Volumetric haemodynamic monitoring and continuous pulse contour analysis – an untapped resource for coronary and high dependency care units?

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Abstract

Critically ill patients in the coronary care or high dependency units (CCU, HDU) need accurate assessment of their haemodynamic status to guide fluid or vasoactive drug therapy. Both central venous pressure and pulmonary artery occlusion pressure are poor guides to cardiac filling and pulmonary oedema, and using a pulmonary artery catheter often fails to improve clinical outcome.

The PiCCO system is a relatively new and less invasive approach to cardiac monitoring. It has been used extensively in intensive care and is reviewed in this article. This approach uses thermo-dilution techniques to reliably calculate volumetric measurements of cardiac preload and cardiac output, and can provide continuous real-time cardiac output and stroke volume variation measurements through pulse contour analysis. The reliability and accuracy of this method has drastically refined fluid and vasopressor management of the hypotensive patient and the management and prevention of pulmonary oedema. This method of measuring cardiac output correlates well with gold standard methods of cardiac output calculation and has been validated in adults and children.

The PiCCO system can be an invaluable tool in the optimisation of the circulation in cardiac, medical and surgical patients commonly seen in the CCU and HDU.

Key words: haemodynamic monitoring, pulse contour analysis, cardiac output, pulmonary oedema, coronary care unit.

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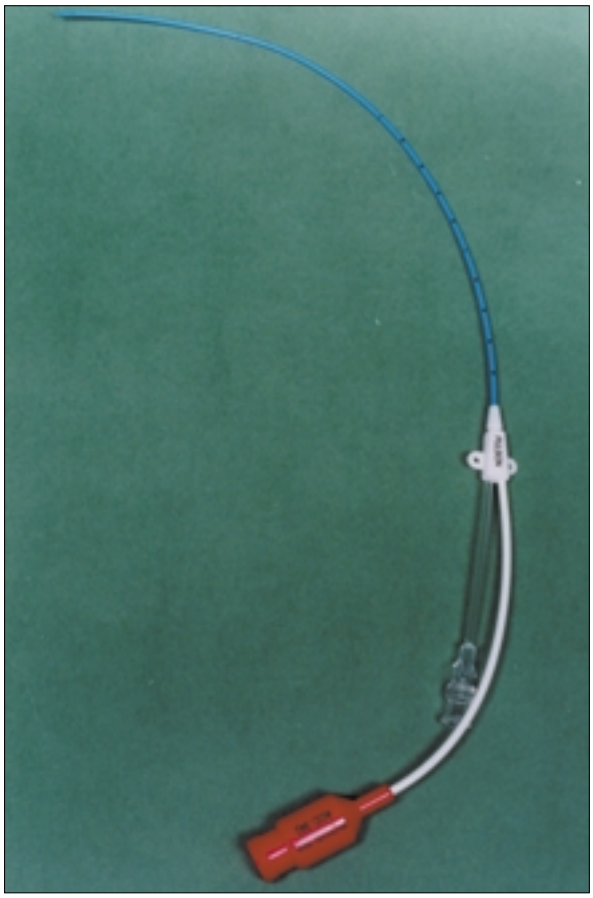
Introduction

Astute clinical acumen is an essential starting point in the haemodynamic evaluation of patients encountered in the coronary or high dependency care unit (CCU, HDU). Evaluations have to be made of cardiac preload or filling, cardiac output (CO) or global flow, and systemic vascular resistance (SVR) or afterload. Even minor clinical misjudgment may lead to inappropriate use of fluids, diuretic therapy or vasoactive drugs, with adverse effect. In a hypotensive patient, for example, the use of low-dose dopamine without ensuring adequate intravascular filling results in detrimental myocardial strain and oxygen consumption. This may also cause hypoperfusion of other organs such as the kidney, contributing to the risk of developing multiple organ failure.

Monitoring central venous pressure (CVP) and pulmonary artery occlusion pressure (PAOP) is almost universally thought to provide the best guide to cardiac filling and, consequently, clinical management. However, this widely held view needs to be challenged. There are valid reasons to explain why the CVP and PAOP are poor guides both to cardiac filling and the risk of pulmonary oedema.[1,2] This may be a significant contributory factor to explain why using a pulmonary artery catheter (PAC) fails to improve clinical outcome, and may even increase mortality, in the majority of critically ill patients.[3,4]

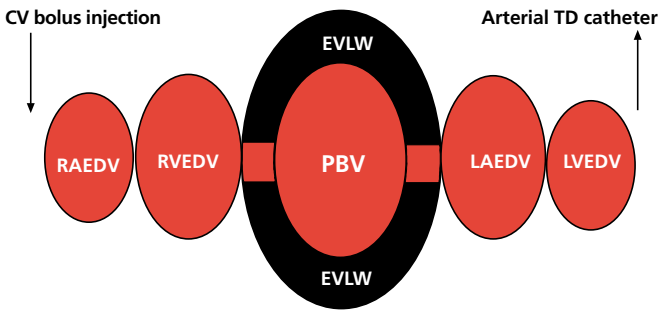
There are alternatives to using a PAC. Echocardiography and Doppler can estimate left- and right-sided filling pressures, quantify stroke volume and hence quantify cardiac output. However, echocardiography provides only a snapshot assessment of circulatory status. It requires a trained operator and is of limited use in monitoring patients with a dynamic and rapidly changing circulation. Oesophageal Doppler is relatively simple and non-invasive, but is not feasible in awake, unintubated patients. Newer methods of cardiac monitoring, such as thermodilution and pulse wave analysis, are well established in intensive care medicine and anaesthesia, and may also have a valuable role in the CCU and HDU. Some of these alternatives are simpler to apply and also give additional clinically relevant information to enable more accurate decision-making regarding diagnosis and therapy. This article reviews one system that has been used extensively in the intensive care unit at Guy's and St Thomas' Trust for the last five years.

Figure 1. PULSIOCATH femoral arterial catheter



Courtesy Pulsion Medical Systems

Figure 2. Schematic representation of the thermal distribution volumes



Key: RAEDV = right atrial end-diastolic volume; RVEDV = right ventricular end-diastolic volume; EVLW = extravascular lung water; PBV = pulmonary blood volume; LAEDV = left atrial end-diastolic volume; LVEDV = left ventricular end-diastolic volume

Pressure or volumetric measurements?

In clinical practice the CVP and, to a lesser extent, PAOP are most often used as estimates of circulating intravascular volume. However, they are both dependent on cardiac contractility, vascular compliance and intrathoracic pressure. A study in shocked patients demonstrated that the degree of change in CVP and PAOP during known quantities of intravascular volume depletion was relatively small.[5] Although the PAOP was better than the CVP, neither was very sensitive to small variations in intravascular volume. Measuring an alternative parameter, the 'intrathoracic blood volume' (ITBV), has been shown to correlate much more closely with intravascular blood volume, and hence preload. Another physiological study demonstrated the ITBV to have superior sensitivity compared with the PAOP and CVP, in response to changes in blood volume during acute hypovolaemia.[6] Up to 50 ml/kg of blood withdrawal was required to change the CVP by 1 mmHg, and up to 16 ml/kg to change PAOP by the same amount; by contrast, only 2.8–3.8 ml/kg of blood withdrawal was required to change the ITBV by 1 ml/kg.

Practical issues also make reliable measurement of the CVP and PAOP difficult. The site of insertion, tortuosity of tissue passage and kinking of the lumen can all interfere with readings. Patient movement necessitates repeated re-zeroing for accurate readings. Furthermore, the use of vasopressor drugs such as dopamine and adrenaline will also influence the measurement, potentially leading to miscalculation of the true volume status. PACs also pose a significant risk of complications, including arrhythmias, valvular damage, pulmonary infarction, pulmonary arterial rupture and endocarditis.

The PiCCO system

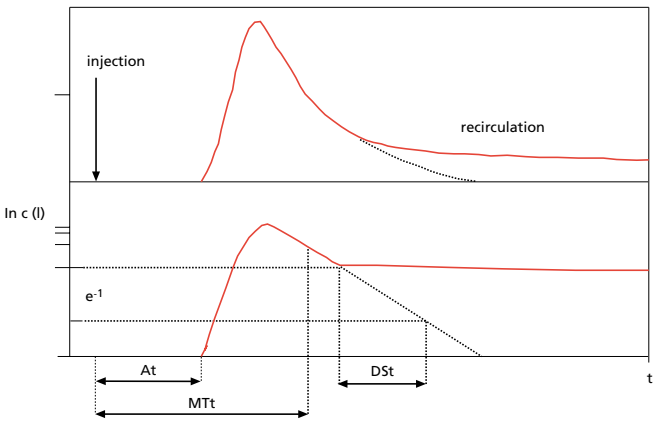
A simpler, less invasive, approach that avoids many of the complications of the PAC is to use the PiCCO system (Pulsion Medical Systems, Munich, Germany). Central venous access is required along with a femoral arterial thermistor-tipped catheter (figure 1). The femoral catheter is simultaneously used for arterial pressure, bolus transpulmonary thermodilution with pulse contour analysis resulting in continuous cardiac output. The novelty of this approach is that calculation of reliable volumetric measurements of preload, ie. intrathoracic blood volume (ITBV) and global end-diastolic volume (GEDV), is possible. Moreover, estimates of extravascular lung water (EVLW) can be calculated, which may help in the management or prevention of pulmonary oedema.

The PiCCO system works on the principle that a known volume of thermal indicator (ice-cold saline) is injected into a central vein. After this the injectate rapidly disperses, volumetrically and thermally, within the pulmonary and cardiac volumes. This volume of distribution is termed the intrathoracic thermal volume (ITTV). The ITTV is the sum of the ITBV and EVLW. The ITBV comprises the end-diastolic volumes of all four cardiac chambers, the global end-diastolic volume (GEDV), and the pulmonary blood volume (PBV) (figure 2).

This is summarised by the three equations below:

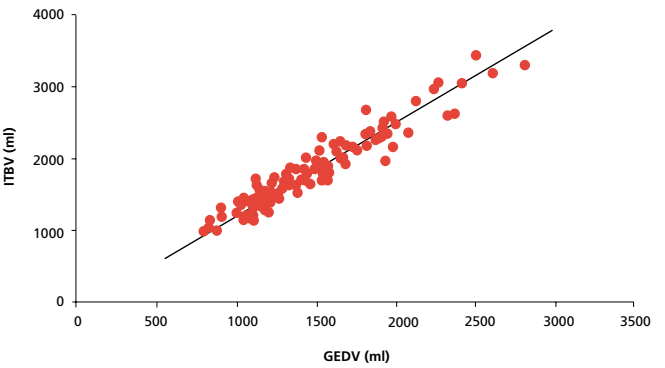
- GEDV = RAEDV + RVEDV + LAEDV + LVEDV
- ITBV = GEDV + PBV
- ITTV = ITBV + EVLW

Figure 3. Graphical representation of the PiCCO thermo-indicator dilution curve



Key: ln c(l) = logarithm of concentration of Indicator; e^{-1} = natural logarithm of decay; At = Appearance time; MTt = mean transit time; DSt = exponential down slope time

Figure 4. The relationship between ITBV and GEDV in 57 intensive care patients, calculated with double indicator (cold indocyanine green), r = 0.96



Key: ITBV = intrathoracic blood volume; GEDV = global end-diastolic volume
Adapted from: Sakka SG *et al*. *Intensive Care Med* 2000;**26**:180-7.

Calculation of cardiac output, GEDV, ITBV and EVLW

When the thermal signal reaches the arterial thermistor placed in the femoral artery, a temperature difference is detected and a dissipation curve is generated (figure 3). When thermal energy is neither lost nor gained in a closed flow system, the cardiac output (CO) is derived from the area under the curve using the Stewart Hamilton equation.

$$CO = \frac{\mathbf{m0}}{\int_0^{\infty} -\Delta \mathbf{T} dt}$$

T = temperature, **V** = volume.
m0 = (**T** blood – **T** injectate) ● (**V** injectate – **V** deadspace) ● 1.102

The time taken for the cold injectate to reach the femoral thermistor from the time of injection is the appearance time (At). From the At and the dissipation curve, the mean transit time (MTt) can be measured. The product of MTt and CO will give the volume of distribution of the cold injectate between the point of injection and the point of detection, ie. the intra-thoracic thermal volume, ITTV.

ITTV = MTt ● CO = GEDV + PBV + EVLW

As the cold injectate is injected into the central venous catheter, it travels through a series of mixing chambers in the heart and lungs. It follows, therefore, that the dissipation curve generated is actually a composite of a group of curves, with the largest mixing chamber in the series producing the longest curve. If the thermal dissipation curve is then plotted on a semi-logarithmic scale, the exponential decay time (DSt) can be calculated (figure 3). The product of CO and DSt is the volume of the largest single mixing volume between the point of injection and the point of detection, which for the thermal indicator is the pulmonary thermal volume (PTV). The PTV is the sum of the pulmonary blood volume, PBV, and extravascular lung water, EVLW.

PTV = DSt ● CO = PBV + EVLW

It is logical, therefore, that global end-diastolic volume is derived by subtracting the PTV from the ITTV.

GEDV = ITTV – PTV

Experimental series with a double indicator (cold indocyanine green) have demonstrated a close linear correlation between the global end-diastolic volume and intrathoracic blood volume,[7] see figure 4.

From these data the ITBV can be calculated from the GEDV using the following formula:

ITBV = 1.25 ● GEDV + 28 ml

From the calculated ITBV an estimated EVLW can be derived:

EVLW = ITTV – ITBV

Validation of transpulmonary thermodilution techniques

A number of studies have shown that the PiCCO system transpulmonary thermodilution method of measuring CO correlates well with PAC thermodilution techniques, and with the

Fick method of CO determination.[8,9] This correlation has been demonstrated in children and adults.[10-13] In low cardiac output states the thermal signal has a longer transit time through the systemic circulation. Thus there is greater scope for thermal dissipation and for possible overestimation of cardiac output. One study demonstrated a direct negative correlation between thermal indicator loss and cardiac output, resulting in an overestimate of cardiac output of 7% using transpulmonary dilution compared to PAC, at low cardiac output states.[11] To overcome this problem the injectate would need to be introduced instantaneously and re-circulation would have to be stopped, both of which are impossible physiologically. More recent studies have demonstrated a negligible overestimate at low output states, but an overall excellent correlation of PiCCO cardiac output with the PAC.[12-14] The PiCCO system provides an additional advantage in that monitoring of continuous real-time cardiac output is possible using pulse contour analysis.

Continuous CO measurement with pulse contour analysis

The PiCCO system initially uses a transpulmonary thermodilution run to calibrate the femoral arterial waveform and, more specifically, the area below it. Continuous CO readings are then achieved using the area under the systolic part of the curve, a calibration factor (cal) derived from the thermodilution run, the heart rate (HR) and the individual's aortic compliance (which is termed C (p) and characterised by the thermodilution CO and the measured BP). This is shown in figure 5.

The reliability of systems such as the PiCCO using continuous pulse contour analysis has been validated.[15-17] To maintain the accuracy of the contour analysis, bolus recalibration thermodilution is required at least every eight hours. More frequent calibration may be needed after significant circulatory changes or after manipulation of vasoactive infusions.

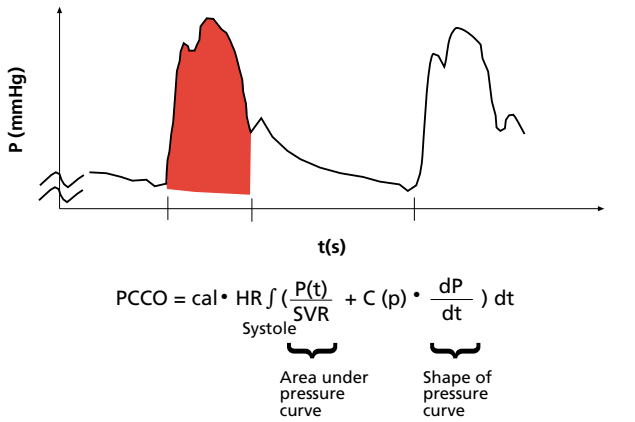
Other parameters monitored by the PiCCO system include:

- Heart rate;
- Arterial blood pressure;
- Stroke volume;
- Stroke volume variation; and
- Systemic vascular resistance.

Stroke volume variation

With continuous CO calculation using pulse contour analysis, continuous stroke volume can also be calculated by dividing the CO by heart rate. From this, beat-to-beat and minute-to-minute variations in stroke volume can be displayed. Stroke volume variation (SVV) has proven to be a useful baseline predictor of the volume responsiveness of patients. In a study of 20 ventilated patients,[18] percentage changes of CO were significantly correlated with percentage changes in SVV, ITBV and PAOP during volume challenges. However, baseline values of SVV also correlated with percentage change in CO, highlighting the value of SVV as a monitor and a predictor of response to volume administration, obviating its potential value in haemodynamic management.

Figure 5. Calculation of cardiac output with pulse contour analysis



Key: cal = patient-specific calibration factor (determined with thermodilution); HR = heart rate; C(p) = aortic compliance

GEDV and EVLW – general principles and clinical applications

GEDV

Cardiac preload is strictly defined as the myofibril stretch length; however, a parameter that reflects this measure is not currently available. This stretch is often translated in clinical practice to end-diastolic ventricular volume. GEDV represents the total end-diastolic volumes of all four cardiac chambers and theoretically provides a reasonable estimate of cardiac preload.

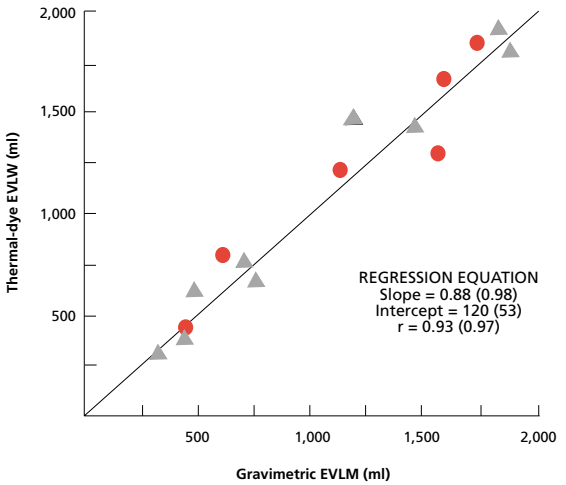
A number of studies have demonstrated that the GEDV reflects change in volume status and cardiac performance better than CVP, PAOP, RVEDV and stroke volume index.[9,19] More importantly, the GEDV and its correlation to cardiac preload are not inexorably linked to cardiac output. It is evident that GEDV and preload follow a Starling curve-like relationship to cardiac output. This is particularly apparent during bolus fluid challenges, as a point can be determined where increasing GEDV no longer leads to increased CO, presumably when the apex of the Starling curve is reached.

GEDV (and the closely related intrathoracic blood volume) is an accurate and validated guide to cardiac preload that is superior to conventional CVP and PAOP.[20] This measure of preload, together with the derived parameter EVLW, solve most haemodynamic and fluid balance conundra.

EVLW

With conventional monitoring it is often difficult to avoid pulmonary venous congestion and oedema when optimising a critically ill patient's cardiac preload. Until recently, estimates of the severity of pulmonary oedema were largely clinical and radiological, with PAOP acting as a useful guide to help distinguish hydrostatic from oncotic and endothelial permeability-related aetiologies. Studies comparing EVLW using thermodilution to chest X-ray scores of pulmonary oedema have demonstrated at best a

Figure 6. Comparison of ante-mortem thermal run and post-mortem gravimetric values for EVLW in 16 patients



With kind permission, Dr Johannes A Sturm, Klinikum Lippe-Detmold, Detmold, Germany

poor correlation.[14,21,22] This is unsurprising considering that interpretation of portable chest X-rays depends heavily on the quality of the film, positioning of the patient and the experience of the physician.

A true measure of pulmonary oedema can only be obtained at post mortem using gravimetric analysis. Both animal and human studies show close correlation between the thermal estimate of EVLW and gravimetric measurements (figure 6).[23,24]

The thermal dilution technique as used in the PiCCO system is both sensitive and specific to changes in EVLW and can be an invaluable tool in the optimisation of the circulation whilst avoiding pulmonary oedema, impaired gas exchange and the requirement for ventilatory support. The normal EVLW is between 3–8 ml/kg. Impaired gas exchange (due to oedema) does not usually occur until the EVLW exceeds 10 ml/kg: initial fluid accumulation occurs at the alveolar-capillary interface.[23,25]

What is the effect on clinical outcome?

The theory and application of monitoring techniques such as those adopted by the PiCCO system has been esoteric to most and largely confined to the arena of anaesthesia and intensive care medicine. Furthermore, monitoring parameters and protocols have only recently been established. These reasons partially explain why there have not been many studies comparing outcome of patients managed with this technique with other techniques. One outstanding study in intensive care patients[26] compared a fluid management strategy based on targeting the EVLW to one based on targeting the PAOP. Fifty-two patients were randomised to the EVLW strategy and 49 were randomised to targeting PAOP. Both groups had entirely comparable demographics at baseline, yet ventilator days and ICU length of stay were significantly shorter in patients whose haemodynamic management strategies were based on EVLW targets compared to those with PAOP targets.

Key messages

- Central venous pressure and pulmonary artery occlusion pressure may both be poor guides to cardiac filling and the risk of pulmonary oedema
- The PiCCO system avoids many of the complications of the pulmonary artery catheter
- The system accurately calculates volumetric cardiac preload and measures continuous real-time cardiac output and stroke volume variation
- The accuracy of the system has been well validated

Limitations of PiCCO

There are very few contraindications to the use of PiCCO. They include femoral artery grafting, trauma and severe local burns or soft tissue infection. The true limitations of PiCCO are particular physiological conditions which affect thermodilution results or the arterial waveform. These include:

Intracardiac shunts

Right to left shunts would result in premature delivery of the cold injectate, before appropriate mixing in the true ITTV, and hence an overestimate of CO. Conversely, left to right shunts would result in re-mixing of the injectate within the ITTV before reaching the femoral thermistor and hence an underestimate of CO.

Severe aortic valve disease

Aortic stenosis will not affect CO measurement based on thermodilution, although interpretation of a waveform with a flatter systolic gradient can impair continuous contour analysis. In significant aortic incompetence, however, there is re-mixing of the cold injectate within the left ventricle with the regurgitant back flow. Thus the indicator decay time is prolonged and the CO is underestimated.

Lung perfusion (Q) deficit

Pulmonary macroemboli causing significant perfusion deficits will result in gross underestimation of intrathoracic volumes. This is because the cold injectate will not perfuse and thermally disperse in the non-perfused areas.

Intra-aortic balloon counterpulsation (IABC)

The diastolic augmentation of arterial pressure afforded by IABC alters the waveform of the arterial pulsation, which cannot therefore allow for accurate calculation of continuous cardiac output based on the principles mentioned above. Moreover, the initial calculation of CO during the thermodilution calibration is also affected during IABC.

Conclusions

The applications of the use of the PiCCO are diverse and its accuracy has been validated. When used appropriately, its assistance in the fluid and vasopressor management of critically ill patients can be invaluable. Even with a high level of clinical expertise the management of cardiac, medical and surgical patients commonly encountered in the CCU and HDU could be made much easier with such a system.

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