Review of the PiCCO device; our experience in the ICU

RBP de Wilde, PCM van den Berg, JRC Jansen

Department of Intensive Care, Leiden University Medical Center, The Netherlands

Introduction
Many intensivists consider it very useful to know the cardiac output of haemodynamically unstable patients. For more than 30 years the pulmonary artery catheter (PAC) has been delivering this information. Modern PACs also permit continuous monitoring of right atrial pressure (RAP), right ventricular pressure (RV), pulmonary artery pressure, pulmonary artery wedge pressure, continuous cardiac output (CCO), mixed venous oxygen saturation, RV ventricular ejection fraction and RV end diastolic volume. These parameters allow diagnosis of right ventricular failure (low mean arterial pressure, low CCO, and low mixed venous oxygen saturation, combined with a high RAP) as well as pulmonary hypertension. Besides the pulmonary artery catheter, echocardiography is the most commonly-used technique to diagnose right heart failure and pulmonary hypertension.

Nowadays, some authors consider the pulmonary artery catheter to be out of date, [1]. However, we should realize that the long history of monitoring with the PAC has resulted in a great deal of experience with its technology and its clinical implications and inadequacies, whereas the new techniques are still standing on the threshold of being tested in clinical practice and their shortcomings are still to be discovered. Besides giving information on cardiac output, these modern devices provide specific information about intra-vascular volume status. In mechanically ventilated subjects, physiological experiments on heart lung interaction showed that stroke volume decreases during inspiration and recovers during expiration. In the early nineteen-eighties, a strong relationship between the magnitude of these tidal changes in stroke volume variations and haemodynamic filling status was shown in animals [2]. Several modern cardiac output devices are using this physiological principle to offer information about fluid responsiveness, i.e. they provide information to answer the question: Will fluid administration increase cardiac output in this patient? This clinical application has generated many papers and reviews over the past few years [3-7].

In this review we focus on the PiCCO device (Pulsion Medical Systems, Munich, Germany): the first widely available commercial system for measuring and monitoring of cardiac output by arterial pulse contour analysis. We will describe the basic principle of the device and the monitoring approach. Furthermore, we will review the main parameters and we will discuss the use as well as the limitations of this device in the light of our own experience.

The PiCCO system
This system combines a transpulmonary thermodilution technique and an arterial pulse contour method into one instrument (Fig. 1).

PiCCO’s pulse contour method
The estimation of cardiac output via pulse contour analysis is an indirect method, computed from arterial pressure pulsation based on a model of the circulation. The original concept of the pulse contour method for estimation of beat-to-beat stroke volume was first described by Otto Frank in 1899 as the classic Windkessel model. Most pulse contour methods used today are derived from this model.

The PiCCO - system utilizes pulse contour analysis according to a modified version of Wesseling’s c2 algorithm (8,9). This pulse-contour algorithm analyzes the actual shape of the pressure waveform in addition to the area under the systolic portion of the pressure wave (Fig. 2). The software takes into account the individual aortic compliance and systemic vascular resistance based on the following considerations. During systole, more blood is ejected from the left ventricle into the aorta than blood that actually leaves the aorta. During the subsequent diastole, the volume stored in the aorta flows into the arterial network at a rate determined by the aortic compliance (C), systemic vascular resistance (R), and the blood pressure (Windkessel effect). The shape of the arterial pressure curve (exponential decay time = R x C) after the dicrotic notch is representative for this passive emptying of the aorta. The systemic vascular resistance, R, is determined by the quotient of mean arterial pressure (MAP) and cardiac output measured by the reference method (R=MAP/CO). As the decay time and R are known, compliance, C, can be computed. The PiCCO algorithm is summarized in the equation in figure 2.

\[ \text{PiCCO} = \text{cal} \times \text{HR} \times \int \left( \frac{P'}{PV} \right) dP + \text{cal} \times \frac{dP}{dt} \] Where: PiCCO, cardiac output; cal, calibration factor; HR, heart rate; P', arterial blood pressure; \( \int \left( \frac{P'}{PV} \right) dP \), area under the systolic part of the pressure curve; SVR, systemic vascular resistance; C(P'), pressure dependent arterial compliance; dP/dt, describes the shape of the pressure wave.

This version of the PiCCO device was published by Godje et al. [10] in 2002.

Input pressure for pulse contour analysis
In clinical practice, aortic pressure cannot be measured and the radial artery or femoral artery pressure are used instead. Although radial and femoral pressure waves are distorted by reflections, pulse contour methods should accept these pressures. As was shown by Wesseling KH et al. [9], cardiac output derived from aortic pressure is not different from that derived from radial artery pressure. Recently, we [11] showed the interchangeability of femoral and radial pressure signals as input for the PiCCO device. These findings are in agreement with the results reported by Mignini et al. [12] who demonstrated that mean arterial blood pressure from radial or femoral arteries are clinically interchangeable. In addition, Soderstrom et al. [13] showed that left ventricular afterload can be derived from the radial artery pressure, after backward filtering to the aortic pressure. It is not clear which type of backward filtering has been integrated into the PiCCO device.
combination with a false high value of stroke volume variation. In these circumstances we found false high cardiac output values in false detection of the dicrotic notch in the pressure recording. Under namely the phenomenon of misclassification of a heartbeat, and at 4-6 hr intervals seems necessary in postoperative cardiac surgical first few hours on the ICU, a regular recalibration of cardiac output the studies. Therefore, in our opinion, due to re-warming during the in vascular compliance and to peripheral vascular resistance during explanations of these phenomena are probably related to alterations agreement show considerable differences between studies. Possible comparisons have been made between PiCCO's new pulse contour cardiac output and conventional bolus thermodilution (COpa) \([10,16-20]\) (Table 1). An individual example of COpa was found, explained by incomplete recovery of cold indicator after its passage through the pulmonary circulation.

**PiCCO’s transpulmonary thermodilution method**

To derive the calibration factor “cal” and the individual compliance function \(C_p\) a reference cardiac output is needed. PiCCO utilizes a transpulmonary thermodilution technique, where cardiac output is determined after central venous injection of a volume \(V_i\) of at least 10 ml. Indicator with a temperature \(T_i\) of at least 10°C below blood temperature \(T_b\). After passage through the right heart, lungs and left heart (Figure 1), the resulting temperature change \(\Delta T_b\) is measured with a thermistor tipped catheter, usually sited in the femoral artery. Cardiac output is calculated by the classical Steward-Hamilton equation: \(CO_ao = k * (T_b - T_i) * V_i / (\int dt)\), where: \(\int dt\) is the area under the thermodilution dilution curve (Figure 1), \(k\) is a computation constant depending on type of injection catheter and on specific heat and specific mass of blood and injection fluid respectively. To measure the transpulmonary thermodilution curve, L’E Orme et al. [14] tested an alternative site. They compared the results obtained with a standard femoral artery catheter with a thermistor tipped, 50 cm long, radial artery catheter. With a bias, for the difference between the two approaches, of 0.38 (SD 0.57), they concluded that both approaches are interchangeable. Many authors compared conventional pulmonary thermodilution (COpa) with transpulmonary thermodilution (COao) and found an acceptable agreement between the two methods, see [15] for references. However, in most papers a small overestimation of COao compared to COpa was found, explained by incomplete recovery of cold indicator after its passage through the pulmonary circulation.

**Validation studies on accuracy and precision**

Several comparisons have been made between PiCCO’s new pulse contour cardiac output and conventional bolus thermodilution cardiac output (COpa) [10,16-20] (Table 1). An individual example of such a comparison is given in Figure 3. Although these evaluations of the PiCCO pulse contour device reveal acceptable results with respect to the bias (range from -0.40 to 0.31 L/min), the limits of agreement show considerable differences between studies. Possible explanations of these phenomena are probably related to alterations in vascular compliance and to peripheral vascular resistance during the studies. Therefore, in our opinion, due to re-warming during the first few hours on the ICU, a regular recalibration of cardiac output at 4-6 hr intervals seems necessary in postoperative cardiac surgical patients.

During our studies [11,15,20] two more problems came to light, namely the phenomenon of misclassification of a heartbeat, and false detection of the dicrotic notch in the pressure recording. Under these circumstances we found false high cardiac output values in combination with a false high value of stroke volume variation. In using the radial artery pulse wave with the PiCCO [11], we incidentally also encountered temporarily false low cardiac output values, due to damping of the arterial waveform by clotting and due to local vasospasm after flushing the arterial line.

**Why not comparing PCCO with COao?**

In a recent study, Della Rocca et al. [17] compared the results of cardiac output of two intermittent methods; pulmonary thermodilution (COpa) and transpulmonary thermodilution (COao)- with the results of two continuous cardiac output methods -PCCO (PiCCO) and CCO (Edwards)-(Table 1). Measurement of COpa by the PiCCO device results in an automatic recalibration of PiCCO’s pulse contour cardiac output, PCCO. Therefore, during each comparison of COao and PCCO the system automatically recalibrates PCCO. Tzenkov and Perez Peña [21] questioned, correctly, the method of automatic recalibration of the PiCCO system as used by Della Rocca and colleagues [17] as well as by other authors. Because of this automatic recalibration of the PiCCO system, the value of PCCO after recalibration is in principle equal to thermodilution COao. This automatic recalibration was considered to be misleading [21], see Figure 4. When performing a comparative study it is normal that the necessary practical operations are first carried out before recording the results of COao and PCCO. But, with the PiCCO it is necessary to record COao results first and then perform three or more thermodilution measurements and to make a note of the average results of these three measurements afterwards.

In their answer to Tzenkov and Perez Peña, Della Rocca and colleagues stated: “As previously reported by Rödig et al. [22], Gödje et al. [23,24] and Bottiger et al. [25], we measured PCCO immediately before and after the series of intermittent COao measurements, and the averages of these data pairs were recorded”. If we understand this statement correctly, the difference found between PCCO and COao must be multiplied by two, because PCCO after performing the measurement of COao (recalibration) is equal to COao. Differences COao-(PCCO before + PCCO after)/2, as PCCO after COao it follows that the computed Difference (COao-COao before)/2. To prevent such uncertainty about the presented data, authors should explicitly mention the way in which they performed their study. In addition,
the manufacturer should adapt the software in such a way that the user gets the simultaneously collected values of PCCO and COao as well as the choice of deciding whether to calibrate or not. A remarkable difference in study setup compared to Della Rocca et al. has become apparent from the study of Rödig et al. [22]. Rödig et al. as well as Rauch et al. [26] explicitly mentioned that they used the transpulmonary thermodilution technique (COao) only to calibrate PCCO at two or three points (at the start and after transfer to the ICU). Further comparisons were made with the conventional thermodilution (COopa) instead of the COao method to prevent a sequential automatic recalibration of PCCO.

**Comparison with other pulse contour methods**

In a recent publication [20] we compared the bias precision and the tracking ability of five pulse contour methods. The bias between the methods was low; however the limits of agreement differed between the methods for the PCCO pulse contour; these values were 0.14 and -1.60 to 1.89 L/min. For the LiDCO-PulseCO device (LiDCO, Cambridge, UK) they were -0.17 and -1.35 to 1.20 L/min. The Modelflow method (BMEYE, Academic Medical Center, Amsterdam, The Netherlands) and the Hemac program (author JRC Jansen) performed the best with 0.00 and -0.74 to 0.74 L/min. and 0.06 and -0.81 to 0.91 L/min. respectively. Also tracking changes in cardiac output were performed significantly better by the Modelflow and Hemac methods.

**SVV and PPV as spin-offs of pulse contour analysis**

Measurement of left ventricular stroke volume variation due to mechanical ventilation has become clinically available since the introduction of pulse contour analysis. Stroke volume variation (SVV) is the difference between maximal and minimal stroke volume during a mechanical breath divided by the average of the two values, see Figure 5. SVV has been shown to be a functional indicator to predict the effects of volume loading on cardiac output [3]. In general, a patient with a SVV larger than 9.5 to 15% will respond with a positive increase in CO after volume loading with 500 mL [27]. A similar approach has been introduced for pulse pressure variation (PPV). Here, a PPV value larger than 13% predicts an increase in CO larger than 15% after volume loading of the patient with 500 mL fluid [3]. These precise percentage value of SVV and PPV were postulated despite Reuter et al. [38] having shown SVV and PPV to be dependent on tidal volume. De Bakker et al. [29] recommended tidal volumes larger than 8 mL/kg body weight. However, the use of larger tidal volumes is in contradiction with the recommendations in the literature which advises that patients be ventilated with low tidal volumes and PEEP to prevent barotrauma [30,31]. Nevertheless, because of their high sensitivity and specificity, SVV and PPV are the most popular haemodynamic monitoring parameters in recent literature [32-36].

**Quality control of conditions.** The use of SVV and PPV as predictors of fluid responsiveness is only possible in fully ventilator-dependent patients with a regular heart rate. However, in many postoperative cardiac surgical patients weaning from a ventilator has already started on arrival in the ICU, or is started shortly after. Furthermore, irregular heart rates are quite common in cardiac surgical patients. The software in the PICCO device does not perform a quality check for these conditions which impels the physician to do so, especially in the event of a high SVV or PPV value. In our opinion, this all makes the use of SVV or PPV as predictors for volume loading on cardiac output of limited value in daily clinical use.

**GEDV and ITBV as spin-off of transpulmonary thermodilution**

Transpulmonary thermodilution-derived global end-diastolic volume index (GEDVI) and intrathoracic blood volume index (ITBVI) may reflect left ventricular end-diastolic volume and are supposed to reflect preload and predict fluid responses after cardiac surgery much better than cardiac filling pressures [37-41]. The superior value of these volume indices over pressures is questionable, since fluid loading guided by CVP changes has been shown to increase volumes and cardiac output in patients after cardiac surgery for instance [43]. In addition, the predictive value may be confounded by mathematical rather than physiological coupling, as in the PICCO system both cardiac output and volumes are derived from the same transpulmonary thermodilution curve. The coupling may contribute to falsely high correlations between volumes and cardiac output (changes) as a consequence of shared measurement error [44]. Mundigler et al. [45] demonstrated the insensitivity of GEDV or ITBV in monitoring the effects of volume loading in patients with reduced left ventricular function. They concluded that cardiac filling pressures rather than intra-thoracic volumes should be used to monitor fluid loading. Remark: consider a patient with a normal heart having an end diastolic volume of 100 mL, the same volume in a patient with a large heart due to cardiomyopathy will not generate an end diastolic wall tension at all! Furthermore, based on theory and observation, we have the impression that the precision of these variables is dependent on SVV.

In a recent prospective multicentre study, Uchino et al. [46] compared haemodynamic monitoring by PAC with that by PICCO-derived variables. The major outcome of this study was that on direct comparison, the use of the PICCO was associated with a greater positive fluid balance and fewer ventilator-free days. After
adjustments for confounding variables, the choice of monitoring technique was shown not to predict outcome, but a large positive fluid balance was a significant predictor of greater mortality.

As many of our patients have congestive heart failure we found GEDV and ITBV of limited use, despite the publications that demonstrate the superiority of these parameters [37-42].

Limitations and remarks based on own experience

Quality control of the arterial pressure waveform. Radial artery pressure is usually measured with fluid-filled catheter-transducer systems. The catheter lines are routinely kept open with continuous flush devices. Malfunction of flush devices or catheter-related problems are of direct influence on the measured pulse contour cardiac output and derived variables. Therefore, frequent visual control of the pressure wave form is advisable, or better still, a detection of damped waveforms is greatly needed and should be built into pulse contour systems.

Patient related concerns. The performance of all pulse contour methods is compromised in those patients who have aortic valve regurgitation, an aortic aneurysm or an intra-aortic balloon pump, as well as during cardiopulmonary bypass and aortic clamping. Also, the physiological properties of the aorta may change with the patient’s position. No data is available on changes when going from supine to upright - nor on changes from supine to prone position.

In two adult patients, we [15] showed clinical significant differences in PiCCO cardiac output values for PCCO and COao compared with the continuous thermodilution cardiac output from the pulmonary artery catheter (Vigilance, Edwards). These differences appeared to be dependent upon the site of measurement and the underlying pathology. In one patient with a severe haemorrhage the difference in CO was related to excessive loss of cold indicator during the passage through the pulmonary circulation. In the other patient, the difference could be explained by the presence of a partial anomalous pulmonary vein entering the right atrial cavity. From these observations we learned that improved analysis of the transpulmonary dilution curve may help to alert the operator in the event of intrathoracic abnormalities. Detection of the false high cardiac output by the PiCCO system in the patient with severe haemorrhage and the real difference between the output of the right and left heart in the patient with intrathoracic abnormalities was possible because these patients were participating in a study protocol.

Ong et al. [47] reported a third patient with induced hypothermia for anoxic brain injury, in which the PiCCO system failed to calibrate, even after several attempts with increased injection volumes of cold injectate (temperature lower than 8 °C) and exchange of the PiCCO device and of the femoral arterial line.

Summary and conclusions

From the literature and our own comparative studies using different pulse contour cardiac output systems, we concluded that the accuracy (bias), precision (SD) as well as the tracking of changes in cardiac output by the PiCCO system is inferior to most of its competitors. During our use of the PiCCO system, several technical and patient-related limitations were uncovered by coincidence. The technical limitations were related to i) incorrect detection of heart beats, ii) incorrect detection of ejection phase, iii) no detection of damped arterial pressure tracings, all leading to incorrect computations of cardiac output. Patient-related problems were found during severe episodes of bleeding and cardio-pulmonary anatomical abnormalities.

In most cardiothoracic patients, SVV or PPV to monitor preload dependency was only useful for a short time as most patients were weaned from the ventilator shortly after arrival in the ICU.

In patients who are candidates for a heart assist device (intra-aortic balloon pump) a femoral arterial puncture for application of the PiCCO device is contra-indicated.

We experienced, consistent with the literature, that measurement of GEDVI and ITBVI in cardiomyoplasty patients is irrelevant. Furthermore we have, based on theory and observation, the impression that the precision of these variables is dependent on SVV.

From the foregoing we consider that the PiCCO system is of limited value in monitoring cardiothoracic patients.
References