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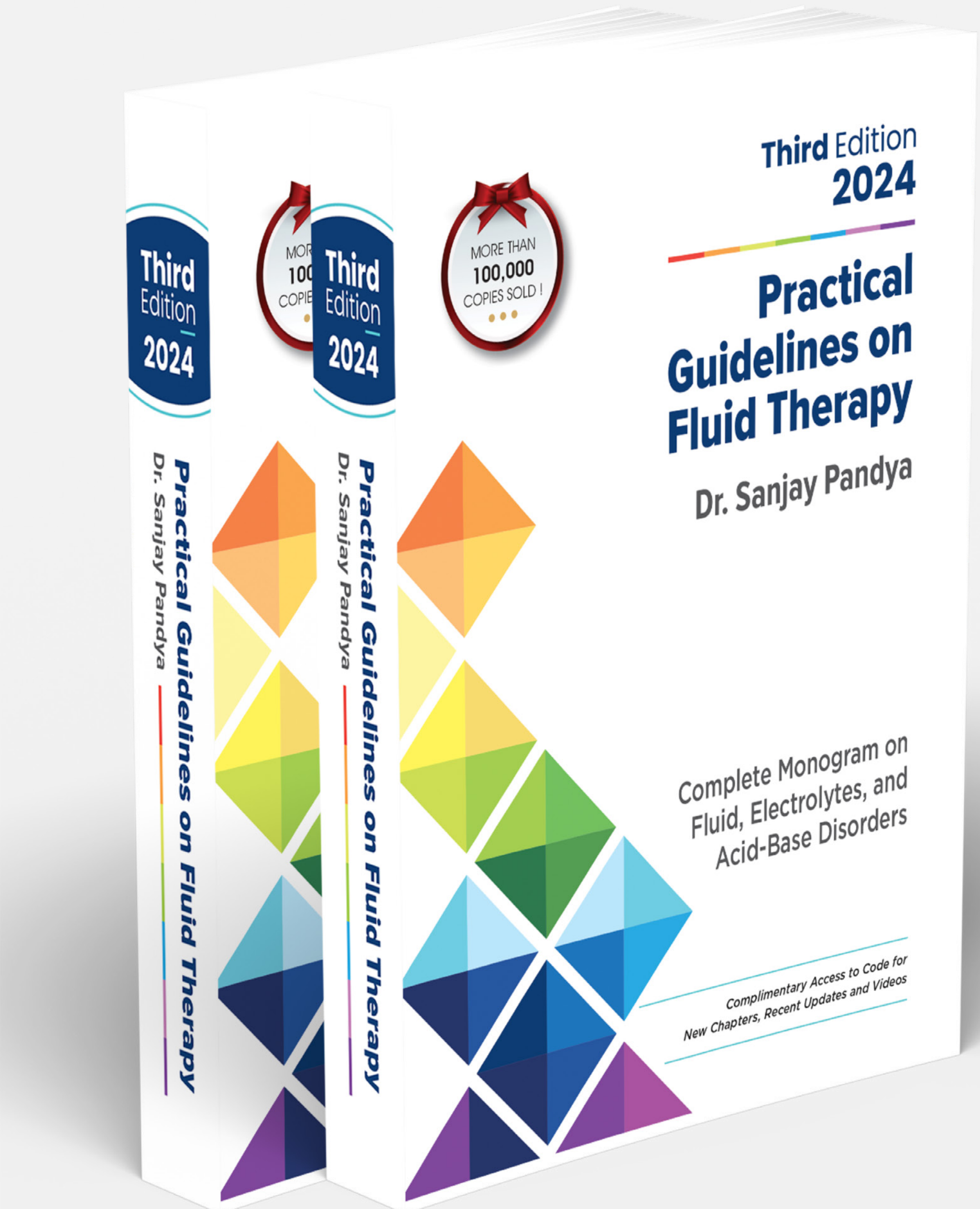
Chapter 19:

Cardiac Output Monitoring



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19 Cardiac Output Monitoring

The accurate measurement of cardiac output (CO) is essential in all high-risk hemodynamically unstable patients.

Several devices for cardiac output measurement are available in the market, which is classified based on invasiveness (Non-invasive, minimally invasive, and invasive systems), the technology used (dilution technique, pulse contour analysis, doppler principle, applied Fick principle bioelectric properties, plethysmographic analysis, etc.), and calibration systems, as summarized (Table 19.1).

CALIBRATED VS. UNCALIBRATED DEVICES

Calibration is the process of comparing an instrument with the known standard. Subsequent adjustment of measured equipment achieves precision and accuracy and produces valid data. In calibrated monitoring devices, the bias in the continuous measurements is reduced or eliminated by calibration [1]. While in non-calibrated monitoring devices, bias is reduced by the pre-programmed correction factors in the monitoring device.

Table 19.1 Hemodynamic monitoring systems			
Methods	**Requirements**	**Calibration**	**Devices**
1. Non-invasive systems			
Transthoracic echocardiography	Thoracic echo probe	Calibrated	US, Echo
Bioimpedance or bioreactance	Specific cutaneous electrodes	Non-calibrated	BioZ Dx ECOM NICOM (Cheetah)
Radial applanation tonometry	Pressure sensor over the radial artery	Non-calibrated	T-line
Volume clamp method	Finger pressure cuff	Non-calibrated	CNAP Clearsight/Nexfin
Ultrasound cardiac output	Transthoracic doppler probe	Non-calibrated	USCOM
Plethysmographic variability index	Specific transcutaneous probe	Non-calibrated	MASSIMO
2. Minimally invasive systems			
Transesophageal echocardiography	Esophageal probe	Calibrated	Cardio Q WAKI TO
Transpulmonary thermodilution	Thermistor-tipped arterial catheter Central venous line	Calibrated	PiCCO VolumeView EV 1000
Lithium dilution	Arterial catheter Central venous line	Calibrated	LiDCO LiDCO Plus PulseCO
Arterial pulse contour analysis	Arterial catheter	Calibrated	PiCCO Plus LiDCO Plus
		Non-calibrated	Flotrac/Vigileo LiDCO rapid PRAM/MostCare ProAQT/PulsioFlex
Partial CO_2 rebreathing	Rebreathing circuit	Non-calibrated	NiCO
3. Invasive systems			
Pulmonary thermodilution	Pulmonary artery catheter Central venous line	Calibrated	Swan-Ganz pulmonary artery catheter

Cardiac output monitoring systems are divided into two groups, calibrated and uncalibrated devices, depending on the method of calibration [1, 2]. Cardiac output monitoring systems based on non-calibrated analysis have been emerging as the preferred modality in the last few years because of their minimally invasive nature and no need for calibration, usual independence from mechanical ventilation, and ease of use in practice [3]. Uncalibrated systems are used selectively in hemodynamically stable patients requiring cardiac output monitoring for a short period, e.g., during surgery [4]. Because of more accuracy and precision, calibrated techniques are preferred over uncalibrated methods in severely shocked hemodynamic unstable patients [2].

NON-INVASIVE SYSTEMS FOR CARDIAC OUTPUT MONITORING

Non-invasive techniques commonly used for measuring cardiac output are transthoracic echocardiography, thoracic electrical bioimpedance, thoracic bioreactance, applanation tonometry, and volume clamp method.

A. Transthoracic echocardiography

Measuring and monitoring cardiac output is valuable for diagnosing and managing critically ill patients. The trend to use transthoracic echocardiography (TTE) for the prompt measurement of cardiac output is increasing because it is a readily available, reproducible, and non-invasive, bedside method [5, 6].

In early literature, in stable patients, TTE was found to be accurate compared to the standard PA thermodilution technique [7–9], but in critically ill patients, predictability was found to be limited [10, 11].

With technological advancements, the ability of TTE to acquire high-quality images of critically ill patients improved [12, 13], and literature supporting the use of TTE to manage critical patients emerged [14–17].

Simultaneously, emerging literature supports the use of echocardiography for the measurement of cardiac output and its role in hemodynamic optimization [18–21].

In current literature, TTE is documented as a reliable, accurate, and highly valuable method to measure cardiac output, which provides rapid and vital diagnostic information and thereby guides clinicians for a wiser therapeutic strategy [6, 22–25].

Recent literature also documented that cardiac output measurement by transthoracic echocardiography was comparable to cardiac output measured by a pulmonary artery catheter thermodilution (TD) technique. Due to its wide availability, great potential to guide therapy, and noninvasive nature, TTE has become a routine and standard practice for bedside cardiac output measurement in the management of critical patients [26, 27].

How to measure and calculate cardiac output by TTE?

Parameters determined for the calculation of cardiac output by TTE are:

- Left ventricular outflow tract velocity time integral (LVOT VTI): Velocity-time integral (VTI) is measured by pulsed wave doppler signal, most commonly at the level of the left outflow tract (LVOT) obtained in the apical 5 chamber view. LVOT-VTI reflects the column of blood that moves through the left ventricle (LV) outflow tract during each systole; therefore, it is a TTE parameter representing stroke volume.
- Cross-sectional area (CSA): Measure the diameter of the LVOT in the parasternal long axis view in systole and calculate the area of the circle.
- Heart rate (HR).

Calculation of cardiac output: After obtaining the above parameters by TTE, cardiac output is calculated with the formula below:

Cardiac Output = Stroke Volume × HR

Cardiac Output =
[LVOT VTI × LVOT CSA)] × HR

To measure cardiac output precisely, averaging three measurements within one TTE examination is recommended in patients with sinus rhythm, and averaging five measurements is necessary for patients with atrial fibrillation [28].

Limitations of TTE are:

- Accuracy is highly dependent on an operator, so the possibility of inter-and intra-observer variability. But even non-cardiologist ICU physicians, after brief training, can accurately estimate cardiac output by TTE [23].
- The probe's position needs to be very accurate, and errors in position can lead to misinterpretations.
- The accuracy of TTE to measure cardiac output is unreliable in patients with high cardiac output, low sedation, or with physiological structural changes.
- TTE provides only intermittent and not continuous cardiac output measurements.

TTE, in addition to calculating cardiac output, measures inferior vena cava diameter and left ventricular size, identifies wall motion abnormalities, and assesses left and right ventricular function. By providing this information, TTE improves diagnostic accuracy, narrows the possible differential diagnosis of shock, and achieves volume status optimization. Small LV size, hyperdynamic LV (left ventricular end-diastolic area in the parasternal short axis view <10 cm2), or papillary apposition (kissing ventricles) are strongly indicative of hypovolemia and predicts fluid responsiveness [29, 30]. Papillary apposition can be false positive in LVH, vasodilatation and high inotropes.

B. Thoracic electrical bioimpedance and bioreactance

1. Thoracic bioimpedance

Thoracic electrical bioimpedance (TEB) is a non-invasive method to continuously estimate cardiac output using pairs of high-frequency but low-voltage disposable electrodes placed on either side of the neck and the lateral aspect of the chest wall.

The fluid offers less resistance to electric flow. A greater volume of blood column during each systole will work as a larger electrical contrast medium, lowering the electrical impedance. This principle is used to calculate stroke volume [31].

A series of signals from sensing electrodes will travels through the thorax and will continuously and accurately measures the cyclic changes in thoracic electrical impedance, which occurs due to changes in intrathoracic blood volume with each heartbeat. Based on these changes in electrical impedance, cardiac output is calculated.

The reliability of TEB is poor in the exact measurement of cardiac output in surgical and critically ill patients [32, 33].

However, as TEB measures cardiac output continuously and non-invasively, its use is rapidly increasing as a bedside cardiac output trend analysis monitor [34, 35].

Thoracic bioimpedance is a simple, easy-to-use, totally safe, and low-cost method that provides rapid, real-time, continuous, and automated cardiac output monitoring. Various factors that can affect the measurement of cardiac output by this method are electrical interference, cardiac arrhythmias, pleural effusions, pulmonary edema, chest tubes, internal or external pacemakers, or patient movement.

2. Thoracic bioreactance

Thoracic bioreactance is a modified, improved bioimpedance technology which measures time delay called a phase shift in alternating current voltage across the thorax rather than changes in impedance.

Electrodes applied on either side of the chest detect phase shifts, which almost exclusively depend on pulsatile flow (e.g., blood flow) but are less affected by static fluids (e.g., intravascular and extravascular fluids), electrical noise, patient movement, electrode positioning, and respiratory effort. In addition, because of newer technology-related improvements in the signal-to-noise ratio, bioreactance is theoretically superior to bioimpedance [36].

Thoracic bioreactance is found to be a reliable technique to measure cardiac output in many studies (but not in all studies) [37–41]. In a recent meta-analysis of the accuracy and precision of non-invasive cardiac output monitoring devices, percentage errors were 42% for bioimpedance and bioreactance [42].

Applanation tonometry and volume clamp method

Radial artery applanation tonometry and volume clamp method are two non-invasive uncalibrated techniques that provide continuous blood pressure monitoring and real-time cardiac output from the pulse contour analysis.

C. Radial artery applanation tonometry

In this method, the transducer is strapped over the radial artery with a bone underneath. Optimal pressure is adjusted to flatten the artery, and using an electromechanically driven sensor; continuous arterial pressure waveform is recorded. Then, cardiac output is estimated with the help of autocalibrating pulse contour analysis.

As this novel method is extremely easy to use, and its initial clinical data are promising, it is an attractive alternative to measure cardiac output in practice [43, 44]. However, evidence suggests that this method is not suitable for measuring cardiac output in hemodynamically unstable critically ill patients [45–47].

D. Volume clamp method

In this technique, a non-invasive pulse oximeter using finger cuff devices continuously measures cardiac output and finger arterial blood pressure in addition to peripheral oxygen saturation [48].

This method is an extension of conventional photoplethysmography whereby using an inflatable cuff at the finger, the digital arterial waveform is obtained. With a photodiode device, the diameter of the artery in the finger is measured. By adjusting the pressure in the cuff, the diameter of the artery is kept constant during pressure waveform analysis. Arterial pressure waveform is continuously recorded from the pressure changes in the cuff, and cardiac output is calculated.

This simple and convenient method for cardiac monitoring is promising in surgical and non-critical cases [49–51], but its use is discouraged in obese, cardiac surgery, and ICU patients because of poor accuracy [52–57].

This method is not suitable for patients with gross peripheral edema or severe peripheral vasoconstriction.

MINIMALLY INVASIVE AND INVASIVE SYSTEMS FOR CARDIAC OUTPUT MONITORING

Minimally invasive and invasive methods for cardiac output monitoring are used in hemodynamically unstable patients in intensive care and perioperative medicine when initial resuscitation measures fail to improve the patient's hemodynamic and/or respiratory status. Accurate measurement of cardiac output with advanced hemodynamic monitoring will guide appropriate management with fluid resuscitation, vasopressors, or inotropic agents.

MINIMALLY INVASIVE SYSTEMS

Minimally invasive techniques commonly used for measuring cardiac output are transesophageal echocardiography, transpulmonary thermodilution, arterial pulse contour analysis, and partial CO2 rebreathing [58].

A. Transesophageal echocardiographic

Transesophageal echocardiography (TEE) is a minimally invasive technique to measure cardiac output. This method is widely used for diagnosing and monitoring critical and perioperative patients.

Technique

In TEE ultrasonic probe is placed into the esophagus under sedation. Placement of the TEE probe is similar to the insertion of a nasogastric tube, and the depth of the tube inserted in the esophagus is to place the tip of the probe at descending thoracic aorta level (between the fifth and sixth intercostal space), which will be roughly 35–45 cm mark on the probe.

TEE probe obtains a doppler flow signal and measures the blood velocity in the descending thoracic aorta. From different data obtained, such as heart rate, peak velocity, flow time corrected (FTc), and others, hemodynamic monitor derives cardiac output, Stroke volume, and systemic vascular resistance.

The use of TEE is expanding with growing technology [59]. In addition to standard 2D technology, TEE probes are available with different modalities such as doppler, pulse wave doppler, continuous wave doppler, color flow doppler, and 3D echocardiography.

Use

TEE plays a vital role in the management of perioperative and critical patients by providing valuable diagnostic and therapeutic information such as:

- Assessment of the volume status (detects hypovolemia early or excludes volume overload).
- Serve as a dynamic parameter to assess fluid responsiveness and guides clinicians for fluid management (i.e., goal-directed fluid therapy).
- Measures cardiac output, detects ventricular dysfunction, and diagnose coexisting problems like valvular structural and functional abnormalities, pericardial effusion, and cardiac tamponade.

The results of studies about the reliability of TEE in predicting cardiac output were conflicting [60, 61]. However, in a recent systematic review and meta-analysis, cardiac output measurement by TEE was accurate [27].

Advantages

Different advantages of TEE are:

- Provides superior quality image, accurate assessment of heart and great vessels, and greater diagnostic accuracy than transthoracic echocardiography because the probe is much closer to the heart, and bone and lung tissue do not interfere with imaging [62].
- As the TEE probe is just adjacent to posterior cardiac structures, TEE provides its superior quality image. On the contrary, the point of examination of the TTE transducer is more distant from the posterior

cardiac structures, i.e., at the anterior aspect of the chest. Therefore its visualization by TTE is poor.

- TEE monitoring does not disturb the surgical field and ensures continuous imaging in all stages of surgery [63].
- TEE is less dependent on the operator than TTE.

Indications

As TEE provides valuable information about several structural, functional, and hemodynamic parameters, its use is gaining popularity. But TEE is a semi-invasive method and therefore is used selectively when TTE cannot provide the required information, and the potential benefits of TEE outweigh the possible risks. Common indications of TEE are [62, 64–66]:

a. Intraoperative/Perioperative

TEE is indicated in high-risk surgical patients (e.g., significant coronary artery disease or poor cardiac status), patients with a risk of intraoperative hemodynamic instability (e.g., major vascular or abdominal surgery), major cardiac surgery like the repair of congenital heart lesions, repair of valvular lesions or thoracic aortic procedures, and as a rescue TEE in unexpected or unexplained hemodynamic unstable patients.

TEE monitoring and TEE-guided optimization of fluid administration improve outcomes, reduce postoperative complications, and shorten hospital stay in patients undergoing major or high-risk surgery [67–69].

b. Critically ill patients

TEE is useful in hemodynamically unstable critically ill patients because it calculates cardiac output, provides excellent visualization of cardiac structures, and is less dependent on the operator. TEE is used selectively in sedated ICU patients, usually on a mechanical ventilator [70]:

- For the assessment of unexplained persistent hypotension or hypoxemia when TTE or other modalities cannot obtain diagnostic information.
- For assessing volume status and cardiac output during fluid administration when no other hemodynamic monitoring systems are available.

c. Diagnostic modality

TEE is useful in diagnosing wall motion abnormalities, pericardial effusion, pulmonary hypertension, potential cardiac source of embolus, assessing valves for endocarditis, or excluding thrombi in patients with atrial fibrillation.

Contraindications

TEE's potential contraindications are previous esophagectomy, tracheoesophageal fistula, postesophageal surgery, esophageal trauma, esophageal pathologies such as varices, diverticulum, stricture or tumor; coagulopathy, thrombocytopenia, upper gastrointestinal bleeding, and hiatus hernia [70, 71].

Limitations

Although TEE is more useful than TTE, it is used in selected indications and not used routinely. TEE is used more frequently in the operating theater than in the ICU [72]. Limitations of TEE are:

- The minimally invasive technique (usually needs tracheal intubation, under sedation).
- Do not calculate cardiac output continuously compared to other hemodynamic monitoring devices, such as the pulmonary artery catheter (PAC) or transpulmonary thermodilution.
- Movement of the patient can change the position of the probe, and repositioning becomes necessary.
- Higher cost, time-consuming method (compared to TTE), can be performed

only on one patient at a time and needs cleaning and disinfection after each use.

- Do not measure blood pressure, so critical patients need an additional device for continuous blood pressure measurement.

B. Transpulmonary thermodilution

Transpulmonary thermodilution (TPTD) is a minimally invasive technique (requires two catheters, a central venous catheter, and an arterial line), which is considered a new gold standard in measuring cardiac output [2, 73]. This advanced diagnostic modality using two distinct techniques, transpulmonary thermodilution and pulse contour analysis, provides continuous cardiac output measurements.

Technique

A bolus of a cold solution of known temperature is injected rapidly into the superior vena cava through an internal jugular or subclavian central venous catheter. The injected solution will mix with blood and traverse through the right heart chambers, pulmonary circulation, and finally, through the left heart chambers reaches the systemic artery.

An arterial cannula placed in a large peripheral artery (femoral, axillary, or brachial artery) with a thermistor tip will sense and measure the drop in blood temperature across the cardiopulmonary system [74]. Temperature fall between the injection site and measurement site is inversely proportional to cardiac output. Using a change in blood temperature over time, computer software plots a thermodilution curve and calculates cardiac output and other relevant hemodynamic parameters.

Calculation of cardiac output by transpulmonary thermodilution intermittently calibrates pulse contour analysis, and therefore TPTD provides precise, continuous, and real-time measurement of cardiac output by taking advantage of both techniques [74].

Use

Valuable information provided by TPTD is [74]:

- Cardiac output: TPTD calculates cardiac output and stroke volume by analyzing an arterial pulse contour waveform. TPTD is a reliable method for the continuous and real-time monitoring of cardiac output [75]. This method also measures stroke volume variation (SVV)/PVV and predicts fluid responsiveness [76].
- TPTD is also helpful in measuring various parameters such as, global end-diastolic volume, cardiac function index and global ejection fraction, extravascular lung water index, pulmonary vascular permeability index, which helps in assessment of volume status [74, 77–82].

Advantages

Transpulmonary thermodilution is used more frequently and has replaced the conventional intermittent thermodilution (TD) method through PAC to calculate cardiac output because:

- TPTD method is less invasive and avoids PAC-related serious complications [74].
- TPTD measures cardiac output with the same accuracy and is interchangeable with PAC thermodilution [83–86].
- It provides continuous and real-time monitoring of cardiac output in contrast to intermittent measurement by the conventional TD method.
- Provides robust support in the therapeutic management of hemodynamically unstable patients by

providing several additional information such as measurement of SVV and pulse pressure variation (PPV) to predict fluid responsiveness, calculates extravascular lung water to quantify pulmonary edema, and estimates lung permeability to quantify the pulmonary leak [82].

Indications

This advanced but invasive hemodynamic monitoring is indicated over less invasive devices in selected most critically ill and/or complex patients such as:

- Perioperatively, during complex cardiac and prolonged major surgery.
- During major liver surgery, when less invasive techniques are unreliable [87].
- In ICU patients with severe shock, especially with acute respiratory distress syndrome, and high or increasing requirements of vasopressors [4, 72]. In ICU patients with severe shock, especially with acute respiratory distress syndrome, and high or increasing requirements of vasopressors [4, 72].

Limitations

- It is an invasive method that needs the placement of a central venous line and a large arterial line.
- This method does not provide information such as PA pressure and SvO_2 (unlike the PA thermodilution method).
- Needs manual calibration with cold water.
- It provides inaccurate measurements in patients with very low cardiac output (<2 L/min) [74].
- Unable to detect short-term hemodynamic changes induced by ventilation during passive leg raising or end-expiratory occlusion tests [74].

C. Lithium dilution

The lithium dilution technique is a minimally invasive method that measures cardiac output based on indicator dilution principles [88].

In this modality, a small dose of lithium is injected via any vein (peripheral vein or central), and a lithium-selective sensor connected to any peripheral arterial line (e.g., radial artery) measures the concentration of lithium ions in the arterial blood [89]. The lithium dilution curve (lithium concentration vs. time) is constructed, and cardiac output is derived from this data.

Lithium dilution is a less invasive method than transpulmonary thermodilution. It is performed using peripheral venous and arterial cannulation and, therefore, is without the risks of the pulmonary artery or central venous catheterization [90]. This method can measure cardiac output accurately [91].

Lithium is selected as an indicator for this dilution technique because this element is not found in the bloodstream; it is non-diffusible; a small dose is non-toxic but generates a plasma concentration that can be measured.

Lithium is not lost during the first pass in pulmonary circulation, so its assessment provides reliable value. Additionally, lithium is cleared rapidly from systemic circulation [92].

Avoid this technique during pregnancy and in patients weighing less than 40 kg, receiving lithium therapy, or high doses of nondepolarizing neuromuscular blockers [93].

D. Arterial pulse contour analysis

Arterial pulse contour analysis is a commonly used minimally invasive technique for continuous, beat-to-beat cardiac output measurement. Based on it, a computerized algorithm measures cardiac output.

In addition to cardiac output, arterial pulse contour analysis also calculates dynamic parameters such as pulse pressure variation and stroke volume variation, which is helpful for determining fluid responsiveness [4].

Several commercially available devices use pulse contour wave analysis for the continuous measurement of cardiac output and stroke volume. These devices are broadly divided into two groups, the calibrated (PiCCO Plus and LiDCO plus) and the uncalibrated systems (FloTrac/Vigileo and LiDCO rapid), as summarized in Table 19.1.

The advantages of the pulse contour analysis method are:

- Less invasive compared to cardiac output measurement by pulmonary artery catheter and transpulmonary thermodilution, as it requires only a peripheral arterial catheter (usually the radial artery).
- Easy method: An arterial line is frequently inserted in ICU so existing access can be utilized for pulse contour analysis.
- Continuously and real-time measurement of cardiac output.
- Effectively monitor volume responsiveness. In addition to the accurate measurement of stroke volume, cardiac output, and CI, pulse contour analysis also calculates dynamic indexes such as pulse pressure variation and stroke volume variation. These parameters help to determine response to a fluid challenge, passive leg raising, or end-expiratory occlusion in patients on a ventilator [4, 76].
- Operator independent and needs minimal training.

Limitations of arterial pulse contour wave analysis are:

- It is a less accurate technique in critically ill patients with low SVR (sepsis and chronic liver failure) [94], left ventricular dysfunction [95], norepinephrine infusion [96], in open aortic abdominal aneurysm repair [97], and off-pump coronary artery bypass surgery [98].
- An accuracy of PCA is low in patients with spontaneous breathing, cardiac arrhythmias, low tidal volume ventilation, positive-end expiratory pressure <5 mmHg, or abnormal abdominal pressure [99].
- Data suggesting that this device improve patient outcome are lacking [100, 101].
- This method is less reliable than the transpulmonary thermodilution technique in septic patients [102].
- The uncalibrated systems need frequent recalibration in patients with hemodynamic instability or requiring vasoactive drugs.

E. Partial CO_2 rebreathing

Partial CO_2 Rebreathing is a minimally invasive technique which uses indirect Fick's principle to calculate cardiac output [103]. This method can be used only in intubated, sedated patients on volume-controlled ventilation who are hemodynamically stable.

This technique is easy to use, safe, does not require a PAC, can be repeated every few minutes without substantial risk of CO_2 accumulation, and provides almost continuous cardiac output measurements.

This technique's accuracy and precision are similar to esophageal doppler ultrasound, pulse contour analysis, and thoracic bioimpedance [33].

Currently, this technique is mainly focused on short-term intraoperative applications or mechanically ventilated postoperative patients [104].

This modality is not used routinely in ICU because its predictability is poor in common problems in critical patients like hemodynamic instability, anemia, or significant pulmonary disease (such as acute respiratory distress syndrome, pneumonia, atelectasis, shunting, etc.). Additionally, it does not provide information about the intravascular volume status or fluid responsiveness [105].

Avoid using this technique in patients with severe hypercapnia, raised intracranial pressure, or pulmonary hypertension because arterial CO_2 tension rises transiently in the rebreathing period, which may be harmful [106].

INVASIVE SYSTEMS

Pulmonary artery thermodilution is an invasive technique frequently used for hemodynamic monitoring.

Pulmonary artery thermodilution

Cardiac output measured invasively with the pulmonary artery using the thermodilution principle is traditionally considered as a gold standard method [107]. Modalities to measure cardiac output by pulmonary thermodilution (TD) are divided into two types: intermittent bolus and continuous cardiac output methods.

1. Intermittent thermodilution using the "bolus" technique

In the bolus technique of pulmonary thermodilution, about 10 ml of cold saline solution is injected via the proximal lumen of PAC in the right atrium. Cold saline mixes adequately with surrounding blood while traversing from the right atrium to the pulmonary artery (by passing through two valves and a right ventricle), which decreases blood temperature transiently. A thermistor on the tip of the PAC senses and measures changes in the blood temperature over time at a downstream side in the pulmonary artery [84].

The fall in the temperature is inversely proportional to the blood flow and cardiac output. Electronic monitors calculate cardiac output using a modified Stewart–Hamilton equation [108]. Usually, three measurements are performed and averaged to obtain a more reliable result [109].

Major advantages of the pulmonary artery thermodilution method are:

- Uses thermal energy (i.e., cold water) as an indicator which is non-toxic.
- Repeated measurement of cardiac output is safe, provided there is no constraint to administer the fluid.
- No requirement for manual calibration.
- The major advantage of this technique is that it provides an additional measurement of hemodynamic parameters such as pulmonary artery pressures, right-sided and left-sided filling pressures, and mixed venous oxyhemoglobin saturation (SvO_2).

Major limitations of the pulmonary artery thermodilution method are:

- The technique is invasive, so it carries the risk associated with placement and presence of a PAC, such as infection, pulmonary artery rupture, arrhythmias on insertion, thrombosis, and embolism [110].
- Fail to detect abrupt changes in cardiac output promptly because this technique measures cardiac output with some delay [107].
- Error in measuring cardiac output in the presence of low cardiac output,

hypothermia, shunts, and cardiac valvular abnormalities.

- Error in measuring cardiac output in the presence of low cardiac output, hypothermia, shunts, and cardiac valvular abnormalities [111].
- Poor predictor of fluid responsiveness [112].
- Need to avoid magnetic resonance imaging as well as the use of electrocautery in patients with PAC.

2. Continuous thermodilution technique

Commercially available catheters with newer technologies now provide continuous cardiac output monitoring. This method uses the same thermodilution principles but uses a warmed bolus rather than a cold bolus [113].

This special catheter has a special blood-warming thermal filament or coil at the level of the right ventricle. Thermal filament heats the blood in a semi-random binary fashion. The thermistor at the tip of the PAC records changes in temperature and calculates the cardiac output by thermodilution.

This method's major benefits are a continuous display of cardiac output, avoidance of repeated boluses (which reduces the risk of infection), and avoids operator errors [114].

Details about pulmonary artery catheters, including description, insertion technique, use in clinical practice, indications, and complications, are covered in the pulmonary artery catheter monitoring part of the Chapter 17 on "Static Hemodynamic Monitoring Techniques."

REFERENCES

1. Peeters Y, Bernards J, Mekeirele M, et al. Hemodynamic monitoring: To calibrate or not to calibrate? Part 1 - Calibrated techniques. Anaesthesiol Intensive Ther. 2015;47(5):487–500.
2. Bernards J, Mekeirele M, Hoffmann B, et al. Hemodynamic monitoring: to calibrate or not to calibrate? Part 2 - Non-calibrated techniques. Anaesthesiology Intensive Ther. 2015;47(5):501–516.
3. Sakka SG. Hemodynamic monitoring in the critically ill patient – current status and perspective. Front Med (Lausanne). 2015;3;2:44.
4. Teboul JL, Saugel B, Cecconi M, et al. Less invasive hemodynamic monitoring in critically ill patients. Intensive Care Med. 2016;42(9):1350–9.
5. Ayuela Azcarate JM, Clau Terré F, Ochagavia A, et al. Role of echocardiography in the hemodynamic monitorization of critical patients. Med Intensiva. 2012;36(3):220–232.
6. Kiefer JJ, Raiten J, Gutsche J. Point-of-care transthoracic echocardiography: a growing body of evidence, an educational need J Cardiothorac Vasc Anesth. 2020;34(1):97–98.
7. Schuster AH, Nanda NC. Doppler echocardiographic measurement of cardiac output: comparison with a non-golden standard. Am J Cardiol 1984;53(1):257–259.
8. Evangelista A, Garcia-Dorado D, Del Castillo H. Cardiac index quantification by Doppler ultrasound in patients without left ventricular outflow tract abnormalities. J Am Coll Cardiol 1995;25(3):710–716.
9. Axler O, Megarbane B, Lentschener C. Comparison of cardiac output measured with echocardiographic volumes and aortic Doppler methods during mechanical ventilation. Intensive Care Med 2003;29(2):208–217.
10. Vignon P, Mentec H, Terre S. Diagnostic accuracy and therapeutic impact of transthoracic and transesophageal echocardiography in mechanically ventilated patients in the ICU. Chest 1994;106(6):1829–1834.
11. Mayer SA, Sherman D, Fink ME. Noninvasive monitoring of cardiac output by Doppler echocardiography in patients treated with volume expansion after subarachnoid hemorrhage. Crit Care Med 1995;23(9):1470–1474.
12. Bergenzaun L, Gudmundsson P, Ohlin H, et al. Assessing left ventricular systolic function in shock: evaluation of echocardiographic parameters in intensive care. Crit Care. 2011;15(4):R200.
13. Dinh VA, Ko HS, Rao R, et al. Measuring cardiac index with a focused cardiac ultrasound examination in the ED. Am J Emerg Med. 2012;30(9):1845–51.
14. Mayo PH, Beaulieu Y, Doelken P. American College of Chest Physicians/La Société de Réanimation de Langue Française statement on competence in critical care ultrasonography. Chest 2009;135(4):1050–1060.
15. Expert Round Table on Ultrasound in ICU. International expert statement on standards for critical care ultrasonography. Intensive Care Med 2011;37(7):1077–1083.
16. Kanji HD, McCallum J, Sirounis D, et al. Limited echocardiography-guided therapy in subacute shock is associated with change in management and improved outcomes. J Crit Care 2014;29(5):700–5.

17. Orde S, Slama M, Hilton A, et al. Pearls and pitfalls in comprehensive critical care echocardiography. Crit Care 2017;21(1):279.
18. Marcelino P, Germano N, Marum S, et al. Hemodynamic parameters obtained by transthoracic echocardiography and Swan-Ganz catheter: a comparative study in liver transplant patients. Acta Med Port. 2006;19(3):197–205.
19. Tchorz KM, Chandra MS, Markert RJ, et al. Comparison of hemodynamic measurements from invasive and noninvasive monitoring during early resuscitation. J Trauma Acute Care Surg. 2012;72(4):852–60.
20. Gassner M, Killu K, Bauman Z, et al. Feasibility of common carotid artery point of care ultrasound in cardiac output measurements compared to invasive methods. J Ultrasound. 2014;18(2):127–33.
21. Olivieri PP, Patel R, Kolb S, et al. Echo is a good, not perfect, measure of cardiac output in critically ill surgical patients. J Trauma Acute Care Surg 2019;87(2):379–85.
22. Villavicencio C, Leache J, Marin J, et al. Basic critical care echocardiography training of intensivists allows reproducible and reliable measurements of cardiac output. Ultrasound J 2019;11:5.
23. Bergamaschi V, Vignazia GL, Messina A, et al. Transthoracic echocardiographic assessment of cardiac output in mechanically ventilated critically ill patients by intensive care unit physicians. Rev Bras Anestesiol. 2019;69(1):20–26.
24. Zarragoikoetxea I, Vicente R, Pajares A, et al. Quantitative transthoracic echocardiography of the response to dobutamine in cardiac surgery patients with low cardiac surgery output syndrome. J Cardiothorac Vasc Anesth 2020;34(1):87–96.
25. Martin ND, Codner P, Greene W, et al. Contemporary hemodynamic monitoring, fluid responsiveness, volume optimization, and endpoints of resuscitation: an AAST critical care committee clinical consensus. Trauma Surg Acute Care Open 2020;5(1):e000411.
26. Gorrasi J, Pazos A, Florio L, et al. Cardiac output measured by transthoracic echocardiography and Swan-Ganz catheter. A comparative study in mechanically ventilated patients with high positive end-expiratory pressure. Rev Bras Ter Intensiva. 2019;31(4):474–482.
27. Zhang Y, Wang Y, Shi J, et al. Cardiac output measurements via echocardiography versus thermodilution: A systematic review and meta-analysis. PLoS ONE 2019;14(10):e0222105.
28. Jozwiak M, Mercado P, Teboul J, et al. What is the lowest change in cardiac output that transthoracic echocardiography can detect? Crit Care 2019;23(1):116.
29. Leung JM, Levine EH. Left ventricular end-systolic cavity obliteration as an estimate of intraoperative hypovolemia. Anesthesiology. 1994;81(5):1102–1109.
30. Mok KL. Make it SIMPLE: enhanced shock management by focused cardiac ultrasound. J Intensive Care. 2016;4:51.
31. Jakovljevic DG, Trenell MI, MacGowan GA. Bioimpedance and bioreactance methods for monitoring cardiac output. Best Practice & Research Clinical Anaesthesiology. 2014;28(4):381–394.
32. Nguyen LS, Squara P. Non-Invasive Monitoring of Cardiac Output in Critical Care Medicine. Front Med (Lausanne). 2017;4:200.
33. Peyton PJ, Chong SW. Minimally invasive measurement of cardiac output during surgery and critical care: a meta-analysis of accuracy and precision. Anesthesiology 2010;113(5):1220–1235.
34. Critchley LAH, Huang L, Zhang J. Continuous Cardiac Output Monitoring: What Do Validation Studies Tell Us? Curr Anesthesiol Rep 2014;4:242–250.
35. Harford M, Clark SH, Smythe JF, et al. Non-invasive stroke volume estimation by transthoracic electrical bioimpedance versus Doppler echocardiography in healthy volunteers, Journal of Medical Engineering & Technology 2019;43(1):33–37.
36. Saugel B, Cecconi M, Wagner JY, et al. Noninvasive continuous cardiac output monitoring in perioperative and intensive care medicine. Br J Anaesth 2015;114(4):562–575.
37. Squara P, Denjean D, Estagnasie P, et al. Noninvasive cardiac output monitoring (NICOM): a clinical validation. Intensive Care Med 2007;33(7):1191–1194.
38. Marik PE, Levitov A, Young A, et al. The use of bioreactance and carotid Doppler to determine volume responsiveness and blood flow redistribution following passive leg raising in hemodynamically unstable patients. Chest 2013;143(2):364–370.
39. Han S, Lee JH, Kim G, et al. Bioreactance Is Not Interchangeable with Thermodilution for Measuring Cardiac Output during Adult Liver Transplantation. PLoS One 2015;10(5):e0127981.
40. Jones TW, Houghton D, Cassidy S, et al. Bioreactance is a reliable method for estimating cardiac output at rest and during exercise. Br J Anaesth. 2015;115(3):386–91.
41. Galarza L, Mercado P, Teboul JL, et al. Estimating the rapid hemodynamic effects of passive leg raising in critically ill patients using bioreactance. Br J Anaesth 2018;121(3):567–573.
42. Joosten A, Desebbe O, Suehiro K, et al. Accuracy and precision of noninvasive cardiac output monitoring devices in perioperative medicine: A systematic review and meta-analysis. Br J Anaesth 2017;118(3):298–310.
43. Saugel B, Meidert AS, Langwieser N, et al. An autocalibrating algorithm for non-invasive cardiac output determination based on the analysis of an arterial pressure waveform recorded with radial artery applanation tonometry: a proof of concept pilot analysis. J Clin Monit Comput 2014;28(4):357–362.
44. Wagner JY, Sarwari H, Schön G, et al. Radial artery applanation tonometry for continuous noninvasive cardiac output measurement: A comparison with intermittent pulmonary artery thermodilution in patients after cardiothoracic surgery. Crit Care Med. 2015;43(7):1423–1428.

45. Compton F, Wittrock M, Schaefer JH, et al. Noninvasive cardiac output determination using applanation tonometry-derived radial artery pulse contour analysis in critically ill patients. Anesth Analg. 2008;106(1):171–4.
46. Wagner JY, Langemann M, Schön G, et al. Autocalibrating pulse contour analysis based on radial artery applanation tonometry for continuous non-invasive cardiac output monitoring in intensive care unit patients after major gastrointestinal surgery—A prospective method comparison study. Anaesthesia and intensive care 2016;44(3):340–345.
47. Gonzalez-Represas A, Mourot L. Stroke volume and cardiac output measurement in cardiac patients during a rehabilitation program: comparison between tonometry, impedancemetry and echocardiography. Int J Cardiovasc Imaging. 2020;36(3):447–455.
48. Bartels K, Thiele RH. Advances in photoplethysmography: beyond arterial oxygen saturation. Can J Anaesth. 2015;62(12):1313–28.
49. Broch O, Renner J, Gruenewald M, et al. A comparison of the Nexfin(R) and transcardiopulmonary thermodilution to estimate cardiac output during coronary artery surgery. Anaesthesia 2012;67(4):377–383.
50. Chen G, Meng L, Alexander B, et al. Comparison of noninvasive cardiac output measurements using the Nexfin monitoring device and the esophageal Doppler. J Clin Anesth 2012;24(4):275–283.
51. Pour-Ghaz I, Manolukas T, Foray N, et al. Accuracy of non-invasive and minimally invasive hemodynamic monitoring: where do we stand? Ann Transl Med. 2019;7(17):421.
52. Schraverus P, Kuijpers MM, Coumou J, et al. Level of agreement between cardiac output measurements using Nexfin® and thermodilution in morbidly obese patients undergoing laparoscopic surgery Anaesthesia 2016;71(12):1449–1455.
53. Fischer MO, Avram R, Cârjaliu I, et al. Non-invasive continuous arterial pressure and cardiac index monitoring with Nexfin after cardiac surgery. Br J Anaesth 2012;109(4):514–21.
54. Monnet X, Picard F, Lidzborski E, et al. The estimation of cardiac output by the Nexfin device is of poor reliability for tracking the effects of a fluid challenge. Crit Care 2012;16(5):R212.
55. Fischer MO, Coucoravas J, Truong J, et al. Assessment of changes in cardiac index and fluid responsiveness: a comparison of Nexfin and transpulmonary thermodilution Acta Anaesthesiol Scand 2013;57(6):704–712.
56. Taton O, Fagnoul D, De Backer D, et al. Evaluation of cardiac output in intensive care using a non-invasive arterial pulse contour technique (Nexfin((R))) compared with echocardiography. Anaesthesia 2013;68(9):917–923.
57. Fischera MO, Joosten A, Desebbe O, et al. Interchangeability of cardiac output measurements between non-invasive photoplethysmography and bolus thermodilution: A systematic review and individual patient data meta-analysis Anaesth Crit Care Pain Med. 2020;39(1):75–85.
58. Click RL, Abel MD, Schaff HV. Intraoperative transesophageal echocardiography: 5-year prospective review of impact on surgical management. Mayo Clinic Proceeding 2000;75(3):241–247.
59. Mahmood F, Shernan SK. Perioperative transoesophageal echocardiography: current status and future directions. Heart. 2016;102(15):1159–67.
60. Parra V, Fita G, Rovira I, et al. Transoesophageal echocardiography accurately detects cardiac output variation: a prospective comparison with thermodilution in cardiac surgery. Eur J Anaesthesiol 2008;25(2):135–43.
61. Møller-Sørensen H, Graeser K, Hansen KL, et al. Measurements of cardiac output obtained with transesophageal echocardiography and pulmonary artery thermodilution are not interchangeable. Acta Anaesthesiol Scand 2014;58(1):80–8.
62. Hahn RT, Abraham T, Adams MS, et al. Guidelines for performing a comprehensive transesophageal echocardiographic examination: recommendations from the American Society of Echocardiography and the Society of Cardiovascular Anesthesiologists. J Am Soc Echocardiogr. 2013;26(9):921–64.
63. Wally D, Velik-Salchner C. Perioperative transesophageal echocardiography in non-cardiac surgery. Update. Anaesthesist. 2015;64(9):669–682.
64. Rebel A, Klimkina O, Hassan ZU. Transesophageal echocardiography for the noncardiac surgical patient. Int Surg. 2012;97(1):43–55.
65. Fayad A, Shillcutt SK. Perioperative transesophageal echocardiography for non-cardiac surgery. Can J Anesth/J Can Anesth 2018;65(4):381–398.
66. Elsherbiny M, Abdelwahab Y, Nagy K, et al. Role of intraoperative transesophageal echocardiography in cardiac surgery: an observational study. Open Access Maced J Med Sci. 2019;7(15):2480–2483.
67. Abbas SM, Hill AG. Systematic review of the literature for the use of oesophageal Doppler monitor for fluid replacement in major abdominal surgery. Anaesthesia 2008;63(1):44–51.
68. National Institute for Health and Clinical Excellence. Medical technologies guidance MTG3: CardioQ-ODM oesophageal doppler monitor. March 2011. http://www.nice.org.uk/MTG3 (accessed 19.4.20).
69. Dhawan R, Shahul S, Roberts JD, et al. Prospective, randomized clinical trial comparing use of intraoperative transesophageal echocardiography to standard care during radical cystectomy. Ann Card Anaesth. 2018;21(3):255–261.
70. Practice guidelines for perioperative transesophageal echocardiography. An updated report by the American Society of Anesthesiologists and the Society of Cardiovascular Anesthesiologists Task Force on transesophageal echocardiography. Anesthesiology. 2010;112(5):1084–96.
71. Hauser ND, Swanevelder J. Transoesophageal echocardiography (TOE): contra-indications, complications and safety of perioperative TOE. Echo Res Pract. 2018;5(4):R101–R113.
72. Cecconi M, De Backer D, Antonelli M, et al. Consensus on circulatory shock and hemodynamic

monitoring. Task force of the European Society of Intensive Care Medicine. Intensive Care Med. 2014;40(12):1795–815.

73. Tibby S. Transpulmonary thermodilution: Finally, a gold standard for pediatric cardiac output measurement. Pediatr Crit Care Med. 2008;9(3):341–2.
74. Monnet X, Teboul JL. Transpulmonary thermodilution: advantages and limits. Critical Care. 2017;21(1):147.
75. Sakka SG, Reuter DA, Perel A. The transpulmonary thermodilution technique. J Clin Monit Comput. 2012;26(5):347–53.
76. Marik PE, Cavallazzi R, Vasu T, et al. Dynamic changes in arterial waveform derived variables and fluid responsiveness in mechanically ventilated patients: a systematic review of the literature. Crit Care Med 2009;37(9):2642–2647.
77. Perny J, Kimmoun A, Perez P, et al. Evaluation of cardiac function index as measured by transpulmonary thermodilution as an indicator of left ventricular ejection fraction in cardiogenic shock. BioMed Research International. 2014;2014:598029.
78. Michard F. Bedside assessment of extravascular lung water by dilution methods: temptations and pitfalls. Crit Care Med. 2007;35(4):1186–1192.
79. Jozwiak M, Teboul JL, Monnet X. Extravascular lung water in critical care: recent advances and clinical applications. Ann Intensive Care. 2015;5(1):38.
80. Sakka SG, Klein M, Reinhart K, et al. Prognostic value of extravascular lung water in critically ill patients. Chest 2002;122(6):2080–6.
81. Kushimoto S, Endo T, Yamanouchi S, et al. Relationship between extravascular lung water and severity categories of acute respiratory distress syndrome by the Berlin definition. Crit Care 2013;17(4):R132.
82. Beurton A, Teboul JL, Monnet X. Transpulmonary thermodilution techniques in the hemodynamic ally unstable patient. Curr Opin Crit Care. 2019;25(3):273–279.
83. Mielck F, Buhre W, Hanekop G, et al. Comparison of continuous cardiac output measurements in patients after cardiac surgery. J Cardiothorac Vasc Anesth. 2003;17(2):211–216.
84. Reuter DA, Huang C, Edrich T, et al. Cardiac output monitoring using indicator-dilution techniques: Basics, limits, and perspectives. Anesth Analg 2010;110(3):799–811.
85. Marik PE. Obituary: pulmonary artery catheter 1970 to 2013. Ann Intensive Care. 2013;3(1):38.
86. Vilchez Monge AL, Tranche Alvarez-Cagigas I, Perez-Peña J, et al. Cardiac output monitoring with pulmonary versus transpulmonary thermodilution during liver transplantation: interchangeable methods? Minerva Anestesiol. 2014;80(11):1178–87.
87. Benes J, Giglio M, Brienza N, et al. The effects of goal-directed fluid therapy based on dynamic parameters on post-surgical outcome: a meta-analysis of randomized controlled trials. Crit Care. 2014;18(5):584.
88. Linton RAF, Band DM, Haire KM. A new method of measuring cardiac output in man using lithium dilution. Brit J Anaesth.1993;71(2):262–266.
89. Jonas MM, Tanser SJ. Lithium dilution measurement of cardiac output and arterial pulse waveform analysis: an indicator dilution calibrated beat-by-beat system for continuous estimation of cardiac output. Curr Opin Crit Care. 2002;8(3):257–61.
90. Garcia-Rodriguez C, Pittman J, Cassell CH, et al. Lithium dilution cardiac output measurement: a clinical assessment of central venous and peripheral venous indicator injection. Crit Care Med. 2002;30(10):2199–2204.
91. Kurita T, Morita K, Kato S, et al. Comparison of the accuracy of the lithium dilution technique with the thermodilution technique for measurement of cardiac output. British Journal of Anaesthesia. 1997;79(6):770–775.
92. García X, Mateu L, Maynar J. Estimating cardiac output. Utility in the clinical practice. Available invasive and non-invasive monitoring. Med Intensiva. 2011;35(9):552–61.
93. Geerts BF, Aarts LP, Jansen JR. Methods in pharmacology: measurement of cardiac output. Br J Clin Pharmacol. 2011;71(3):316–330.
94. Grensemann J. Cardiac output monitoring by pulse contour analysis, the technical basics of less-invasive techniques. Front Med (Lausanne). 2018;5:64.
95. Wernly B, Lichtenauer M, Franz M, et al. Pulse contour cardiac output monitoring in acute heart failure patients: Assessment of hemodynamic measurements. Wien Klin Wochenschr. 2016;128(23-24):864–869.
96. Monnet X, Anguel N, Jozwiak M, et al. Third-generation floTrac/Vigileo does not reliably track changes in cardiac output induced by norepinephrine in critically ill patients. Br J Anaesth 2012;108(4):615–22.
97. Kusaka Y, Yoshitani K, Irie T, et al. Clinical comparison of an echocardiograph-derived versus pulse counter-derived cardiac output measurement in abdominal aortic aneurysm surgery. J Cardiothorac Vasc Anesth 2012;26(2):223–6.
98. Jeong YB, Kim TH, Roh YJ, et al. Comparison of uncalibrated arterial pressure waveform analysis with continuous thermodilution cardiac output measurements in patients undergoing elective off-pump coronary artery bypass surgery. J Cardiothorac Vasc Anesth 2010;24(5):767–71.
99. Lansdorp B, Lemson J, van Putten MJ, et al. Dynamic indices do not predict volume responsiveness in routine clinical practice. Br J Anaesth 2012;108(3):395–401.
100. Marik PE. Non-invasive cardiac output monitors: a state-of the-art review. J Cardiothorac Vasc Anesth. 2013;27(1):121–134.
101. Reisner A. Academic assessment of arterial pulse contour analysis: missing the forest for the trees? Br J Anaesth. 2016;116(6):733–736.
102. Sakka SG, Kozieras J, Thuemer O, et al. Measurement of cardiac output: a comparison between transpulmo-

nary thermodilution and uncalibrated pulse contour analysis. Br J Anaesth 2007;99(3):337–342.

103. Jaffe MB. Partial CO2 rebreathing cardiac output - operating principles of the NICO system. J Clin Monit. 1999;15(6):387–401.
104. Miller RD, Cohen NH, Eriksson LI, et al. Miller's anesthesia. 8th ed. Philadelphia, PA: Saunders;2015.p.1391.
105. Chamos C, Vele L, Hamilton M, et al. Less invasive methods of advanced hemodynamic monitoring: principles, devices, and their role in the perioperative hemodynamic optimization. Perioper Med (Lond). 2013;2(1):19.
106. Kerstens MKM, Wijnberge M, Geerts BF. Non-invasive cardiac output monitoring techniques in the ICU. Neth J Crit Care 2018;26(3):104–110.
107. Lee AJ, Cohn JH, Ranasinghe JS. Cardiac output assessed by invasive and minimally invasive techniques. Anesthesiol Res Pract 2011;2011:475151.
108. Moise SF, Sinclair CJ, Scott DHT. Pulmonary artery blood temperature and the measurement of cardiac output by thermodilution Anaesthesia 2002;57(6):562–566.
109. Stetz CW, Miller RG, Kelly GE, et al. Reliability of the thermodilution method in the determination of cardiac output in clinical practice. The American Review of Respiratory Disease. 1982;126(6):1001–1004.
110. Drummond KE, Murphy E. Minimally invasive cardiac output monitors, Continuing Education in Anaesthesia Critical Care & Pain 2012;12(1):5–10.
111. Nishikawa T, Dohi S. Errors in the measurement of cardiac output by thermodilution. Can J Anaesth 1993;40(2):142–53.
112. Robin E, Costecalde M, Lebuffe G, et al. Clinical relevance of data from the pulmonary artery catheter. Critical Care 2006;10 Suppl 3(Suppl 3):S3.
113. Argueta EE, Paniagua D. Thermodilution cardiac output: A concept over 250 years in the making. Cardiol Rev. 2019;27(3):138–144.
114. Mehta Y, Arora D. Newer methods of cardiac output monitoring. World J Cardiol. 2014;6(9):1022–1029.