Cardiac output (CO) monitoring is an invaluable tool for management of critically ill patients in the intensive care units (ICU) and high-risk patients undergoing surgery.

Measurements of CO were not available until 1970, when Swan et al introduced the flow-directed balloon-tipped pulmonary artery catheter (PAC); this catheter is inserted at the bedside and is considered the gold standard for accurate CO measurements. Recently, minimally invasive and non-invasive alternative CO monitors have emerged that not only overcome the PAC’s invasive limitations, but are also able to guide fluid optimization, which has been shown to improve the outcome after major surgery.

This is a review of the characteristics of the PAC and compares it with other less invasive and non-invasive CO monitors currently available.

We will look at issues of accuracy, dependability, complications, limitations to use, the ability to give continuous readings and how these monitoring systems could be used to guide fluid status optimization.

The systems we will review include the following:

- **Pulmonary artery catheter (as the gold standard)**
- **LiDCO Plus™ (LiDCO Ltd, London, UK)**
- **LiDCO Rapid™ (LiDCO Ltd, London, UK)**
- **PiCCO Plus™ (Pulsion Medical Systems, Munich, Germany)**
- **The Edwards FloTrac™ sensor/Vigileo™ monitor (Edwards Lifesciences, Irvine, USA)**
- **Oesophageal Doppler Ultrasound**
- **Finometer™ (Finapres Medical Systems, Amsterdam, Netherlands)**
- **Nexfin™ (Bmeye B.V., Amsterdam, Netherlands)**

The PAC involves introducing a balloon-tipped catheter into the superior vena cava through one of the central veins, through the right side of the heart and into the pulmonary circulation. Inflation of the balloon would allow the catheter to float in the pulmonary circulation until it wedges in a distal branch of the pulmonary artery. Pulmonary capillary wedge pressure (PCWP) is then measured at the catheter tip. In addition, it could provide intermittent, accurate estimates of the central venous pressure (CVP), right-sided intracardiac pressures, pulmonary artery pressure (PAP), CO, systemic vascular resistance (SVR) and pulmonary vascular resistance (PVR). These indices are measured by using the Fick’s principle, which measures CO by the intermittent thermo dilution technique.

Since it was the first modality to measure the CO accurately, it gained immense popularity among anesthetists and intensivists. It was used as a diagnostic tool in critically ill patients, such as for differentiating between cardiogenic and non-cardiogenic pulmonary edema, evaluating pulmonary artery hypertension (PAH), atrial septal defects (ASD), ventricular septal defects (VSD), mitral regurgitation, cardiac tamponade and restrictive cardiomyopathy (RCM). In addition, it was found to be helpful in guiding fluid infusions, inotropes and vasopressor therapies in shock, heart failure, renal failure and cardiac surgery patients.

However, with increased use, various complications, such as thromboembolism, pulmonary valvular endocarditis, air embolism, pulmonary hemorrhage, pulmonary infarction and distal pulmonary artery rupture were recognized. In recent years, its usefulness has been questioned as many trials have shown conflicting results regarding both benefit and mortality. With the availability of less invasive hemodynamic monitoring tools, its use has significantly declined and is mostly limited to diagnosis and perioperative management of patients with PAH and intracardiac shunts.

**LiDCO Plus™** (LiDCO Ltd, London, UK)

The LiDCO Plus™ requires the insertion of an arterial line and a peripheral/central venous line.
It is a continuous CO monitor utilizing the lithium indicator dilution cardiac output (LiDCO™), and the pulse CO realtime technology (Pulse CO™).

The LiDCO™ measures the CO intermittently and accurately by using the indicator dilution technique, where intravenous lithium acts as the indicator (using the Fick’s principle as in PAC).

The Pulse CO™ measures mean arterial pressure (MAP), systolic blood pressure (SBP), diastolic blood pressure (DBP), heart rate (HR), stroke volume (SV) and CO continuously on beat-by-beat by analyzing the whole arterial waveform. It also has the advantage of monitoring the preload responsiveness parameters including the stroke volume variation (SVV) and the pulse pressure variation (PPV)17.

The CO measurements generated by the LiDCO™ component are used to calibrate the CO measurements obtained by the Pulse CO™ once every 8 hours. After calibration, the Pulse CO™ would provide a reliable, continuous beat-by-beat CO measurement. It is widely validated for its accuracy regarding CO monitoring17-22.

However, LiDCO Plus™ could not be used in patients weighing < 40 kg, pregnant and those on oral lithium medications. Its measurements are unreliable in patients receiving muscle relaxant infusions23,24. It is time-consuming, and staff would require training in order to perform the calibration.

**LiDCO Rapid™** (LiDCO Ltd, London, UK)

The LiDCO Rapid™ is a new monitor technically identical to the Pulse CO™ component of the LiDCO Plus™ monitor, only requiring the insertion of an arterial line. The LiDCO Rapid™ is compact, easily applied and does not require lithium calibration; therefore, it avoids the limitations of LiDCO Plus™. This device does not provide absolute estimates of the CO; however, it tracks the trend of change in flow and resistance, thus, providing continuous monitoring of the BP, HR, SV, CO and also preload responsiveness parameters (SVV and PPV).

**PICCO Plus™** (Pulsion Medical Systems, Munich, Germany)

This technology is similar in principle to the LiDCO Plus™. It requires the insertion of an arterial line and a central line. The PICCO Plus™ involves two separate components: the Stewart-Hamilton principle intermittent transpulmonary thermodilution (TPTD) technique and the pulse contour analysis.

The TPTD technique is used intermittently to obtain accurate estimates of the CO. Cold saline is injected into the superior vena cava via a central venous line, and the change in temperature downstream is measured in the femoral artery via a femoral arterial catheter.

The CO measurements generated by the TPTD component are used to calibrate the CO measurements obtained by the pulse contour once every 8 hours. After calibration, the pulse contour would provide a reliable continuous beat-by-beat CO measurement. The PICCO Plus™ is widely validated for its accuracy25.

In addition to the parameters assessed by the LiDCO Plus™, the PICCO Plus™ measures the cardiac function index (CFI), global end-diastolic volume (GEDV), Global ejection fraction (GEF), intra-thoracic blood volume (ITBV) and extra-vascular lung water (EVLW). These parameters could help the clinician at the bedside to determine whether the pulmonary edema is of cardiogenic origin or not, the volume of blood in the cardiac chambers (which reflects the volume status of the patient) and the amount of pulmonary edema fluid26-31.

**Edwards FloTrac™ sensor and Vigileo™ monitor** (Edwards LifeSciences, Irvine, USA)

This is a minimally invasive, reliable, continuous CO monitoring device which requires only a peripheral arterial line (PAL). It provides accurate measurements of CO, without the necessity of calibrating against other CO monitoring techniques. The FloTrac™ sensor is connected to the patient’s PAL. The Vigileo™ monitor processes arterial signals obtained from the FloTrac™ sensor to generate an accurate estimate of the CO, SV and SVV that are displayed at 20-second intervals. In addition, connecting the monitor to a central venous catheter could provide estimates of the SVR35,36. Limitations to its use include the presence of aortic regurgitation or irregular pulse. In addition, a ventricular assist device or an intra-aortic balloon pump (IABP) may affect the accuracy of the FloTrac™ readings37.

**Esophageal Doppler Ultrasound**

A flexible probe containing a Doppler ultrasound in its tip is inserted orally into the esophagus and is positioned at the mid-thoracic level. It measures the flow of blood in the descending aorta and estimates the CO by multiplying the velocity of the blood flow with the cross-sectional area of the aorta. It measures the SV, CO and SVR35-36.

**Finometer™** (Finapres Medical Systems, Amsterdam, Netherlands)

The Finometer™ is a non-invasive, beat-by-beat hemodynamic monitor that generates a continuous pulse waveform using a finger cuff, which is then computed to provide continuous blood pressure and CO measurements. The continuous BP measurements are further calibrated against the brachial arterial pressure35-40.

This device is accurate regarding BP monitoring and tracking the trends of change in CO. It could not be used in conditions associated with hypoperfusion of the extremities and in patients below six years of age41-44.

**Nexfin™** (BMEYE B.V, Amsterdam, Netherlands)

The Nexfin™ is similar in principle to the Finometer™. It also measures the hemodynamics continuously through a finger cuff with a similar level of accuracy45. The Nexfin™, compared to the Finometer™, is smaller in size and takes less time to operate. It also does not require physical calibration against the brachial arterial pressure. A built-in computational algorithm is used for the purpose. A summary of the different methods of calculating CO could be seen in table 1.
Table 1: Comparison of Hemodynamic Monitoring Techniques

<table>
<thead>
<tr>
<th>Technology</th>
<th>Invasiveness*</th>
<th>Principle</th>
<th>Major Parameters Measured</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Reliability</th>
<th>Proposed Area of Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulmonary Artery Catheter</td>
<td>3</td>
<td>Thermodilution</td>
<td>CVP, PCWP, CO, SVR</td>
<td>Measures PCWP</td>
<td>Invasive, Complications, Requires expertise</td>
<td>Validated for Accuracy</td>
<td>Cardiac surgery, Contraindications for less invasive modalities</td>
</tr>
<tr>
<td>LiDCO Plus™</td>
<td>2</td>
<td>Calibrated Pulse waveform analysis</td>
<td>CVP, CO, SVR, SVV, PPV</td>
<td>Accuracy</td>
<td>Lithium injection, Pregnancy, Lithium therapy, Muscle relaxant infusions, Weight &lt; 40 kg, Does not measure intrathoracic volume indices</td>
<td>Validated for Accuracy</td>
<td>Routine hemodynamic monitoring, Shock</td>
</tr>
<tr>
<td>LiDCO Rapid™</td>
<td>1</td>
<td>Uncelebrated Pulse waveform analysis</td>
<td>CO, SVV, PPV</td>
<td>Lithium not required, Trend Monitor</td>
<td>Inaccurate</td>
<td>Follows the trends of change in CO</td>
<td>Routine hemodynamic monitoring, Goal-directed fluid management</td>
</tr>
<tr>
<td>PiCCO Plus™</td>
<td>2</td>
<td>Calibrated Pulse waveform analysis</td>
<td>CVP, CO, SVR, SVV, PPV, GEDV, EVLW, PVPI, CFI, GEF</td>
<td>Accuracy, Measures Intrathoracic volume indices</td>
<td>Invasive, Unreliable in arrhythmias</td>
<td>Validated for Accuracy</td>
<td>Routine invasive hemodynamic monitoring, Multifactorial shock, Quantify pulmonary edema</td>
</tr>
<tr>
<td>Edwards FloTrac™/Vigileo™</td>
<td>1</td>
<td>Uncelebrated Pulse waveform analysis</td>
<td>CO, SVV, PPV</td>
<td>Built in calibration, Acceptable accuracy</td>
<td>Does not measure intrathoracic volume indices</td>
<td>Validated for Accuracy</td>
<td>Routine hemodynamic monitoring, Shock</td>
</tr>
<tr>
<td>Oesophageal Doppler</td>
<td>1</td>
<td>Doppler Ultrasound</td>
<td>CO, SVV</td>
<td>Accuracy, Does not require invasive lines</td>
<td>Training required, Limited parameters?</td>
<td>Validated for Accuracy</td>
<td>Routine hemodynamic monitoring, Goal-directed fluid management</td>
</tr>
<tr>
<td>Finometer™</td>
<td>0</td>
<td>Uncelebrated Pulse waveform analysis</td>
<td>BP, CO, SVR</td>
<td>Rapid assembly, Easy to use, No invasive lines</td>
<td>Requires brachial arterial pressure calibration, Not reliable in shock or arrhythmias (limited utility in ICU)</td>
<td>Follows the trends of change in CO</td>
<td>Perioperative hemodynamic monitoring</td>
</tr>
<tr>
<td>Nexfin™</td>
<td>0</td>
<td>Uncelebrated Pulse waveform analysis</td>
<td>BP; CO; SVR</td>
<td>Rapid assembly, Easy to use, Does not require invasive lines, Compact machine, Brachial arterial pressure calibration not required</td>
<td>Not reliable in shock or arrhythmias (limited utility in ICU)</td>
<td>Follows the trends of change in CO</td>
<td>Perioperative hemodynamic monitoring</td>
</tr>
</tbody>
</table>

BP: blood pressure  
CVP: central venous pressure  
GEDV: global end-diastolic volume  
SVR: systemic vascular resistance  
PVPI: pulmonary vascular permeability index  
* 0: non-invasive; 1: minimally invasive; 2: invasive; 3: highly invasive  
CO: cardiac output  
SVV: stroke volume variation  
CPI: cardiac function arrest  
GEF: global ejection fraction  
PPV: pulse pressure variation  
EVLW: extravascular lung water  
PCWP: pulmonary capillary wedge pressure

**CONCLUSION**

A variety of CO monitors exists with different features regarding the degree of invasiveness, accuracy, limitations, range of hemodynamic variables provided and the ability to guide for fluid optimization.

CO monitoring with a PAC should be kept as a last resort because it is highly invasive. PiCCO Plus™, LiDCO Plus™ and the Edwards FloTrac™/Vigileo™ systems are suitable, less invasive alternatives that provide accurate estimates of the CO. LiDCO Rapid™ is a trend CO monitor (tracks the trend of change in CO values) that in contrast with the LiDCO Plus™, saves the hassle of lithium calibration and could be used for fluid optimization guiding. Non-invasive finger arterial CO monitoring using Nexfin™ or Finometer™ devices could provide reliable trend CO monitoring by just using a finger cuff in non-shocked states.

Up to date, there is no such thing as an ideal monitor that could be employed in all clinical scenarios. The choice of a monitor should be tailored upon availability and the patient’s condition.

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REFERENCES


