

Measuring cardiac output

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Table 1 Comparison of the methods of measuring cardiac output

	Catheterisation of pulmonary artery	Central venous cannulation	Arterial cannulation	Continuous real-time measurement possible	Totally non-invasive	Validated by trials in all groups of patients
Pulmonary artery catheter	Yes	Yes	No	Yes	No	Yes
Lithium dilution	No	No	Yes	No	No	Yes
PiCCO	No	Yes	Yes	Yes	No	Yes
Pulse CO	No	No	Yes	Yes	No	No
Oesophageal Doppler	No	No	No	Yes	No	? Yes
Transoesophageal echo	No	No	No	No	No	Yes
NICO	No	No	No	Yes	Yes	Yes

Cardiac output is defined as the volume of blood ejected from the left ventricle per minute; it is determined by heart rate, myocardial contractility, pre-load and after-load. Inadequate cardiac output, even with adequate haemoglobin concentration and oxygen saturation, will result in cellular hypoxia and eventual loss of cellular viability. It is known that a persistently low cardiac output predicts poor outcome after major surgery. Knowledge of a patient's cardiac output can have a significant bearing upon peri-operative management but its estimation using clinical parameters is unreliable. The ideal device would be continuous, automated, non-invasive, operator independent, cost-effective, validated and self-calibrating. However, such a device is not currently available.

This article explores the methods available that may be appropriate for use in a peri-operative or intensive care setting (Table 1). Knowledge of their function is required to ensure reliable data collection and interpretation. The accuracy of new devices has been determined by comparison with the thermodilution technique using a pulmonary artery

flotation catheter which is regarded as the gold standard.

Clinical assessment of cardiac output

Clinical parameters may be used to infer cardiac output during circulatory disturbance. The normal distribution of cardiac output is altered during low output pathological states allowing clinical detection of reduced organ perfusion. Poor cerebral perfusion leads to agitation, confusion and eventually unconsciousness. Increasing metabolic acidosis from inadequate tissue perfusion produces a rapid respiratory rate with large tidal volumes. Reduction in urine output is progressive leading to anuria.

Cardiac output is a measure of flow and not pressure. Blood pressure measurements have been shown to correlate poorly with changes in cardiac output. However, narrowing of the pulse pressure may be associated with decreased stroke volume. Hypotension resulting from a low cardiac output is often an ominous sign.

Skin perfusion is a clinically useful sign. Following cutaneous pressure on a digit for 5

Key points

Clinical parameters are often a poor predictor of cardiac output.

Cardiac output can be measured using invasive or non-invasive methods.

Thermodilution is considered as the gold standard.

Indirect techniques allow improved management of those patients unsuitable for invasive monitoring.

Presently, there is no ideal method of measuring cardiac output in the clinical setting.

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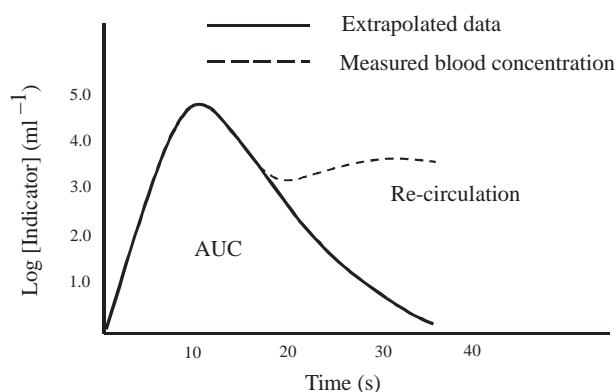


Fig. 1 Determination of cardiac output by indicator dilution.

sec, reperfusion of the capillary bed should occur within 2 sec. Progressive prolongation of the capillary refill time is seen with reducing cardiac output; the skin becomes progressively cold, pale and mottled. Although capillary refill is a reproducible sign, interpretation may be altered by ambient or patient temperature and pharmacological therapy. Conversely, high cardiac output states may manifest as warm peripheries and bounding peripheral pulses.

The difficulty and inaccuracy of quantifying cardiac output using clinical parameters has been a significant driving force in the development of so many different monitoring techniques.

Pulmonary artery flotation catheter

For the past 30 years, the pulmonary artery flotation catheter (PAFC) has been the main-stay of haemodynamic monitoring for the critically ill and cardiovascularly unstable. It was initially used to measure intracardiac pressures. The application of the Fick principle provides an accurate and reproducible measure of cardiac output. The Fick principle, based upon the conservation of mass, states that the amount of a substance taken up by an organ (or whole body) per unit time is equal to the arterial minus venous concentration of the substance multiplied by blood flow. Mixed venous samples provided by the PAFC allow arteriovenous oxygen content difference to be calculated. Oxygen consumption is calculated by spirometry.

Development of dye dilution and thermodilution techniques increased the clinical usefulness of the PAFC. For dye dilution, a known quantity of dye (normally indocyanine green) is injected into the pulmonary artery and timed arterial samples are analysed using a photo-electric spectrometer. Plotting the

concentration of dye against time on a semi-logarithmic plot (with extrapolation of the straight line created to correct for dye re-circulation) allows calculation of cardiac output by knowledge of the mass of injectate used and the area under the extrapolated curve (Fig. 1). The thermodilution technique is easier to perform and the most commonly used method presently. A known volume of cold saline is injected via the proximal PAFC port into the right atrium; the change in temperature is measured by a thermistor at the catheter tip located in the pulmonary artery. Computer analysis of the temperature change – time curve allows a repeatable calculation of cardiac output. However, the accuracy of the thermodilution technique can be influenced by various factors:

1. Right and left ventricular output may differ in the presence of a cardiac shunt.
2. Tricuspid or pulmonary valve regurgitation can cause underestimation of cardiac output.
3. Variations in blood temperature affect measurements, *e.g.* after cardiopulmonary bypass, intravenous fluid administration.
4. Positive pressure ventilation produces beat-to-beat variations in right ventricular stroke volume during the respiratory cycle. Measured cardiac output will depend on the timing of the bolus injection.

Recent advances in technology have allowed the development of continuous cardiac output monitoring by the use of a random sequence of temperature changes generated by a heating coil within the pulmonary artery catheter which is located in the right ventricle (CCO_{mb}, Edwards Lifesciences). Fractional changes in temperature detected distally are used to compute cardiac output in real time (Vigilance, Edwards Lifesciences). Other pulmonary artery catheters are available which utilise the principle of mass heat-transfer. They obtain their data from the measured amount of energy required to maintain a thermistor, located in the right atrium, at 1°C above the measured blood temperature in the pulmonary artery (truCATH, BD Medical Systems). Delays in data acquisition prevent these systems from being truly real-time as there is an inherent delay in response to sudden flow changes. However, there is a reduced need for bolus injections and they provide a better average cardiac output over time compared with intermittent bolus techniques. Reduced demands on the time of carers and, possibly, earlier warning of changing haemodynamic conditions are advantages of these modern systems.

Complications of central venous cannulation and those more specifically associated with the use of the PAFC (*e.g.* arrhythmias, pulmonary infarction) limit the use of this technique. Furthermore, there is no conclusive evidence to date that it improves outcome in critically ill patients. However, this is the subject of an ongoing multicentre study.

Lithium dilution

Indicator dilution methods have been developed using lithium. Excluding subjects treated for mania, lithium chloride is a safe, non-toxic substance when injected in the measurement dose of 0.15 mmol. Plasma concentrations resulting from this can be accurately measured by an ion selective electrode located in the arterial line. Following a bolus injection, the cardiac output can be calculated from the area under the concentration–time curve allowing for re-circulation. Most commonly, this technique is employed in patients who have central venous access and studies have shown good correlation with PAFC data. Some work has demonstrated that administration of lithium by peripheral venous injection can produce reliable data without the need for central venous access.

Arterial waveform analysis

Cardiac output can be quantified without a PAFC. PiCCO (Pulsion Medical UK Ltd) calculates cardiac output continuously from pulse contour analysis of the aortic waveform via a femoral, brachial or axillary arterial catheter. This system requires central venous access to perform a transcardiopulmonary thermodilution cardiac output measurement for calibration (analysed by a thermistor present in the arterial catheter tip) but cannulation of the right heart or pulmonary artery is not required. The area under the measured waveform is analysed to derive ejection systolic area by identifying ventricular ejection and the appearance of the dicrotic notch (closure of the aortic valve). Beat-to-beat calculations are averaged over 30-sec cycles and displayed as a numerical value. Problems encountered with abnormal waveforms and arrhythmias may affect performance but available data show that PiCCO measurements correlate well with thermodilution techniques.

Combined lithium dilution and pulse contour analysis

A new continuous technique uses the lithium dilution method for initial calibration followed by a novel pulse contour algorithm to

determine beat-to-beat stroke volume from a mathematical analysis of the peripheral arterial waveform (PulseCO system, LiDCO Cardiac Sensors Ltd). The PulseCO system uses pulse contour analysis of a radial artery waveform providing continuous real-time cardiac output. Stroke volume and systemic vascular resistance can also be derived. Studies in intensive care and cardiac surgery patients have shown close correlation with dilution techniques but experience is limited in other clinical settings.

Fick partial rebreathing method

Application of the Fick principle in combination with the physiological elimination of CO₂ allows a totally non-invasive method of cardiac output quantification in intubated patients receiving positive pressure ventilation. The application of the Fick principle to CO₂ elimination can be expressed as:

$$Q = \frac{V_{CO_2}}{C_aCO_2 - C_vCO_2}$$

where Q is cardiac output, VCO₂ is CO₂ elimination and C_vCO₂ and C_aCO₂ are the CO₂ contents in the mixed venous and arterial blood, respectively. Expired gas from the lungs provides estimations of arterial CO₂, whilst end-alveolar CO₂ can be estimated by use of the CO₂ dissociation curve to relate it to the blood concentration.

Modification of these principles is used in the differential CO₂ Fick partial rebreathing method utilised by the NICO sensor. Inserted into the ventilator circuit between the patient and the Y connector is a pneumatically controlled rebreathing valve sited within a large bore tubing loop and a CO₂/flow sensor. Data are obtained by timed cyclical measurements of airway flow, pressure and concentration of CO₂. The rebreathing valve cycles through two phases. During baseline phase, flow is directed straight through the valve. However, during the second phase of rebreathing, positive pressure activates the valve to direct a volume of end-expired gas into the expandable large bore tubing loop. This end-exhaled gas is accumulated for inspiration during the patient's next breath. Rebreathing CO₂, thereby reducing the blood-alveolar gradient, reduces the CO₂ flux. This elevates arterial CO₂ content which re-stabilises during the next baseline phase. Comparison of the measurements taken during the rebreathing and the non-rebreathing periods allows the ratio of the change in CO₂ elimination and thereby cardiac output to be calculated. Recent studies have shown good correlation with thermodilution

methods in some patients, implying that this technique may be useful without the inherent risks of invasive techniques.

Thoracic electrical bioimpedance

The ejection of blood from the left ventricle into the ascending aorta is associated with changes in the electrical impedance of the thoracic cavity. A high frequency, low voltage alternating current is applied across the chest and sensed by electrodes placed at the neck and at the level of the xiphoid cartilage. Stroke volume and cardiac output can be derived using mathematical models to interpret alterations in thoracic impedance. Studies in healthy volunteers have produced results comparable with other methods. However, trials performed in patients have been unsuccessful in demonstrating reliable comparisons with thermodilution techniques. Advancing age, peri-operative fluid shifts, pulmonary oedema, myocardial ischaemia and electrical interference may cause errors.

Doppler ultrasound techniques

Doppler ultrasound can provide a non-invasive, continuous, real-time quantification of cardiac output. It allows for calculation of cardiac output from the velocity of blood flow in the descending aorta, as the frequency of the reflected ultrasound signal changes with velocity of flow. The change in frequency is proportional to the velocity and, when the cross-sectional area of the flow is known, cardiac output can be calculated. Blood flow velocity is calculated by the following equation:

$$V = \frac{2 F_o}{C F_d \cos\theta}$$

where V is blood velocity, F_o is the transmitted ultrasound frequency, C is a constant (velocity of ultrasound in blood) and F_d is the Doppler shift. Cosine of the angle of incidence of the ultrasound wave corrects for any misalignment of the Doppler beam. Underestimation of velocity becomes significant with an angle of incidence of $> 20^\circ$. Measurement can be made at the suprasternal notch (ascending aorta) and from the trachea or oesophagus (descending aorta). The latter technique is available as a device that corrects for redistribution of flow to the cranium and upper extremities.

The oesophageal Doppler probe is almost the same size as a standard oesophageal stethoscope. A Doppler transducer is fitted at the end of the probe and measures the descending aortic blood flow velocity. A second ultrasound M mode transducer

measures the aortic cross-sectional area directly. Stroke volume is then derived from the flow velocity, ejection time and aortic cross sectional area. It is important to note that, because the measurements are made in the descending aorta, it represents only 70% of the total cardiac output. So far, use of the oesophageal Doppler has been limited to intubated patients but, in future, a decrease in probe size may allow wider use. Following positioning and calibration, the oesophageal probe can provide a continuous, real-time assessment of cardiac output. Recent studies have produced variable results and some operator dependence has been noted.

Transoesophageal echocardiography

Transoesophageal echocardiography (TOE) is a sophisticated endoscopic probe which is placed in the oesophagus. It also uses Doppler ultrasound to measure cardiac output. The multiplane probe obtains images through a 180° scanning arc and can utilise multiple modalities of echo imaging. In addition to cardiac output measurement, it allows for the assessment of ventricular function, wall motion abnormalities during myocardial ischaemia, cardiac anatomy and valve function. Oesophageal Doppler probes (see above) cannot obtain this additional information.

Real-time echo images of left ventricular filling and ejection allows accurate qualitative evaluation of cardiac output. To quantify cardiac output with TOE, an accurate measurement of the velocity of blood flow across a specific valve (*e.g.* aortic) has to be made by Doppler. The area under the flow velocity curve or velocity time integral (VTI) represents a specific distance along which the column of blood is projected during one cardiac cycle. The VTI is, therefore, directly related to systolic function of the ventricle. It is also necessary to determine the specific cross-sectional area (CSA) of the conduit at the site of flow velocity measurement. This can be done with 2-dimensional echo to accurately trace the area of the open aortic valve. Flow velocity across the left ventricular outflow tract, pulmonary artery or aorta can also be used as long as the CSA across that specific conduit can be obtained. Cardiac output can now be calculated as follows:

$$VTI \text{ (cm)} \times CSA \text{ (cm}^2\text{)} = \text{Stroke volume (cm}^3\text{)}$$

$$\text{Stroke volume} \times \text{Heart rate} = \text{Cardiac output}$$

TOE is repeatable but not continuous; it is very dependent on operator skill. Some studies have indicated that, for 95% of the time, a properly performed TOE estimate of cardiac output

should be within 1 litre min^{-1} of the thermodilution measurement. However, others have shown that TOE has significant limitations as an accurate monitor of cardiac output. Transoesophageal echocardiography has been reviewed in more detail in this journal (see key references).

Key references

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See multiple choice questions 14–16.