Chapter 10

Monitoring of the Heart and Vascular System

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Key Points

1. Patients with severe cardiovascular disease and those undergoing surgery associated with rapid hemodynamic changes should be adequately monitored at all times.
2. Standard monitoring for cardiac surgery patients includes invasive blood pressure, electrocardiography, central venous pressure, urine output, temperature, capnometry, pulse oximetry, and intermittent blood gas analysis.
3. Additional monitoring is based on specific patient, surgical, and environmental factors.
4. The Society of Cardiovascular Anesthesiologists and the American Society of Echocardiography have published recommendations for intraoperative transesophageal echocardiography (TEE). TEE is recommended for all patients undergoing cardiac surgery, unless contraindications to probe insertion apply.
5. Ultrasound-guided vascular access is now routinely practiced in many institutions.
6. The use of pulmonary artery catheters (PACs) has been steadily declining. Guidelines for PAC use have been published. Many practitioners still use PACs to guide treatment in patients with low cardiac output or pulmonary arterial hypertension.
7. The use of additional highly invasive monitoring techniques, such as coronary sinus pressures and cerebrospinal fluid pressures, are restricted to very specific indications.

HEMODYNAMIC MONITORING

The availability of monitoring devices is increasing continually. These devices range from those that are completely noninvasive to those that are highly invasive, such as the pulmonary artery catheter (PAC). Limitations to less invasive monitoring technologies often apply, and interventions based on information gained from noninvasive monitoring carry intrinsic risks. To make the best use of any monitoring technology, the potential benefits to be gained from the information must outweigh the potential complications. This risk-benefit ratio is highly variable and must be evaluated for each clinical scenario individually. Although outcome changes are difficult to prove, the assumption that appropriate hemodynamic monitoring should reduce the incidence of major cardiovascular complications is reasonable. This is based on

BOX 10.1 ***Standard Monitoring for Cardiac Surgical Patients***

(Invasive) blood pressure
Electrocardiogram
Pulse oximetry
Capnometry
Temperature
Central venous pressure
Transesophageal echocardiography
Urine output
Intermittent arterial blood sampling for blood gas and laboratory analyses
Neuromonitoring (cerebral oximetry, processed electroencephalography)

BOX 10.2 ***Extended Monitoring for Patients Based on Case-Specific Factors***

Retrograde cardioplegia pressure
Pulmonary artery catheter
Cardiac output measurements
Left atrial pressure
Cerebrospinal fluid (intrathecal) pressure

the presumption that the data obtained from these monitors are interpreted correctly and that therapeutic interventions known to improve outcomes are implemented in a timely fashion.

Standard monitoring for all patients undergoing surgery has been defined by the American Society of Anesthesiologists (ASA) practice guidelines. In patients undergoing cardiac or major noncardiac surgery with expected large fluid shifts or hemodynamic instability, invasive blood pressure (BP) monitoring is nearly universally employed, which also enables frequent arterial blood sampling. Transesophageal echocardiography (TEE), a less invasive technology, provides extensive hemodynamic data and other diagnostic information. The Society of Cardiovascular Anesthesiologists and the American Society of Echocardiography have published recommendations for intraoperative TEE use. Unless contraindications to probe insertion apply, TEE is now recommended for all patients undergoing cardiac surgery. Box 10.1 summarizes monitoring typically used in cardiac surgeries.

The next tier of monitoring is typically more invasive, including PACs with thermodilution cardiac output (CO). The interpretation of these complex data requires an astute clinician who is aware of the patient's overall condition and the limitations of the monitors. Additionally, with the expansion of less invasive surgical techniques, the anesthesiologist is getting more involved in guiding cardiopulmonary bypass (CPB) cannulation and adequacy of cardioprotection techniques. This includes retrograde cardioplegia cannula positioning in the coronary sinus (CS) and pressure monitoring. Advanced monitoring is summarized in Box 10.2.

ARTERIAL PRESSURE MONITORING

Anesthesia for cardiac and major noncardiac surgeries is frequently complicated by rapid and sudden changes in BP. Sudden losses of large amounts of blood, direct compression of the heart, impaired venous return attributable to retraction and cannulation of the vena cavae and aorta, arrhythmias, and manipulations that may impair right ventricular outflow and pulmonary venous return all contribute to hemodynamic instability. Therefore a safe and reliable method of measuring acute changes in BP is indispensable. Direct intraarterial monitoring remains the gold standard, providing a continuous, beat-to-beat indication of the arterial pressure and waveform and allowing frequent sampling of arterial blood for laboratory analyses.

The magnitude of BP is directly related to CO and systemic vascular resistance (SVR). This is conceptually similar to Ohm's law of electricity (voltage = current × resistance), in which BP is analogous to voltage, CO to current flow, and SVR to resistance. An increase in BP may reflect an increase in CO or SVR, or both.

Mean arterial pressure (MAP) is probably the most useful parameter when assessing overall end-organ perfusion. MAP is measured directly by integrating the arterial waveform tracing over time or using the formula: $MAP = (SBP + [2 \times DBP]) \div 3$ (where SBP is systolic blood pressure and DBP is diastolic blood pressure). Perfusion of the heart differs from most other organs, with coronary perfusion of the left ventricle mostly occurring during diastole. Coronary blood flow to the normal right ventricle (RV) is maintained during systole and diastole.

Arterial Cannulation Sites

Factors that influence the site of arterial cannulation include the location of surgery, the possible compromise of arterial flow attributable to patient positioning or surgical manipulations, CPB cannulation and perfusion techniques, and any history of ischemia or prior surgery on the limb to be cannulated. Monitoring arterial BP at two or more sites may be warranted in complex cases with complex perfusion techniques.

Temporary central aortic pressure monitoring can be achieved by using a needle (attached to pressure tubing) that is placed in the aorta or by pressure tubing connected to the aortic CPB cannula or the anterograde cardioplegia cannula. Central aortic monitoring is usually only necessary for several minutes until the problem resolves; in rare cases, a femoral arterial cannula is placed from the surgical field.

The radial artery is the most commonly used artery for continuous BP monitoring because it is easy to cannulate, readily accessible during surgery, and the collateral circulation is usually adequate and easy to check. The ulnar artery provides most of the blood flow to the hand in approximately 90% of patients. The radial and ulnar arteries are connected by a palmar arch, which provides collateral flow to the hand in the event of radial artery occlusion. Some clinicians perform the Allen test before radial artery cannulation to assess the adequacy of collateral circulation to the hand; however, the predictive value of the Allen test has been challenged.

The brachial artery lies medial to the bicipital tendon in the antecubital fossa in close proximity to the median nerve. Brachial artery pressure tracings resemble those in the femoral artery with less systolic augmentation than radial artery tracings. Brachial arterial pressures were found to reflect central aortic pressures more accurately than radial arterial pressures before and after CPB. A few series of patients with perioperative brachial arterial monitoring have documented the relative safety of this technique.

The femoral artery may be cannulated for monitoring purposes and typically provides a more reliable central arterial pressure after discontinuation of CPB. In

BOX 10.3 *Indications for Intraarterial Monitoring*

Major surgical procedures involving large fluid shifts or blood loss
Surgery requiring cardiopulmonary bypass
Surgery of the aorta
Patients with pulmonary disease requiring frequent arterial blood gases
Patients with recent myocardial infarctions, unstable angina, or severe coronary artery disease
Patients with decreased left ventricular function (congestive heart failure) or significant valvular heart disease
Patients in hypovolemic, cardiogenic, or septic shock, or with multiple organ failure
Procedures involving the use of prolonged deliberate hypotension or deliberate hypothermia
Massive trauma cases
Patients with right-sided heart failure, chronic obstructive pulmonary disease, pulmonary hypertension, or pulmonary embolism
Patients requiring inotropes or intraaortic balloon counterpulsation
Patients with electrolyte or metabolic disturbances requiring frequent blood samples
Inability to measure arterial pressure noninvasively (eg, extreme morbid obesity)

patients undergoing thoracic aortic surgery, distal aortic perfusion (using partial CPB, left-sided heart bypass, or a heparinized shunt) may be performed during aortic cross-clamping to preserve spinal cord and visceral organ blood flow. In these situations, measuring the distal aortic pressure at the femoral artery or a branch vessel is useful (ie, dorsalis pedis or posterior tibial artery) to optimize the distal perfusion pressure. Consulting the surgeon before cannulating the femoral vessels is necessary, because these vessels may be used for extracorporeal perfusion or placement of an intraaortic balloon pump during the surgical procedure.

The indications for invasive arterial monitoring are provided in Box 10.3.

Insertion Techniques

Direct Cannulation

Proper technique is helpful in obtaining a high degree of success in arterial catheterization. The wrist is often placed in a dorsiflexed position on an armboard over a pack of gauze and immobilized in a supinated position. Overextension of the wrist should be avoided, since this flattens and decreases the cross-sectional area of the radial artery and may cause median nerve damage by stretching the nerve over the wrist. When the artery is entered, the angle between the needle and skin is reduced to 10 degrees, the needle is advanced another 1 to 2 mm to ensure that the tip of the catheter also lies within the lumen of the vessel, and the outer catheter is then threaded off the needle. If blood ceases flowing while the needle is being advanced, then the needle has penetrated the back wall of the vessel.

Alternatively, the artery can be transfixed by the passage of the catheter-over-needle assembly "through-and-through" the artery. The needle is then completely withdrawn. As the catheter is slowly withdrawn, pulsatile blood flow emerges from the catheter when its tip is within the lumen of the artery. At this point the catheter can either be advanced in the lumen of the artery or a guidewire advanced into the lumen first,

Fig. 10.1 Demonstration of aseptic technique for ultrasonic guidance of radial artery cannulation.

followed by advancing the catheter over the wire (modified Seldinger technique). Compared with a direct cannulation method, using the Seldinger technique increases the success rate of arterial catheter placement.

Ultrasound and Doppler-Assisted Techniques

An ultrasound-guided (UG) technique is probably most useful in patients with severe peripheral vasculopathy, as well as in infants and small children. The use of ultrasound in guiding arterial catheter placement is easy to learn when proper training in this technique is provided. There is, however, a significant learning curve. Fig. 10.1 shows a proper full-sterile set up for UG arterial cannulation. Fig. 10.2 demonstrates the "triangulation" technique typically applied with UG arterial cannulation. The ultrasound imaging plane and the needle plane can be viewed as the two sides of a triangle that should meet and intersect at the depth of the structure (eg, radial artery) for which cannulation is attempted. The experienced operator will choose the distance (needle insertion site vs imaging plane) and insertion angle, depending on the depth of the target vessel. After perforating the skin, the ultrasound plane and the needle insertion angle both have to be adjusted further to follow the needle tip when viewed in the transverse (short-axis) approach. Failure to align the ultrasound plane accurately with the needle tip results in viewing the needle shaft instead. Fig. 10.3 shows a typical ultrasound image obtained during short-axis (transverse) cannulation. After puncturing the vessel, the catheter can be advanced into the lumen. A significantly higher success rate can usually be achieved using the through-and-through and modified Seldinger techniques.

If a longitudinal ("in-plane") approach is chosen (ie, the vessel is viewed in its long axis), the needle tip can be followed more easily as it is advanced; however, structures adjacent to the ultrasound plane (lateral to the vessel) cannot be viewed simultaneously. Exactly aligning the needle and vessel axis together in a 2D echo plane, particularly with a tortuous atherosclerotic artery, is technically more difficult. Fig. 10.4 shows the arterial catheter entering the radial artery using the longitudinal (in-plane) approach. A high-frequency linear array ultrasonic transducer (8 to 12 MHz) is optimal for UG arterial catheter placement, since higher frequencies are needed

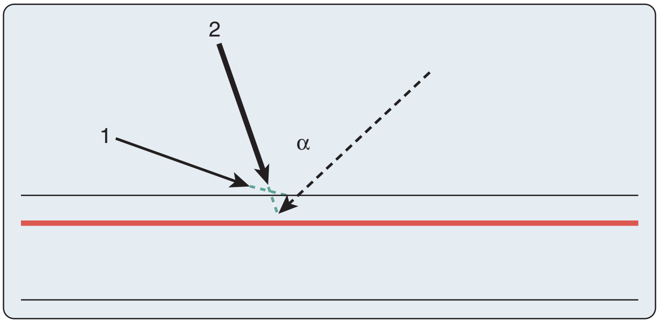

Fig. 10.2 Demonstration of the "triangulation" technique typically applied with ultrasound-guided (UG) venous and/or arterial cannulation in the transverse imaging approach. The echo imaging plane and the needle plane can be viewed as the two sides of a triangle that should meet and intersect at the depth of the structure (eg, radial artery *[red line]*) for which cannulation is attempted. The experienced operator will change the angle *(α)* between the two planes (ultrasound and needle) and the distance (needle insertion site vs imaging plane), depending on the depth of the structure. To follow the needle tip in the transverse approach (vessel viewed in short axis), the echo plane or needle insertion angle has to be further adjusted from needle entry through the skin to the perforation of the vessel. A greater angle is used (echo plane angled toward the skin *[1]*) to visualize the needle tip after it penetrates the skin, and then a more perpendicular angle relative to the skin is applied to see the needle tip entering the vessel lumen (*2*).

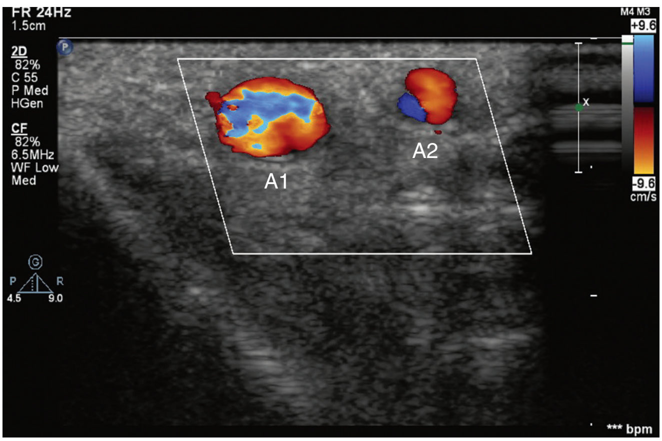

Fig. 10.3 A typical ultrasound image with color Doppler during short-axis (transverse) cannulation. Note the anatomic variation with a larger radial artery (*A1*) next to a smaller artery (*A2*) positioned laterally.

for high-resolution imaging of the near field. Box 10.4 summarizes the potential benefits and concerns related to UG arterial catheter placement.

CENTRAL VENOUS PRESSURE MONITORING

Central venous pressure (CVP) catheters are used to measure the filling pressure of the RV, give an estimate of the intravascular volume status, assess right ventricular function, and serve as a site for volume or drug infusions. For accurate pressure measurement, the distal end of the catheter must lie within one of the large intrathoracic

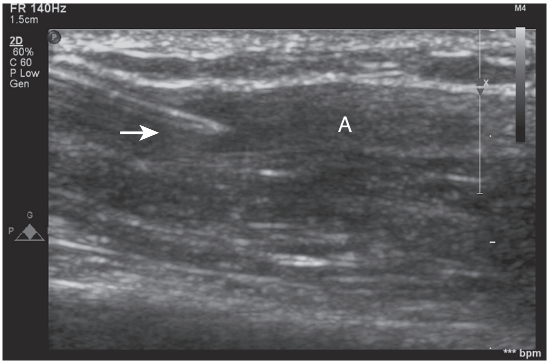

Fig. 10.4 Catheter entering the radial artery using the longitudinal (in-plane) approach.

BOX 10.4 *Ultrasound-Guided Arterial Cannulation*

Benefits

- Higher success rate on first attempt
- Fewer overall attempts
- Increased patient comfort (fewer attempts)
- Fewer complications (eg, anticoagulated patients)
- Demonstration of vessel patency, anatomic variants
- Low pulsatile or nonpulsatile flow (eg, nonpulsatile assist devices, extracorporeal membrane oxygenation, shock)
- Nonpalpable or weakly palpable pulses (eg, peripheral edema, hematoma)
- Emergency access (eg, catheter placement during resuscitation)

Concerns

- Risk of catheter-related infections if poor aseptic technique is applied
- Additional training required
- Costs involved with equipment required

veins or the right atrium (RA). As in any pressure monitoring system, having a reproducible landmark, such as the midaxillary line with a closed chest or the left atrium (LA) during surgery, as a zero reference is necessary. Frequent changes in patient positioning without proper leveling of the transducers relative to the heart produce proportionately larger errors compared with arterial pressure monitoring.

The normal CVP waveform consists of three upward deflections (A, C, and V waves) and two downward deflections (X and Y descents). The A wave is produced by right atrial contraction and occurs just after the P wave on the electrocardiogram (ECG). The C wave occurs because of the isovolumic ventricular contraction, forcing the tricuspid valve (TV) to bulge upward into the RA. The pressure within the RA then decreases as the TV is pulled away from the atrium during right ventricular ejection, forming the X descent. Right atrial filling continues during late ventricular systole, forming the V wave. The Y descent occurs when the TV opens and blood from the RA empties rapidly into the RV during early diastole. The CVP waveform may be useful in the diagnosis of pathologic cardiac conditions. For example, the onset of an irregular rhythm and loss of the A wave suggest atrial flutter or fibrillation.

Cannon A waves occur as the RA contracts against a closed TV, as occurs in junctional (atrioventricular [AV] nodal) rhythm, complete heart block, and ventricular arrhythmias. This occurrence is clinically relevant because nodal rhythms are frequently seen during anesthesia and may produce hypotension attributable to a decrease in stroke volume (SV).

The CVP is a useful monitor if the factors affecting it are recognized and its limitations are understood. Thromboses of the vena cavae and alterations of intrathoracic pressure, such as those induced by positive end-expiratory pressure (PEEP), also affect measurement of the CVP. The correlation with left-sided heart filling pressures and assessment of left ventricular preload is poor. Clinically, following serial measurements (trends) rather than individual numbers is often more relevant. The response of the CVP to a volume infusion, however, is a useful test.

Internal Jugular Vein

Cannulation of the internal jugular vein (IJV) has multiple advantages, including the high success rate as a result of the relatively predictable relationship of the anatomic structures: a short, straight course to the RA that almost always ensures RA or superior vena cava (SVC) localization of the catheter tip; and easy access from the head of the surgical table. The IJV is located under the medial border of the lateral head of the sternocleidomastoid (SCM) muscle (Fig. 10.5). The carotid artery is usually deep and medial to the IJV; however, this spatial relationship can vary, and puncture of the carotid artery is best avoided by using an UG technique. The right IJV is preferred, because this vein takes the straightest course into the SVC, the right cupola of the lung may be lower than the left, and the thoracic duct is on the left side.

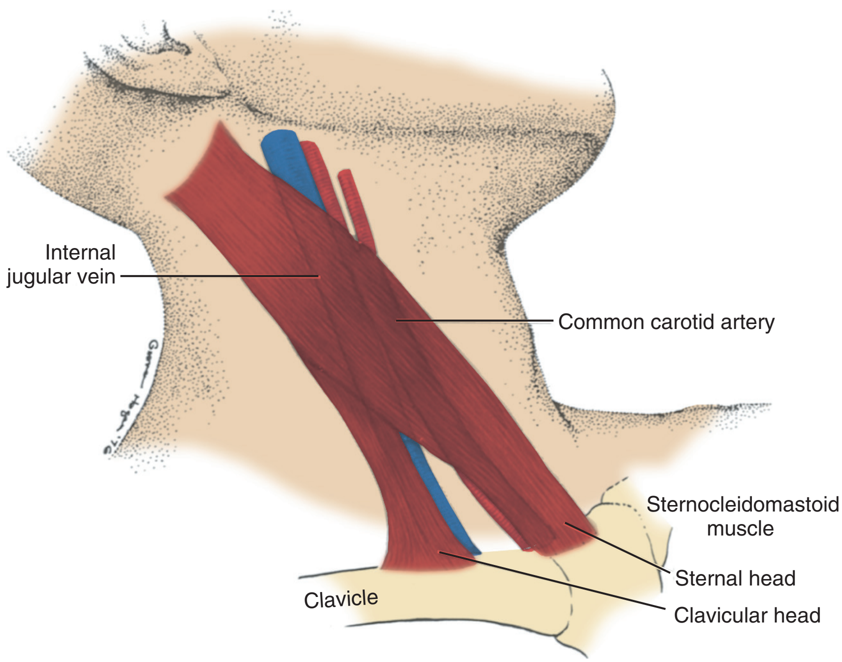

Fig. 10.5 The internal jugular vein is usually located deep to the medial border of the lateral head of the sternocleidomastoid muscle, just lateral to the carotid pulse.

Fig. 10.6 Preferred middle approach to the right internal jugular vein. The needle enters the skin at the apex of the triangle formed by the sternal and clavicular heads of the sternocleidomastoid muscle. The needle is held at a 30- to 45-degree angle to the skin and directed toward the ipsilateral nipple.

The *middle approach* to the right IJV is shown in Fig. 10.6. The Trendelenburg position is chosen to distend the IJV. The head is then turned toward the contralateral side, and the fingers of the left hand are used to palpate the two heads of the SCM muscle and the carotid pulse. The needle is inserted slightly lateral to the carotid pulse at a 45-degree angle to the skin and directed toward the ipsilateral nipple until venous blood return is obtained. Alternatively, the use of a small-gauge *finder* needle can be used to avoid carotid puncture with a large-bore needle. When venous return is present, the whole assembly is lowered to prevent the needle from going through the posterior wall of the central vein and advanced an additional 1 to 2 mm until the tip of the catheter is within the lumen of the vein. Aspiration of blood must be confirmed before the catheter is then threaded into the vein. It is recommended by the ASA practice guidelines, and often mandated by institutional protocols, that the correct intravenous catheter position be confirmed before placing a large-bore introducer sheath. Various techniques have been suggested. The small-bore catheter can be attached to a transducer by sterile tubing to observe the pressure waveform. Another option is to attach the cannula to sterile tubing and allow blood to flow retrograde into the tubing. The tubing is then held upright as a venous manometer, and the height of the blood column is observed. If the catheter is in a vein, then it will stop rising at a level consistent with the CVP and demonstrate respiratory variation. Despite its reported use in the past, color comparison and observation of nonpulsatile flow are notoriously inaccurate methods of determining that the catheter is not in the carotid artery. A guidewire is then passed through the 18-gauge catheter, and the catheter is exchanged for the wire. With the more widespread use of echocardiography, the correct intravenous position can also be confirmed by following the Seldinger wire along its course in the IJV more distally by handheld transcutaneous probes or demonstrated within the RA if the TEE probe was inserted before IJV cannulation. The use of more than one technique to confirm the venous location of the guidewire may provide additional reassurance of correct placement before cannulation of the vein with a larger catheter or introducer. Once it is certain that the guidewire is in the venous circulation, the CVP catheter is passed over it and the wire is removed.

Ultrasound-Guided Internal Jugular Vein Cannulation

Ultrasound has been increasingly used for central venous access, in particular to guide IJV cannulation and to define the anatomic variations of the IJV. Using ultrasound to guide central venous cannulation increases the success rate and helps prevent complications and thus may ultimately help improve patient outcomes. Most studies have demonstrated that 2D UG IJV cannulation has a higher success rate on the first attempt and fewer complications. Those findings also were confirmed in pediatric patients.

Box 10.5 lists some of the recognized benefits and concerns of UG central venous cannulation. Circumstances in which ultrasound guidance of IJV cannulation can be particularly advantageous include patients with difficult neck anatomy (eg, short neck, obesity), prior neck surgery, anticoagulated patients, and infants.

Ultrasound provides instantaneous and patient-specific information regarding the structural relationship between the IJV, the carotid artery, and adjacent anatomic structures (Fig. 10.7). The spatial relationships can vary significantly, and the IJV may be absent or completely or partially overlapping the carotid artery. Box 10.6 summarizes some of the positional considerations in UG IJV cannulation.

For central venous catheterization, full aseptic technique is mandatory. Although the long-axis (in-plane) approach allows better visualization of the true needle tip throughout the insertion and vessel penetration, the simultaneous display of the IJV and its relationship to the carotid artery is lost. Additionally, the size of the ultrasound probe in patients with short neck anatomy often does not provide adequate room for an in-plane approach to the IJV. Most practitioners therefore choose the short-axis (out-of-plane) approach to UG IJV cannulation. The most important aspect of imaging a needle out of plane is avoiding the mistake of visualizing the needle shaft rather than the needle tip. Otherwise, the needle tip could be in a structure not being imaged, such as the carotid artery or pleura. With training and experience, the practitioner learns to sweep the ultrasonic plane inferiorly along the course of the needle shaft until the needle tip is identified. Adjusting the ultrasonic plane and the angle of the needle insertion enables visualization of the needle tip as it enters the IJV. An extremely

BOX 10.5 ***Ultrasound-Guided Central Venous Cannulation***

Benefits

- Higher success rate on first attempt
- Fewer overall attempts
- Facilitates access with difficult neck anatomy (obesity, prior surgery)
- Fewer complications (eg, carotid artery puncture, anticoagulated patients)
- Demonstration of vessel patency, anatomic variants
- Relatively inexpensive technology

Concerns

- Training personnel to maintain aseptic technique when using sterile probe sheaths
- Additional training required
- Lack of observation of surface anatomy
- Potential loss of landmark-guided skills when needed for emergency central venous catheterization.

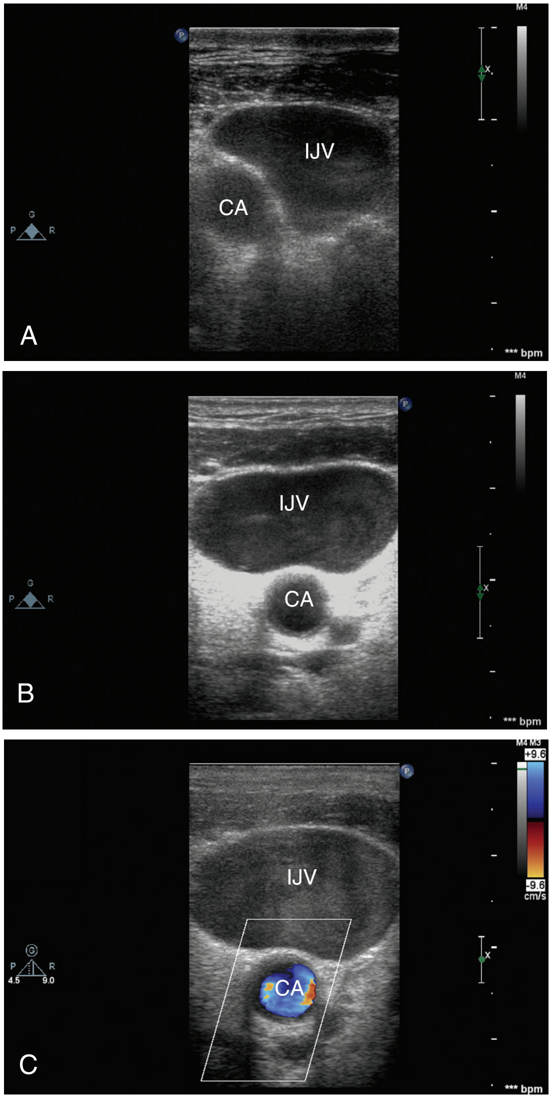

Fig. 10.7 Anatomic relationship between the internal jugular vein (*IJV*) and the carotid artery (*CA*) in two patients. (A) The IJV partially overlies the CA. (B) The CA is situated deep to the IJV. (C) Color Doppler demonstrates the flow in the CA.

favorable sign of needle tip visualization during needle advancement is indentation of the anterior wall of the IJV as the needle tip encounters the vessel wall.

It is important to realize that UG IJV cannulation has reduced, but not eliminated, inadvertent carotid arterial cannulation, and that the insertion of large catheters into the carotid artery with ultrasound guidance has been reported. Venous cannulation always should be confirmed before advancing the dilators or inserting the large-bore catheter and introducer sheath.

In addition to hemodynamic monitoring, central venous access is typically warranted to establish a secure venous access route for the administration of vasoactive or irritating

BOX 10.6 ***Positional Considerations in Ultrasound-Guided Right Internal Jugular Venous Cannulation***

Slight Trendelenburg position
Head turned slightly away from the cannulation side (turning too far may flatten the internal jugular vein [IJV] and rotate the IJV above the carotid artery)
Overextension of the head should be avoided; mild head elevation can be advantageous (overextension flattens IJV)
Minimal neck pressure by manual palpation and/or ultrasonic probe to avoid compression of the IJV
Ultrasound probe should scan the course of the IJV to find the best cannulation site (largest IJV diameter and least overlap with the carotid artery)

BOX 10.7 ***Indications for Central Venous Catheter Placement***

Major operative procedures involving large fluid shifts or blood loss in patients with good heart function
Intravascular volume assessment when urine output is not reliable or unavailable (eg, renal failure)
Major trauma
Surgical procedures with a high risk of air embolism, such as sitting-position craniotomies during which the central venous pressure catheter may be used to aspirate intracardiac air
Frequent venous blood sampling
Venous access for vasoactive or irritating drugs
Chronic drug administration
Inadequate peripheral intravenous access
Rapid infusion of intravenous fluids (only when using large-bore cannulae)
Total parenteral nutrition

drugs, the rapid infusion of intravenous fluids, and total parenteral nutrition. Perioperative indications for the insertion of a central venous catheter are listed in Box 10.7.

The complications of central venous cannulation can be divided into three categories: vascular access, catheter insertion, and catheter presence. These complications are summarized in Box 10.8.

PULMONARY ARTERIAL PRESSURE MONITORING

At the time of the introduction of the flow-directed PAC in 1970, the amount of diagnostic information that could be obtained at the bedside dramatically increased. Some of the earlier studies showed that clinicians were often unaware of hemodynamic problems or incorrectly predicted preload and CO without PAC monitoring. Although PAC-derived data can help in the differential diagnosis of hemodynamic instability and guide treatment, the clinical significance has been questioned.

Between 1993 and 2004 PAC use in the United States alone decreased by 65% for all medical admissions. The most significant decrease in PAC use was documented

BOX 10.8 *Complications of Central Venous Catheterization*

Complications of Central Venous Access and Cannulation

- Arterial puncture with hematoma
- Arteriovenous fistula
- Hemothorax
- Chylothorax
- Pneumothorax
- Nerve injury
- Brachial plexus injury
- Stellate ganglion injury (Horner syndrome)
- Air embolus
- Catheter or wire shearing
- Guidewire loss and embolization
- Right atrial or right ventricular perforation

Complications of Catheter Presence

- Thrombosis, thromboembolism
- Infection, sepsis, endocarditis
- Arrhythmias
- Hydrothorax

in patients with acute myocardial infarction, whereas those patients diagnosed with septicemia showed the least decline in use. These findings were almost identical to the surgical patient population, in which PAC use decreased by 63% in the same observed period.

Currently, the incidence of right heart (PAC) catheterization is highly variable among hospitals. A recent survey among the members of the Society of Cardiovascular Anesthesiologists found that a majority of practitioners (68.2%) still frequently (>75%) use a PAC for cases with CPB. However, the use of a PAC differed significantly between private (79.2%), academic (64.5%), and governmental (34%) practice settings. With decreasing exposure to PACs, clinicians may become less likely to make the best use of PAC-derived hemodynamic data.

Placing a PAC is a highly invasive procedure. Vascular structures are accessed with large-bore introducer sheaths with all the possible complications listed. Most important, even in the best of all circumstances with uncomplicated PAC placement and correct data collection and interpretation, it has to be recognized that a PAC is only a monitoring tool. As such, a change in patient outcome cannot be expected unless the treatment that is initiated based on the PAC measurements is effective for improving patient outcome. In some of the most critically ill patients, mortality remains high despite efforts to find new treatment strategies. Furthermore, diagnoses often can be made on clinical grounds only, and treatment strategies once thought to improve patient outcome actually may be harmful.

Technical Aspects of Pulmonary Artery Catheter Use

Considerations for the insertion site of a PAC are the same as for CVP catheters. Infection guidelines list specific recommendations regarding PAC use, strongly recommending use of a sterile sleeve to protect the PAC during insertion (category IB). The right IJV approach remains the preferred access route for many practitioners. This is because of the direct path between this vessel and the RA during IJV approach and the frequent kinking of the introducers during sternal retraction when subclavian access is chosen.

Passage of the PAC from the vessel introducer to the PA can be accomplished by monitoring the pressure waveform from the distal port of the catheter or under fluoroscopic or echocardiographic (TEE) guidance. Waveform monitoring is the most common technique for perioperative right-sided heart catheterization. First, the catheter must be advanced through the vessel introducer (15 to 20 cm) before inflating the balloon. The inflation of the balloon facilitates further advancement of the catheter through the RA and RV into the pulmonary artery (PA). Normal intracardiac pressures are shown in Table 10.1. The pressure waveforms seen during advancement of the PAC are illustrated in Fig. 10.8. Catheter manipulation and positional changes may be useful. Trendelenburg positioning places the RV more superior to the RA and thus may aid in advancing the PAC past the TV. TEE guidance can prove invaluable in these cases. The experienced echocardiographer can assist in guiding the catheter tip toward the TV orifice by directing catheter and positional manipulations. The right atrial waveform is seen until the catheter tip crosses the TV and enters the RV. In the RV, there is a sudden increase in SBP but little change in DBP, compared with the right atrial tracing. Arrhythmias, particularly premature ventricular complexes, usually

Table 10.1 Normal Intracardiac Pressures

Location	Mean (mm Hg)	Range (mm Hg)
Right atrium	5	1–10
Right ventricle	25/5	15–30/0–8
Pulmonary arterial systolic and diastolic pressures	23/9	15–30/5–15
Mean pulmonary arterial	15	10–20
Pulmonary capillary wedge pressure	10	5–15
Left atrial pressure	8	4–12
Left ventricular end-diastolic pressure	8	4–12
Left ventricular systolic pressure	130	90–140

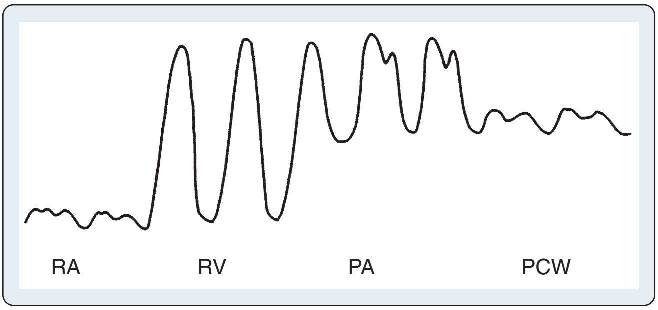

Fig. 10.8 The waveforms encountered during the flotation of a pulmonary artery catheter from the venous circulation to the pulmonary capillary wedge *(PCW)* position. Notice the sudden increase in systolic pressure as the catheter enters the right ventricle *(RV)*, the sudden increase in diastolic pressure as the catheter enters the pulmonary artery *(PA)*, and the decrease in mean pressure as the catheter reaches the PCW position. *RA,* Right atrium.

occur at this point, but they almost always resolve without treatment once the catheter tip has crossed the pulmonary valve. The catheter is advanced through the RV toward the PA. As the catheter crosses the pulmonary valve, a dicrotic notch appears in the pressure waveform, and the diastolic pressure suddenly increases. The pulmonary capillary wedge pressure (PCWP; also termed *pulmonary capillary occlusion pressure*) tracing is obtained by advancing the catheter approximately 3 to 5 cm farther until a change in the waveform associated with a drop in the measured mean pressure occurs. Deflation of the balloon results in the reappearance of the PA waveform and an increase in the mean pressure value. Using the right IJV approach, the RA is entered at 25 to 35 cm, the RV at 35 to 45 cm, the PA at 45 to 55 cm, and the PCWP at 50 to 60 cm in most patients.

If the catheter does not enter the PA by 60 cm (from the right IJV approach), the balloon should be deflated and the catheter should be withdrawn into the RA or the inflow portion of the RV. Further attempts can then be made to advance the catheter into proper position using the techniques previously described. Excessive coiling of the catheter in the RA or RV should be avoided to prevent catheter knotting. The balloon should be inflated only for short periods to measure the PCWP. The PA waveform should be monitored continually to be certain that the catheter does not advance into a constant wedge position, which may lead to PA rupture or pulmonary infarction. Not infrequently, the PAC must be withdrawn a short distance because the catheter softens and advanced more peripherally into the PA over time, or on CPB attributable to the decreased size of the heart.

Specific information that can be gathered with the PAC and the quantitative measurements of cardiovascular function that can be derived from this information are listed in Table 10.2. One of the primary reasons that clinicians measure PCWP and PA diastolic (PAD) pressure is that these parameters are estimates of left atrial

Table 10.2 Derived Hemodynamic Parameters

Formula	Normal Values
Cardiac index (CI) CI = CO/BSA	2.6–4.2 L/min/m^2
Stroke volume (SV) SV = CO*1000/HR	50–110 mL (per beat)
Stroke index (SI) SI = SV/BSA	30–65 mL/beat/m^2
Left ventricular stroke work index (LVSWI) LVSWI = 1.36* (MAP–PCWP)* SI/100	45–60 gram-meters/m^2
Right ventricular stroke work index (RVSWI) RVSWI = 1.36* (MPAP–CVP)* SI/100	5–10 gram-meters/m^2
Systemic vascular resistance (SVR) SVR = (MAP–CVP)* 80/CO	900–1400 dynes·s·cm^{-5}
Systemic vascular resistance index (SVRI) SVRI = (MAP–CVP)* 80/CI	1500–2400 dynes·s·cm^{-5}/m^2
Pulmonary vascular resistance (PVR) PVR = (MPAP–PCWP)* 80/CO	150–250 dynes·s·cm^{-5}
Pulmonary vascular resistance index (PVRI) PVRI = (MPAP–PCWP)* 80/CI	250–400 dynes·s·cm^{-5}/m^2

BSA, Body surface area; *CO,* cardiac output; *CVP,* central venous pressure; *HR,* heart rate; *MAP,* mean arterial pressure; *MPAP,* mean pulmonary artery pressure; *PAP,* pulmonary arterial pressure; *PCWP,* pulmonary capillary wedge pressure.

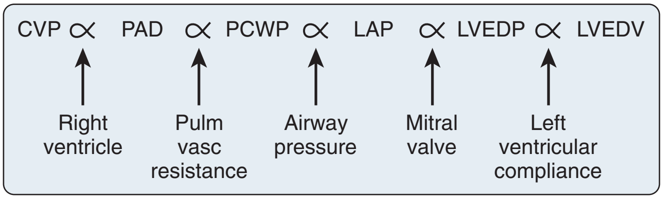

Fig. 10.9 The left ventricular end-diastolic volume (*LVEDV*) is related to left ventricular end-diastolic pressure (*LVEDP*) by the left ventricular compliance. The LVEDP is related to the left atrial pressure (*LAP*) by the diastolic pressure gradient across the mitral valve. The pulmonary capillary wedge pressure (*PCWP*) is related to the LAP by the pulmonary capillary resistance. The pulmonary artery diastolic (*PAD*) pressure is an estimate of the PCWP. The central venous pressure (*CVP*) will reflect the PAD pressure if right ventricular function is normal.

pressure (LAP), which can serve as an estimate of left ventricular preload. The relationship between left ventricular end-diastolic pressure (LVEDP) and left ventricular end-diastolic volume (LVEDV) is described by the left ventricular compliance curve. This nonlinear curve is affected by many factors, such as ventricular hypertrophy and myocardial ischemia. The relationship of these parameters is illustrated in the diagram in Fig. 10.9. In the echo era, left ventricular preload in the surgical unit is better evaluated using TEE measures, such as end-diastolic area or volume. However, elevation of either PCWP or LAP is still a useful criterion in estimating acute exacerbation of heart failure.

The indications for using a PAC are assessing hemodynamic parameters such as loading conditions of the heart (preload, afterload), CO, and indices useful in assessing oxygen delivery and demand (ie, SvO_2). In 2003, the American Society of Anesthesiologists Task Force on Pulmonary Artery Catheterization published updated practice guidelines for PA catheterization. These guidelines emphasized that the patient, surgery, and practice setting had to be considered when deciding on the use of a PAC. Generally, the routine use of PACs is indicated in high-risk patients (eg, ASA IV or V) and high-risk procedures, during which large fluid changes or hemodynamic disturbances are expected. The practice setting is important, because evidence suggests that inadequate training or experience may increase the risk for perioperative complications associated with the use of a PAC. The recommendation is that the routine use of a PAC should be confined to centers with adequate training and experience in the perioperative management of patients with PACs (Box 10.9). The authors of this chapter have composed a list of possible procedural indications (Box 10.10). Contraindications to PA catheterization are summarized in Box 10.11.

Complications

The complications associated with PAC placement include almost all of those of CVP placement. Additional complications that are unique to the PAC are detailed. The ASA Task Force on Pulmonary Artery Catheterization concluded that serious complications attributable to PAC catheterization occur in 0.1% to 0.5% of patients monitored with a PAC.

Arrhythmias

The most common complications associated with PAC insertion are transient arrhythmias, especially premature ventricular contractions. However, fatal arrhythmias have rarely been reported. A positional maneuver entailing 5-degree head-up and

BOX 10.9 *American Society of Anesthesiologists' Practice Guidelines for Pulmonary Artery Catheter Use*

Opinions

- PA catheterization provides new information that may change therapy, with poor clinical evidence of its effect on clinical outcome or mortality.
- There is no evidence from large, controlled studies that preoperative PA catheterization improves outcome regarding hemodynamic optimization.
- Perioperative PAC monitoring of hemodynamic parameters leading to goal-directed therapy has produced inconsistent data in multiple studies and clinical scenarios.
- Having immediate access to PAC data allows important preemptive measures for selected subgroups of patients who encounter hemodynamic disturbances that require immediate and precise decisions about fluid management and drug treatment.
- Experience and understanding are the major determinants of PAC effectiveness.
- PA catheterization is inappropriate as routine practice in surgical patients and should be limited to cases in which the anticipated benefits of catheterization outweigh the potential risks.
- PA catheterization can be harmful.

Recommendations

- The appropriateness of PA catheterization depends on a combination of patient-, surgery-, and practice setting–related factors.
- Perioperative PA catheterization should be considered in patients with significant organ dysfunction or major comorbidities that pose an increased risk for hemodynamic disturbances or instability (eg, ASA IV or V patients).
- Perioperative PA catheterization in surgical settings should be considered based on the hemodynamic risk of the individual case rather than generalized surgical setting–related recommendations. High-risk surgical procedures are those during which large fluid changes or hemodynamic disturbances can be anticipated and procedures that are associated with a high risk of morbidity and mortality.
- Because of the risk of complications from PA catheterization, the procedure should not be performed by clinicians or nursing staff or in practice settings in which competency in safe insertion, accurate interpretation of results, and appropriate catheter maintenance cannot be guaranteed.
- Routine PA catheterization is not recommended when the patient, procedure, or practice setting poses a low or moderate risk for hemodynamic changes.

ASA, American Society of Anesthesiologists; *PA*, pulmonary artery; *PAC*, pulmonary artery catheter.
From American Society of Anesthesiologists. Practice guidelines for pulmonary artery catheterization. Available at: http://www.asahq.org/~/media/sites/asahq/files/public/resources/standards-guidelines/practice-guidelines-for-pulmonary-artery-catheterization.pdf

right lateral tilt was associated with a statistically significant decrease in malignant arrhythmias (compared with the Trendelenburg position) during PAC insertion.

Complete Heart Block

Complete heart block may develop during PA catheterization in patients with preexisting left bundle branch block. This potentially fatal complication is most likely due to electrical irritability from the PAC tip causing transient right bundle branch block as it passes through the right ventricular outflow tract. The incidence of developing right bundle branch block was 3% in a prospective series of patients undergoing PA

BOX 10.10 *Possible Clinical Indications for Pulmonary Artery Catheter Monitoring*

Major procedures involving large fluid shifts or blood loss in patients with:

- Right-sided heart failure, pulmonary hypertension
- Severe left-sided heart failure not responsive to therapy
- Cardiogenic or septic shock or with multiple-organ failure
- Orthotopic heart transplantation
- Left ventricular–assist device implantation

BOX 10.11 *Contraindications for Pulmonary Artery Catheterization*

Absolute Contraindications

- Severe tricuspid or pulmonary stenosis
- Right atrial or right ventricular mass
- Tetralogy of Fallot

Relative Contraindications

- Severe arrhythmias
- Left bundle branch block (consider pacing PAC)
- Newly inserted pacemaker wires, AICD, or CRT
- Severe coagulopathy

AICD, Automatic implantable cardioverter defibrillator; *CRT,* cardiac resynchronization therapy; *PAC,* pulmonary artery catheter.

catheterization. Having an external pacemaker immediately available or using a pacing PAC when placing a PAC in patients with left bundle branch block is imperative.

Endobronchial Hemorrhage

The incidence of PAC-induced endobronchial hemorrhage in one large series was 0.064% to 0.20%. The ASA PAC guidelines report an incidence of 0.03% to 1.5% from the reviewed literature. Regardless of the exact incidence, this rare complication is associated with a high mortality rate. From these reports, several risk factors have emerged: advanced age, female sex, pulmonary hypertension, mitral stenosis, coagulopathy, distal placement of the catheter, and balloon hyperinflation. Balloon inflation in distal PAs is probably accountable for most episodes of PA rupture because of the high pressures generated by the balloon. Hypothermic CPB also may increase risk attributable to distal migration of the catheter tip with movement of the heart and hardening of the PAC. Pulling back the PAC approximately 3 to 5 cm when CPB is instituted is common practice.

Consideration of the cause of the hemorrhage when forming a therapeutic plan is important. If the hemorrhage is minimal and a coagulopathy coexists, then correction of the coagulopathy may be the only necessary therapy. Protection of the uninvolved lung is of prime importance. Tilting the patient toward the affected side and placing a double-lumen endotracheal tube, as well as other lung-separation maneuvers, should protect the contralateral lung. Strategies proposed to stop the hemorrhage include the application of PEEP, the placement of bronchial blockers, and pulmonary resection. The clinician is obviously at a disadvantage unless the site of hemorrhage is known. A chest radiograph will usually indicate the general location of the lesion. Although the cause of endobronchial hemorrhage may be unclear, the bleeding site must be unequivocally located before surgical treatment is attempted. A small amount of radiographic contrast dye may help pinpoint the lesion if active hemorrhage is present. In severe hemorrhage and with recurrent bleeding, transcatheter coil embolization has been used and may emerge as the preferred treatment method.

Pulmonary Infarction

Pulmonary infarction is a rare complication of PAC monitoring. An early study suggested that a 7.2% incidence of pulmonary infarction was reported with PAC use. However, continuously monitoring the PA waveform and keeping the balloon deflated when not determining the PCWP (to prevent inadvertent wedging of the catheter) were not standard practice at that time. Distal migration of PACs may also occur intraoperatively as a result of the action of the RV, uncoiling of the catheter, and softening of the catheter over time. Inadvertent catheter wedging occurs during CPB because of the diminished right ventricular chamber size and retraction of the heart to perform the operation. Embolization of thrombus formed on a PAC also could result in pulmonary infarction.

Catheter Knotting and Entrapment

Knotting of a PAC usually occurs as a result of coiling of the catheter within the RV. Insertion of an appropriately sized guidewire under fluoroscopic guidance may aid in unknotting the catheter. Alternatively, the knot may be tightened and withdrawn percutaneously along with the introducer if no intracardiac structures are entangled. If cardiac structures, such as the papillary muscles, are entangled in the knotted catheter, then surgical intervention may be required. Sutures placed in the heart may inadvertently entrap the PAC. Reports of such cases and the details of the percutaneous removal have been described.

Valvular Damage

Withdrawal of the catheter with the balloon inflated may result in injury to the tricuspid or pulmonary valves. Placement of the PAC with the balloon deflated may increase the risk of passing the catheter between the chordae tendineae. Septic endocarditis has also resulted from an indwelling PAC.

Pacing Pulmonary Artery Catheters

Electrode-coated PACs and pacing wire catheters are available commercially. The possible indications for placement of a pacing PAC are shown in Box 10.12.

The multipurpose PAC (Edwards Lifesciences Corp., Irvine, CA) contains three atrial and two ventricular electrodes for atrial, ventricular, or AV sequential pacing. The intraoperative success rates for atrial, ventricular, and AV sequential capture have been reported as 80%, 93%, and 73%, respectively.

The Paceport and A-V Paceport PA catheters (Edwards Lifesciences Corp., Irvine, CA) have lumens for the introduction of a ventricular wire or both atrial and ventricular wires for temporary transvenous pacing. The success rate for ventricular and AV capture with Paceport PACs is higher, compared with electrode-pacing PACs.

BOX 10.12 ***Indications for Perioperative Placement of Pacing Pulmonary Artery Catheters***

Sinus node dysfunction or symptomatic bradycardia
Hemodynamically relevant second-degree (Mobitz II) atrioventricular block
Complete (third-degree) atrioventricular block
Need for atrioventricular sequential pacing
Left bundle branch block

Mixed Venous Oxygen Saturation Catheters

Monitoring the $SvO2$ is a means of providing a global estimation of the adequacy of oxygen delivery relative to the needs of the various tissues (oxygen supply-demand ratio). The formula for SvO_2 calculation can be derived by modifying the Fick formula and assuming that the effect of dissolved oxygen in the blood is negligible:

$$SvO_2 = SaO_2 - \frac{\dot{V}O_2}{CO \cdot 1.34 \cdot Hb}$$

A decrease in the SvO_2 can indicate one of the following situations: decreased CO, increased oxygen consumption, decreased arterial oxygen saturation, or decreased hemoglobin (Hb) concentration. To measure SvO_2 in the laboratory, blood is aspirated from the distal port of the PAC slowly, so as not to contaminate the sample with oxygenated alveolar blood.

The addition of fiberoptic bundles to PACs has enabled the continuous monitoring of SvO_2 using reflectance spectrophotometry. The catheter is connected to a device that includes a light-emitting diode and a sensor to detect the light returning from the PA. SvO_2 is calculated from the differential absorption of various wavelengths of light by the saturated and desaturated Hb. The values obtained with various fiberoptic catheter systems showed good agreement with in vitro (co-oximetry) SvO_2 measurements.

CARDIAC OUTPUT MONITORING

The CO is the amount of blood delivered to the tissues by the heart each minute. This measurement reflects the status of the entire circulatory system, not just the heart, because it is governed by autoregulation from the tissues. The CO is equal to the product of the SV and the HR. Preload, afterload, HR, and contractility are the major determinants of the CO.

Thermodilution

Intermittent Thermodilution Cardiac Output

The thermodilution method, using the PAC, is the most commonly used method at present for invasively measuring CO in the clinical setting. With this technique, multiple CO measurements can be obtained at frequent intervals using an inert indicator and without blood withdrawal. A bolus of cold fluid is injected into the RA, and the resulting temperature change is detected by the thermistor in the PA. When a thermal indicator is used, the modified Stewart–Hamilton equation is used to calculate CO:

$$CO = \frac{V(T_B - T_I) \times K_1 \times K_2}{\int_0^\infty \Delta T_B(t)dt}$$

in which CO is the cardiac output (L/min), V is the volume of injectate (mL), T_B is the initial blood temperature (degrees Celsius), T_I is the initial injectate temperature (degrees Celsius), K_1 is the density factor, K_2 is the computation constant, and $\int_0^\infty \Delta T_B(t)dt$ is the integral of blood temperature change over time.

A computer that integrates the area under the temperature versus time curve is used to perform the calculation. CO is inversely proportional to the area under the curve.

The temperature-versus-time curve is the crux of this technique, and any circumstances that affect it have consequences for the accuracy of the CO measurement. Specifically, anything that results in less "cold" reaching the thermistor, more "cold" reaching the thermistor, or an unstable temperature baseline will adversely affect the accuracy of the technique. Less "cold" reaching the thermistor would result in overestimation of the CO, which could be caused by a smaller amount of indicator, an indicator that is too warm, a thrombus on the thermistor, or partial wedging of the catheter. Conversely, underestimation of the CO will occur if excessive volume of injectate or injectate that is too cold is used to perform the measurement. In patients with large intracardiac shunts, PAC-derived thermodilution CO is not recommended for accurate CO measurement. Box 10.13 lists common errors in PAC thermodilution CO measurements.

Continuous Thermodilution Cardiac Output

Pulmonary arterial catheters with the ability to measure CO continuously were introduced into clinical practice in the 1990s. The method that has gained the

BOX 10.13 ***Common Errors in Pulmonary Artery Catheter Thermodilution Cardiac Output Measurements***

Underestimation of True Cardiac Output

- Injectate volume greater than programmed volume (typically 10 mL)
- Large amounts of fluid administered simultaneous to cardiac output measurement (rapid infusions should be stopped)
- Injectate colder than measured temperature injectate (injectate temperature probe next to heat-emitting hardware instead of injectate fluid)

Overestimation of True Cardiac Output

- Injectate volume less than programmed volume
- Injectate warmer than measured temperature injectate

Other Considerations

- Surgical manipulation of the heart
- Fluid administration from aortic cardiopulmonary bypass cannula
- Arrhythmias

most clinical use functions by mildly heating the blood. Good correlations exist between this method and other measures of CO. Unfortunately, the correlation with CO measurements using the intermittent thermodilution method is inconsistent, particularly with rapidly changing hemodynamics; for example, in the initial phase after separating from CPB. In contrast, an excellent correlation exists between intermittent and continuous CO measurements obtained in more physiologically stable periods. Perhaps the reason for this observation lies in the unstable thermal baseline after hypothermic CPB.

CORONARY SINUS CATHETERIZATION

In some centers, an endovascular CS catheter is placed to enable the administration of retrograde cardioplegia during minimally invasive cardiac surgical procedures. It is usually the responsibility of the cardiac anesthesiologist to place the CS catheter via the right IJV while being guided by TEE and fluoroscopy. The CS pressure and waveform can be measured during insertion and cardioplegia infusion. This procedure raises a number of issues, including how deep to place the catheter and what pressures and flows to use with the administration of the cardioplegia. Retrograde cardioplegia flow rate is usually set at 150 to 200 mL/min with CS pressure over 30 mm Hg.

The insertion of the CS catheter can be difficult even with TEE and fluoroscopic monitoring. A modified bicaval view at approximately 110 degrees allows visualization of the catheter from the SVC to the CS. After the catheter enters the CS, its final position is usually guided by fluoroscopy. The balloon is then inflated while looking for a change in the pressure tracing from a typical venous pressure tracing to a pulsatile tracing attributable to the transmission of the pressure back from the left ventricle (ventricularizaton).

SUGGESTED READINGS

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