Cardiac Output Measurement by Thermal Dilution

Reproducibility and Comparison with the Dye-Dilution Technique

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Cardiac output estimates by the principle of thermodilution (CO_{th}) was compared with dye-dilution estimates (CO_{dye}) in pigs. For CO_{th} estimates a Swan-Ganz 7 F floating thermodilution catheter and a 9500 Edwards Computer®, were used. The CO_{dye} estimates were obtained by the apparatus constructed by Zijlstra and Mook. The effect of the thermistor position in the pulmonary artery on the CO_{th} estimates was also investigated. The reproducibility of CO_{th} was examined by duplicate determinations. Based on 101 simultaneous estimates of CO_{th} and CO_{dye} the correlation was found $CO_{th} = 1.020\ CO_{dye} + 0.2378$, $r = 0.971$ for cardiac outputs between 0.65 l/min and 11 l/min. For 111 duplicate determinations of CO_{th} between 2 and 9 l/min the coefficient of variation was 4.74%. The thermistor position in the pulmonary artery had no influence on the CO_{th} estimates provided an undamped pressure curve could be monitored from the tip of the catheter. Cardiac output can thus be measured rapidly with good accuracy also for low values by means of a blindly inserted thermistor catheter positioned without x-ray control and a computer with digital display.

KNOWLEDGE of the cardiac output is useful in monitoring the circulation of the critically ill patient, especially if repeated information can be obtained speedily and easily, causing the least possible interference with treatment or nursing of the patient. In this laboratory the dye-dilution technique (CO_{dye}) has been used for the past 10 years. The accuracy and reproducibility of this method is well known[9,15,17,18] and for a long time it has been accepted as a method of reference as reliable as the Fick method over a wide range of clinical conditions.[14] It is however rather laborious, requires insertion of an arterial catheter and is not very accurate at low output stages.[17] Measurement of cardiac output by thermal dilution (CO_{th}) is easy to perform and can be repeated almost without limitations at very short intervals. This is especially so when the floating Swan-Ganz thermodilution catheter is used in combination with a cardiac output computer. The catheter allows injection of the cold charge as well as registration of the subsequent temperature changes in the pulmonary artery. The computer presents the cardiac output figure in less than 40 seconds, thus allowing one determination per minute. The purpose of this report is to determine the reproducibility of the CO_{th} estimates, to investigate the extend to which the site of the thermistor in the pulmonary artery affects the estimates and to determine the measure of agreement between CO_{dye} and CO_{th}. Several reports deal with the agreement of the two methods[1,6,13] they are however mainly concerned with the agreement in the normal and high ranges. As cardiac output estimates in the clinic are often of special interest at low output stages, when errors of measurement for CO_{dye} as mentioned are considerable, the present experimental study was designed to deal also with comparison of the two methods at low outputs.

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Method

The thermodilution principle as introduced by Fegler[2-4] is based on the injection of a quantified cold charge and registration of its dilution i.e. the subsequent change in temperature of the blood at a point further on in the direction of the blood stream. As heat unlike dye will mix well irrespective of laminar flow in the blood vessels, the thermoindicator can be injected into the right atrium and the temperature registered in the pulmonary artery. From the area under the recorded dilution curve CO_{th} is

derived according to the *Steward-Hamilton* equation[8] modified to calculate cardiac output by thermodilution.

$$CO_{th} = \frac{V_I \cdot (T_B - T_I) \cdot S_I \cdot C_I \cdot K \cdot 60}{S_B \cdot C_B \cdot \int_0^\infty \Delta T_B(t)dt} \quad (1)$$

where V_I is the volume of injectate in ml; T_B and T_I are the temperatures of the blood in the right atrium and of the injectate arriving into the blood stream, respectively. S_B and S_I are specific gravity, C_B and C_I specific heat of respectively blood and injectate. When 5% dextrose is used as indicator we have:

$$\frac{S_I \cdot C_I}{S_B \cdot C_B} = 1.08$$

For the loss of indicator by transit of the cold solution through the catheter into the right atrium a correction factor is introduced:

$$K = \frac{T_b - T_m}{T_b - T_I}$$

where T_b is blood temperature, T_m is the mean temperature of indicator leaving the catheter tip and T_I the temperature of injectate immediately prior to injection. For the present Swan-Ganz® 7 F catheter, according to the manufacturer* K = 0,827, when 10 ml of 5% dextrose at 0 C is injected rapidly into the catheter. K has been found almost independent of injection time and the length of the catheter placed intravascularly.[5] When the known values have been inserted in equation (1), we have:

$$CO_{th} = \frac{10 \cdot 1.08 \cdot (T_B - T_I) \cdot 0.827 \cdot 60}{\int_0^\infty \Delta T_B(t)dt} \quad (2)$$

or

$$CO_{th} = \frac{53.6 \cdot (T_B - T_I)}{\int_0^\infty \Delta T_B(t)dt} \quad (3)$$

From this equation cardiac output is calculated by a small battery driven computer* by digital display showing the actual cardiac output between 1.5 l and 10 l per minute. A thermodilution curve also can be recorded from the computer; this was done by a Servograph®. The value 53.6, called the computation factor, is fed into the computer, and corresponds to a constant voltage in the computer, not to be changed unless the factor is changed. As there are certain limits to the size of the values the computer can handle, the computation factor must be altered for very low and for very high outputs. For CO_{th} lower than 1.5 l the computation factor has to be increased by 3/2 and the computed CO_{th} accordingly to be multiplied by 2/3 to give the actual CO_{th}, conversely for cardiac outputs higher than 10 l the computation factor must be reduced by 2/3 and the computed output consequently multiplied by 3/2. With the computation factor set, it will be necessary before each measurement only to feed the computer with the temperature difference between blood and indicator, and the desired computation time. This can be varied at intervals of 5 sec between 5–35 sec, and is adjusted to include the downslope of the recorded temperature curve just beyond the point where it becomes indistinguishable from the base line.

As a thermo-indicator was used 10 ml 5% dextrose injected at a temperature between 0 C and 2 C. Tricarbocyanin (Cardiogreen®) was used as a dye-indicator, the dye-curve being registered by the apparatus of Zijlstra and Mook.[19] Through the thermodilution catheter 0.2 ml of the dye was injected into the right atrium, the cold charge being used to flush the catheter. Blood for registration of the dye curve was continuously sampled at a rate of 0.4 ml per second from a catheter in the carotid artery. CO_{dye} was calculated by planimetry of the dye-dilution curve. As to the part of the investigation concerned with the influence of catheter position on the CO_{th} estimate an electromagnetic square-wave flowmeter (Nycotron®) was employed to ensure a constant cardiac output while CO_{th} measurements were carried out with the catheter in different positions.

Procedure

Eight pigs weighing from 68 kg to 72 kg were anesthetized with halothane and nitrous oxide. After injection of d-tubocurachloride intubation was carried out and they were ventilated with a Bird® ventilator. With the animal in supine position the neck vessels were exposed on the right side. A Swan-Ganz 7 F catheter was introduced under pressure registration through the jugular vein to the pulmonary artery. For arterial sampling and pressure recording a catheter was introduced into the carotid artery. The neck incision was closed, leaving approximately 60 cm of the Swan-Ganz catheter intracorporally. Rectal temperature was considered representative for the blood temperature. The reproducibility of the thermodilution estimates was determined on two of the pigs. A preliminary CO_{th} estimate was carried out to allow determination of the optimal computation time from the length of the recorded thermo-dilution curve. Double determinations were then carried out within less than 2 minutes. During the few seconds of manual indicator injection the ventilator was stopped and the animals were apneic. To prevent cold indicator loss to the catheter, withdrawal of 1 ml blood into the syringe immediately succeeded the injection. After determination of the basal cardiac outputs the pigs were hypo-

* Edwards Laboratories: The Edslab. Thermodilution catheter and 9500 Edwards cardiac output computer.

ventilated and the ensuing rising outputs were recorded. Under following normoventilation the animals were subsequently bled slowly into hypovolaemic shock, while the declining outputs were recorded. On the assumption that errors of method and instrumentation are normally distributed the variance is calculated as:

$$S^2 = \frac{1}{2n} \cdot \sum_{1}^{n} d^2,$$

where d is the difference between two double estimates and n is the number of observations. The *t-test* for pair samples was applied to assess the significance of any difference between first and second measurement.

Simultaneous CO_{th} and CO_{dye} estimates were carried out in 4 pigs prepared as described above. Injections of both indicators together were made manually in less than 5 seconds. In order to investigate whether the site of the thermistor in the pulmonary artery influenzed the CO_{th} estimates, median sternotomy was performed in two pigs and an 18 mm electromagnetic flow probe (Nycotrom^R) was fitted around the pulmonary trunk. Pulmonary artery flow was recorded in order to ascertain a stable cardiac output during measurements with the cathether in two different positions. Due to difficulties in obtaining a zero reading for a flow probe on the pulmonary artery absolute values have not been considered for the electromagnetic measurements. Initially the extend to which the catheter influenzed the electromagnetic field was studied. Then during constant pulmonary artery flow CO_{th} was measured first with the tip of the Swan-Ganz catheter in the pulmonary trunk controlled by digital palpation, then with the tip advanced to the most peripheral position allowing an undamped pulmonary artery pressure curve to be recorded. The difference between the two positions of the catheter was approximately 8 cm. All determinations were duplicate. These measurements were also carried out at different levels of cardiac output obtained as above described by hypoventilation and slow bleeding respectively.

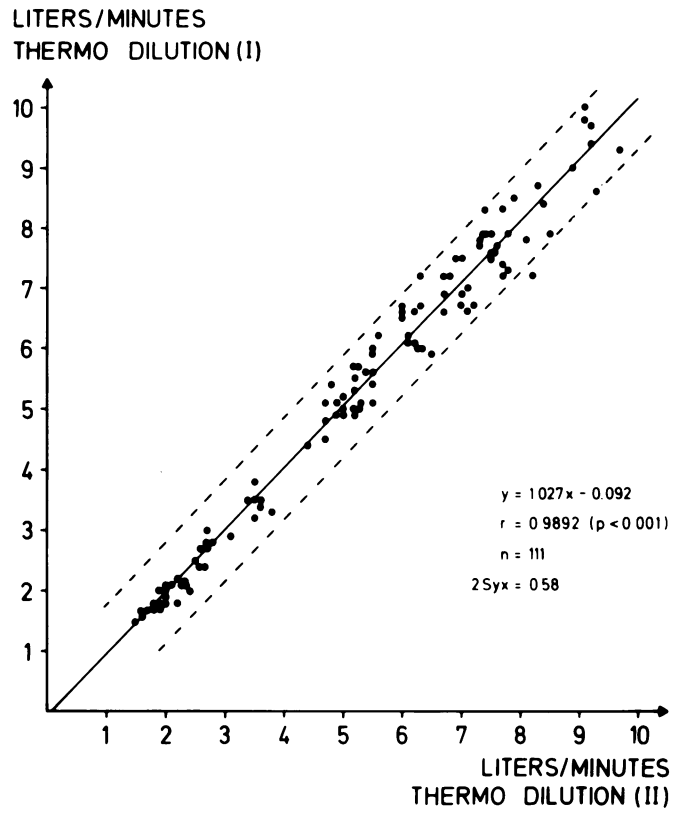

FIG. 1. The reproducibility of CO_{th} estimates in pigs. 111 double estimates, each set performed within 2 minutes.

Results

For 111 double determinations of CO_{th} no significant difference was found between the first and the second measurement completed within 2 minutes from the first injection (Fig. 1). The material has been divided into 6 subgroups according to the size of CO. As seen from Table 1 the coefficient of variation between measurements does not exceed 5.45% in any of the subgroups and for the whole series amounts to 4.74%. Correspondingly the 99% confidence limit does not exceed 10.6% for CO_{th} between 2 l/min and 9 l/min. Whether or not the Swan-Ganz catheter interfered with the elec-

TABLE 1. *Reproducibility of Cardiac Output (CO) Determination Calculated from 111 Double Measurements*

CO (l/min)	n	$\bar{x}$	s	$\frac{s \cdot 100}{\bar{x}}$	95% limit		99% limit	
					liter	% of $\bar{x}$	liter	% of $\bar{x}$
1.5–2.99	29	2.17	0.1181	5.45	0.1708	7.9	0.2302	10.6
3.00–4.99	14	4.13	0.1627	3.94	0.2468	6.0	0.3425	8.3
5.00–5.99	18	5.35	0.2355	4.40	0.3498	6.5	0.4793	9.0
6.00–6.99	19	6.53	0.2911	4.46	0.4308	6.6	0.5889	9.0
7.00–7.99	21	7.63	0.2977	3.90	0.4378	5.7	0.5960	7.8
8.00–10.01	10	9.00	0.3788	4.20	0.5968	6.6	0.8489	9.4
All CO	111	5.32	0.2526	4.74	0.3539	6.7	0.4601	8.6

Number of observations (n). Standard deviation of the mean (s). Coefficient of variation $\frac{s \cdot 100}{\bar{x}}$ · 99 per cent limit $\left(\frac{s}{\sqrt{2}} \cdot t_n\right)$.

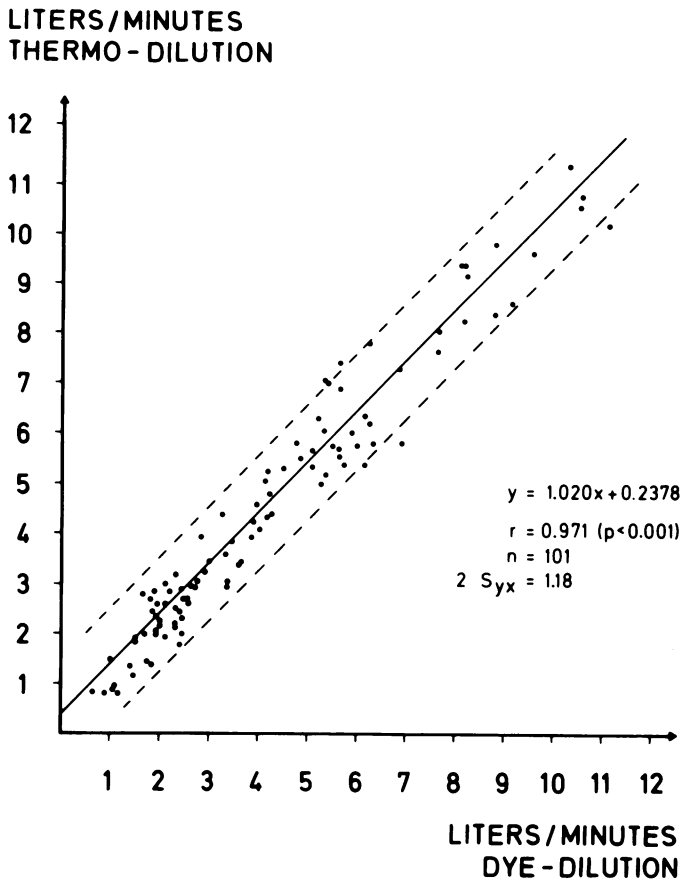

FIG. 2. Simultaneous CO_{th} and CO_{dye} estimates in pigs. The results of 101 measurements.

tromagnetic measurements was examined for flows ranging from 0.84 l/min to 8.16 l/min, 18 sets of measurements were carried out, each comprising duplicate determinations with, respectively without the catheter under the flow probe. The difference was 0.118 l/min ranging from + 0.256 l/min to − 0.030 l/min ($P > 0.05$). Thus no significant difference could be demonstrated between electromagnetic flow measurements with and without the catheter under the flow probe.

To test whether the site of the thermistor in the pulmonary artery affects the estimation of CO_{th}, 21 sets of CO_{th} measurements were taken of flows ranging from 1.46 l/min to 6.31 l/min as measured by the electromagnetic flowmeter. Each set of measurements comprised duplicate determinations of CO_{th} and electromagnetic flow with the catheter tip in the pulmonary trunk (CO_{th} central) as well as peripherally (CO_{th} peripheral) in the artery respectively. No significant change in cardiac output took place between measurements of CO_{th} with the catheter in the two different positions. The difference CO_{th} peripheral-CO_{th} central between the mean values of the duplicate thermal dilution determinations was 105 ml, ranging from +210 ml to −420 ml ($P > 0.05$). Thus no significant differences could be demonstrated between CO_{th} determined with the catheter in a central and in a peripheral position in the pulmonary artery, provided an undamped pulmonary artery pressure curve was observed.

The CO_{th} and CO_{dye} estimates were compared from 101 simultaneous measurements carried out on 4 pigs with 15 to 35 determinations for each animal. Cardiac outputs expressed as CO_{th} ranged from 0.65 l/min to 11.4 l/min (Fig. 2). Linear regression analysis yielded the equation: $CO_{th} = 1.020\ CO_{dye} + 0.2378$. The coefficient of correlation between the two estimates was $r = 0.971$. The intersection of the regression line on the Y-axis (CO_{th}) seems to differ from zero ($0.02 < P < 0.05$). The mean values of the estimates were $CO_{th} = 4.519$ l/min and $CO_{dye} = 4.198$ l/min respectively, the mean difference being $CO_{th} - CO_{dye} = 0.321$ l/min (SD = 0.056). For cardiac outputs about 4 l/min. CO_{th} is thus estimated 7.7% higher than is CO_{dye}.

Discussion

The great advantages of the thermal dilution method over other methods for estimation of the cardiac output are the simplicity of the operational procedure, the almost unlimited number of observations allowed and especially compared with the dye-dilution technique, that no arterial catheter is needed.

Loss of the indicator outside the blood stream constitute the most serious error of the thermal dilution technique. The correction factor C = 0.827 implies that about 17% of the cold charge of 10 ml 5% glucose at 0 C will be lost under optimal conditions before the injectate leaves the catheter. Any delay in handling the syringe after its removal from the ice water bath will increase the extracorporeal indicator loss unaccountably. Such risks may be avoided by injecting the indicator at room temperature. This however decreases the sensitivity of the method by 2–3 times, necessitating a corresponding increase in volume of the injectate.[16] Included in the indicator loss corrected for is the amount contained in the catheter at the end of the injection and subsequently removed by withdrawal of blood into the catheter. Leaving the injectate in the catheter causes additional cooling of the blood by conduction across the wall of the catheter. The time lag before equilibrium has been reached between blood and catheter will delay the return of the downslope of the thermal curve to the base line, resulting in an ill-defined tail.

The temperature of pulmonary artery blood shows variations with the heart rate as well as with the respiratory rate. Especially frequencies in the respiratory range are clearly seen on the base line during work and may well make the interpretation of a baseline for calcula-

tion of the dilution area more difficult. Olsson et al.[10] stress the importance of a steady state including avoidance of movements and deep-breaths. They also point out that the return of cold venous blood resulting from raising of an extremity may give a decrease in temperature of the pulmonary artery blood of the same order of magnitude as the thermodilution curve itself. A more stable base line is obtained if thermal dilution is registered from the aorta. On the other hand highly unreliable estimates will result if the thermal indicator has to traverse pathological lungs as pointed out by Pavek et al.[11] The particular influence of all these possible sources of error can be estimated only in well controlled model experiments from which on the other hand little can be deducted about their combined effect on the accuracy and reproducibility of the CO_{th}-estimates under clinical conditions.

In the surgical clinic the main indication for repeated cardiac output estimates will be low and/or unstable output states in the severely ill patient or the patient subjected to major surgery. The experimental condition of this study answers well to this description. It should be especially noted that cardiac output, except for the basal values, were too unstable both under hypoventilation and bleeding of the animal to allow an evaluation of the reproducibility of the dye dilution method which requires steady state for well defined 5 minute periods.

With a coefficient of variation not exceeding 5.45% for outputs down to 1.5 l/min, the reproducibility of the thermal dilution estimates in animals of approximately 70 kg compares favorably with clinical results obtained by the dye dilution method. Wiberg-Jørgensen et al.[17] found thus, in a series of patients subjected to cardiac surgery, during steady states, coefficients of variations for double dye estimates between 7 and 26% corresponding to cardiac indices between 4.0 and 0.92.

It is of great importance for the clinical use of the method that no significant difference could be demonstrated between thermal dilution estimates obtained with the catheter in the pulmonary trunk and with the catheter as far out in the artery for an undamped pressure curve still to be obtained.

The simultaneous thermal and dye-dilution estimates showed a good correlation between the two methods over a wide range of outputs from 0.65 l/min to 11.4 l/min. Cardiac output determined by thermal dilution is however higher than by the dye method. The equal distribution of observations over the whole range covered allows the difference to be expressed as the difference between mean values. This calculated CO_{th} yields 7.7% higher values than does CO_{dye}. This is in accordance with the observation of Jose et al.[7] and Rahimtoola and Swan[12] who in normal subjects found cardiac output determined 7% higher with left atrial or left ventricular injection than with pulmonary artery injection. Also Wiberg-Jørgensen et al.[17] found cardiac output underestimated by 5% using right atrial injection compared with estimates from left-sided injection during operations for valvular disease. As discussed by these authors the underestimation in right sided injection is due to the early recirculation of dye particles from the coronary circulation.

Though inference between clinical and experimental series should be drawn with caution, it seems reasonable to conclude that thermal dilution estimates of cardiac output are not only highly reproducible but also more accurate than estimates from dye-dilution curves in the lower flow ranges and during unstable flow conditions. Considering the nature of the dilution curves this should also be expected: whereas the dye curve becomes more flat and ill defined at low outputs, the thermal curve becomes steeper and covers a larger area, allowing a more accurate estimate either by computation or planimetry.

While a detailed analysis of methodological and instrumental errors of a thermal dilution system is hardly practicable in a clinical laboratory, the overall reliability of any commercial equipment should always be evaluated against an accepted reference method. If a thermodilution system compares favorably in the flow range best suited to the reference method it should offer advantages over other methods in low flow ranges.

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