# CARDIAC OUTPUT MONITORS

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Cardiac output can be measured in a number of ways, from simple clinical observation to invasive haemodynamic monitoring. Estimation of cardiac output has an important role in patient management during anaesthesia and critical care. This ranges from monitoring the predictable changes of anaesthetic induction to assessing cardiac output during anaesthesia for major surgery or resuscitation of trauma victims and critically ill patients. Advanced monitoring techniques are often used when clinical signs are difficult to interpret.

## DEFINITIONS

**Cardiac output** is the volume of blood ejected from each of the ventricles of the heart per minute, and is therefore the product of stroke volume and heart rate. The unit of cardiac output is l/min. **Cardiac index** is the cardiac output of a patient referenced to their body surface area and has units of l/min/m$^2$. The stroke volume is the volume of blood ejected by each contraction of the ventricle and is determined by the **preload**, the **contractility** and the **afterload**.

**Preload** describes the tension developed in the ventricle wall at end-diastole (i.e. at maximal filling just prior to contraction). This tension is difficult to measure and end-diastolic pressure is taken as a surrogate measurement.

**Contractility** refers to the amount of work the heart can generate, at given levels of preload and afterload, and is estimated by the maximum rate at which the ventricle can generate a change of pressure over time. Inotropy is used to explain an increase in the work done by the heart, that is independent of heart rate, preload and afterload.

**Afterload** is the tension that needs to be generated in the ventricle wall in order to eject blood into the arterial system during systole. This is largely determined by the resistance of the arterial system – **the systemic vascular resistance** (SVR). It is calculated by:

$$SVR = \frac{\text{mean arterial pressure (mmHg)} - \text{central venous pressure (mmHg)}}{\text{cardiac output (l/min)}} \times 8$$

(Recall that Ohm's Law describing electrical resistance is analogous to this: V=IR)

The units of the SVR are dyne second/cm$^5$.

The cardiac output is determined by, and therefore can be manipulated by, alterations to the **heart rate** or **rhythm**, the **preload**, the **contractility** and the **afterload**.

Cardiac output informs us of global blood flow and therefore oxygen delivery (the product of cardiac output and blood oxygen content) and does not describe delivery of oxygen to each organ, whose function must be assessed individually.

An appreciation of how information is measured and derived using a cardiac output monitor is essential in order to use the information accurately and appropriately.

Thorough assessment of a patient's clinical status strongly influences interpretation of the measurements made. For example, cardiogenic shock and obstructive shock due to tamponade will both give a low cardiac output, but can be differentiated by the patient's clinical signs. There is a wide variability between practitioners in the measurement and interpretation of cardiac output data, using the various techniques that are currently available. For this reason, clear evidence that they benefit patient outcome is difficult to obtain.

## MEASURING CARDIAC OUTPUT

The interpretation of data from invasive haemodynamic monitoring is made in light of the clinical examination. Heart rate, blood pressure, pulse strength at various sites, patient colour, respiratory rate and core to peripheral temperature gradient all give an indication of a patient's haemodynamic status. A patient's ability to compensate for a haemodynamic insult is highly variable, depending on age, premorbid status and other comorbidities. An example is the rise in the diastolic pressure in early hypovolaemic shock, associated with peripheral vasoconstriction, that is usually only seen in young fit individuals. In addition, clinical parameters such urine output, capillary refill time and cognitive function give a guide to end organ perfusion.

Measurement of lactate and base deficit in arterial blood and, in particular, the trend of these variables over time gives non-specific information about a patient's organ perfusion. The oxygen saturation in central venous blood ($S_{CV}O_2$) also gives a global indication of haemodynamic status, is useful in directing fluid therapy[1] and is a reliable surrogate of mixed venous oxygen saturation (see under pulmonary artery flotation catheters, PAFC - below).

**Oesophageal Doppler**

*Theory of technique*

A Doppler probe is inserted into the distal oesophagus and is directed to measure the blood flow in the descending aorta at about 35 to 40cm from the incisors. The monitor calculates cardiac output using descending aorta diameter, which is either obtained from an age-related nomogram or measured directly (in newer machines). The ventricular ejection time corrected for heart rate (the corrected flow time, FTc) gives an indication of preload, and the peak flow velocity (PV), estimates the contractility of the ventricle. Newer probes incorporating M-mode Doppler measurement may improve accuracy and reliability.

*Practical application*

The technique is straight-forward, easily learned, and relatively non-invasive. The disposable probes are easy to insert, however some expertise must be gained in recognition of intracardiac and pulmonary artery signals. Continuous measurement is possible, although frequent positional adjustments are needed. Some user variability is inevitable.

*Advantages*

The system is small and relatively portable, but requires an electrical power source. The calculated cardiac output correlates well with that of the PAFC. The cardiac output data is best used as a trend to guide the effectiveness of interventions such as fluid challenges. Paediatric probes are available.

*Disadvantages*

Few complications have been described, but oesophageal injury is possible. Oesophageal Doppler use is contraindicated in the presence of oesophageal varices. When patients are positioned on their side for surgery, movement of the mediastinum with ventilation (particularly during thoracotomy) makes reliable probe positioning impossible. The probe is poorly tolerated in awake patients, although thinner nasal probes are available.

**Transoesophageal Echocardiography (TOE)**

*Theory of Technique*

A specialized oesophageal probe is inserted into the oesophagus, providing real-time, high resolution ultrasound images. Both qualitative and quantitative values for cardiac output are available, using a two dimensional cross-sectional area measurement, a Doppler flow measurement at that point and the heart rate.

*Practical application*

A multiplane transducer is inserted into the oesophagus and stomach, where various standardized views are gained.

*Advantages*

A large amount of haemodynamic information is available beyond just cardiac output.

*Disadvantages*

The probes are still expensive and the machinery is large and bulky. Various levels of examination skill are required and these take time and resources to learn. A full study can take over twenty minutes. Some form of local pharyngeal anaesthesia or sedation is required to tolerate the probe. There is a risk of trauma from the probe, although the risks are low in patients with no oesophageal disease. The probes generate a degree of heat and are therefore not suited to continuous measurement. As the technology advances and costs decrease, TOE may find more applications in theatre and the ICU.

**Lithium Dilution Monitoring – Lidco and PulseCO and Lidcoplus**

*Theory of Technique*

This technique combines the techniques of lithium dilution (Lidco and Lidcoplus) and pulse contour analysis (PulseCO). A small dose of lithium is injected into a peripheral vein and an ion selective electrode is attached to a peripheral arterial line. The area under the curve of a plot of lithium concentration against time allows accurate calculation of the cardiac output. This information is then used to calibrate the PulseCO which provides 'beat-to-beat' cardiac output measurement, using pulse contour analysis of the arterial waveform.

*Practical Application*

The convenience of this system is that it uses catheters which are likely to be already in place or are likely to be needed in a critically-ill patient. The system requires some familiarity to set up, but is relatively quick. The total dose of lithium is small and is clinically insignificant. Calibration is recommended every 8 hours, or after any significant change in the patient's clinical condition.

*Advantages*

A figure for stroke volume variation is produced and provides an indicator of volume responsiveness to fluid therapy.

*Disadvantages*

The system cannot be used for patients taking lithium and those who have recently received vecuronium or atacurium. The monitor performs poorly in the presence of atrial fibrillation and other tachyarrhythmias. The system is prone to technical difficulties related to damping and resonance within the measurement system.

**Thermodilution Pulse Contour Monitoring – PiCCOplus**

*Theory of Technique*

This technique uses arterial pulse contour analysis (PulseCO) to measure cardiac output and correlates well with the PAFC (below). 'Stroke volume variation' (the mean difference between the highest and lowest arterial pressure wave peaks over 30 seconds) gives and indication of the blood volume status of the patient.

The system is calibrated using intermittent cold transpulmonary thermodilution, where cold fluid is injected through a central venous catheter and traverses the pulmonary circulation. A curve of blood thermodilution is measured in a systemic artery and, in addition to cardiac output, other data is derived. The calculated extra-vascular lung water (EVLW) gives an indication of the water content of the lungs and is increased in left ventricular failure, pneumonia and sepsis. The normal range is 3-10ml/kg and values greater than 14ml/kg are associated with an increased mortality. The intra-thoracic blood volume index gives an indication of blood volume status (normal value 850-1000 ml/m$^2$).

PiCCOplus replaced the original PiCCO machines in 2002 and have improved displays, automated features and allow the use of room-temperature injectate for calibration.

*Practical Application*

A specialised arterial catheter, inserted into either the brachial artery or femoral artery is required, along with either a thoracic or femoral central line. Some centres use treatment algorithms based on these variables, to guide use of fluid and inotropes in an attempt to maximize intravascular filling, without increasing the EVLW and causing pulmonary oedema. The use of EVLW as an endpoint for resuscitation has not been validated.

*Advantages*

The arterial line can be simultaneously used for blood pressure monitoring and for blood sampling. The system is relatively easy to set up and calibrate.

*Disadvantages*

The arterial catheter is relatively large gauge and expensive, although few complications have been reported. Recalibration is required every 12 hours or following a major change in the patient's clinical condition.

**Pulmonary artery flotation catheters (PAFC)**

Dye dilution is the gold standard for measurement of cardiac output, but is impractical for clinical practice. Thermodilution using a PAFC uses similar principals. However, use of PAFCs has been hotly debated in recent years and use in the United Kingdom is currently low. The recent PAC-Man trial showed no improvement in survival for patients randomised to have a PAFC inserted, compared to those who were not[2].

*Theory of technique*

A flexible balloon-tipped, flow-directed catheter is inserted via a wide-bore catheter sited in a central vein. The catheter is 'floated' through the right atrium and ventricle to enter the pulmonary trunk. From this position it can intermittently be 'wedged' in one of the pulmonary arteries.

The catheter allows a number of variables to be measured and others to be derived.

The measured variables are pulmonary artery pressure, pulmonary capillary wedge pressure (PCWP), cardiac output and mixed venous oxygen saturation. Traditionally, cardiac output is measured by thermodilution of 10ml iced water injected through the proximal lumen of the catheter. Measurement of the fall in blood temperature against time from injection, as the cooled blood passes the distal end of the catheter allows calculation of the cardiac output of the right (and therefore the left) ventricle. Semi-continuous cardiac output measurements are now available which use warming coils in the right ventricular portion of the catheter. A sequence of heating and recording gives an averaged cardiac output after a short delay.

*Practical Application*

The catheter is inserted with reference to the wave-forms seen (see figure 1). Insertion may take several attempts and is more difficult in patients with a low cardiac output.

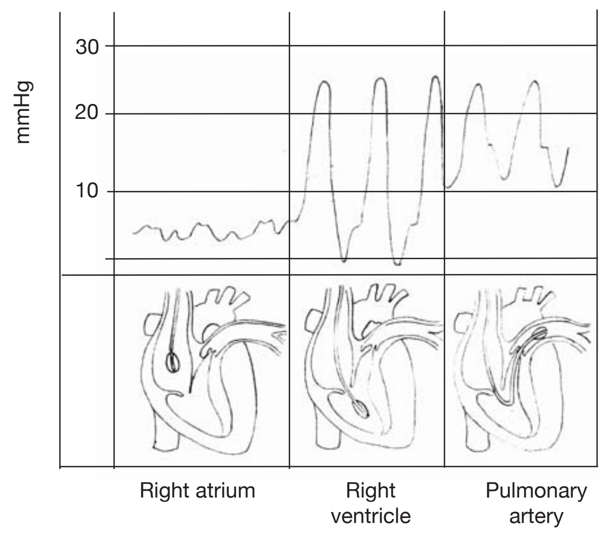


Figure 1: Pulmonary artery catheter pressure waveforms

*Advantages*

Measurement of cardiac output is probably the most reliable of the variables measured using a PAFC and is therefore a valuable guide to interventions introduced to increase cardiac output. The numerous assumptions made in interpretation of the PCWP as a measure of preload or ventricular filling make the PCWP a less reliable measurement. Some units use the mixed venous oxygen saturation, measured using a sample taken slowly from the pulmonary artery aperture of the catheter, as a further indicator of a patient's overall tissue perfusion.

*Disadvantages*
This invasive monitor is associated with a number of potential complications. The PAC-Man study recorded non-fatal complications in 10% of insertions. In addition to the usual complications of central venous access, PAFCs may cause arrhythmias, heart block, rupture of the right heart or pulmonary artery, thromboembolism, pulmonary infarction, valvular damage and endocarditis.

**Partial $CO_2$ rebreathing Fick monitoring or NICO**
*Theory of Technique*
The NICO monitor uses a rearrangement of the Fick equation for $CO_2$ elimination. It is relatively non-invasive, although it can only be used for patients who are intubated.

*Practical Application*
A small, disposable plastic loop is placed between the ventilator Y-piece and the patient. It contains a rebreathing valve, a differential pressure pneumotachograph and mainstream infrared $CO_2$ analyser. Only one calibration is required for setup. A bedside computer induces episodes of re-breathing every 3 minutes, each lasting 50 seconds. This raises the end-tidal $CO_2$ by 0.4-0.6 kPa. By a rearrangement of the Fick principle for $CO_2$ elimination, a value for the total pulmonary blood flow (i.e. cardiac output) can be calculated. Assumptions are made about the shunt fraction and $PaCO_2$ being equal to end-tidal $CO_2$.

*Advantages*
These include the easy setup. Various pulmonary volumes, such as dead space are available.

*Disadvantages*
Although sold as non-invasive it requires the patient to be ventilated, and preferably have access to arterial blood measurements. Its main area of use has been in cardiac surgical patients and in relatively stable ICU patients.

**Thoracic Bioimpendance**
*Theory of technique*
The technique depends on the change in bioimpedance of the thoracic cavity during systole.

*Practical application*
A series of ECG type electrodes are placed on the thorax and neck. A small, non-painful current is passed and measurements made.

*Advantages*
Derived stroke volume is calculated and cardiac output computed. Thoracic fluid content is also measured. This is the least invasive method of cardiac monitoring and was initially conceived for space flight monitoring.

*Disadvantages*
It is not useful with significant aortic regurgitation and open chest procedures. The correlation with PAFC in critically ill patients is inconsistent.

**SUMMARY**
At present no perfect system exists, but each of the monitors above, can aid the clinician when uncertain about the patient's condition. The information gained must be understood in the context of how it was gathered and interpreted alongside clinical evaluation of the patient. Only then can it be safely used to guide subsequent therapeutic strategies.

**Further reading**
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4.Kuper M, Soni N. Non-invasive Cardiac Output Monitors. CPD Anaesthesia (2003); 5: 17-25.

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