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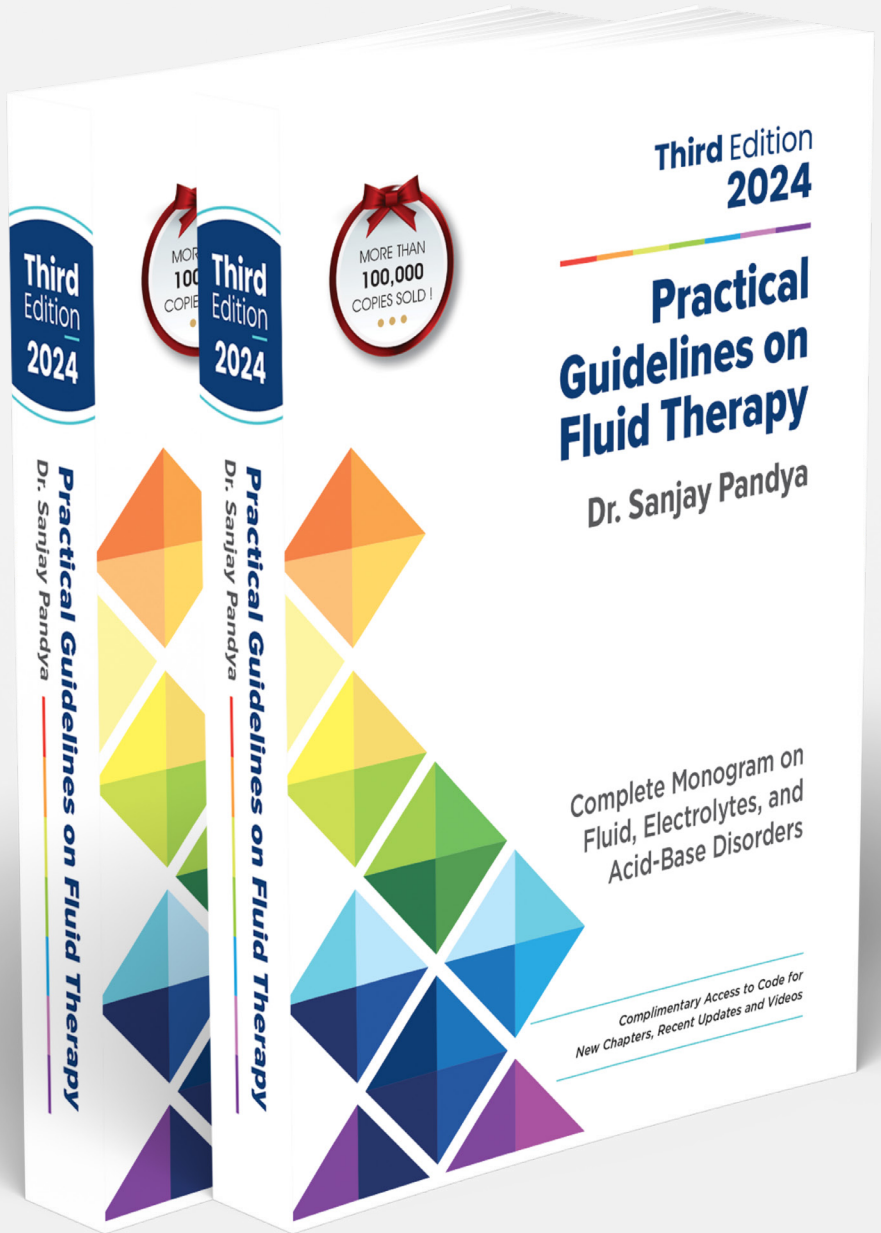
Chapter 19:

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."

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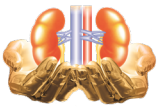
KidneyEducation 

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