Minimally invasive haemodynamic monitoring

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Introduction

Haemodynamic monitoring is typically used in critically ill patients to assess and optimise cardiac function in order to achieve and maintain adequate tissue perfusion. The use of the pulmonary artery catheter (PAC) for this task has been challenged in the last few years and there is an ongoing debate regarding its impact on outcome. Conflicting findings have been published and some of the findings may be explained by better patient selection, lack of specific indications and differences in the treatment protocols (or the lack of it) than by the type of monitoring (the PAC) itself [1]. Based on this development, there is an increasing clinical acceptance of minimally invasive haemodynamic monitoring. Different techniques are commercially available and in recent years they have proved adequate in replacing the PAC under certain clinical conditions. Moreover, easier handling of these techniques (compared with the PAC) may result in a widespread, early application to larger patient populations at risk for haemodynamic instability. In order to avoid inadequate tissue perfusion in these situations ‘early goal-directed haemodynamic therapy’ is a promising concept [2]. However, for early use in daily clinical practice the diversity of minimally invasive haemodynamic monitoring demands knowledge of the different techniques, the different parameters provided by the devices and their clinical validity.

The aim of this lecture is, therefore, to review the most widely used minimal invasive cardiac output monitoring techniques, emphasise the new parameters available for preload assessment and propose a modular stepwise monitoring concept.

Minimally invasive cardiac output monitoring techniques

The minimally invasive haemodynamic monitoring techniques discussed in this review are: pulse wave analysis, Doppler measurement techniques and partial carbon dioxide re-breathing using the applied Fick’s principle. Specific features (such as invasiveness, technical details of cardiac output assessment, additional variables and limitations) of each presented technique are summarised in Figure 1.

Figure 1

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<td>Severe vascular disease (PCO), IABP, arrhythmias (all devices)</td>
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Specific features of different minimally invasive haemodynamic monitoring techniques

CO = cardiac output, EVLV = extravascular lung volume, GEDV = global end-diastolic volume, IABP = intra-aortic balloon pump, SVV = stroke volume variation, PPV = pulse pressure variation.

Pulse wave analysis
Pulse wave analysis - also referred as ‘pulse pressure analysis’ or ‘pulse contour analysis’, is based on the principle that the stroke volume can be tracked continuously by analysis of the arterial pressure waveform. Because the arterial pressure wave form is the result of an interaction between stroke volume and the vascular structure, resistance, compliance and characteristic impedance have to be considered. The first successful algorithm was developed by Wesseling more than 30 years ago [3]. He used a computer-based algorithm in order to monitor stroke volume and calculations were performed on the hypothesis that the area under the curve of the systolic part of the arterial pressure waveform is proportional to the stroke volume. For this calculation calibration using thermodilution was needed. However, different mathematical models are used today in order to assess stroke volume/cardiac output in the commercially available pulse wave analysis devices (PiCCO plus, Pulsion Medical Systems, Munich, Germany; PulseCO, LiDCO Ltd, London, UK and FloTrac/Vigileo, Edwards LifeSciences, Irvine, USA).

PiCCOplus system

The first pulse contour device for cardiac output measurement based on the Wesseling algorithm in clinical practice was the PiCCO system. A dedicated thermistor-tipped catheter, usually introduced via the femoral artery, tracks stroke volume on a beat-by-beat basis after calibration by transpulmonary thermodilution. After observing inaccurate measurements as a result of variations in systemic vascular resistance the PiCCO algorithm has been modified in order to better address the individual patient’s aortic compliance using more information related to the systolic but also the diastolic arterial waveform [4]. Different studies in a variety of clinical settings have been performed in the last years validating the PiCCOplus system against intermittent pulmonary artery thermodilution [5]. The algorithm now appears to be more reliable in situations of rapid haemodynamic changes. However, despite these improvements frequent recalibrations for accurate measurements are required [6].

PulseCO system

Continuous cardiac output measurement by the PulseCO technique via a standard peripheral arterial line is usually classified as a pulse contour method, although strictly speaking it is not a pulse contour device. This technique relies on a pulse power analysis which is based on the principle of mass/power conservation in a system and the assumption that following the correction for compliance and calibration there is a linear relationship between net power and net flow in the vascular system. With PulseCO the entire pulse wave (the systolic and the diastolic part of the pressure curve) is analysed. Thus, the problem of wave reflections in the vascular system is considered, but a so called ‘autocorrelation’ is needed to determine ‘change of power’ caused by the heart. Similar to harmonic waveform analysis, autocorrelation is a mathematical function analysing repetitive signals in cycles over time (i.e. the stroke volume and thus cardiac output). The system is calibrated using transpulmonary lithium indicator dilution (LiDCO) [7] and as long as no major haemodynamic changes (alterations of vascular compliance and resistance) occur, reliable continuous cardiac output measurements were demonstrated in clinical studies [8]. In contrast to thermodilution, the LiDCO is not sensitive to blood temperature changes, but electrolyte and haematocrit changes may have a negative effect. Moreover, the number of lithium injections is limited.

FloTrac/Vigileo system

In this system continuous cardiac output assessment requires a FloTrac sensor, a specific transducer, attached to an existing standard arterial line. In contrast to the PiCCOplus and the PulseCO system this device does not require external calibration. For cardiac output measurement the standard deviation of pulse pressure sampled during a time window of 20 s is correlated to the ‘normal’ stroke volume based on underlying demographic data. Impedance is also derived from this data, whereas vascular compliance and resistance are determined using arterial waveform analysis. With the initial software versions of the algorithm (1.01-1.03) adaption of the vascular status was performed every 10 min. Based on the results of early validation studies [9] a major modification of the algorithm was a reduction of this time window to 1 min (software versions 1.06 and higher). Studies using these software versions showed improved cardiac output assessment [10]. Further software modifications addressing the issue of limited accuracy during hyperdynamic situations are currently being tested.
As a result of the general principles used, all pulse wave analysis devices share the need for an optimal arterial signal quality for valid cardiac output assessment. Moreover, arrhythmias and the use of an intra-aortic balloon pump preclude reliable measurements. It has to be emphasised that with the PICCOplus system the insertion of the femoral catheter is contra-indicated in patients with severe atheromatosis.

**Doppler techniques**

**Trans-oesophageal echocardiography (TOE or TEE)**

Flow measurement by pulsed-wave Doppler across a cardiac valve or in the left ventricular outflow tract and the assessment of the cross-sectional area at the site of the flow quantification (the aortic valve) allow cardiac output measurement by TOE. A Doppler beam orientation strictly parallel to the blood flow and an unchanged cross-sectional area over time are needed for optimal measurements. TOE measurements are time consuming and require a high level of operator skill and knowledge. Limited reliability is typically related to technical TOE problems (image quality, variations in orifice area determination, excessive Doppler beam angle) and considerable inter-observer variability.

**Trans-oesophageal Doppler flow probes**

Doppler flow measurements for cardiac output determination can also be performed in the descending aorta, where adequate characteristic flow signals can be obtained as a result of the close proximity to the oesophagus and the aorta. Different Doppler probes are available (ODM II, Abbott, Maidenhead, UK; CardioQ/Medicina TECO, Deltex Medical Ltd, Chichester, UK; HemoSonic100, Arrow, Reading, USA) and cardiac output is typically calculated from measured aortic blood flow and aortic cross-sectional area obtained either from nomograms or by M-mode ultrasound quantification (HemoSonic 100). Cardiac output is assessed assuming a constant partition between caudal and cephalic blood supply since brachiocephalic flow can not be measured. The probes are smaller than conventional TOE probes and steep learning curves for probe positioning have been observed. However, validation studies in the last few years have revealed inconsistent results. Limited accuracy may result from signal detection failure, the assumption of fixed regional blood flow or the use of nomograms to determine aortic cross-sectional area [11]. The HemoSonic 100 device was developed to eliminate the use of nomograms by echocardiographic aortic assessment, but optimal adjustment of both Doppler and ultrasonic signal at the same time may be challenging [12]. Therefore, the value of this minimally invasive technique may be limited in clinical practice. However, Doppler devices may be used in specific situations by skilled observers. Based on the ability to reliably track stroke volume changes over time early-goal directed therapy in a peri-operative setting may be a typical indication.

**Applied Fick’s principles: partial CO\textsubscript{2} rebreathing**

Fick’s principle applied to carbon dioxide (CO\textsubscript{2}) is used by the NICO system (Novametrix Medical Systems, Wallingford, USA) for cardiac output measurement. CO\textsubscript{2} analysis is performed using a mainstream infrared and airflow sensor. CO\textsubscript{2} production is calculated as the product of CO\textsubscript{2} concentration and air flow during a breathing cycle and arterial CO\textsubscript{2} content is derived from end-tidal CO\textsubscript{2} and the corresponding dissociation curve. An intermittent partial re-breathing state in intervals of 3 min can be induced by a disposable re-breathing loop. The re-breathing cycle results in an increased end-tidal CO\textsubscript{2} and mimics a drop in CO\textsubscript{2} production. The differences of these values are then used to calculate cardiac output. Validation studies showed conflicting results. However, clinically acceptable cardiac output assessment is possible in intubated mechanically ventilated patients with minor lung abnormalities and fixed ventilatory settings [13].

In contrast, variations in ventilatory modalities, mechanically assisted spontaneous breathing or use of this technique in patients with lung pathologies (increased shunt fraction) resulted in decreased accuracy. Thus, this technique may be applied in a precisely defined clinical setting to mechanically ventilated patients only.
Parameters of preload assessment

Volume expansion is the most often performed intervention to improve the haemodynamic status of critically ill patients. Several minimally invasive monitoring devices provide different preload parameters and allow an assessment of the fluid status. These parameters are reviewed in the following section. However, since standard pressure parameters are still widely used in clinical practice, these parameters are also discussed.

Static preload parameters

Pressure parameters

Preload according to Frank-Starling is defined as the end-diastolic myocardial fibre tension. Unfortunately, this cannot be assessed in a clinical setting and, therefore, only surrogate markers of preload can be measured. Traditionally, monitoring of central venous pressure is used as global parameter of the heart filling, that is - right and left ventricular preload, in patients without significant pulmonary diseases or impaired right ventricular function. In the presence of these pathologies, pulmonary artery occlusion pressure assessed by a pulmonary artery catheter is usually considered to be the only reliable indicator of left heart filling. Studies in the last few years, however, have shown a lack of correlation between cardiac filling pressures and stroke volume [14, 15]. Transduced intrathoracic pressures interfering with the pressure preload measurements may predominantly explain these findings. Pressure is an important determinant of a compliant system (such as the heart) but this refers to transmural and not intravascular pressure. Moreover, frequently observed alterations of the cardiac valves or cardiac obstructions can introduce a measurement error. Still, cardiac filling pressures are often easily available and based on their limitations interpretation of these parameters has to be undertaken in the clinical context. Moreover, trends are more important than absolute value and the dynamics of changes is essential.

Volumetric parameters

With the limitations of pressure preload parameters, assessment of end-diastolic volume is desirable in daily clinical practice. Two thermodilution based techniques provide volumetric preload parameters which are calculated from cardiac output and indicator passage times. Continuous end-diastolic volume index (CEDVI) can be assessed by a modified pulmonary artery catheter (CCombo CCO/SvO2/CEDV catheter 774HF75, Edwards Lifescience, Irvine, USA) and as a result of the measurement site, the assessed volume is restricted to the right sided heart chambers. Global end-diastolic volume index (GEDVI) and the closely related intrathoracic blood volume index (ITBVI) are determined via transpulmonary thermodilution, which is used for the calibration of the PiCCO system. The PiCCO approach assumes that the thermal indicator travels from its application (via the central venous access) through the different central compartments connected in series to the indicator detection site. Based on different indicator detection times, the different volumes can be calculated. All volumetric preload parameters have shown to be superior as preload indicators than cardiac filling pressures [14, 16]. In addition to these parameters, extravascular lung water index (EVLWI) can be determined by the PiCCO system. EVLWI may be useful for the diagnosis of pulmonary oedema and the evaluation of different ventilatory strategies in ARDS patients.

Echocardiographic preload assessment

Different echocardiographic approaches allow preload assessment either by measuring left ventricular end-diastolic area (LVEDA) or calculating volume (LVEDV). LVEDA is determined at the mid-papillary level in a short axis view, whereas for the volumetric assessment different echocardiographic positions and measurements are needed for the calculation of LVEDV. These calculations are based on the Simpson algorithm and assume that the ventricle consists of the sum of small cylinders and a truncated ellipse. Conflicting results have been reported using the Simpson algorithm and, typically, LVEDA is used as surrogate of left ventricular preload [17]. However, because this technique is highly operator dependent, the real benefit of echocardiography is the visualisation of ventricular function, wall motion abnormalities and cardiac filling as well as the ‘real-time’ guidance of fluid therapy in acute, critical haemodynamic situations. Moreover, echocardiography is of invaluable practical use as diagnostic tool (for example the detection of papillary muscle rupture, pericardial tamponade or dissection of the ascending aorta).
Dynamic preload parameters

Stroke volume variation (SVV) and pulse pressure variation (PPV) occur due to cyclic changes of intra-thoracic pressure induced by inspiration and expiration during mechanical ventilation (Figure 2A). SVV and PPV have been recognized as an interesting concept for guiding fluid replacement therapy more than 20 years ago. Only since the introduction of the minimally invasive haemodynamic monitoring devices based on pulse wave analysis has automated quantification of this phenomenon been possible (Figure 2B). The method appears to visualise the individual cardiac response (changes in stroke volume) related to myocardial contractility due to diastolic volume loading. In presence of hypovolaemia, large stroke volume variations can be observed and the preload dependence of left ventricular function is pronounced, that is the ventricle operates on the ascending limb of the Frank-Starling curve. During volume expansion, there is a right-ward shift of left ventricular function on the Frank-Starling curve, which corresponds to the observed decrease of stroke volume variation (Figure 2C). Both parameters have been used to assess fluid responsiveness and have been shown in a number of investigations to be sensitive in predicting the ventricular response to fluid administration, that is - the detection of fluid responders [18, 19]. However, alteration of vasomotor tone may influence PPV more than SVV. Moreover, it is crucial to realise, that this dynamic preload assessment is only reliable in fully sedated, mechanically ventilated patients with a relatively high tidal volume. Finally, a regular heart rhythm is mandatory. In the presence of these limitations the ‘passive leg raising concept’ can be applied instead. This concept relies on the response of stroke volume to an internal fluid shift induced by a modified Trendelenburg position and has shown to reliably predict fluid responsiveness [20].

Figure 2

A. Pulse pressure and stroke volume variation (SVV and PPV); B. Calculation of SVV and PPV; C. Virtual Frank-Starling curve resulting from an individual patient’s response to volume administration (change of EDV) on SV and SVV. δ = changes related to volume administration, EDV = end-diastolic volume, PP = pulse pressure, PPV = pulse pressure variation, SV = stroke volume, SVV = stroke volume variation
Modular stepwise monitoring concept

All of the preceding minimally invasive monitoring techniques can be integrated in a modular stepwise monitoring concept (Figure 3). Haemodynamic assessment of critically ill patients can range from invasive blood pressure measurement and central venous catheterisation including the interpretation of blood gas analysis (with the measurement of lactate levels and central venous oxygenation) to the use of a pulmonary artery catheter. The indications for the next step in the concept may be determined by the patient’s response to an initial fluid trial, but may also be based on the patient’s physical status, related cardiovascular or respiratory co-morbidities and, in the peri-operative setting, by the performed intervention. Moreover, limitations of minimally invasive haemodynamic monitoring systems have to be considered and in selected situations a pulmonary artery catheter may be mandatory. Transthoracic or transoesophageal echocardiographic evaluation of an uncertain haemodynamic situation is a cornerstone in this concept.

**Figure 3**

**Level 1**
- Monitoring: arterial line, central venous catheter
- Targets:
  - MAP: $\geq 65$ mmHg
  - Diuresis: $\geq 1$ ml kg$^{-1}$ h$^{-1}$
  - Lactate: $\leq 4$ mmol l$^{-1}$
  - CVP: $\leq 8$-12 mmHg
  - ScvO$_2$: $\geq 70$
  - Hb: $\geq 8-10$ g l$^{-1}$

**Consider level 2 or 3 if**
- Diuresis: $< 1$ ml kg$^{-1}$ h$^{-1}$
- Lactate: $> 4$ mmol l$^{-1}$
- ScvO$_2$: $< 70$
- despite early initial fluid trial

**Level 2**
- Monitoring: minimal invasive HD monitoring, continuous ScvO$_2$ catheter
- Targets:
  - CI: $> 2.5$ l min$^{-1}$ m$^{-2}$
  - SVV: $< 12$
  - PPV: $< 12$

* Consider level 3 if:
- Left/right heart failure
- Pulmonary artery hypertension
- Contraindications/limitations of minimal invasive HD monitoring

**Level 3**
- Monitoring: Pulmonary artery catheter
- Targets:
  - CI: $> 2.5$ l min$^{-1}$ m$^{-2}$
  - PCWP: $= 12-15$ mmHg
  - ScvO$_2$: $> 65$
  - CEDVI: $= 110-130$ ml m$^{-2}$

**Echocardiographic evaluation**

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**Modular stepwise monitoring concept**

CI = cardiac index, CVP = central venous pressure, CEDVI = continuous end-diastolic volume index, EVLWI = extravascular lung water index, GEDVI = global end-diastolic volume index, HD = haemodynamic, HR = heart rate, MAP = mean arterial pressure, ScvO$_2$ = central venous oxygenation, SvO$_2$ = mixed venous oxygenation, PCWP = pulmonary capillary wedge pressure, PPV = pulse pressure variation, SVV = stroke volume variation. *Level 2: parameters assessed by the PiCCOplus system using transpulmonary thermodilution, *Level 3: parameters assessed by a specific pulmonary artery catheter (CCOmbo CCO/SvO2/CEDV catheter 774HF75 Edwards Lifescience LLC, Irvine, USA).
Summary

Different minimally invasive haemodynamic monitoring systems can be reliably used in daily practice and have replaced the pulmonary artery catheter in many clinical settings. However, the specific properties and limitations of these systems have to be considered. Devices based on pulse wave analysis may have the best potential for routine continuous cardiac output measurement. In addition, this technique allows the assessment of fluid responsiveness through the measurement of pulse pressure or stroke volume variation. Minimally invasive monitoring techniques may be integrated in a modular stepwise concept ranging from invasive blood pressure monitoring to the use of the pulmonary artery catheter based on an initial fluid response, patient related factors and limitations of all monitoring systems. Echocardiographic evaluation has to be considered a clinical standard in the assessment of a critical haemodynamic situation.

Key learning points

- Minimally invasive haemodynamic monitoring systems, primarily devices based on pulse wave analysis can be reliably used in daily practice.
- They have replaced the clinical standard, the pulmonary artery catheter, in many clinical settings. However, based on the limitations of these minimally invasive systems and patient related factors the use of a pulmonary artery catheter may still be required.
- Apart from continuous cardiac output measurement the devices based on pulse wave analysis allow the assessment of fluid responsiveness through the measurement of pulse pressure or stroke volume variation (PPV and SVV). Alternatively the 'passive leg raising concept' can be applied in the presence of limitations for reliable PPV and SVV assessment.
- All haemodynamic monitoring devices can be integrated in a modular stepwise concept ranging from invasive blood pressure measurement to pulmonary artery catheter
- Echocardiographic evaluation has to be considered a clinical standard in the assessment of a critical haemodynamic situation.

References


