

REVIEW ARTICLE

UPDATES IN CARDIAC OUTPUT MONITORING

By

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Overview of cardiac output monitoring techniques (**Mathews and Singh, 2008**)

| | |
|----------------------------|---|
| Invasive methods | -Fick's Principle -Thermodilution technique |
| Minimally invasive methods | -Doppler Ultrasound -Echocardiography -Partial CO ₂ Rebreathing technique -Indicator dilution method -Pulse contour analysis |
| Noninvasive methods | -Thoracic Electrical Bioimpedance -Thoracic Bioreactance |

Invasive Methods

Fick's Principle: The first method to find cardiac output in humans was described by Adolph Fick in 1870. He postulated that oxygen uptake in the lungs is completely transferred to the blood and the total uptake or release of oxygen by lungs is the product of blood flow through the lungs and the arterio-venous oxygen content difference. Therefore cardiac output can be computed by relating oxygen consumption to arterial and mixed venous oxygen content using the equation:

$$\text{Cardiac Output} = \frac{\text{VO}_2}{(\text{CaO}_2 - \text{CvO}_2)}$$

Where VO₂ is the oxygen content difference between inspired and exhaled gas, CaO₂ is oxygen content of arterial blood and CvO₂ is oxygen content of

mixed venous blood (**Mathews and Singh, 2008**).

Pulmonary Artery Catheter (PAC): It is a multi-lumen plastic catheter, 110 to 150 cm long with a balloon located just proximal to the tip of the distal lumen, a thermistor which measures temperature changes for the assessment of cardiac output, is located proximal to the balloon. Two additional lumens (right ventricular port and venous infusion port, if present) located at 19 cm and 30 cm from the tip reach the right ventricle and right atrium or superior vena cava. The PAC is connected to the monitoring equipment through a semi-rigid, noncompliant fluid-filled tube and pressure transducer. The movements in the transducer membrane generate electrical impulses that are

amplified and transmitted to a monitor (**Balk et al., 2008**).

Apart from its pressure monitoring capabilities, undoubtedly the most important feature of PAC is its ability to measure CO using the thermodilution method. The thermodilution technique has become the clinical standard for CO determination (**Mathews and Singh, 2008**)

Monitoring of cardiac output using PAC:

Intermittent thermodilution technique:

This technique relies on principle similar to indicator dilution, but uses heat instead of color as an indicator. To do this, cold saline is rapidly injected through the proximal central venous port. A thermistor located at the distal end of the pulmonary artery catheter senses the change in temperature. Because blood flow is the source of dilution of temperature, the flow, or cardiac output, can be calculated. It is the right ventricular cardiac output that is actually measured by this technique, whereas left ventricular cardiac output can only be estimated based on the results (**Pinsky, 2007**)

Continuous mixed venous oximetry:

The physiologic relations described by the Fick's equation form the basis for another PAC-based monitoring technique termed continuous mixed venous oximetry

$$S_vO_2 = S_aO_2 - \frac{VO_2}{Q \cdot 1.36 \cdot Hgb}$$

To the extent that arterial oxygen saturation, oxygen consumption, and hemoglobin concentration remain stable, mixed venous oxygen saturation may be used as an indirect indicator of cardiac output (**Pinsky, 2007**).

Errors in PAC: Signal loss/dampening can result from intracatheter air bubbles, debris, loose connections, vessel wall impingement, and transducer malfunction. Potential sources of error include timing, duration, volume and temperature of the injectate used. Malposition of the catheter (i.e. lodging in the RV) or displaced injectate port into the RA and misconnection of pressure monitors should be considered (**Evans et al., 2009**).

Complications Of PAC: Catheter site infection, bacteremia/sepsis, and right-sided infective endocarditis are well described complications in patients with indwelling venous catheters and devices, including the PAC (**McGee and Gould, 2003**).

Complications of CV access include arterial puncture, arterial or venous hematoma, arteriovenous fistula (AVF), pseudo aneurysm formation, thoracic duct injury, pneumothorax/hemothorax, thrombosis and air embolization. The thoracic duct may be injured during attempts to cannulate the left internal jugular or subclavian vein, potentially resulting in chylothorax or lymphatic cutaneous fistula. Attempted venous cannulation can cause pneumothorax in ~0.5% of CV catheter placement cases (**Evans et al., 2009**).

Contraindications of PAC: Absolute contraindications for PAC are not highlighted. However, in conditions such as cyanotic heart disease, tricuspid or pulmonary valve stenosis and severe arrhythmias in which the risks outweigh benefits or measurements obtained will be redeemed inaccurate (not useful). PAC

can be considered as contraindications (**Summerhill and Baram, 2005**).

MINIMALLY INVASIVE METHODS

Doppler ultrasound: Ultrasound easily penetrates skin and other body tissues. As it encounters tissues of different acoustic density, a fraction of emitted ultrasound signal is reflected. When an ultrasound beam is directed along the path of the flow of blood in the aorta, using a probe, a fraction of the ultrasound signal is reflected by the moving red blood cells. The shift in the frequency of the reflected waves (Doppler shift) is proportional to the velocity of blood flow and is expressed by the equation:

$$F_d = 2f_0/C V \cos\theta$$

Where F_d is the change in frequency or Doppler shift, f_0 is the transmitted frequency, V is the velocity of moving blood, C is the velocity of ultrasound in blood, $\cos\theta$ is cosine of the angle between the direction of ultrasound beam and blood flow. The esophageal Doppler monitoring (ODM) is a widely applied method of minimally invasive cardiac output monitoring performed currently in critically ill patients (**Mathews and Singh, 2008**).

The first description of an esophageal probe measuring aortic blood flow velocity was in 1971. Suprasternal or transthoracic probes were used initially, but the difficulty of probe positioning and instability on the chest wall made their use for repeated measurements limited. This led to the development of the esophageal doppler probe. It had several advantages, including the ability to remain in position for days to weeks and its proximity to the

aorta. The esophageal doppler probe is approximately the size of a nasogastric tube and can be positioned easily (**Funk et al., 2009**).

In suprasternal technique, the blood flow velocity is measured in the distal aortic arch with an ultrasound transducer applied to the suprasternal notch. Because they provided only intermittent measurements at best, clinical acceptance of this method was limited (**Thom et al., 2009**).

In transesophageal technique, a Doppler probe is inserted into the distal esophagus, and is directed to measure the blood flow in the descending aorta at about 35 to 40cm from the incisors of an intubated patient. Measurement of the Doppler frequency shift of the reflected ultrasound waves allows calculation of blood velocity. Cardiac output may then be calculated by one of two methods: The first involves measurement of the aortic cross-sectional area, measured using M mode ultrasound visualisation of the aorta and then multiplying this value by blood velocity to calculate flow. The spectral analysis of the Doppler shift gives velocity-time waveforms. A simpler, and seemingly equally reliable method is simply to derive a value of total cardiac output from a nomogram using aortic blood velocity, height, weight and age (**Cholley and Singer, 2003**).

Transesophageal echocardiography: 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. Blood leaves the left ventricular outflow tract (LVOT) as a cylinder. In

order to calculate the volume of the cylinder, which is equal to the stroke volume, the echocardiographer must obtain the diameter of the LVOT and velocity time integral (VTI) of the blood measured at the same exact location (**Prabhu, 2007**).

In addition to cardiac output assessment, there are other uses of transesophageal echocardiography including managing the response to fluid resuscitation in critically ill patients at risk for heart failure or tissue hypoperfusion, critical care monitoring, pulmonary embolism therapy monitoring, prosthetic valve thrombosis monitoring, detection of myocardial ischemia, assessment of RV systolic function, and assessment of IVC size (**Porter et al., 2015**).

Ultrasonic cardiac output monitors (USCOM, Sydney, Australia) is a portable device which is non-invasive, and uses a probe placed suprasternally to measure flow through the aorta or on the left chest to measure transpulmonary flow. It uses the Doppler principle as used with ED and TEE. Main advantage is the portability of the device, and it can be used with ease in ER, OR, ICU and even in wards. Since it is a non-invasive device, it can be used by trained nursing staff and is an important screening tool for postoperative cardiac surgical patients as well (**Meyer et al., 2008**).

Pulse contour analysis: Pulse wave analysis is based on the principle that SV can be derived from continuous pressure waveform measurement via an arterial line. The characteristics of the arterial pressure waveform are determined by the interaction between SV and vascular compliance, aortic impedance, as well as

peripheral arterial resistance (**Hofer et al., 2009**).

PICCO System: incorporates a transpulmonary thermodilution technique (TPTD) and continuous pulse contour analysis. It is a minimally invasive technique, which gives beat-by-beat monitoring of cardiac output, and can provide accurate information on volume status and pulmonary edema (**Grinberg, 2010**).

The draw back to this system is the need for a central line, recalibration every 8 hours and, cannulation of a large artery. However, it has been shown that several patient populations may benefit from central and arterial catheter measurements (**Porhomayon et al., 2012**).

Flo-Trac: It is another pulse contour CO monitoring system (Vigileo, Edwards Life Sciences) that was introduced in 2005. A special blood flow sensor, which is connected to an arterial line (radial, brachial, axillary or femoral artery), is needed. No external calibration is necessary (**Scheeren and Wiesenack, 2008**).

Several studies have been performed concerning the accuracy of Vigileo CO monitoring that includes a variety of patients with different software versions of the device. Newer studies demonstrate a clinically acceptable precision in comparison with a standard technique of known accuracy. However, the validity depends clinically on the software version (**Yeo et al., 2010**).

The Nexfin (BMEYE, Amsterdam, The Netherlands) is a newer device that has been introduced into practice. It provides beat-to-beat stroke volume and CO

measurements by analysis of a non-invasive finger arterial blood pressure trace, derived continuously from an inflatable finger cuff. A study in 40 patients suggests that this method correlates reasonably well with transcatheter pulmonary thermodilution in cardiac surgery patients (**Broch et al., 2012**).

The esCCO monitor (ECG-SPO₂ estimated continuous cardiac output, Nihon Kohden®) is a new non-invasive tool for estimating cardiac output (CO). It derives CO from the pulse wave transit time (PWTT) estimated by the ECG and the plethysmographic wave (**Bataille et al., 2012**).

Lithium indicator dilution: In this technique, a bolus of isotonic lithium chloride (LiCl) solution (150mM) is injected via a central or peripheral vein, and the resulting arterial lithium concentration - time curve is recorded by withdrawing blood past a lithium sensor attached to an already existing arterial line. The CO is calculated from the lithium dose and the area under the concentration - time curve (**Costa et al., 2008**).

It has been reported that it underestimates cardiac output by 5% compared to intermittent thermodilution technique. This technique is contraindicated in patients on lithium therapy and atracurium therapy (**Prahu, 2007**).

The LiDCO system combines pulse contour analysis with lithium indicator dilution for continuous SV and SVV monitoring. The arterial pressure waveform is interpreted as a continuous curve describing the volume of the arterial tree in arbitrary units (standardized

volume waveform). The effective value (approximately 0.7 times the original amplitude) of this volume waveform is determined using the root mean square, a mathematic principle to calculate the magnitude of a varying quantity. The root mean square value is called “nominal SV”, and is scaled to an “actual SV” using a patient-specific calibration factor (**Montenij et al., 2011**).

NON-INVASIVE METHODS

Electrical impedance cardiography: Bioimpedance is a non-invasive technique involves the application of a small alternating current across the chest via topical electrodes. This current is thought to distribute primarily to blood because of its high electrical conductivity compared with muscle, fat and air. Pulsatile changes in thoracic blood volume result in changes in electrical impedance. The rate of change of impedance during systole is measured allowing a value of cardiac output to be derived. A number of studies have compared bioimpedance to alternative methods of cardiac output measurement, although the findings have proved inconsistent (**De Waal et al., 2008**).

In order to improve the processing of the bioimpedance signal, i.e. in order to improve the signal-to-noise ratio, a modification of the thoracic electrical bioimpedance technology, the so-called ‘thoracic bioreactance’ technology has been developed. ‘Bioreactance’ represents the phase shift in voltage across the thorax (**Marik, 2013**).

Available Monitoring Devices techniques: Advantages and Disadvantages (Giraud and Bendjelid, 2016)

| Technology | System | Invasiveness | Mechanism | Advantages | Disadvantages | Outcome studies |
|-------------------------------------|--------------------|--------------|--|---|---|-----------------|
| Pulmonary artery catheter | Vigilance | +++ | Thermodilution | Gold standard for continuous/intermittent cardiac output monitoring. Allows measurement of pulmonary pressures and mixed venous oxygen saturation | No dynamic parameters of fluid responsiveness. Provides cardiac output information every few minutes | - |
| Calibrated pulse contour analysis | PiCCO ₂ | ++ | Transpulmonary thermodilution + pulse contour analysis | Continuous cardiac output monitoring. Central venous oxygen saturation with specific device. Good accuracy | Remains significantly invasive. Requires a specific femoral artery catheter | 0 |
| | VolumeView | + | Transpulmonary thermodilution + pulse contour analysis | Continuous cardiac output monitoring. Central venous oxygen saturation with specific device. Good accuracy | Remains significantly invasive. Requires a specific femoral artery catheter | 0 |
| Uncalibrated pulse contour analysis | LiDCOplus | + | Lithium dilution | Continuous cardiac output monitoring | Lithium very expensive | + |
| | PulsioFlex | + | Pulse wave analysis | Continuous cardiac output monitoring. Mini-invasive, self-calibrated systems. Can be used with any arterial line and arterial pressure sensor | No validation studies | 0 |
| | LiDCOrapid | + | Pulse wave analysis | Continuous cardiac output monitoring. Mini-invasive, self-calibrated systems. Can be used with any arterial line and arterial pressure sensor | Not enough validation studies | 0 |
| | FloTrac | + | Pulse wave analysis | Continuous cardiac output monitoring. Mini-invasive, self-calibrated systems | Accuracy of cardiac output has been a concern. Sensitive to changes in vasomotor tone. Requires a specific arterial pressure sensor | + |
| | PRAM | + | Pulse wave analysis | Continuous cardiac output monitoring. Mini-invasive, self-calibrated systems | Not enough validation studies. Requires a specific arterial kit | 0 |
| | Nexfin | 0 | Noninvasive pulse wave analysis | Continuous cardiac output monitoring. Completely noninvasive, self-calibrated system | Not enough validation study. Motion artifact | 0 |

| Ultrasound | Cardio Q | 0+ | Doppler ultrasound | Less invasive than arterial-based systems, qualifies for billable monitoring in the USA | Requires frequent manipulation for proper position, significant potential for user variability | +++ |
|---------------------------|----------|----|-------------------------|---|--|-----|
| | USCOM | 0 | Suprasternal ultrasound | Noninvasive cardiac output measurement | Intermittent. Operator dependent | 0 |
| Bioreactance | NiCOM | 0 | Bioreactance | Noninvasive continuous cardiac output monitoring | Few validation studies. Requires a specific arterial kit and a specific endotracheal tube | 0 |
| Endotracheal bioimpedance | ECOM | + | Bioimpedance | Mini-invasive and continuous cardiac output monitoring | Few validation studies. Requires a specific arterial kit and a specific endotracheal tube | 0 |
| Thoracic bioimpedance | BioZ | 0 | Bioimpedance | Noninvasive cardiac output measurement | Many negative studies in the critical care setting | 0 |

0, None; 0+, very slight; + slight; ++, intermediate; +++, severe. PiCCO plus, Pulsion Medical Systems, Irving, TX, USA; Volume View, Edwards, Irvine, CA, USA; LiDCOplus, LiDCO Ltd, London, UK; FloTrac, Edwards, Irvine, CA, USA; LiDCORapid, LiDCO Ltd, London, UK; PulsioFlex, Pulsion Medical Systems, Irving, TX, USA; PRAM, Multiple Suppliers; Nexfin, BMEye, Amsterdam, Netherlands; Cardio Q, Deltex Medical Limited, Chichester, West Sussex, UK; USCOM, Uscom, Sydney, Australia; NiCOM, Cheetah Medical, Tel Aviv, Israel; ECOM, ConMed, Irvine, CA, USA; BioZ, CardioDynamics, San Diego, CA, USA

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التحديثات في مجال رصد وقياس كمية الدم المندفع من القلب

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قسم التخدير والرعاية المركزة كلية الطب جامعة الأزهر

يمكن قياس كمية الدم المندفع من القلب بطريقتين إما نافذة أو غير نافذة:

* الطرق النافذة:

1- طريقة فيك (Fick) : كمية الدم المتدفق من القلب = نسبة إستهلاك الأوكسجين ÷ فرق نسبة تركيز الأوكسجين بين الشريان والوريد.

2- قياس نسبة الأوكسجين في الدم الوريدي المختلط : عندما تكون نسبة تشبع الدم الشرياني بالأوكسجين، نسبة إستهلاك الأوكسجين وتركيز الهيموجلوبين ثابتة، فإن نسبة الأوكسجين في الدم الوريدي المختلط تعتبر كمثال غير مباشر لقياس كمية الدم المتدفق من القلب وهي تعتمد علي تركيب قسطرة شريانية رئوية.

3- إستخدام الدلائل: كمية معينة من مادة خاصة (دليل) تحقن في الدورة الدموية، ثم يتم قياس نسبة تغيرها في التركيز أو الحرارة أو اللون. وهي تعتمد علي اما الحقن من خلال القسطرة الشريانية الرئوية أو من خلال قسطرة وريدية مركزية او طرفية. ومن أشهر الدلائل محلول الملح البارد والليثيوم. ومن أشهر الأجهزة التي تعتمد علي إستخدام الدلائل جهاز الLIDCO، والقسطرة الشريانية الرئوية.

4- تغير قوة النبض للضغط الشرياني: يمكن قياس كمية الدم المتدفق من القلب بإستخدام الحاسب الآلي عن طريق تغير منحى الضغط بالشريان الأورطي أو شريان الرسغ، أو حتى بطريقة غير نافذة من الإصبع السبابة بإستخدام مجس خاص. ومعظم هذه الطرق تحتاج إلى وضع قسطرة شريانية طرفية وقسطرة وريدية مركزية. ويوجد العديد من الاجهزة التي تعتمد علي هذه الطريقة ومنها جهاز PICCO، وجهاز LIDCO الذي يجمع طريقتي إستخدام الدلائل وتغير قوة النبض. وما تزال بعض الاجهزة الجديدة محل الدراسة والمقارنة بالطرق التقليدية مثل جهاز Nexfin و Flo-Trac.

*** الطرق الغير نافذة:**

هي طرق جديدة لقياس كمية الدم المتدفق من القلب والتي لا تعتمد على تركيب قسطرة الشريان الرئوي وبالتالي فهي لا تحتاج إلى مهارة خاصة وأدت إلى تقليل نسبة المضاعفات التي قد تحدث، وكذلك فهي تعطي نتائج إلى حد ما متطابقة مع مثيلاتها النافذة.

وعلى صعيد آخر، فإن هذه الطرق تلقي بعض الضوء على معلومات إضافية عن الدورة الدموية مثل كمية الدم القادم إلى القلب وقوة انقباض عضلة البطين، وبالتالي فهذه الطرق فوائد جمة علاوة على قياس كمية الدم المتدفق من القلب وهي تتمثل في التشخيص المبكر وبالتالي محاولة تفادي أو سرعة إصلاح أي خلل في الدورة الدموية قبل التأثير الواضح الذي قد يحدث لخلايا الجسم نتيجة انخفاض نسبة الأكسجين القادمة.

ومن هذه الطرق:

1- الموجات فوق صوتية (الأشعة التلفزيونية) عن طريق المرئ أو من الخارج ما بين عظمة القص والرقبة أو من خلال القصبة الهوائية عن طريق الأنبوبة الحنجرية.

2- المقاومة الكهربائية للتجويف الصدري: ومن الطرق الحديثة لهذه الوسيلة توصيل الكابلات الخاصة بالجهاز إلى الأنبوبة الحنجرية. وهناك جهاز جديد يعمل بطريقة فيك (Fick) الغير مباشرة في قياس كمية الدم المتدفق من القلب وذلك بشهيق المريض الجزئي لزيده، علاوة على أن هذه الطريقة غير نافذة فهي سهلة للغاية ولا تحتاج سوى لتوصيل الجهاز بالأنبوبة الحنجرية ونتائجها مبهرة.

من الحكمة أن نستخدم كل الخيارات المتوفرة لمراقبة الناتج القلبي على أسس فردية أفضل من أسس عامة، حيث أن الاضطرابات الدينامية الدموية لمرضى الحالات الحرجة قد تكون متعددة الأسباب وعلاج هؤلاء المرضى يجب أن يكون عملية ديناميكية متضمنة:

- 1- وسائل المراقبة.
- 2- التقييم.
- 3- إشراف وتحديد العلاج.
- 4- الحس الإكلينيكي.
- 5- إعادة التقييم.

وهذه النقاط الخمس يجب أن تؤخذ في الاعتبار عند تقديم الخدمة الطبية لمرضى الحالات الحرجة، وأيضاً إرشاد الطبيب للتحويل من وسيلة تداخلية إلى وسيلة أقل تداخلاً والعكس صحيح