Despite advances in cardiac monitoring, the thorough, focused physical examination remains an essential part of assessment of cardiovascular function. The physical examination is vital to the initial assessment and resuscitation of the patient and provides impetus for more advanced hemodynamic monitoring. All available data, including that from advanced hemodynamic monitoring, should be evaluated in the context of the physical examination. Serial examinations during treatment yield important information about the patient’s cardiovascular state and the response to treatment.

The general appearance of the patient should be noted, to include mental status and level of consciousness before sedation. Vital signs should be reviewed, and trends noted (eg, increases or decreases in heart rate); these should be considered in light of the patient’s current therapy. The respiratory examination may be particularly revealing. In the absence of sedation, metabolic acidosis may cause a compensatory tachypnea, which is frequently the first sign of hemodynamic compromise. Cheyne-Stokes pattern of respiration frequently is seen in heart failure (Fig. 1). Auscultation of the lungs can reveal rales, particularly at the lung bases, which may be indicative of congestive heart failure (CHF). Skin temperature, capillary refill time, and strength and quality of peripheral pulses can provide important information. Patients with cardiogenic, hypovolemic, or septic shock frequently will have reduced skin temperatures and delayed capillary refill, whereas those with neurogenic shock, or those being treated with vasodilators, frequently have brisk capillary refill.

The characteristics of the arterial pulse should be examined. A low-volume, rapid pulse signifies inadequate perfusion or low cardiac output. A rapid, bounding pulse in the presence of shock suggests vasodilatory shock, treatment with vasodilator chugs, or severe aortic regurgitation. The presence of pulsus paradoxus in...
a spontaneously breathing patient may be a reflection of severe obstructive lung disease or of cardiac tamponade. Diminished pulse volume and blood pressure after initiation of positive pressure ventilation may suggest hypovolemia. Water-hammer pulse (bounding and forceful) and Quincke’ sign (pulsation of the capillary bed in the nail) can reveal the presence of severe aortic insufficiency.

Assessment of neck veins, while frequently confounded in severely ill patients can provide useful information. The height of neck veins and the qualities of the venous pulsations can provide information regarding ventricular function, intravascular volume status, pulmonary artery (PA) pressures, and right heart valvular function. Acutely distended neck veins may indicate intravascular volume overload, right or left ventricular failure, pulmonary hypertension with an incompetent pulmonic valve, noncompliance of the right ventricle, right ventricular outflow obstruction, or pericardial tamponade as examples. Abnormalities of the pulse contour can indicate abnormalities of valve or myocardial function. Cannon A waves are caused when the atrium contracts against a closed tricuspid valve and indicate atrio–ventricular dysynchrony. Kussmaul’s sign is the observation of a jugular venous pressure that rises with inspiration and is seen with impediment to right heart filling. Abdomino–jugular reflux (increase in the jugular venous pulse with pressure on the abdomen) suggests the presence of right ventricular failure as the right ventricle is unable to accept the increased venous return.1,2 Heart failure can lead to passive congestion of the liver, and assessing liver size while assessing for abdomino–jugular reflux can provide useful information. Assessment of heart rate and rhythm should be performed, keeping age-related norms and medications in mind. Auscultation of the heart sounds, noting the presence or quality of the first and second heart sounds, the presence or absence of third or fourth heart sounds, the presence and quality of murmurs, clicks, or friction rubs is important both during the initial assessment and as a means to assess response to therapy or changes in function. The development of a friction rub after cardiac surgery is not unexpected, but the development of such a rub during treatment for septic shock may indicate the presence of pericardial inflammation and effusion. Similarly, the development of an S3 gallop may be the first clear indication of worsening heart failure.

MEASURING CARDIAC OUTPUT

Means of measuring cardiac output include
- Pulmonary artery catheter (PAC)
- Transpulmonary thermodilution (TD)—PiCCO monitor (Pulsion Medical Systems, Munich, Germany)
- Lithium dilution—LiDCO (LiDCO Group Plc, London UK)
- Pulse contour analysis—calibrated (PiCCO, PulseCO system [LiDCO Ltd])—noncalibrated (Flo-trac Vigileo system [Edwards Life Sciences, Irvine California])
- Mixed and central venous saturation.

Fig. 1. Cheyne-Stokes respiration. An abnormal type of breathing characterized by alternating periods of shallow and deep breathing.
The PAC first was introduced by Swan and Ganz in 1970. The balloon-tipped, flow-directed catheter allowed clinicians for the first time to assess advanced parameters of hemodynamics and gas exchange at the bedside. It was widely adopted, so much so that it helped define the modern intensive care unit (ICU) in the coming years. But the PAC was introduced without any clinical trials establishing benefit in critically ill patients, and after several years of use concerns over its safety and efficacy were raised. The device never has been shown to improve major clinical outcomes, and in fact might increase mortality and morbidity. Furthermore, there is a growing body of evidence that the PAC adds little to information attainable by less invasive measures, and as such, it has been suggested that it no longer be used as part of routine management of the critically ill for conditions other than right heart failure, disorders causing abnormalities of pulmonary arterial pressure, and congenital heart disease.

Cardiac output can be determined by different methods using the PAC. It can be measured using the Fick principle, which is a variation of the law of conservation and states that consumption of oxygen must equal the product of blood flow and the difference between the arterial and venous concentrations of the oxygen:

\[
\text{CO} = \frac{(\text{VO}_2)}{(\text{CaO}_2) - (\text{CvO}_2)}
\]

where \(\text{VO}_2\) is the oxygen consumption per minute; \(\text{CaO}_2\) is the arterial oxygen content, and \(\text{CvO}_2\) is the mixed venous oxygen content.

Systemic arterial and mixed venous blood samples are taken, and \(\text{VO}_2\) is either measured using a calorimeter or is estimated. The Fick method is quite accurate for measuring CO when \(\text{VO}_2\) is measured directly. It loses accuracy, however, if supplemental oxygen is given at \(\text{FiO}_2\) greater than 0.6 or when there is significant oxygen consumption in the lung itself and \(\text{VO}_2\) is estimated as, as is frequently the case in critically ill patients.

TD remains the most commonly used technique for obtaining cardiac output in critically ill patients. When using the PAC, 5 to 10 mL of cold saline (<25°C) is injected through the catheter into the right atrium, where it mixes with venous blood, causing it to cool slightly. Cooled blood then passes through the right heart into the PA and by a thermistor near the tip of the PAC, and a TD curve is generated. CO then is calculated using the modified Stewart-Hamilton equation for TD.

\[
Q = \frac{VI \times (TB - TI) \times SI \times CI \times 60 \times CT}{SB \times CB \times \int_0^\infty \Delta TB(t) \, dt}
\]

where \(Q\) is the CO (L/min), \(VI\) is the volume of injectant (milliliters); \(TB\) is the blood temperature (°C). \(SI\) is the specific gravity of injectant; \(CI\) is the specific heat of injectate, and 60 is a constant for number of seconds per minute. \(CT\) is the correction factor, and \(SB\) is the specific gravity of blood, \(CB\) is the specific heat of blood, and \(\int_0^\infty \Delta TB(t)\) is the integral of blood temperature change (°C/sec) (area under the TD curve). The correction factor \(CT\) depends on the length from the proximal port of the PA catheter to the thermistor and the response time and sensitivity of the thermistor and electronic circuitry supplied by the manufacturer. Wide variation in CO occurs over the course of the respiratory cycle, and it is important to begin and complete each injection at the same time in the cycle. Injection is done in triplicate, and values are averaged. As the injections are being done, it is important to remember any loss of thermal indicator through right-to-left intracardiac shunts or remixing across incompetent pulmonary or tricuspid valves will cause erroneous increases in CO. Similarly,
a large volume of injectate or too slow an injection can lead to a falsely low CO measurement. Temperature errors can occur with concomitant continuous intravenous infusions into the central veins. Thrombus or vessel wall impingement also can alter the thermistor function. Arrhythmias and atrial or ventricular ectopy can cause wide swings in preload and CO, confounding average CO determination. It is important to remember that even in the best circumstances, accuracy is only to 10% to 15% of the actual value, and any change in CO less then that should not be interpreted as significant.3

Complications of PAC are:

Line-related complications (pneumothorax, bleeding or infections)
Arrhythmias (benign and life-threatening ventricular arrhythmias and right bundle branch block)
PA-related complications (rupture, infarction, thrombi, hemorrhage, vegetations).

Transpulmonary TD

Whereas the PAC remains widely used, controversy surrounding its safety and efficacy has prompted development of newer less invasive techniques. For these purposes, the transpulmonary thermodilution technique (TPT) allows assessment of volumetric preload, cardiac output, and extravascular lung water without the need to pass a catheter through the right heart.

The PiCCO monitor is currently the only commercially available device that uses the TPT method to measure cardiac output. The device requires only central venous access and a specialized femoral or axillary arterial catheter with a thermistor at its tip. A known volume of thermal indicator (ice-cold saline) is injected via a central venous catheter. The resulting packet of cooler blood traverses the thorax and is sensed by a thermistor in the femoral or axillary position generating a TD dissipation curve. Cardiac output is then calculated from the curve using the modified Stewart-Hamilton equation for TD (as described in the PAC section). The average result from three consecutive bolus injections is recorded.

The technique is less invasive than the PAC, requiring only central venous and arterial lines, which many critically ill patients already will have required. Earlier studies9 found the measurements of PiCCO are more consistent and are not influenced by respiratory cycle as compared with PAC. Its suitability to use in pediatric patients and reliability in cardiac unstable patients also are accepted.10 TPT may give inaccurate measurements in patients with intracardiac shunt, aortic stenosis, aortic aneurysm, and extra corporeal circulation. Complications are all catheter-related to include infection (<0.3%) thrombosis, bleeding, and vascular injury resulting in limb ischemia or pseudoaneurysm (all combined approximately3%).

Lithium Dilution

Instead of using cold injectate indicator dilution, methods using intravenous lithium have been developed to determine CO (LiDCO). The advantage in doing this is that lithium can be injected via central or peripheral venous catheters and detected in a standard radial arterial line, negating the need to place a catheter across heart valves (PAC) or to place a femoral or axillary arterial catheter (TPT). Small amounts of lithium are injected intravenously and then detected in a specialized device attached to a standard radial artery catheter. A dye dissipation curve is generated, and cardiac output is determined using principles of Stewart-Hamilton similar to the special equation for TD. The technique has been found to provide accurate measurement of CO in critically ill patients.11
**Pulse Contour Waveform Analysis**

Pulse contour analysis uses pressure waveforms in arterial blood in the periphery to continuously calculate CO. Wesseling first described a clinically usable technique in 1983.\(^{12}\) The arterial pressure waveform is obtained in the axillary or femoral arteries, and then assumptions are made to calculate predicted changes in pulse wave contour measured in the periphery in an attempt to estimate stroke volume (SV). The area under the systolic portion of the pressure waveform is proportional to the SV as the integral of the change in pressure from end diastole (t\(_0\)) to end systole (t\(_1\)) over time and inversely proportional to the impedance of the aorta (Z).

\[
SV = \frac{\int_{t_0}^{t_1} dP/\, dt}{Z}
\]

Sophisticated waveform analyses are employed, which account for finite pulse wave velocity and wave reflections. Accuracy then is enhanced further by calibration with an indicator dilution technique: transpulmonary TD for the PiCCO system and lithium chloride dilution for the PulseCO system (LiDCO Ltd). Studies comparing CO by pulse contour analysis techniques to the PA TD technique have found fairly good correlations with a correlation coefficient (r) ranging from 0.88 to 0.98 and precisions of ±0.3 to 1.26 L/min.\(^{13,14}\) Variable results have been reported in studies involving patients with rapidly changing hemodynamics after initial calibration, but it is felt that the negative impact that hemodynamic instability has on this technique can be minimized by more frequent calibrations.\(^{15}\)

Neither system requires right heart catheterization, making them less invasive than PACs, but they do require placement of both arterial and venous lines. Factors affecting accuracy include: nonlinearity of aortic compliance, differences in proximal aortic pressure to measure peripheral pressure, damped waveforms, variability of aortic diameter, aortic valve and vessel pathology, and body position.\(^{16}\)

**Pulse Contour Cardiac Output (Noncalibrated)—Flo-trac Vigileo System**

The FloTrac system, comprised of the FloTrac sensor and Vigileo monitor, attempts to determine CO by pulse contour analysis without employing a second technique for calibration. Calibration allows a way to account for changes in vascular compliance, which cannot be easily measured clinically. The makers of the Flo-Trac device claim to have solved this problem using continuous self-calibration through an automatic vascular tone adjustment involving complex algorithms based on mean arterial pressure, age, height, weight, and gender of patients. Although accuracy of this system has been promising in limited studies involving fairly stable patients, further validation studies in severely ill patients are required.\(^{17,18}\)

**Mixed Venous Oxygen Saturation—Surrogate of CO**

Mixed venous oxygen saturation requires sampling of blood in the pulmonary artery with a pulmonary artery catheter (PAC). A low mixed venous saturation (Svo2) in the absence of arterial hypoxemia is considered as a surrogate marker of poor cardiac output. Normal mixed venous saturation is approximately 70%. A very low mixed venous saturation (Svo2) is indicative of excessive extraction of oxygen per unit blood—under-resuscitation. A very high Svo2 value is difficult to interpret. It may represent the inability of the tissues to extract oxygen (cytopathic dysoxia seen in sepsis, mitochondrial poisoning and dysfunction seen in various conditions and exposures, or increased CO and oxygen delivery).
Because of the need to place a PAC to obtain mixed venous oxygen saturation, the use of central venous blood saturation has recently gained popularity. A study of 12 patients undergoing abdominal aortic surgery showed good correlation \( (P < .001) \) between Svo2 and CI measured by TD method (PAC). Another study of 18 severe heart failure patients treated with milrinone and dobutamine showed excellent correlation of Svo2 and CI as measured by the PAC. Newer devices that can measure central venous blood saturation continuously, such as PiCCO and Swan-Ganz CCOmbo PAC (Edwards Life Sciences) have been developed and can measure CO by TD technique along with continuous measurement of mixed venous saturations.

**NONINVASIVE TECHNIQUES**

Noninvasive techniques include
- Thoracic bioimpedence (TEB)
- Electrical bioreactance cardiography
- Esophageal Doppler
- Transgastric Doppler
- Ultrasonic cardiac output monitor (USCOM, USCOM Pty Ltd, Coffs Harbour NSW Australia).

Echocardiography and carbon dioxide rebreathing method (non-invasive continuous cardiac output) are discussed in other articles in this issue.

**TEB**

TEB is a noninvasive technique developed by Kubicek\(^{20}\) to measure cardiac output in astronauts. It involves delivery of low-amplitude high-frequency electrical current across the thorax (Fig. 2). A series of sensing electrodes measuring impedence are placed around the thorax. Hemodynamic measurements of CO using TEB devices relate to change in the thoracic electrical conductivity to changes in thoracic aortic blood volume and blood flow. This form of impedence cardiography has been proposed as a simple and readily reproducible noninvasive technique for the determination of CO, specifically, SV, contractility, systemic vascular resistance, and thoracic fluid content and filling index.\(^{21}\) Proponents have claimed that TEB can measure CO with the same clinical accuracy as either the Fick or TD technique and that it offers the potential for sequential measurements of CO in patients for whom invasive measurements are impractical or contraindicated. Variations due to the heart beat in blood flow and volume in the ascending aorta cause a change in the total chest impedance, which, when continuously recorded, produces a \(\frac{dZ}{dt}\) wave (\(dZ = \text{impedence change, } dt = \text{change in time}\)).

Factors affecting measurement of impedence include height, weight, sex, circumference of chest, and hemoglobin. Models using algorithms based on these factors have been developed to improve accuracy of measurements. Newer technology uses chest baseline impedence-independent electrical impedence cardiography systems. This technique improves accuracy in those patients with large amounts of thoracic fluid that was a source of significant interference in older model measurements. This accuracy significantly increases the technique’s usefulness in patients with pulmonary edema, chest trauma, congestive heart failure, and acute respiratory distress syndrome (ARDS). Meta-analysis, however, has shown a broad range of correlation to TD determinations of CO \((r = .44 \text{ to } .74)\).\(^{22}\) Despite recent advances, the technique remains confounded by positive end-expiratory pressure (PEEP), chest wall edema, obesity, pleural fluid, and severe pulmonary edema.\(^{23}\) One study has
shown that when patients with these confounders were excluded, correlation to TD determination of CO was improved to $r = .93$.24

**Electrical Bioreactance Cardiography**

To overcome some of the limitations and clinical confounders of bioimpedence, bioreactance recently has been employed as a means to measure CO noninvasively. Whereas bioimpedence is based on changes in amplitude of electrical resistivity as a function of CO, bioreactance is based on changes in frequency. Similar to FM radio, the signal is less susceptible to interference from chest wall movement, chest wall and lung edema, and pleural fluid (Fig. 3). Additionally, detection of frequency modulation is not as affected by the distance of electrode placement, so the electrodes can be placed anywhere on the chest.

The method used by the CheetahTM monitor (Cheetah Medical, Tel Aviv, Israel and Portland, Oregon) has shown good correlation with TD in several studies in critically ill patients.25,26 A recent prospective pilot study between septic and nonseptic patients revealed significant differences in SV, cardiac index and peripheral vascular resistance, and predicted the need for hospitalization in sepsis.27 Another study in

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**Figure 2.** Thoracic bioimpedence uses a tetrapolar system of electrodes, separating the current pathway from the sensing pathway. Current is injected, and the impedance against the flow of the current through the thorax along the path of least resistance is measured (ie, the great vessels).

**Figure 3.** Difference of AM and FM modulation. Bioimpedence with amplitude variability and Bioreactance with frequency variability or phase shift.
postoperative cardiac surgery patients compared bioreactance and pulse contour analysis (Flo-Trac Vigileo) with PAC TD and showed similar correlations of the two techniques to TD (0.77 and 0.69, respectively). Sensitivity and specificity for predicting trends in changes in cardiac output changes were 0.91 and 0.95, respectively, for the bioreactance and 0.86 and 0.92, respectively, for the FloTrac-Vigileo.

**Esophageal Doppler Technique**

The esophageal Doppler technique measures blood flow velocity in descending aorta by a Doppler transducer (4 MHz continuous or 5 MHz pulsed wave) placed on the tip of an esophageal probe. The probe is introduced in the esophagus and rotated toward the descending aorta. The depth, rotation of the probe, and gain are adjusted to obtain an optimal aortic velocity signal. The positioning of probe is critical in estimating CO, as poor positioning can lead to underestimation of CO. It is operator-dependent and requires specialized training to use effectively. Studies have shown good correlation to TD ($r = .95$). Advantages to its use are that it is relatively less invasive than a PAC, and it provides continuous flow information. Disadvantages are its initial cost, the need for sedation, and the need for a specialist trained in its use.

**Transgastric Doppler Technique**

Transgastric Doppler is a similar technique to esophageal Doppler with the probe positioned in the stomach instead of esophagus. In this technique, a thinner silicone probe (6 mm) is used, and its placement usually does not require sedation. The thinner probe can be more difficult to position, and it requires frequent repositioning. It has been shown to have acceptable correlation to TD in a study of 31 patients with 57 simultaneous TD and Doppler readings, which revealed a close correlation with $r = .91$, and $P<.001$, making it a promising new technique that may be used in selected patients for accurate measurement of cardiac output.

**USCOM**

The USCOM ultrasonic cardiac output monitor is a noninvasive device that determines cardiac output by continuous-wave Doppler ultrasound. The flow profile is obtained using a transducer (2.0 or 3.3 MHz) placed on the chest in either the left parasternal position to measure transpulmonary blood flow or the suprasternal position to measure transaortic blood flow. This flow profile is presented as a time–velocity spectral display showing variations of blood flow velocity with time. Comparison of the technique with TD in one study of 22 cardiac patients showed a bias of 0.18 and limits of agreement of −1.43 to 1.78. The agreement was not as good between techniques at higher cardiac output values. Its suitability for use in high and low cardiac output states requires further validation.

**SUMMARY**

Bedside determination of cardiac function and output is an evolving field. Several techniques are now available, each with their pros and cons. Clearly less invasive techniques are desired. Most lack clear clinical validation, however, and further study is required both in terms of determining accuracy and in demonstrating efficacy for improving outcome. It must be remembered that the ability to improve outcome will never rest solely on a device but rather on how it is used. New algorithmic strategies employing these various devices and techniques must be studied for their ability to improve outcome if bedside hemodynamic monitoring is to advance.
REFERENCES