Non-invasive cardiac output monitoring

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Summary Outcomes in the management of critically ill patients may be improved using goal-directed peri-operative haemodynamic monitoring. A conservative approach may no longer be acceptable but in view of the significant morbidity associated with balloon tipped flow directed pulmonary artery catheters a non-invasive approach would be preferable. In this review we consider the different non-invasive techniques available and discuss the advantages and disadvantages of each technique.

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Introduction

Management of cardiac output is an important part of the peri-operative management of high-risk surgical patients and of the management of the critically ill patient in Intensive Care. Cardiac output cannot be estimated reliably by physical examination or routine assessment and therefore some means of measurement is required (Eisenberg et al., 1984). In the late 19th century Adolph Fick described how the changes in the concentration of a substance dissolved in blood could be used as an indicator for determining the blood flow. The concept of determining blood flow over time (cardiac output) by measuring the dilution of a known substance in the blood has become known as the Fick principle. Historically indocyanine green was the dye that was used but this technique was never translated into clinical practice. The development of the pulmonary artery catheter using the thermodilution technique of cardiac output monitoring remain the most common approach in use today and is considered to be the "gold standard" approach to cardiac output monitoring. However, it is not without risk. Numerous complications of pulmonary artery catheters have been described and include damage to carotid and subclavian artery, pneumothorax, dysrhythmias, perforation of chamber of the heart, tamponade, valve damage, pulmonary artery rupture and catheter knotting (Boyd et al., 1983; Horst et al., 1984). Randomized controlled clinical trials relating to the usage of pulmonary artery catheters have not been undertaken and some studies suggest that the usage of these catheters may be related to an increase in mortality (Connors et al., 1996). Questions remain as to whether the mortality is as a result of complications of the catheters themselves as described above or as a result of the treatments initiated as a result of the measurements obtained.

New technology that computes cardiac output non-invasively and which is safe, reliable, reproducible and simple to use would have significant advantages over the use of pulmonary artery catheters. Alternative techniques currently avail-
able include oesophageal Doppler ultrasonography, transoesophageal echocardiography, thoracic electrical bioimpedance devices, lithium dilution and pulse wave analysis. All of these techniques are relatively non-invasive compared to the use of pulmonary artery catheters.

**Oesophageal Doppler ultrasonography**

Oesophageal Doppler monitoring measures blood flow velocity in the descending thoracic aorta. Using the change in frequency of an ultrasound beam as it reflects off a moving object (Doppler shift), blood flow velocity can be measured. If this measurement is then combined with an estimate of the cross-sectional area of the aorta which is derived from the patient’s age, height and weight it allows haemodynamic variables including stroke volume, cardiac output and cardiac index to be calculated. This method has the advantage of providing continuous measurements although the following three conditions must be met to guarantee accuracy:

1. the cross sectional area must be accurate;
2. the ultrasound beam must be directed parallel to the flow of blood;
3. the beam direction cannot move to any great degree between measurements.

Variations in these conditions lead to inaccuracies. Oesophageal Doppler derived cardiac output and stroke volumes have been compared with the thermodilution technique in a number of studies and the results from these studies range from poor correlation (Donovan et al., 1987; Siegel et al., 1991) to good agreement (Perrino et al., 1990; Roidi et al., 1999) (Fig. 1).

Oesophageal Doppler ultrasonography is a non-invasive technique which has been used successfully to direct intraoperative fluid administration (Mythen and Webb, 1995). The main problem with its use as a continuous cardiac output monitor relates to its precision which indicates the reproducibility of a measurement. It is operator dependant and it is very easy for the position of the probe to change between measurements which will reduce the precision of the monitor (Perrino et al., 1991). This in turn will reduce the correlation between oesophageal Doppler and other cardiac output monitoring techniques. The probe can be tolerated by an awake patient but is much more likely to require frequent repositioning and is therefore not ideal in these circumstances.

**Transoesophageal echocardiography**

This technique can be used to calculate stroke volume which can then be multiplied by heart rate to give a measurement of cardiac output. For the assessment of stroke volume two steps are necessary; the measurement of flow velocity and determination of area through which the flow is pushed forward. Flow velocity is calculated from the area under the Doppler velocity waveform which gives us the time velocity integral (TVI). This represents the distance a red blood cell is projected forward in one cardiac cycle. The second step is to measure the cross-sectional area of the vessel or heart chamber at the site of flow velocity management. This can be calculated from the diameter assuming a circular shape or determined by direct planimetry. Measurements can be performed at the level of the pulmonary artery, mitral valve or the aortic valve although studies have shown that it is very difficult to measure the diameter of the pulmonary artery which may explain the lower correlation between Doppler and thermodilution cardiac outputs. Multiplane technology has improved the accuracy. Measurement at the mitral valve is even more difficult because the shape and size of the valve changes during the cardiac cycle. The aortic valve is the third option for Doppler assessment which can be performed using transgastric or deep transgastric views. In the absence of aortic stenosis this method is the most accurate for cardiac output measurements (Poelaert et al., 1999). Studies have demonstrated good correlation with thermodilution cardiac output measurements providing that the mi-
Non-invasive cardiac output monitoring 105

Non-invasive cardiac output monitoring

Tracheal valve is competent (Ryan et al., 1992). Transesophageal echocardiography cannot be tolerated by an awake patient as a continuous cardiac output monitor and the probe has to be manipulated with care at all times to avoid esophageal damage.

Thoracic electrical bioimpedance

The concept of thoracic impedance waveform analysis was first introduced in 1966 by Kubicek (Kubicek et al., 1966). Impedance plethysmography is based upon determination of the pulsatile changes in resistance occurring during ventricular systole and diastole. Four electrodes are applied to the neck and thorax and a small electric current passed across the thorax. Impedance measurements are made using two thoracic electrode pairs. The first derivative of the impedance waveform \( \frac{dz}{dt} \) is related linearly to aortic blood flow. Changes in impedance correlate with stroke volume and allow stroke volume to be calculated using either Kubicek’s equation or the equation derived by Sramek (Sramek et al., 1983). Cardiac output can then be derived using stroke volume and ventricular ejection time. Electrode placement can be using a band array which is difficult to place and uncomfortable for the patient or a spot electrode array. Electrode placement is an important source of error. Other factors influencing bioimpedance measurements include intrathoracic fluid shifts and changes in haematocrit. Whilst offering clinicians a simple quick method to determine cardiac output with minimal patient risk, impedance plethysmography has not gained wide acceptance (Donovan et al., 1986). One of the reasons for this is the substantial degree of methodological diversity that exists with its use in that different electrode arrays and equations can be used and will produce widely differing results (Wolcjer et al., 1966).

Lithium dilution cardiac output

This relatively new indicator dilution technique which is minimally invasive, requiring only a venous line and an arterial catheter was first described in 1993 (Linton et al., 1993). The indicator is isotonic (150 mM) lithium chloride (LiCl) which is injected as a bolus via the venous line. This line can either be central or peripheral as this does not affect the accuracy of cardiac output measurements. The usual dose for an adult is 0.3 mmol which is a very small dose but adequate since ion-selective electrodes respond to percentage change in ion concentration and lithium is not normally present in the plasma. It is not metabolized and is excreted almost entirely in the urine. The clinical margin of safety, compared to the lowest clinical doses of lithium treated patients, is about a factor of 100. Overall no more than 10-20 boluses of lithium should be administered (Fig. 2).

The arterial plasma concentration is measured using a sensor which consists of a poly carbonate flow-through cell which contains a lithium-selective electrode. Arterial blood is sampled through this cell with a peristaltic pump which limits flow to 4 ml min\(^{-1}\). The voltage across the lithium selective membrane is related by the Nernst equation to plasma lithium concentration. It is measured using an isolated amplifier, digitized, analyzed and stored.

Cardiac output is calculated as

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\text{Cardiac output} = \frac{\text{LiCl dose} \times 60 \text{ area}}{(1 - \text{haematocrit}) \times \text{l min}^{-1}}
\]

where LiCl is the dose in mmol; area is the integral of the primary curve in mmol l\(^{-1}\) s which is the curve that would have been produced had the lithium only circulated once; haematocrit can be calculated as haemoglobin concentration (g dl\(^{-1}\)) divided by 34—this correction is needed because lithium is distributed in the plasma. Lithium dilution has been shown to be at least as accurate (Linton et al., 1997) or more accurate than (Kurita et al., 1997) bolus thermodilution. It has the added benefit of being simple to perform and safe and does not elicit any haemodynamic changes that are sometimes seen with injections of cold saline. Although the amount of lithium administered by the intravenous route in one measurement is much less than that administered by the oral route in the treatment of affective disorders, the side-effects of multiple injections over a short time should be investigated.

Pulse pressure analysis techniques of cardiac output monitoring

Insertion of an arterial catheter is considered a minimally invasive procedure that is widely used in critical care to facilitate obtaining frequent blood samples and the pulse pressure waveform for blood pressure assessment. Arterial pulse pressure waveform analysis can also be used for measuring beat to beat cardiac output. This method involves measuring the area under the systolic portion of the arterial pulse wave from the end of diastole to the end of the ejection phase, together with an individual calibration factor to account for individual vascular
impedance. Cardiac output determined by an arterial indicator dilution technique, is used for calibration of the device which determines the nominal cardiac output via autocorrection from a non-linear transformation of the input analogue arterial pressure. Improved design and wave form algorithms (Wesseling et al., 1993) along with accurate initial calibration using indicator dilution have made this technique more robust and accurate than previous pulse contour analysis cardiac output monitors. Pulse pressure analysis used in conjunction with the lithium dilution technique as a means of calibrating the system offers beat to beat non-invasive cardiac output measurement. Studies have shown that pulse contour analysis is a reliable and precise non-invasive method to determine cardiac output, stroke volume, systemic vascular resistance and blood pressure. It offers a level of accuracy that is comparable to thermodilution (Rodig et al., 1999) and if calibrated using the lithium dilution method beat to beat analysis of cardiac output is sufficiently accurate that frequent recalibration is not required.

Discussion

The measurement of cardiac output remains an important technique in the management of critically ill patients. The concept of actively managing oxygen delivery and transport by cardiovascular optimization in high-risk surgery has been extensively researched. Whilst some controversy still remains it appears that cardiovascular optimization using oxygen delivery as a therapeutic endpoint has many benefits when managing the high-risk patient (Shoemaker et al., 1999; Wilson et al., 1999). The most important feature of this strategy appears to
be the presence of monitoring, which could determine optimal cardiac output and stroke volume and also allow the correct volume of fluid to be given (Boyd et al., 1993; Sinclair et al., 1997).

Given that a substantial body of opinion exists that suggests that mortality following major surgery could be significantly reduced by the adoption of certain goal directed approaches to peri-operative haemodynamic management, it is possible that a conservative approach to these patients will no longer be acceptable. This being the case there will be an even greater requirement for peri-operative measurement of cardiac output in the high-risk patient than currently occurs. Questions remain over the safety of pulmonary artery catheters due mainly to the associated morbidity. Recent studies have shown that the mortality of patients on intensive care is greater in the group that have pulmonary artery catheters inserted and it has been suggested that a moratorium on their use should be issued until randomized controlled clinical trials are undertaken (Dalen and Bone, 1996).

The requirement for the development of a simple, safe, reliable and cheap method of non-invasive cardiac output measurement remains but current practice still regards the pulmonary artery catheter to be the ‘gold standard’ despite the development of several non-invasive techniques. Part of the reason that these techniques have failed to supersede the pulmonary artery catheter is that when multiple studies are performed, as is the case for many of these non-invasive technologies, a wide range of results are reported and full acceptance of the technique never occurs. Frequently initial reports demonstrate considerable promise but significant doubts are then expressed as a result of subsequent studies. In a typical validation study difficulty arises with the value that demonstrates a marked difference from the validation method. The decision may be made to discard the result, recalibrate the monitor or reposition the probe until good correlation is obtained. In everyday clinical use the clinician may well use results which have discrepancies so large as to result in little utility of the device.

Statistical analysis of validation studies is complicated by the combination of intersubject and intrasubject variability. This is especially important when standard correlation and regression analyses are used. The reporting of precision and bias as described by Bland and Altman (1986) is a significant improvement. Problems still occur if devices can be repositioned or recalibrated unless this would occur in clinical practice. Publication bias is also a feature of validation studies in that a report that suggests a new device is inaccurate is much less likely to get accepted for publication.

Conclusion
Cardiac output monitoring is likely to become more commonplace as a result of improved outcomes in critically ill patients who are aggressively managed in terms of oxygen delivery, fluids and monitoring. A simple, safe, reliable and cheap non-invasive cardiac output monitor would reduce the need to expose this group of patients to the risks involved in the use of the pulmonary artery catheter. Several techniques have been described but none has yet been accepted as an alternative to the pulmonary artery catheter. Lithium dilution associated with pulse contour analysis offers accurate beat to beat monitoring in the awake and asleep patient. It is not operator dependant and requires no additional skills to interpret the results. Of all the monitors available it is the most promising but requires further studies in order to gain the confidence of the critical care clinicians.

References


