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Review Article

Non-Invasive Cardiac Output Measurement: Where Are We Now?

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ABSTRACT

Aim of review: Cardiac output measurement has been the centerpiece of hemodynamic monitoring for the last several decades since the introduction of Swan-Ganz catheter in 1970's. This review is aimed to review the current status of available techniques for non-invasive cardiac output measurement.

Methods: This manuscript reviews recently published literature and discusses currently available techniques based on different mechanisms for the non-invasive measurement of cardiac output.

Recent findings: There are multiple complications associated with Swan-Ganz catheterization. It is controversial whether the use of Swan-Ganz catheter improves clinical outcome. Enormous efforts have been made to develop minimally invasive and non-invasive technologies as an alternative to Swan-Ganz catheter. In this review, we discussed the currently available non-invasive cardiac output measurement techniques, which include the arterial waveform analysis-based techniques (ClearSight, CNAP) and bioimpedance-based technologies (Transthoracic electric bioimpedance, Electric bioreactance, Electric cardiograph).

Summary: Each of the discussed technology in non-invasive cardiac output measurement has its advantages and disadvantages. The major concerns in applying these new technologies are their accuracy and bias. Selection of patients and surgical conditions are also contributing to their accuracy and error. Many new technologies are still in developing phase, and new integration of different technologies to offset their drawbacks and better determine the cardiovascular function status of perioperative patients will emerge in the near future.

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Cardiac output (CO) measurement has gone through centuries of evolvement. One of the landmarks in this process is the introduction of the balloon-tipped pulmonary artery catheterization (PAC) by Drs. Swan and Ganz in 1970 (1, 2), thus also called Swan-Ganz catheter. PAC brought CO measurement into the reality of bedside clinical application (2). However, it has been controversial for over half a century whether clinical management based on PAC parameters improves clinical outcomes or not (3). PAC-related complications are multiple-faceted. These complications include central venous access-related (arterial puncture, pneumothorax, air embolism), catheterization-related (dysrhythmias, tricuspid regurgitation, right bundle-branch block, complete heart block, and catheter indwelling-related (pulmonary artery rupture, thrombophlebitis, mural thrombus, infection and sepsis). These potential serious complications and the lack of strong proof in improving clinical outcomes by PAC-based management have led to the enor-

Figure 1. The ClearSight system.

Figure 2. CNAP system.

mous efforts to develop other techniques as alternatives for the CO measurement (3, 4). Currently, available CO measurement technologies include minimally invasive techniques as Flo-Trac, LiDCO, PiCCO, PRAM, and transesophageal echocardiography, and noninvasive technologies as ClearSight, Cheetah, CNAP, and bioimpedance-based techniques (2). Transthoracic echocardiography is also noninvasive, but it won't be discussed in this article. In this mini-review, we will discuss the current status of relatively new non-invasive CO measurement technologies.

Arterial Waveform Analysis Based Technologies

ClearSight (by Edwards Life Science, San Diego, California)

Edwards Life Science introduced this noninvasive, continuous monitoring system of arterial pressure, cardiac output and stroke volume by using a digital sensor and wrist cuff (Figure 1), initially as the ccNexfin system, later integrated into the ClearSight system. The continuous monitoring of blood pressure by this technique was validated in cardiothoracic surgery (2). This monitoring system has been used for moderate-to high-risk surgical patients who are not typically getting an arterial line. The ClearSight system can provide a series of parameters as stroke volume (SV), stroke volume variation (SVV), cardiac output (CO), systemic vascular resistance (SVR), pulse pressure variations (PPV), and continuous arterial blood pressure (cABP). The ClearSight system can also send an analog pressure to visualize noninvasive BP on a bedside monitor (5).

The CNAP (Continuous non-invasive arterial pressure, Biopac systems, California; CNSystems Medizintechnik AG, Graz, Austria).

The CNAP's algorithm is relatively new, but its basic theory "the Penaz principle" was described by Dr. Saugel in as early as 1973 as a method to generate arterial waveform (6). The CNAP system allows continuous noninvasive beat-by-beat recording of the arterial pressure waveform. For accurate arterial waveform recording, this system uses an inflatable finger cuff applied to the patient's finger (Figure 2, Figure 3), so the finger artery's diameter is assessed by an integrated photoplethysmograph which maintains the blood volume in the finger artery relatively constant. A controller device constantly adjusts the finger cuff pressure to keep the blood volume constant throughout the cardiac cycle. The pressure required to keep the volume constant corresponds to the arterial blood pressure waveform. The original Penaz principle won't work if the arterial diameter and wall tension are altered due to vasoconstriction and vasodilation. The CNAP system eliminates such vasomotoric effects by using concentrically interlocking loops and a VERI-

FI-algorithm ("Vasomotoric Elimination and Reconstructed IdentiFication of the Initial set-point") (7). This new algorithm continuously analyzes the waveform shapes and allows distinguishing between blood volume shifts due to alterations in arterial pressure and those secondary to the changes of the arterial diameter. This distinction is critical for stable longer-term tracking of arterial blood pressure. The arterial pressure signal from this finger cuff technique is calibrated by fitting them to repeated upper-arm oscillometric will emerge in the near future ally obtained blood pressure measurements. The CNAP system maintains a zero-transmural pressure state with the addition of proprietary methods (interlocking control loops arranged concentrically). The new algorithm also analyzes the arterial blood pressure waveforms and responds to any deviations from the set point to maintain it at unloaded cuff pressure. The CNAP system is relatively easy to uses. A recent clinical study conducted by Wagner et al. compared CNAP technique with intermittent invasive CO measurements by pulmonary artery catheter in 51 postoperative cardiothoracic surgery patients at three different time points (8). They found very good agreement when CNAP was compared with pulmonary artery catheterization technique, the concordance rate was 100%.

The functioning of ClearSight and CNAP systems may be affected in critically ill patients by exogenous administration of vasoconstrictors and by systemic sepsis. Extremity movement also affects CNAP measurements when it is used on patients who are awake. The clinical utility of these devices will likely be an ongoing discussion in the medical community. Crucial to this discussion will be weighing the inaccuracy and imprecision of these devices, demonstrated with relatively large bias and SD, against the potential benefits that they may have on patient safety (9). The clinicians who are interested in using these devices in the clinical setting need to be aware of these potential drawbacks.

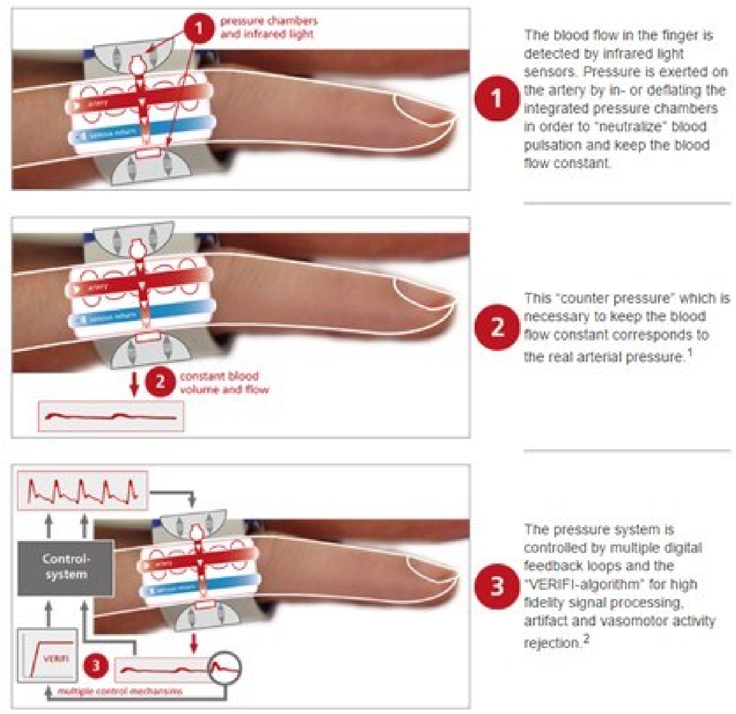

Figure 3. The Vascular Unloading Technique is The Basic Principle for Detecting Blood Volume Changes in the Finger and Transforming Plethysmographic Signals into Continuous Blood Pressure Information.

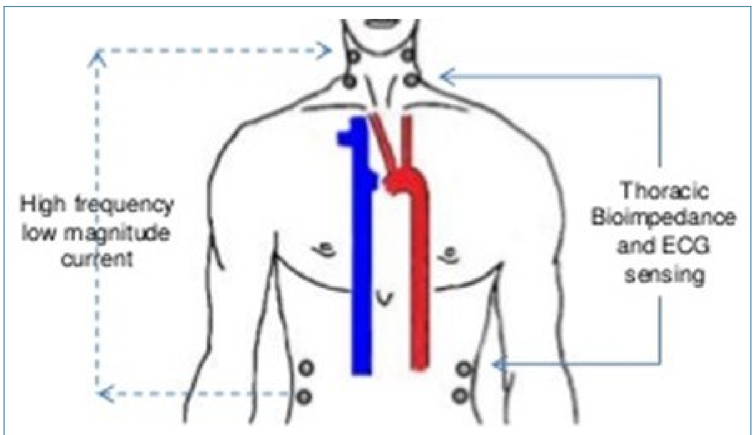

Figure 4. TEB Probe Placement.

Bioimpedance-Based Technologies

Thoracic Electrical Bioimpedance (TEB)

TEB basically determines the change of impedance by delivering a low-amplitude high-frequency electrical current across the thorax. The TEB sensing electrodes measuring impedance are usually placed on the upper and lower thorax (Figure 4). Hemodynamic parameters are measured by TEB devices based on changes in the thoracic electrical conductivity to changes of thoracic aortic blood flow during the cardiac cycle. By mea-

Figure 5. The CHEETAH Monitor.

Figure 6. Volume Status on Frank-Starling Curve.

suring the impedance changes generated by the pulsatile flow and the time intervals between the changes, cardiac stroke volume can be calculated. TEB is an alternative technique to invasive hemodynamic monitoring of SV, CO, and CI (10). CO measurement by TEB and Swan-Ganz catheterization technique was compared in patients undergoing cardiac surgery. TEB had an acceptable accuracy but it might be more useful as a hemodynamic trending analysis, not as a diagnostic interpretation tool (11).

TEB is a completely noninvasive CO monitoring technique but it can be limited by cardiac arrhythmia, fluid content in the thoracic component, and background noise from mechanical ventilation or electrocautery. Patients need to be intubated for the use of TEB. Additionally, TEB signal stability usually fades after 24 hours of the application (12). Therefore, TEB is less likely to be routinely used in CO monitoring alone in current technological status.

Electrical Bioreactance-Based the Cheetah NICOM

Electric bioreactance (EB) was developed to overcome the TEB limitations. EB analysis is also based on alterations in the frequency of electrical resistivity across the thorax, but it is significantly less susceptible to interference from chest wall movement, lung edema and pleural effusion (13). EB technology is commercially available as the Cheetah NICOM (Non-invasive cardiac output measurement) system in the USA. The system provides critical hemodynamic data by measuring CO centrally. The Cheetah NICOM is based on bioreactance. When an alternating current is applied to the human thorax, the pulsatile blood flow taking place in the large thoracic arteries causes phase shifts or time delays between the measured thoracic voltage and the applied alternating current. Extensive studies have found that these phase shifts are closely correlated with cardiac SV. By continuously measuring these phase shifts, SV can be determined (13).

The CHEETAH NICOM monitor can also display all important hemodynamic parameters including CO, CI, SV, SVI, SVRI (Figure 5). It can also indicate a patient's volume status in relation to current position on the Frank-Starling curve (Figure 6). The Cheetah NICOM hemodynamic monitoring system can obtain hemodynamic assessments 100% noninvasively by placing four dual-electrodes on the chest wall. Each sticker contains electrode to inject an alternating current (i) with the frequency 75 kHz into the body and the other electrode is the voltage input amplifier (v) to detect and summarize the return signal. The NICOM system measures the time delay between "i and v" signals, which is called "phase shifts". The majority of phase shifts are pulsatile flow from the aorta in human beings. The NICOM monitor applies a high sensitive "Phase detector", which detects phase shifts and analyze them into the NICOM signals. These NICOM signals are mainly correlated with aortic blood volume. Thus, SV and CO can be calculated from these signals.

Bioreactance-based Cheetah NICOM is totally non-invasive, continuous monitoring with a variety of clinical applications and very safe for clinical use. However, there are drawbacks for the Cheetah NICOM system, signal interference by electrocautery may transiently cause bad signals, and NICOM signal may lose their accuracy during very low flow status. NICOM was compared to Swan-Ganz thermodilution technique and a good correlation was established (14). In a multicenter study of ICU patients, the NICOM, PAC, Fick' s principle and Bioreactance technique were simultaneously compared. In subsets analysis, NICOM had a better correlation to PAC than other techniques (14).

Impedance Cardiography

CNSystems' approach uses a new electrical thorax model based on Ohm's law. The changes of the thoracic impedance of blood and tissue induced by cardiac cycles are measured with very unique short-band electrodes placed on thorax and neck allowing a reproducibility of 97% (15). CO and other important hemodynamic parameters are derived from this information with special algorithms. This algorithm automatically eliminates the effects of breathing through an adaptive filtering mechanism. When compared with the thermodilution technique, this method achieves 88% correlation in an interval of -0.24±0.47 L/min (PE = 22.9%) in patients with severe left-heart insufficiency (12). And the reliability of this device was proven in more than 100 peer-reviewed publications (15). This technique is completely noninvasive, almost risk-free, and the patient setup is fast and easy. This technique has significantly improved its signal-to-noise ratio although the patient auxiliary current is now under the limit of type-CF conditions (cardiac flow) according to IEEE 60-601 standard (15).

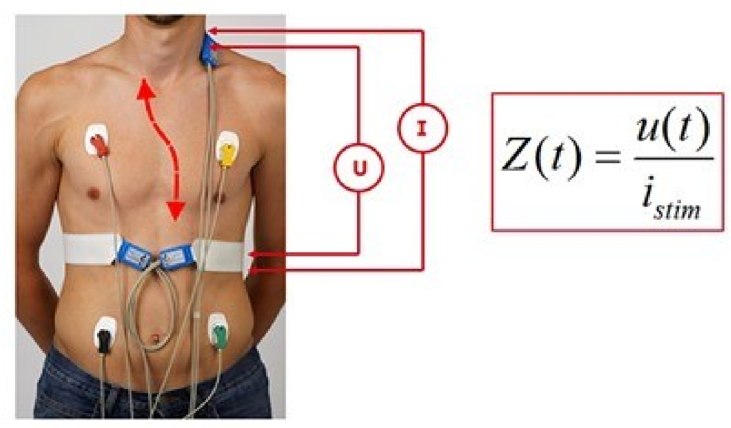

Figure 7. Impedance Cardiography Probe Placement (Different from TEB probe placement).

Transthoracic Echocardiography

Transthoracic echocardiography has been used to measure CO for half a century, and it still is probably the most commonly used technique worldwide. For repetitive measurement of CO in ICU management of severely ill patients and intraoperative measurement of CO, pulmonary artery catheterization with intermittent thermodilution technique has been the gold standard. Transthoracic echocardiography is a completely non-invasive way of hemodynamic assessment which can be done bedside to critically ill patients.

Transthoracic echocardiography can be used to estimate CO in several ways. The most frequently recommended technique is measuring the blood flow velocity by obtaining a Doppler waveform at the left ventricular outflow tract and this technique can also get the stroke volume as well as cardiac output. Echocardiography is basically recommended as the first-line evaluation of the patient in the status of circulatory failure. Mercado et al. adopted the Bland–Altman analyses to have evidenced a small level of bias and a broad limit of agreement with intermittent thermodilution technique. Another technique for transthoracic echocardiography to measure CO is the so-called "Simpson technique" (16). The advantages of transthoracic echocardiography are obvious, completely non-invasive, can be done repetitively, bedside utilization possible and easy, and it can detect many other cardiac functional status and cardiac anatomic abnormalities (16). The disadvantages include it is expensive, sometimes it is very difficult to visualize some cardiac structures, and it cannot be applied during open heart surgery other thoracic procedures.

Summary

Completely noninvasive CO measurement has been slowly but steadily gaining popularity in clinical practice (2, 17). CO measurement is still one of the most important elements of perioperative hemodynamic monitoring in modern medicine ever since the introduction of the Swan-Ganz catheter in 1970 (18).

Perioperatively PAC has been commonly used in patients undergoing major cardiothoracic and vascular surgery, in patients with significant coexisting cardiovascular diseases to undergo non-cardiovascular procedures, in major trauma patients, or other critically ill patients with sepsis (2, 18). PAC has long been considered the "Gold standard" in measuring CO for the last four decades. However, it has been controversial whether management of critically ill patients based on PAC parameters improves or not the clinical outcomes (19) and longer-term prognosis (20).

We believe the claim "Swan-Ganz is dead" might be somewhat premature. The less invasive or completely non-invasive techniques have been increasingly gaining popularity in clinical practice for the last almost two decades (2, 17).

Ironically all newly-developed minimally-invasive or non-invasive CO measurement technologies will be compared with the long-considered "Gold standard", even though the "Gold standard" may not be golden. We believe this trend of increasingly using non-invasive CO techniques will continue for the coming decade(s), more and more combined technologies, such as integrating two or more different technologies in one monitoring system, will emerge and get validated.

By integrating different technologies, we can potentially offset some drawbacks of each technology and more accurately determine the true cardiovascular functional status. On the other hand, each technology will likely get further refined to better reflect the true value of patient's cardiac physiological status. And integration of minimally invasive or noninvasive CO measurement technology with tissue-level oxygenation monitoring technology will likely be unveiled in the near future.

Another trend in hemodynamic monitoring is the interest in monitoring microcirculation at tissue level which should be the target for hemodynamic resuscitation. A better understanding of physiology and pathophysiology of microcirculation at tissue, cellular and molecular level will ultimately determine the applicable technology and monitor design for the future.

The author declares no conflicts of interest.

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