REVIEW

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Invasive and non-invasive methods for cardiac output measurement

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ABSTRACT: The hemodynamic status monitoring of high-risk surgical patients and critically ill patients in Intensive Care Units is one of the main objectives of their therapeutic management. Cardiac output is one of the most important parameters for cardiac function monitoring, providing an estimate of whole body perfusion oxygen delivery and allowing for an understanding of the causes of high blood pressure. The purpose of the present review is the description of cardiac output measurement methods as presented in the international literature. The articles document that there are many methods of monitoring the hemodynamic status of patients, both invasive and non-invasive, the most popular of which is thermodilution. The invasive methods are the Fick method and thermodilution, whereas the non-invasive methods are oeshophaegeal Doppler, transoesophageal echocardiography, lithium dilution, pulse contour, partial CO_2 rebreathing and thoracic electrical bioimpedance. All of them have their advantages and disadvantages, but thermodilution is the golden standard for critical patients, although it does entail many risks. The ideal system for cardiac output monitoring would be non-invasive, easy to use, reliable and compatible in patients. A number of research studies have been carried out in clinical care settings, by nurses as well as other health professionals, for the purpose of finding a method of measurement that would have the least disadvantages. Nevertheless, the thermodilution technique remains the most common approach in use today.

KEY-WORDS: Cardiac output, thermodilution, Fick method, Doppler monitor, bioimpendance, critically ill patients

INTRODUCTION

The hemodynamic status monitoring of high-risk surgical patients and critically ill patients in Intensive Care Units is one of the main objectives of their therapeutic management (Hett & Jonas 2003). Cardiac output is one of the most important parameters for cardiac function monitoring, providing an estimate of whole body perfusion oxygen delivery and allowing for an understanding of the causes of high blood pressure (Berton & Cholley 2002).

Cardiac ouput is the volume of blood pumped by the heart per minute and is the product of the heart rate and stroke volume. The stroke volume of the ventricle is determined by the interactions between its preload, contractility and afterload (Prabhu 2007, Guyton 1991).

Over the past decades, many methods for cardiac output measurement have been developed. The most widely widespread is the invasive method of thermodilution, which, however, involves the danger of inserting a Swan-

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Ganz catheter into the circulatory system. Many alternative methods, both invasive and non-invasive, have been used, but even today, clinical observation is the most important for the clinical decision-making process. In clinical care settings, many extensive research studies are in progress for the purpose of finding a method for cardiac output measurement having as few disadvantages as possible.

The ideal system for cardiac output monitoring would be non-invasive, easy to use, accurate, reliable, consistent and compatible in patients (Mathews & Singh 2008, Yakimets & Jensen 1995). At present, no single technique meets all these criteria (Mathews & Singh 2008).

The purpose of the present review is to describe the cardiac output measurement methods as presented in the international literature.

INVASIVE METHODS

Fick method

This method is based on the principle described by Adolfo Fick in 1870, according to which the total uptake or release of a substance by an organ is the product of the blood flow through the organ and the arteriovenous concentration difference of the substance (Berton & Cholley et al 2002, Prahbu 2007, Mathews & Singh 2008). The oxygen uptake in the lungs is the product of the blood flow through the lungs and the arteriovenous oxygen content difference. Therefore, cardiac output can be calculated using the equation:

$$CO = \frac{V_{O2}}{CaO_2 - CvO_2}$$

Where V_{O2} is the oxygen consumption by the lungs and $CaO_2 - CvO_2$ is the arteriovenous difference in oxygen (Berton &Cholley et al 2002, Engoren & Barbee 2005, Mathews & Singh 2008).

Oxygen consumption is measured with special devices. The arteriovenous difference is computed by receiving samples of arterial blood, and mixed venous blood by receiving blood from the pulmonary artery (Tibby et al 1997, Bougalt et al 2005, Mathews & Singh 2008). The mixed venous blood is received via a catheter that reaches up to the right ventricular and the pulmonary artery (Tibby et al 1997, Mathews & Singh 2008). Mathews & Sigh stated that "the arteriovenous oxygen content difference can be measured *in situ* using a pulmonary artery catheter having fibreoptic bundles incorporated in the catheter"

The Fick method has limitations which are marked in patients with lung abnormalities (Engoren & Barbee 2005); it is costly and may lead to complications (Yung et al 2004). Also, it is considered the most accurate method available to evaluate patients with low cardiac output (Ultman & Burtzstein 1981, Mathews & Sigh 2008).

Thermodilution method

This is an intermittent technique widely accepted in clinical settings (Prahbu 2007). It is a method relying on a principle similar to indicator dilution, but it uses heat rather than colour as an indicator (Mathews & Singh 2008).

This method uses a special thermistor – tipped catheter (Swan-Ganz catheter) inserted from a central vein into the pulmonary artery. A cold solution of D/W 5% or normal saline (temperature 0 °C) is injected into the right atrium from a proximal catheter port. This solution causes a decrease in blood temperature, which is measured by a thermistor placed in the pulmonary artery catheter (Tibby et al 1997, Prahbu 2007). The decrease in temperature is inversely proportional to the dilution of the injectate (Prahbu 2007). The cardiac output can be derived from the modified Stewart-Hamilton conservation of heat equation (Fillipatos & Baltopoulos 1997, Prahbu 2007). The pulmonary artery catheter is attached to the cardiac output computer, which displays a curve and calculates output and derived indices automatically (Prahbu 2007).

Thermodilution technique remain the most common approach in use today and is considered as the golden standard approach to cardiac output monitoring (Hett & Jonas 2003, Prahbu 2007), although it involves many risks, such as pneumothorax, dysrythmias, perforation of the heart chamber, tamponade and valve damage (Hett & Jonas 2003). Also, it is reported that there are some concerns regarding the appropriateness of routine use of pulmonary catheters in critical patients (Albert et al 2004, Connors et al 1996).

Factors that may compuromise this technique are shunts, tricuspid regurgitation, cardiac arrythmias, abnormal respiratory patterns and low cardiac output (Prahbu 2007).

Some studies have supported concerns regarding the appropriateness of pulmonary artery catheters use in critically ill patients, since catheters are associated with increased morbidity and mortality (Connors et al 1996, Sandham et al 2003).

Non-invasive cardiac output monitoring

Oesophageal Doppler

The Oesophageal Doppler monitor was first described in the early 1970s (Gan & Arrowsmith 1997). This technique measures blood flow velocity in the descending thoracic aorta (Gan & Arrowsmith 1997, Poelaert et al 1999, Hett & Jonas 2003, Mathews & Singh 2008, Working Group 2008) using a flexible ultrasound probe about the size of a nasogastric tube (Gan & Arrowsmith 1997). This measurement can be combined with an estimate of the cross-sectional area of the aorta, which is derived from the patient's age, height and weight, and allows hemodynamic variables including stroke volume, cardiac output and cardiac index to be calculated (Gan & Arrowsmith 1997, Hett & Jonas 2003, Mathews & Singh 2008).

The precision of this measurement depends on the following three conditions: the cross-section must be accurate, the ultrasound beam must be directed parallel to the blood flow, the beam direction may not undergo major alteration between measurements (Berton & Cholley 2002, Hett & Jonas 2003).

This technique offers a minimally invasive means for continuous hemodynamic monitoring (King & Lim 2004, Prentice & Sona 2006), because the probe of an oesophageal Doppler monitor can be inserted within minutes, requires minimal technical skill (Gan & Arrowsmith 1997) and is not associated with complications (Gan & Arrowsmith 1997, King & Lim 2004). Also, it is operator dependant, and it is very easy to change the position of the probe between measurements, thus reducing the precision of the monitoring (Hett & Jonas 2003). A comparison of this new monitoring with the pulmonary artery catheter is cited numerous times throughout the literature and correlates well overall (Kauffman 2000).

Transoesophageal echocardiography

Transoesophageal echocardiography provides information on cardiac contractility, filling status and output, valvular morphology and function, as well as on the ascending and descending aorta structure in the critically ill patient (Poelaert et al 1998). With this technique, cardiac output measurement is the result of calculating stroke volume, which can be multiplied by heart rate. In order to assess stroke volume, it is necessary to measure flow velocity and determine the cross-sectional area (Hett & Jonas 2003, Prahbu 2007).

Flow velocity is calculated from the area under the Doppler velocity waveform, which gives the time velocity integral. The cross-sectional area can be calculated based on the diameter, assuming a circular shape, or it can be determined by direct planimetry (Hett & Jonas 2003, Mathews & Sigh 2008). Measurements may be performed at the level of the pulmonary artery, the mitral valve or the aorta valve.

Turner (2004) has stated that "in the hands of a skilled operator, transesophageal echocardiography provides reliable cardiac output determinations'. Also, it is reported that it has been applied widely in ventilated patients with hemodynamic instability (Poelaert et al 1999).

Lithium dilution cardiac output

This technique was first described in 1993 (Linton et al 1993) and is minimally invasive (Hett & Jonas 2003, Mathews & Sigh 2008). It requires a venous line and an arterial catheter. The venous line can be either central or peripheral (Garcia-Rodriguez et al 2002, Hett & Jonas 2003, Prahbu 2007, Mathews & Sigh 2008). A bolus of isotonic (150 mM) lithium chloride (LiCl) solution is injected via the venous line. The usual dose for an adult is 0.3 mmol (Hett & Jonas 2003). Arterial plasma concentration is measured by withdrawing blood across a selective lithium electrode at a rate of 4 mL/min. Cardiac output is calculated based on the lithium dose and the area subject to the concentration–time circulation (Hett & Jonas 2003, Prahbu 2007, Mathews & Sigh 2008). This technique is contra-indicated in patients on lithium therapy (Prahbu 2007, Mathews & Sigh 2008) and atracurium therapy (Prahbu 2007).

The technique is simple to perform, safe (Hett & Jonas 2003) and accurate. It has been reported that it underestimates cardiac output by 5% compared to intermittent thermodilution bolus (Prahbu 2007). Other reports say that it is more accurate than bolus thermodilution (Kurita et al 1997), but recent studies have stated that the method agreed well with intermittent pulmonary thermodilution (Costa et al 2008).

Pulse contour cardiac output

This technique calls for the insertion of an arterial catheter (Hett & Jonas 2003, Mathews & Sigh 2008), and hence is considered a minimally invasive procedure (Hett & Jonas 2003). A long arterial catheter (with a thermistor) placed in the femoral axillary, or brachial artery, and connected to a pulse contour device. With this catheter, a continuous pulse waveform contour analysis is obtained. The technique is calculated by analysis of the area under the systolic portion of the arterial pressures waveform, from the end-diastole to the end of the ejection phase; this corresponds to stroke volume. Also, by virtue of a pulse contour analysis device, a beat-to-beat analysis of cardiac output, averaged at 30 seconds, is displayed. Calibration requires a central venous cannulation, using a transcardiopulmonary thermodilution technique (Prahbu 2007).

This method offers a level of accuracy comparable to thermodilution (Rodig et al 1999)

Partial CO_2 rebreathing

Cardiac output can be estimated by using the Fick principle with carbon dioxide as the marker gas (Berton & Cholley 2002, Mathews & Sigh 2008). A new monitor called NICO is based on the application of the Fick principle to carbon dioxide, in order to estimate cardiac output non-invasively. The monitor consists of a carbon dioxide sensor, a disposable airflow sensor and a pulse oxymeter. VCO_2 is calculated from minute ventilation and its carbon dioxide content. The arterial dioxide content ($CaCO_2$) is estimated from end-tidal carbon dioxide (Jaffe et al 1999, Haryadi et al 2000, Kotake et al 2003, Mathews & Sigh 2008)

The Fick equation for carbon dioxide is:

$$CO=VCO_2/CvCO_2\text{-}CaCO_2$$

where VCO_2, $CvCO_2$, $CaCO_2$ are CO_2 consumption, venous CO_2 concentration and arterial CO_2 concentration respectively (Haryadi et al 2000, Berton & Cholley 2002, Kotake et al 2003, Mathews & Sigh 2008).

We assume that cardiac output remains unchanged under normal (N) and rebreathing conditions (R) (Berton & Cholley 2002).

$$CO=VCO_{2N}/CvCO_{2N}-CaCO_{2N}=VCO_{2R}/CvCO_{2R}-CaCO_{2R}$$

If we subtract the normal and rebreathing ratio, and the equation now reads:

$$CO=VCO_{2N}-VCO_{2R}/(CvCO_{2N}\text{-}CaCO_{2N})-(CvCO_{2R}-CaCO_{2R})$$

Because the diffusion rate of carbon dioxide is 22 times more rapid than that oxygen, it is assumed that no difference in venous CO_2 ($CvCO_2$) will occur, whether under normal or rebreathing conditions. Hence, the above equation becomes

$$CO=\Delta VCO_2/\Delta CaCO_2$$

(Haryadi et al 2000, Berton & Cholley 2002, Kotake et al 2003, Mathews & Sigh 2008).

Thoracic electrical bioimpendance

In the 1960s, the National Aeronautical and Space Administration (NASA) and William Kubicek developed impedance cardiography, using the thoracic electrical bioimpedance (Kubicek et al 1966).

This technique employs four pairs of electrodes. Two pairs are applied to the neck base on opposite sides and two pairs are placed at the level of the xiphoid junction (Bougalt et al 2005, Mathews & Sigh 2008). Each pair of electrodes comprises transmitting and sensing electrodes (Bougalt et al 2005, Mathews & Sigh 2008). With these electrodes, low-level electricity conducted by body fluid is transmitted (Smith 1994, Lavdaniti 1998, Mathews & Sigh 2008). Another set of two electrodes is used to monitor a single ECG signal (Bougalt et al 2005, Mathews & Sigh 2008). This electricity is harmless and not felt by the patient (Smith 1994). The first derivative dZ/dt of the impedance waveform is related linearly to aortic blood flow. Changes in impedance correlate with stroke volume, calculated using the following formula (Hett & Jonas 2003):

$$SV=\rho \frac{L^2}{Z_o^2} (dZ/dt)max \times T$$

where SV=stroke volume

ρ=resistivity of blood (Ω/cm)

L=mean distance between the inner electrodes (the thoracic length)

Zo=basal thoracic impedance

(dZ/dt)max=the maximum value of the first derivative during systole (Ohms/second)

T=ventricular ejection time (sec)

Cardiac output is calculated from the stroke volume and heart rate (Smith 1994, Mathews & Sigh 2008) and the equation is: CO=SVxHR, where HR=Heart Rate

Cardiac output is easier to measure by impedance cardiography than by thermodilution with a pulmonary artery catheter, can be applied quickly, and does not pose a risk of infection, blood loss or other complications associated with arterial catheters (Albert et al 2004).

This method can be used to calculate various other parameters, such as cardiac index, stroke index, end-diastolic index and other hemodynamic parameters including systemic vascular resistance (Smith 1994, Albert et al 2004).

Many researchers have shown that impedance cardiography provides as accurate measurements of cardiac output as does thermodilution (Yakimets et al 1995, Albert et al 2004, Shoemaker et al 2006, Gujjar et al 2008). Thoracic bioimpedance is used in post-cardiac surgery patients (Gujjar et al 2008), in acute emergency trauma patients (Shoemaker et al 2006) and in pulmonary hypertension patients (Yung et al 2004), in critical illness (Silver et al 2004) and post-coronary artery bypass (Van de Water & Miller 2003).

DISCUSSION

Hemodynamic monitoring is essential for the critically ill management. Effective monitoring generates data providing for the analysis of circulatory functions (Cottis et al 2003). As mentioned above, there are many methods of monitoring the haemodynamic status of patients; these can be invasive, less invasive or non-invasive.

All of these have advantages and disadvantages, and there are a number of studies comparing each or both of them to the standard method (i.e. the thermodilution method) (Berton & Cholley 2002, Albert et al 2004, Engoren & Barbee 2005, Bougault et al 2008, Costa et al 2008). There are doubts about the safety of pulmonary artery catheters or about the thermodilution method, which is mainly due to the morbidity rate linked to it (Hett & Jonas 2003). The need to develop a simple, safe, reliable and inexpensive method for non-invasive cardiac output remains, while the thermodilution technique is still the most common approach in use today, even though techniques that are minimally invasive or non-invasive do exist (Hett & Jonas 2003).

In critically ill patients, the nurse's role is crucial, and Cottis et al (2003) stated that "as the scope of nursing evolves, the profession must be self-determining, influencing the boundaries of practice and the development of new skills, roles and knowledge". Wright et al (1996) have stated that nurses play a role in individualizing patient care, and Taylor (1996) explains how doctors and nurses working together in a non-hierarchical manner can contribute to good decision-making with regard to patient treatment.

Most of the above methods call for a peripheral or central venous or arterial line. Consequently, nurses are responsible for maintaining these lines so that the desired methods (such as thermodilution, pulse contour technique, etc.) (Cottis et al 2003), can be applied, providing for infections prevention as well as for electrode placement of electrodes, such as in the case of thoracic electric bioimpendance (Smith 1994). They are also responsible for monitoring the results and determining the effectiveness of drugs as a fluid or vasopressor (Smith 1994).

Cardiac output monitoring provides an excellent area for nursing research. Observing the changes in cardiac output while moving a patient in order to prevent bed sores and measuring cardiac output at various phases of hospitalisation constitutes an area to be dealt with ideally by nurses. Moreover, nurses should study cardiac output during the first hours of post-operative follow-up for patients in Intensive Care Units. Cardiac output monitoring by nurses in the first post-operative twenty-four hours in patients having undergone bypass surgery is an interesting premise for nursing research. In addition, nurses can compare the cardiac output measured by various methods, such as thermodilution and thoracic electrical biompedance, or partial CO_2 rebreathing and thoracic electrical biompedance.

CONCLUSIONS

Accurate monitoring of the hemodynamic status of the critically ill patient is essential for effective management (Cottis et al 2003).

None of above techniques are mutually exclusive, since their advantages and drawbacks are quite different. Futhermore, they are not intended to replace the pulmonary artery catheter, which remains quite unique in providing pressure (right arterial, pulmonary wedge pressure) as well as venous oxygen saturation, in addition to cardiac output.

The main objective of research studies conducted in Greece and abroad with respect to critically ill patients should be the comparison of cardiac output monitoring methods, proving the validity of individual methods and consolidating their use in clinical settings. Also, further research is required to determine which patients will benefit most from the existing methods for cardiac output measuring.

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