Cardiac output measurement in critically ill patients: comparison of continuous and conventional thermodilution techniques

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The purpose of the study was to compare cardiac output (CO) measurement by continuous (CTD) with that by conventional thermodilution (TD) in critically ill patients. In 19 of 20 critically ill patients requiring a pulmonary artery catheterism, 105 paired CO measurements were performed by both CTD and TD. Regression analysis showed that: CTD CO = 1.18 TD CO − 0.47. Correlation coefficient was 0.96. Bias and limit of agreement were − 0.8 and 2.4 L · min^{-1}, respectively. When a Bland and Altman diagram was constructed according to cardiac index ranges, biases were −0.2 and −0.3 and −0.8 L · min^{-1} · m^{-2} and limits of agreement were 0.3, 0.7 and 1.6 L · min^{-1} · m^{-2} for low (<2.5 L · min^{-1} · m^{-2}), normal (between 2.5 and 4.5 L · min^{-1} · m^{-2}) and high (>4.5 L · min^{-1} · m^{-2}) cardiac indexes, respectively. It is concluded that CTD, compared with TD, is a reliable method of measuring CO, especially when cardiac index is ≤4.5 L · min^{-1} · m^{-2}.

Cette étude avait pour but de comparer les mesures du débit cardiaque réalisées par thermodilution continue (CTD) par rapport à la thermodilution classique (TD) chez des patients de réanimation. Cent cinq paires de mesures du débit cardiaque ont été comparées chez 19 des 20 patients de réanimation inclus dans l'étude. L'équation de la droite de régression est CTD CO = 1,18 TD CO − 0,47. Le coefficient de corrélation s'élève à 0,96. L'erreur moyenne et l'intervalle de confiance sont respectivement de −0,8 et 2,4 L · min^{-1}. En réalisant un diagramme de Bland and Altman selon le niveau d'index cardiaque, les erreurs moyennes s'élèvent à −0,2, −0,3 et −0,8 L · min^{-1} · m^{-2} et les intervalles de confiance à 0,3, 0,7 et 1,6 L · min^{-1} · m^{-2}, respectivement pour les index cardiaques bas (<2,5 L · min^{-1} · m^{-2}), normaux (entre 2,5 et 4,5 L · min^{-1} · m^{-2}) et hauts (>4,5 L · min^{-1} · m^{-2}). La thermodilution continue, comparée à la thermodilution classique, est une méthode fiable pour le monitorage du débit cardiaque surtout pour les index cardiaque ≤4,5 L · min^{-1} · m^{-2}.

Key words
INTENSIVE CARE;
MEASUREMENT TECHNIQUES;
CARDIAC OUTPUT.

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Thermodilution is widely used in the Intensive Care Unit to measure cardiac output (CO).[1,2] Cardiac output is measured using injections of cold or room temperature saline. However, a strict technique is required to avoid errors and misinterpretations in data collection that could lead to hazardous mistakes in decision making.[3,4] Moreover, continuous CO monitoring is not possible with conventional thermodilution (TD), especially in the most critically ill patients in whom CO changes occur with no heart rate and/or blood pressure alterations.[5] Cardiac output monitoring using continuous thermodilution (CTD) has been available since 1990.[6] A pulmonary artery catheter is modified to place a 10 cm thermal filament in the right ventricle. This filament continually transfers a safe level of heat directly into blood according to a pseudorandom binary sequence. The temperature alter-

ation is detected downstream in the pulmonary artery and cross-correlated with the input sequence to produce a thermodilution wash-out curve. Cardiac output is computed from a conservation of heat equation using the area under the curve. Every 30 sec, the computer displays an updated CO value, reflecting the average flow of the previous three to six minutes. Yedelman *et al.* showed that continuous thermodilution is a reliable technique in clinical practice.[7] However, few studies have been reported by other authors in critically ill patients.[8,9] The aim of the present study was to compare CO obtained by continuous thermodilution versus conventional thermodilution in critically ill patients.

Methods

After approval of the local ethics committee, 20 consecutive patients requiring a pulmonary artery catheterism were enrolled in the study. Patients <18 yr of age, those having arrhythmia, tricuspid regurgitation or intracardiac shunt were excluded. A pulmonary artery catheter (Intellicath™ CCO/VIP, Baxter Healthcare Corporation, Edwards Critical-Care Division, Irvine, CA) was inserted in the conventional manner and its correct position was confirmed by chest radiography. This catheter allows CO measurement by both continuous thermodilution and conventional thermodilution but continuous thermodilution has to be interrupted to perform bolus injections. Before each paired CO measurement, we verified that continuous CO monitoring showed a steady CO value at least for five minutes. Then, continuous thermodilution CO monitoring was stopped and conventional thermodilution CO measurements were performed by injections of 10 ml cold saline solution, regardless of the respiratory timing. After each injection, a 30 sec pause was observed to avoid cold recirculation. Measurements with irregular temperature curves suggesting an irregular bolus injection or a premature cold recirculation were discarded.[3] The thermodilution CO value was the mean of the first four measurements without artefacts temperature curves and was usually obtained within five minutes. Continuous CO monitoring was then recorded and at least ten minutes were allowed until continuous CO monitoring showed a new stable CO value. The continuous thermodilution CO value was defined as the mean of the two values recorded before and after the sequence of bolus injections.[7] This value was excluded when continuous CO monitoring was not stable before and after bolus injections and when the values recorded before or after bolus injections differed by ≥10% because an alteration of CO was suspected during the paired measurement period. Five to six paired measurements were performed per patient.[10,11] The CO computer was also used to calculate cardiac index (CI) and other haemodynamic variables. Cardiac output measurements were achieved during the first six hours of the pulmonary artery catheter use when different treatments (volume loading, vasoactive and/or inotropic drugs, determination of best PEEP) were applied to improve patient's status. Moreover, an interval of least 30 min was observed between each paired measurement to be sure that the alteration of therapeutic action was effective and continuous CO monitoring was stable.

To compare continuous and conventional thermodilution methods, we used a linear regression analysis, determination of Pearson's correlation coefficient and the Bland and Altman method.[10–12] A Bland and Altman diagram was also constructed according to the ranges of CI. Cardiac index was defined as normal for values between 2.5 and 4.5 $L \cdot min^{-1} \cdot m^{-2}$, low for values <2.5 $L \cdot min^{-1} \cdot m^{-2}$ and high for values >4.5 $L \cdot min^{-1} \cdot m^{-2}$.[13]

Results

Twenty patients undergoing pulmonary ventilation were enrolled in the study. No complications occured during the use of the pulmonary artery catheter. Tricuspid regurgitation was diagnosed by echocardiography-Doppler in a chronic obstructive pulmonary disease patient who was excluded from the study. Comparisons were achieved in 19 patients (12 female and 7 male; age = 61 ± 15 yr; weight = 69 ± 18 kg; height = 163 ± 8 cm). Underlying diseases were septic shock (n = 8), acute respiratory distress syndrome (n = 3), haemorrhagic shock (n = 2), cardiogenic shock (n = 2) and miscellaneous diseases (n = 4). Four paired measurements were excluded because a change >10% in CO was observed during the measurement period. Thus, 105 paired measurements were analysed.

CO comparisons

Cardiac output values ranged from 2.1 to 17.8 $L \cdot min^{-1}$ and from 2.1 to 14.6 $L \cdot min^{-1}$ for continuous thermodilution and conventional thermodilution, respectively. Pearsons correlation coefficient (r) was 0.96. Linear regression equation was: CTD CO = 1.18 TD CO − 0.47 (Figure 1). CO was greater with continuous thermodilution than with conventional thermodilution. Bias and limit of agreement were −0.8 and 2.4 $L \cdot min^{-1}$, respectively (Figure 2).

Bland and Altman diagram according to cardiac index range

Biases were −0.2, −0.3 and −0.8 $L \cdot min^{-1} \cdot m^{-2}$ for low, normal, and high CI, respectively. Limits of agreement were 0.3, 0.7 and 1.6 $L \cdot min^{-1} \cdot m^{-2}$ for low, normal, and high CI, respectively (Figure 3.).

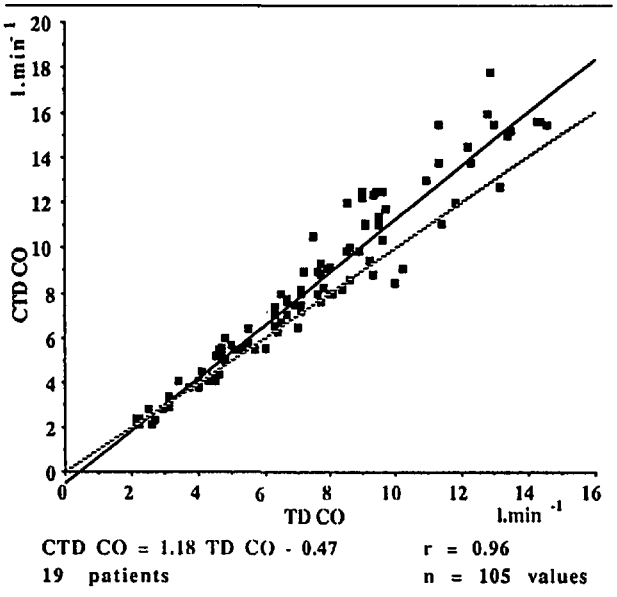

FIGURE 1 Regression analysis and Pearson's correlation coefficient for cardiac output. TD: conventional thermodilution. CTD: continuous thermodilution. CO: cardiac output. Dotted line: identity line.

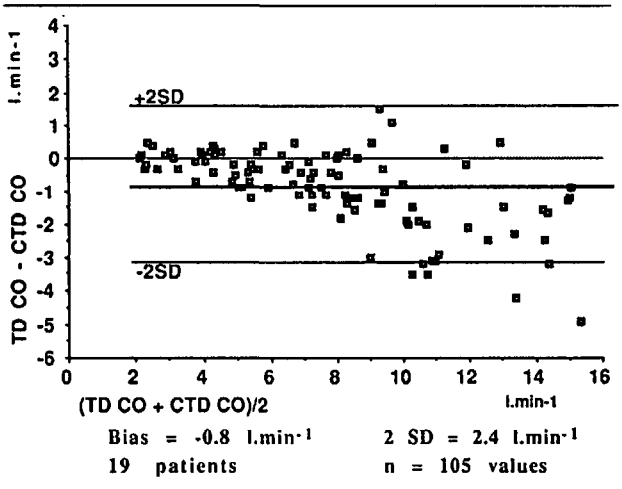

FIGURE 2 Bland and Altman diagram for cardiac output. TD: conventional thermodilution. CTD: continuous thermodilution. CO: cardiac output.

Discussion

In the present study, comparison of the two methods of CO measurement showed that the CO value was greater with continuous thermodilution than with conventional thermodilution. Indeed, the bias was -0.8 L · min^{-1} whereas the limit of agreement was 2.4 L · min^{-1}. The overall inaccuracy and unreliability of continuous thermodilution compared with conventional thermodilution could be explained by a high proportion of high CO values. When cardiac index was >4.5 L · min^{-1} · m^{-2},

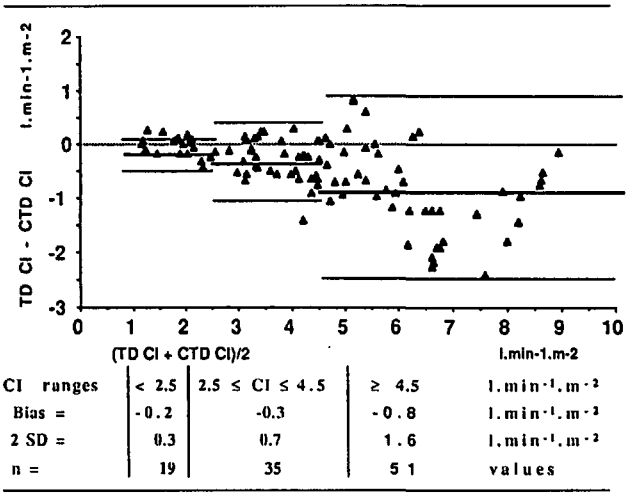

FIGURE 3 Bland and Altman diagram according to cardiac index range. TD: conventional thermodilution. CTD: continuous thermodilution. CI: cardiac index.

a large discrepancy between the two methods was observed (bias = -0.8 L · min^{-1} · m^{-2}, limits of agreements = 1.6 L · min^{-1} · m^{-2}). These high levels of cardiac index are explained because most patients had septic shock or acute respiratory distress syndrome ($n = 11$).

To compare continuous thermodilution with conventional thermodilution, we used the Bland and Altman method.[12] Moreover, the same number of paired CO measurements per patient was performed.[10,11] The main problem was to define the continuous CO value. We averaged the values displayed before and after bolus injections as did Yedelman *et al.*[7] However, we ruled out paired CO measurements in which continuous CO was not stable or in which a CO alteration could occur during bolus injection (difference between continuous CO values before and after bolus injections >10%). We did not conduct a double-blind study because the continuous CO value was always displayed by the computer, independent of the operator.

The present study is in contradiction with the previous studies published by Yedelman *et al.* (bias = 0.02 L · min^{-1}, limits of agreements = 1.05 L · min^{-1})[7], Boldt *et al.* (bias = 0.03 L · min^{-1}, limits of agreements = 1.04 L · min^{-1})[8] and by Jakobsen *et al.* (bias = 0.31 L · min^{-1}, limits of agreements = 1.69 L · min^{-1}).[9] However, Siegel and Pearl recently reported a large difference in high CO values.[14] The differences between continuous and conventional thermodilution methods among these studies could be explained by the principle of thermodilution and by the variability of cardiac output during respiratory cycle. Thermodilution is based on the principle of indicator-dilution method.[1-3] The injection of a known amount of a cold or warm solution (for conventional ther-

modilution and continuous thermodilution, respectively) into the right atrium for TD or into the right ventricle for CTD is detected distally by the thermistor located near the tip of pulmonary artery catheter. CO is determined from the following equation:

$$CO = V_I \cdot (T_B - T_I) \cdot K_1 \cdot K_2 / \int T_B(t)dt$$ [3]

where V_I is injectate volume, T_B is blood temperature, T_I is injectate temperature, K_1 is the product of specific heat and specific gravity of the injectate divided by the product of the 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.[3,15] $\int T_B(t)dt$ corresponds to the area under the thermodilution curve. Thus, every cause of error in the different components of this equation leads to an error in CO value. $V_I \cdot (T_B - T_I) \cdot K_1 \cdot K_2$ represents the quantity of coldness injected into the right atrium. Errors concerning V_I and K_1 are unlikely because we used a ten milliter syringe and a thermistance on the proximal port of pulmonary artery catheter. Conversely, K_2 could vary with the proportion of the catheter inside and outside the patient, the site of insertion and patient's morphologic parameters. Thus, K_2 is not strictly constant and accurate, especially for conventional thermodilution. By contrast, continuous thremodilution directly releases heat into the right ventricle by a thermal filament located 20 to 30 cm from the tip of the catheter. In this way, theoretically, no heat loss could occur. Errors in $\int T_B(t)dt$ depends on the sensitivity of the distal thermistance. Because the CO value is a hyperbolic function of the area under the thermodilution curve, the smaller the area under the curve, the larger the error in the formula.[3] All causes that reduce the area under the curve would enhance the error. In ewes, Renner *et al.*[16] compared the accuracy and the reproductibility of CO measurement by conventional thermodilution with that from an electromagnetic flowmeter. The authors concluded that the reproductibility was impaired when the heat indicator was reduced (bolus performed with 5 ml or with room temperature solution) and when CO range increases. This could explain why Sasse *et al.*[5] found that the standard deviation increased when the conventional thermodilution CO value increased (a phenomenon called heteroscedasticity). Although the injections were performed in this study at end expiration, it could be supposed that there was also heteroscedasticity when injections were performed asynchronously with ventilation. This explains the increase in standard deviation when cardiac index was >4.5 $L \cdot min^{-1} \cdot m^{-2}$. In studies published by Yedelman's *et al.*[7] and by Jakobsen *et al.*,[9] few CO measurements were >8 $L \cdot min^{-1}$. That could explain smaller biases and limits of agreement than in this study. By contrast, in the study reported by Siegel and Pearl,[14] more CO values were >8 $L \cdot min^{-1}$. Other factors that may alter the area under the curve lead to enhance the error in high CO values. Using Flick and conventional thermodilution methods in pigs, Jansen *et al.*[17,18] have shown that timing of injection during the respiratory cycle alters CO measurement. These authors confirmed this in mechanically ventilated critically ill patients.[19] Using echocardiography, Jardin *et al.*[20] demonstrated that right ventricle stroke volume changed according to respiratory timing. Indeed, random injections in the respiratory cycle lead to errors in CO estimation. This error is decreased when injections are spread equally over the respiratory cycle or when the number of random injections increases.[18] In the present study, continuous thermodilution which averages about ten CO measurements over five minutes theoretically decreases the error hazard more than conventional thermodilution does (four random injections). Our timing of bolus injection could also explain the difference with the study published by Boldt *et al.*[8] in which bolus injections were performed at end expiration. Wessel *et al.*[15] have shown in anaesthetized dogs, that catheter position (near the wall or the centre of the artery) could also alter thermodilution curves and, consequently, the CO value. In the present study, it could be questionned whether the tip of the catheter remained in the same place during CO measurements by continuous thermodilution and during bolus injections.

Some theoretical arguments suggest that continuous thermodilution is more accurate and more reliable than conventional thermodilution. Nevertheless, the latter has been studied for >30 yr.[1-3] Its pitfalls were extensively reviewed.[3] In contrast, few studies have been performed to detect potential pitfalls of continuous thermodilution. In clinical practice, continuous thermodilution could have some advantages over conventional thermodilution. For instance, continuous thermodilution may detect CO change earlier and lead to more rapid decision making. The incidence of infective complications could be decreased as continuous thermodilution avoids taps handling to perform bolus injections to measure CO.[21] However, these assumptions need to be confirmed by clinical studies. On the other hand, the pulmonary artery catheter capable of continuous thermodilution measurement is three times more expensive than a pulmonary artery catheter for conventional thermodilution. It could be questioned whether this new method of CO monitoring is cost-effective.

In conclusion, continuous thermodilution, compared with conventional thermodilution, is an accurate and reliable method of measuring CO although there are some

discrepancies between the techniques for cardiac index values >4.5 L · min^{-1} · m^{-2}. Further studies are required to confirm its clinical interest and to define its exact indications.

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