential for error at low CO seems large. Clinical errors should be reduced by observing (a) the thermodilution curve to tell if there is a low flow state and (b) changes in clinical parameters.

Cardiac output indices

The calculation of indices that utilize CO (e.g., systemic vascular resistance (SVR), pulmonary vascular resistance (PVR)) will also depend on the accuracy of the CO determination. If the CO is falsely high then the calculated SVR will be falsely low, suggesting vasodilation.

The clinical message must remain: don't be mislead by these calculations, always evaluate the clinical status of the patient (e.g., peripheral perfusion and urinary output).

References

1 Understanding hemodynamic measurements made with the Swan-Ganz catheter. American Edwards Laboratories California. 1–32.

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

3 *Phillips CM, Davila JC, Sanmarco ME.* Measurement of cardiac output thermal dilution. II. A new computer for rapid convenient determinations. Med Res Eng 1970; 9: 25–9.

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

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

6 *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.

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

8 *Powner D.* Thermodilution technique for cardiac output. N Engl J Med 1975; 293: 1210–1.

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

10 *Ellis R, Gold J, Rees R, Lillehei W.* Computerized monitoring of cardiac output by thermal dilution. JAMA 1972; 220: 507–11.

11 *Goldberg M, Michail S, Niswander D.* An unusual source of error. Anesth Analg 1985; 64: 652.

12 *Sprung CL, Rackow EC, Avetta JM.* Direct measurement and derived calculation using the pulmonary artery catheter. *In*: Sprung Cl, ed. The pulmonary artery catheter: methodology and clinical applications. Baltimore: University Park Press 1983: 105–40.

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

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

15 *Fisher A, Benis A, Jurado R, Seely E, Terstein P, Litwak S.* Analysis of errors in measurement of cardiac output by simultaneous dye and thermal dilution in cardiothoracic surgical patients. Cardiovasc Res 1978; 12: 190–9.

16 *Bjoraker D, Ketcham T.* Catheter thrombus lowers cardiac output determinations by thermal dilution. Anesthesiology 1982; 57: A155.

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

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

19 *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.

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

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

22 *Hillis L, Firth B, Winniford M.* Analysis of factors affecting the variability of Fick versus indicator dilution measurements of cardiac output. Am J Cardiol 1985; 56: 764–8.

23 *Moodie D, Feldt R, Kaye M, Strelow D, VanDerHagen LJ.* measurement of cardiac output by thermodilution: development of accurate measurements at flows applicable to the pediatric patient. Surg Res 1978; 25: 305–11.