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Cardiac Output Monitoring - Continuous Measurement by Heat Transfer

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1. Introduction

1.1. What is Cardiac Output?

The cardiac output is the amount of blood pumped to the peripheral circulation by the heart every minute. It is a measurement that reflects the status of the entire circulatory system, not just the heart, since it is governed by autoregulation and the metabolic demands of the tissues.

Cardiac output (CO) is thus defined as the amount of blood ejected from the ventricle per minute, and is measured in litres per minute (L/min).

1.2. Why Monitor the Cardiac Output?

The care of many critically ill or unstable patients crucially depends on adequate perfusion of tissues and organs with oxygenated blood. The availability and adequacy of oxygenation of the circulating arterial blood is easy to measure. However, the adequacy of delivery of this blood to the peripheral tissues by the pump action of the heart, i.e. the CO, is more difficult to assess accurately.

Clinical indicators provide only an indirect measure of CO, and rely on the skill and experience of the clinician. When using clinical indicators to determine whether the CO is satisfactory or not, they need to be taken as a group and used with cautious extrapolation. Some of these indicators are:

1. skin temperature: if the patient is warm, the CO is probably not abnormally reduced, as the skin is one of the first organs to “shut down” in low CO states.

2. urinary output: if urine output is normal, this suggests adequate perfusion of the kidneys and that the CO is probably not drastically low.

3. blood pressure: mean arterial pressure (MAP) is very easily measured and correlates well with CO provided systemic vascular resistance (SVR) remains constant. (MAP= CO x SVR)

Unfortunately, these assumptions, usually quite reliable in a healthy individual, fall down in the critically ill patient. It is precisely in such patients that these indicators may mislead. Skin temperature is affected by sepsis, cardiac surgery involving systemic cooling, peripheral vascular disease and many other factors. The kidneys themselves may be diseased or malfunctioning, so that they cannot give the desired information, and assumptions about SVR remaining constant simply cannot be made in the critically ill.

2. Methods

2.1. Measuring the Cardiac Output

One might imagine that working out the output of a pump (the heart) should be a relatively easy task in our highly sophisticated technological age. It is not. The simplest, most direct way would be to cut the aorta and measure directly the output of the left ventricle. This method may have limited use in the experimental laboratory, but for obvious reasons is not clinically sustainable. We are therefore forced to develop a subtler approach.

The ideal method of measuring CO should satisfy three criteria:

1. it should have accuracy, including reliability and reproducibility
2. it should be continuous, and therefore respond rapidly to changes in CO, so that an equally rapid therapeutic reaction can be implemented
3. it should be non-invasive, or involve as little invasion as possible

There have been many attempts at achieving the holy grail of a non-invasive, accurate and continuous method of measuring CO. So far, none has succeeded totally. The remainder of this article will address the main methods developed so far, their strengths and their weaknesses.

2.2. Fick

The Fick principle is delightful in its simplicity and to many it states the obvious: If an organ consumes a substance that reaches it via the blood supply, then the amount of that substance it consumes is equal to the blood flow to that organ multiplied by the difference in the concentration of that substance upstream and downstream of that organ. Any substance consumed by the body may be used for this calculation, but the fact that the body consumes oxygen can be put to practical use by adapting Fick to the following:

$$CO = \frac{[\text{oxygen consumption}]}{[\text{arterial oxygen content} - \text{venous oxygen content}]}$$

The three factors in this equation can all be measured with more or less readily available tests as follows:

Oxygen consumption can be measured by analysing the oxygen content of inspired and expired gases and minute ventilation volumes. Arterial oxygen content is the total oxygen carried by haemoglobin or Hb (Hb concentration x arterial oxygen saturation (SaO2) x constant) plus the total dissolved oxygen in the blood (arterial partial pressure of oxygen x constant). Venous oxygen content is calculated in a similar way. It can be immediately seen that haemoglobin concentration, oxygen saturations and partial pressures are all readily available to the physician. Inspired and expired gas analysis is less readily available, but can be obtained, at least in a sophisticated respiratory function laboratory.

Another approach would be to regard the lungs, which receive the full cardiac output, as consumers of carbon dioxide (CO2) and to reverse the formula accordingly:

$$\text{CO} = \frac{[\text{CO2 excretion}]}{[\text{venous CO2 content – arterial CO2 content}]}$$

The great advantage of using Fick is its accuracy, except in patients where an important part of oxygen *consumption* occurs in the lungs, such as severe inflammatory lung disease, where lung oxygen use may increase from around 2% to perhaps 10 or 15% of total consumption. The limitations on the Fick method are in the multiple measurements required, the sophistication of the instruments needed for blood gas analysis and in the fact that continuous measurement is impossible without the development of reliable continuous monitors of haemoglobin concentration, arterial and venous oxygen saturation and partial pressures as well as continuous monitors of blood gas delivery and composition. It can only be used in a ventilated patient or in a patient connected to oxygen delivery by a completely occlusive mask. In other words, Fick is not practical for routine clinical monitoring.

2.3. Indicator dilution

It stands to reason that if one may measure the volume (V) of a body of liquid by diluting a known quantity of indicator (i) in the liquid and measuring the final concentration ([i]). The volume is then:

$$V = i / [i]$$

If the volume in question is the CO, then an indicator injected intravenously can have its concentration measured arterially (after full mixing is assumed to have taken place). Thus:

$$\text{CO} = i / \text{ò}\ [i] \times \text{time}$$

where i is the amount of indicator used and ò [i] is the integral of the downstream (arterial) concentration of the indicator.

The advantage of this technique is its relative simplicity and quite good accuracy. The disadvantages arise from the necessity of injecting an indicator (typically a coloured dye) and of multiple withdrawals of arterial blood samples to calculate [i] over time by photodensimetric analysis. It is clearly not suitable for continuous monitoring, although there is currently work in progress on indicators capable of being measured continuously through an arterial monitoring line.

2.4. Thermodilution

This is an ingenious adaptation of dye dilution by using heat (or cold) as the indicator, and is currently the “gold standard” in clinical cardiac output monitoring. This possibility, first suggested by Fegler in 1954, gained widespread use after the introduction in the early 1970s of the Swan-Ganz pulmonary artery flotation balloon catheter. This device inserted through a large vein into the right atrium, then carried by the blood flow on its own flotation balloon so that its tip lies in a proximal pulmonary artery. Using cold as an indicator, a known volume of fluid (the injectate) at a known, cold temperature is introduced into the right atrium through one of the many lumina of the catheter. The tip of the device houses a thermistor that measures the slight drop in temperature over time as the cooled blood flows past it. Assuming perfect mixing of the injectate with the flowing blood between injection upstream and temperature measurement downstream, the CO can be calculated according to a modification of the indicator dilution formula:

$$\text{CO} = \frac{[\text{injectate volume } (T_{\text{blood}} - T_{\text{injectate}}) \times \text{constant}]}{\text{ò}T\,dt}$$

where T is temperature, the constant adjusts for computation and specific heat capacity of blood and injectate (usually 5% dextrose) and òTdt is the integral of the recorded blood temperature difference over time. In practice, the clinician or nurse carries out the injection, and a computer programme performs the necessary calculations.

The method has many advantages over Fick and indicator dilution. Although the insertion of a pulmonary artery catheter is quite invasive, it is useful in other respects: the measurement of right-sided cardiac pressures as well as the capillary “wedge” pressure (indicating left ventricular filling pressure) are provided as a bonus, thus yielding a huge amount of information about cardiac haemodynamics and justifying the invasive nature of the procedure. It has been shown to be reasonably accurate in the clinical setting and has performed well in comparison with Fick and dye dilution in trials. Its accuracy, however, may be affected by several factors, such as variability in the volume and temperature of the injectate affecting the “signal-to-noise” ratio and the differences between observer technique and speed of injection. In addition, any pulmonary or tricuspid valve regurgitation and incomplete mixing of the injectate with the blood in the right ventricle will affect readings substantially. Common practice is to carry out three to five injections, discard “unbelievable” readings and average the rest. This leads to another disadvantage of the procedure: 5 injections of 10 mls of dextrose every hour is more than a litre of fluid per day, a volume and glucose load that some patients cannot tolerate, especially if other therapies are being administered intravenously. There is also a theoretical risk of introducing infection with every injection. The final disadvantage is that the method is intermittent and requires positive action by the clinician to produce a measurement. It cannot, therefore, act as an early warning system of deteriorating cardiac function.

2.5. Continuous thermodilution

In this relatively recent development, the thermal load is given not as a cold injectate but as an electrically produced heat bolus through a filament incorporated into a pulmonary artery catheter. This allows rapid, frequent and automatic measurements without clinician intervention. The technique is successful but has some limitations, partly due to the smaller temperature differences that can be safely produced within the pulmonary artery by heating a filament in the right atrium. This reduces the signal-to-noise ratio, and requires the use of quite elaborate neural networks to produce information that can be reliably translated into CO measurements. In practice, the system takes a few minutes to stabilise and after that time, produces readings at frequent predetermined intervals, as often as every 30 seconds, but these readings are in fact averages of cumulative readings obtained during the preceding few minutes. The system can be used satisfactorily in the critically ill [Schiller, 1990]. Its main limitation is that it is not truly continuous and it is less accurate and reliable if the patient is pyrexial. The level of invasiveness of the procedure is not different from that of the intermittent thermodilution method.

2.6. Bioimpedance

The volume of blood ejected every heartbeat is called the stroke volume. Multiplying this by the pulse rate gives the cardiac output. The pulse rate is easily available, and bioimpedance techniques are directed towards measuring the stroke volume. The principles of this measurement is that the electrical impedance to a current across any conductor, say the thorax or the body itself, is equal to the voltage divided by the current. The impedance to flow can be divided into two components: that provided by fixed tissues and body cavity content and that provided by mobile contents, the most important of which is the cardiac stroke volume. To put it simply, the variation in impedance across the chest should in principle reflect the volume of blood ejected with every heart beat, and therefore give an indirect measurement of stroke volume.

A number of bioimpedance CO monitors have been developed. Appropriately placed electrodes deliver a certain current across the chest and accurately measure the changes in the voltage across the cardiac cycle. These changes are then adjusted using normograms of thoracic volume and proportion of electrically active tissue based on height, weight and sex of the patient to yield an estimate of the stroke volume and thus of the cardiac output.

The great attraction of bioimpedance technology is that it is non-invasive and can theoretically be continuous on a beat-by-beat basis. Unfortunately, correlation with other methods has not been consistently satisfactory in clinical trials and the method is subject to further errors in patients with dysrhythmia or pulmonary or pleural conditions that affect thoracic water volume, such as oedema or effusions, conditions seen all too frequently in the critically ill.

2.7. Doppler

Doppler echocardiography provides an alternative noninvasive method of measuring total forward blood flow and hence cardiac output. This method relies on combining imaging data from 2-dimensional echocardiography and flow data from spectral Doppler echocardiography. Spectral Doppler allows instantaneous blood flow velocity to be measured, which is expressed in units of distance per time (m/sec). In order to quantitate this as a volume per time i.e. L/min, the velocity must be multiplied by the cross-sectional area of the orifice or tube through which the blood is flowing (2)

$$\text{Cardiac Output (L/min)} = A \times V$$

where

A = cross-sectional area of orifice or tube (cm^2)

V = mean blood flow velocity (cm/sec)

Here we are considering velocity averaged over the cardiac cycle. However spectral Doppler measures instantaneous velocity. Therefore to derive mean velocity over the cardiac cycle, we measure the area under the velocity curve during one heartbeat, the velocity time integral (VTI), and multiply by heart rate (3)

$$\text{Cardiac Output (L/min)} = A \times VTI \times HR$$

Echocardiography is commonly performed by either the transthoracic or transoesophageal approach. By Doppler echocardiography flow can be measured in numerous locations in the heart, through the heart valves, and the great vessels.

There are several other Doppler techniques now currently available although not in widespread clinical use. These include a new pulmonary artery catheter that incorporates an ultrasonic transducer that maintains contact with the pulmonary artery wall. Using the Doppler principle, instantaneous stoke volume is obtained from the mean velocity of blood flow in the main pulmonary artery [Segal et al., 1990; Abrams et al., 1989]. Ultrasonic transducers have also been bonded to endotracheal tubes, which by contact with the wall of the trachea are in close proximity to the ascending aorta where blood flow is measured similarly to transoesophageal Doppler [Rodig et al., 1999].

2.8. Pulse Contour

A new system of pulse contour analysis is now also available, which is less invasive than continuous CO monitoring via a pulmonary artery catheters, and may cost less. The notion that SV (stoke volume) can be quantified from pulse pressure goes back to observations by Erlanger and Hooker in 1904. This technique requires the insertion of an arterial thermodilution catheter via the femoral artery into the aorta for clinical monitoring of the arterial pressure, continuous CO measurements derived from the arterial pressure and intermittent arterial thermodilution CO measurements. [Boldt et al., 1994]

Pulse contour analysis involves calculating the stroke volume from the contour of the arterial waveform. The area under the systolic portion of the arterial pulse wave is measured from the end of diastole to the end of the ejection phase, together with an individual calibration factor to account for individual impedance. To calibrate this system, individual arterial input impedance to arterial pressure is calculated from the area under the systolic potion of the curve arterial pulse wave, and the arterial thermodilution CO. A disadvantage of this technique is that assumptions are made concerning the distensibility of the systemic vascular bed. [Segal et al., 1989]

2.9. Heat Transfer

This new technique, towards which one of the authors (SAMN) is biased, is based on the simple notion that any heat dissipated by the flow of blood is proportional to that flow. The method uses a pulmonary artery flotation catheter (TruCCOM, Aortech, Scotland) which is inserted and advanced into the main pulmonary artery in the same way as a thermodilution catheter. The catheter differs from the standard thermodilution catheter in two ways: firstly, it has two thermistors, one at the tip in the usual position and another proximal (in the right atrium) to the first; secondly, the first thermistor is surrounded by an electrical heating coil. A current is applied to the heating coil to warm the first thermistor to a set temperature slightly higher (1-2 degrees) than that of the blood, as measured by the second thermistor. The amount of heat thus generated is negligible, and does not appreciably alter the temperature of the blood, but the power needed to maintain the temperature difference is proportional to the blood flow that is constantly cooling the coil, in other words , the CO.

This type of heat transfer technology has been used in the past to measure aircraft speed in what is called “hot-wire anemometry”. It can therefore be argued that the method measures velocity more than it measures flow. This argument would be correct if flow through the pulmonary artery was laminar, and the coil was only exposed to a thin stratum of blood during the cardiac cycle. However, pulmonary artery flow is anything but laminar: it is pulsatile with both to-and-from motions and eddy currents, and it is made turbulent by the opening and closing actions of the pulmonary valve. This means that the coil is exposed to more than a thin stratum of laminar-flowing blood, and the method reflects flow better than it reflects velocity.

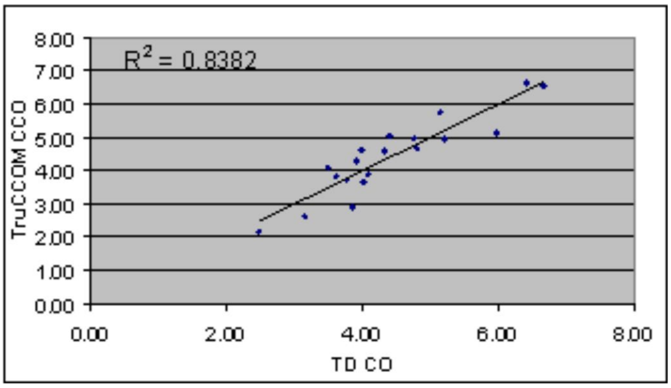

Figure 1. Correlation between simultaneous readings of cardiac output using continuous (TruCCOM) and standard thermodilution (TD). Flows in litre per minute.

The heat transfer technique has been tested in vitro and in experimental animals and has performed well. Early clinical trials suggest that it correlates well with the current clinical “gold standard” of thermodilution (Fig. 1). More importantly, it is probably the only method available that is capable of responding to cardiac output changes within seconds, thus providing clinicians with valuable early warning in deteriorating cardiac output as well as a rapid feedback on the results of their therapeutic intervention (Fig. 2). It is probably the only method which provides truly continuous measurement of CO, and the rapidity of its response has opened possibilities in cardiac output monitoring in situations where such measurement has not been practicable by other techniques because of their inherent slowness, such as during percutaneous coronary angioplasty and “off-pump” coronary artery surgery

The remaining disadvantage is, of course, that the procedure is still an invasive one, requiring the insertion of a pulmonary artery catheter.

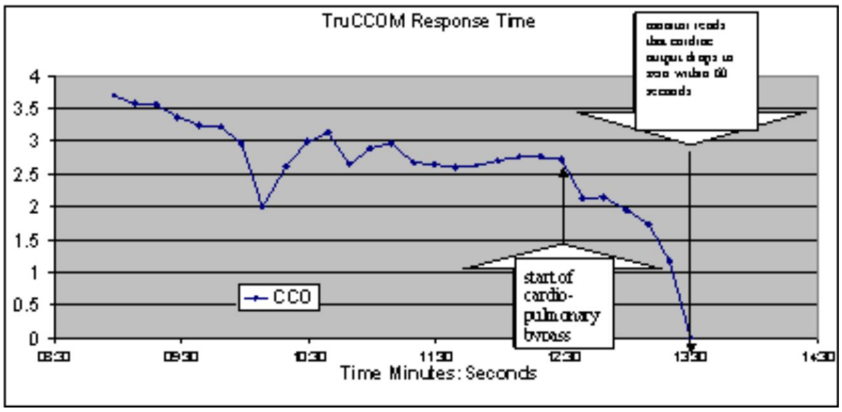

Figure 2. Response of heat transfer cardiac output monitor to the start of cardiopulmonary bypass in a cardiac surgical patient (CCO: continuous cardiac output, litres per minute).

3. Conclusion

Despite the recent controversy surrounding the necessity and clinical usefulness of cardiac output monitoring in the critically ill, most clinicians agree on the need for such monitoring in order to guide therapy. It would be true to say that the perfect, 100% safe, non-invasive, continuous and fully accurate cardiac output monitor has not yet been invented. Many strides have been made towards this goal, and the multiplicity, substantial successes and sheer ingeniousness of the recently developed and currently available methods augur well for the future.

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