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Complications of invasive monitoring

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This chapter discusses the complications of invasive hemodynamic monitoring, which are defined here as central venous pressure (CVP), pulmonary artery (PA), and peripheral arterial catheters. The perspective is that of the anesthesiologist performing these procedures in the operating room or intensive care unit. Accordingly, chronic venous catheterization, which is usually performed by a surgeon, is not specifically addressed. Many possible complications may result from any invasive medical procedure, though they occur rarely. This chapter emphasizes the most common and most clinically significant problems and some methods for avoidance and treatment. It is not intended to be an exhaustive catalogue of every reported complication.

Central access

The first step in placing a CVP or PA catheter is to gain access to the central circulation. Although femoral or antecubital veins are sometimes used, most central lines are inserted in the internal jugular (or occasionally the external jugular) or subclavian veins. Immediate problems that can occur are mainly pneumothorax, damage to veins, and damage to arteries. A classic monograph on central venous catheterization by Rosen, Latto, and Ng contains an extensive review of techniques and complications of central venous access and is highly recommended [1].

Pneumothorax

Pneumothorax is a particularly troublesome problem in the operating room because most patients are subjected to positive pressure ventilation and the risk for tension pneumothorax. Diagnosis of pneumothorax may be delayed because of the many other common causes of hypotension or hypoxemia during general anesthesia that may confuse the diagnosis. Placement of a chest tube may be complicated by the competing logistics of an ongoing surgical procedure.

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The incidence of pneumothorax in larger series of subclavian vein catheterization ranges from 0.3% to 3.0% [1]. The incidence of pneumothorax from internal jugular catheterization is essentially 0%, except for approaches that start very low in the neck (just above the clavicle); for this, an incidence of 0.3% is reported [1]. Not surprisingly, most anesthesiologists choose the internal jugular approach to the central circulation. When a subclavian approach is used in the operating room, consideration should be given to an immediate chest radiograph to verify the absence of pneumothorax. With internal jugular placement, most anesthesiologists would defer the confirmatory chest radiograph until the patient is in the recovery room, given the very low incidence of pneumothorax. However, when the internal jugular vein is approached very low in the neck (just above the clavicle), pneumothorax is more likely than when the approach is higher in the neck (at the apex of the triangle formed by the two heads of the sternocleidomastoid muscle), and care should be taken not to point the needle toward the apex of the lung during insertion.

Damage to veins

The right internal jugular vein is preferred to the left when possible. The left-sided approach is more likely to result in injury to the left innominate vein, the superior vena cava, or the thoracic duct. The left innominate vein crosses the left internal jugular vein at a right angle, posing the risk for perforation of the innominate vein, particularly by rigid devices such as a vein dilator or introducer sheath. A large puncture or tear in a major intrathoracic vein can produce exsanguinating hemorrhage. The innominate vein and the subclavian vein are relatively difficult to access surgically if repair is needed. This is a potentially fatal complication, so avoidance is critical. The first step in avoidance is to use the right internal jugular vein rather than the left because the right internal jugular generally enters the superior vena cava in a relatively direct fashion, without the abrupt bends encountered on the left side. If the left internal jugular vein is used, care should be taken not to insert anything stiff, such as a vein dilator or an introducer sheath, beyond the internal jugular vein. A flexible CVP catheter, placed over a suitable guidewire, should not ordinarily cause a problem. If an introducer sheath must be placed in the left internal jugular vein, it may be preferable to use an exceptionally short introducer sheath (readily available from commercial sources) that will not pass beyond the internal jugular vein. Alternatively, a standard length introducer sheath may be passed into the left internal jugular vein for a few centimeters, leaving the remainder outside the patient; the short introducer sheath is the more elegant approach because it is more easily fastened to the skin and is less likely to be dislodged.

The left internal jugular (or left subclavian) approach has yet another potential problem. The CVP catheter will need to make approximately a 90° turn on reaching the superior vena cava to lie parallel to the walls of the cava, pointing toward the right atrium. If the catheter is not advanced far enough to make the 90° turn, the tip may point into the lateral wall of the cava., which can eventually

result in erosion and perforation, a potentially lethal complication. This is not generally a problem with the right internal jugular approach because the catheter tip tends to enter the vena cava parallel to the wall of the cava.

A problem unique to the left-sided approach is injury to the thoracic duct, which terminates variably in the left internal jugular vein, the left subclavian vein, or the left innominate vein. The duct may be perforated in the process of placing a CVP catheter, and rarely the duct may actually be cannulated. Chylothorax and chylopericardium may result, and infusion of fluids into the thoracic duct may produce cardiac tamponade or constrictive pericarditis by retrograde flow into the pericardial lymphatics [2].

Persistent left superior vena cava is the most common thoracic venous anomaly. The left superior vena cava is a normal counterpart to the right superior vena cava, normally disappearing during embryologic development. The persistent left superior vena cava drains into the right atrium through the coronary sinus. Diagnosis is often made by the characteristic echocardiographic appearance of a markedly dilated coronary sinus. A PA or CVP catheter placed through the left internal jugular vein or the left subclavian vein may enter the persistent left superior vena cava. Although not a complication per se, the chest radiograph of the CVP or PA catheter in the persistent left superior vena cava will reveal an unusual appearance [3].

Damage to arteries

Puncture of the carotid or subclavian artery with a small needle is unlikely to cause a significant problem. Puncture of the carotid artery during internal jugular catheterization is common and occurs with an incidence of approximately 2% [1]. Because arteries, and occasionally nerves [4] or other structures, can be punctured inadvertently, common sense suggests that the smallest practical needle size be used for central venous access. Two commonly used needle and wire combinations are used for central venous access with the Seldinger technique (wire through needle): a 0.035-inch wire through an 18-gauge thin-wall needle or a 0.025-inch wire through a 20-gauge thin-wall needle. Both function effectively for central venous catheterization. The 20-gauge needle is substantially smaller and is preferred by the author when available. When a 0.035-inch wire is used, the author typically uses a smaller ''finder'' needle (eg, 25 gauge) to locate the vessel to avoid multiple sticks with the relatively large 18-gauge needle.

An important caveat for choosing a wire for central venous catheterization is that the tip of the CVP catheter, or the tip of the vein dilator of an introducer sheath, should exactly match the wire. A 0.035-inch wire will typically not pass through a CVP catheter or introducer sheath intended for a 0.025-inch wire. A 0.025-inch wire will pass through a CVP catheter or an introducer sheath intended for a 0.035-inch wire, but there will be a small gap between the wire and the tip of the device. Tissue may become jammed in the gap between the wire and tip of the device and prevent the device from advancing smoothly over the wire and into the vein.

Accidental insertion of a large CVP catheter or, worse, a pulmonary artery catheter introducer sheath into the subclavian or carotid artery is a potentially serious problem [5,6]. A relatively large hole may result in the artery, or the artery may be torn, resulting in significant bleeding when the device is removed. There are two major alternatives for dealing with this situation. The first is simply to remove the device, apply pressure to the site, and hope for the best. Because arteries are relatively thick walled, the entry site, if smooth, may seal with little or no bleeding. Although there are no large series of cases from which to judge the likelihood that the artery will seal itself, anecdotal reports show that this outcome is certainly possible. Unfortunately, there is the possibility that instead of sealing itself, the artery will bleed profusely. This leads to the second alternative, which is to call a surgeon to remove the catheter from the artery with direct visualization of the wall of the artery and surgical closure of the arteriotomy. The disadvantage of this approach is that it requires an operation. An intermediate approach would be to remove the catheter and apply pressure, with a surgeon available to intervene should the artery continue to bleed. Consideration should also be given to the possibility that if the catheter is left in the artery for very long, the artery may become occluded by clot, which may produce its own set of consequences. After extraction of the catheter, by whatever method, ultrasound examination of the artery with color flow Doppler may be advisable to rule out significant flow disturbance in the artery. Retrograde dissection involving the subclavian and innominate arteries and the ascending aorta has been reported after accidental catheterization of the right carotid artery [7].

By far the best strategy is to avoid placing a large venous catheter into an artery by mistake. Several methods have been used to differentiate a vein from an artery, including the color of the blood, the force and pulsatility of blood return in the needle, blood gas analysis, and the pressure waveform. Blood color and force and pulsatility of blood return, though useful signs, are notoriously unreliable. Blood gas analysis, particularly comparison with a definite arterial sample, is reliable but too time consuming to be practical in most settings. Display of the pressure waveform probably represents the best combination of efficiency and reliability [8]. In the author's practice the pressure waveform is displayed routinely during central venous catheterization by interposing a T-shaped connector between the needle and the syringe that is connected to a length of pressure tubing leading to a transducer. After aspirating blood, the pressure waveform is displayed on the monitor, and the characteristic venous (or occasionally arterial) waveform is identified by inspection. The T-shaped connector allows the waveform to be displayed without having to first disconnect the syringe and connect pressure tubing to the needle, with the attendant risk for dislodging the needle from the vessel.

Another method for avoiding arterial catheterization is to use ultrasound (eg, Site-Rite) to identify the vein and artery [9]. This is particularly valuable in difficult catheterizations when the anatomy is abnormal or is not easily identified. In the author's practice, ultrasound is not used routinely but is readily available whenever catheterization is difficult. Common sense suggests that this approach

is safer than making large numbers of needle sticks searching for the vein, and it certainly can reduce the time required for the procedure [10].

Cardiac complications

In 1996 we reviewed 3533 claims in the ASA Closed Claims Project [11] database and found 48 claims related to central venous catheters or pulmonary artery catheters (Table 1) [12]. There were 18 fatalities. Only 2 of the 48 claims were related to pulmonary artery catheters. Injury to arteries (other than the pulmonary artery) and veins, as discussed above, accounted for 13 of the 48 claims. Catheter or wire embolism accounted for 12 of the 48 claims. Perforation of the heart with pericardial tamponade accounted for 11 of the 48 claims. Ten of 11 patients with pericardial tamponade died.

Manufacturers' package inserts often contain explicit and detailed warnings related to perforation of the heart and pericardial tamponade. The Food and Drug Administration has also taken an interest [13]. Numerous reports in the literature reflect the seriousness of this problem [14–20]. The typical scenario that has been reported involves a CVP catheter with the tip inside the right atrium or abutting the wall of the superior vena cava at an acute angle. With repeated motion of the tip against the heart or cava, perforation may occur. Depending on the location of the perforation, blood or intravenous fluid may then enter the mediastinum or pericardium. Blood or intravenous fluid in the pericardium may result in pericardial tamponade. Typically this complication occurs after surgery, after the catheter has been in place for hours or days, though it may occur immediately with catheter placement.

Avoidance of injury to the right atrium depends on keeping the CVP catheter outside the heart. Chest x-rays should be obtained and carefully reviewed as soon as possible after placement of the catheter. Langston [21] reported that of 300

Table 1
Central Line Complications From the ASA Closed Claims Project Database [11][a]

Complication	Total	Fatalities
Cardiac tamponade	11	10
Wire or catheter embolism	12	0
Vascular injuries (non-pulmonary artery)	13	5
Hemothorax	6	4
Hydrothorax	3	1
Carotid artery injury	3	0
Subclavian a. aneurysm	1	0
Pulmonary artery rupture	2	2
Pneumothorax	7	1
Air embolism	2	2
Fluid extravasation in neck	1	0
Total	48	20

[a] These data were recently updated. See Bowdle TA [12]. Central line complications from the ASA Closed Claims Project. American Society of Anesthesiologists Newsletter 1996;60:222–5.

central lines, subsequent chest x-ray showed that 48% were improperly positioned. Trigaux et al [22] published an instructive collection of radiographs of malpositioned catheters. For catheters placed in the operating room, x-rays are usually obtained postoperatively in the recovery room or the intensive care unit. The x-ray should show the catheter in the vena cava, outside the cardiac silhouette. The catheter should be relatively parallel to the walls of the cava, and the tip should not abut the wall of the cava [23]; the latter is particularly likely with left-sided access, as described above. Monitoring the pressure waveform from the CVP catheter may also be useful; the pressure waveform from the superior vena cava and the right atrium are indistinguishable, but the waveform from the right ventricle is easily identified. Intravascular electroencephalography is a quick and accurate method for locating the tip of the catheter with respect to the sinus node. Commonly used for positioning a CVP catheter for air aspiration during sitting craniotomy, intravascular electrocardiography is seldom used except during neuroanesthesia.

Catheter, wire, and air embolism

Catheter or wire embolism accounted for 12 of the 48 claims related to central lines in the ASA Closed Claims Project database in 1996 [12]. These events are usually caused by withdrawing a wire or a catheter through a needle, resulting in shearing of the wire or catheter on the bevel of the needle. Because most CVP catheters are placed over a wire rather than through a needle, shearing a wire is the most common concern. The standard recommendation is to avoid withdrawing a wire or a catheter through a needle. If the wire or catheter cannot be advanced the desired distance because of an obstruction, the needle and wire or catheter should be withdrawn together. In practice, a skilled operator may choose to carefully withdraw a wire from a needle if there is absolutely no resistance; however, there is probably some risk involved in this maneuver.

Air embolism occurs most commonly when a catheter becomes accidentally disconnected and is open to the atmosphere, particularly when the patient is sitting up. Air embolism may also occur during insertion or removal of catheters. Interestingly, the ASA Closed Claims Project database contained 2 fatal cases of air embolism [9]. One review article discusses an astonishing 28 cases of cerebral air embolism associated with catheters, including 6 fatalities [24]. Cerebral air embolism is particularly likely to occur in patients who are sitting up because air bubbles reaching the systemic circulation, through a cardiac septal defect or an intrapulmonary shunt, tend to float upward and to enter the carotid arteries. PA catheter introducer sheaths present a subtle hazard. When a PA catheter is removed from the sheath, the hemostasis valve, which normally forms a tight seal around the catheter, may be stretched open and may allow air to enter. There have been several reports of significant air embolism by this mechanism [25,26]. To prevent air entry into an introducer sheath that does not contain a PA catheter, the opening in the sheath should be occluded; this usually involves placing a cap over the opening, which has been designed by the manufacturer for this purpose.

Infection

Infection from CVP, PA, and arterial catheters continues to be a significant problem. Issues surrounding the prevention and management of these infections include methods of skin preparation, antimicrobial coatings on the catheters, dressings, and suitable intervals and methods for exchanging catheters in patients who require ongoing access. The 2 major categories of infection are local infection and bacteremia. Local infection includes inflammation or purulence at the insertion site or colonization of the catheter tip. Colonization is defined as greater than 15 colonies growing from a semiquantitative roll-plate culture. Bacteremic catheter-related infection is diagnosed when clinical or microbiologic evidence implicates the catheter as the source of bacteremia, isolation of the same organism from blood cultures and the catheter tip or pus from the insertion site, or clinical sepsis that does not resolve until the catheter is removed [27,28].

Hampton and Sheretz [29] evaluated the risk for local infection by pooling data from 25 prospective trials. The risk using peripheral intravenous catheters was 1.3% per day, using systemic arterial catheters was 1.9% per day, and using CVP catheters was 3.3% per day. However, the incidence was not linear, and the rates increased dramatically after 3 days [28]. Pulmonary artery catheters were found to have a rate of infection of less than 1% until day 4, when the rate increased exponentially [30].

Saint and Matthay [31] reviewed the literature and made recommendations for preventing catheter-related infections. They found convincing evidence that chlorhexidine gluconate is the agent of choice for skin disinfection before insertion. In randomized prospective trials, chlorhexidine gluconate was significantly better than povidone-iodine. Gauze dressings appear to be associated with lower rates of infection than transparent dressings, but the evidence is conflicting, and transparent dressings facilitate inspection of the insertion site. Central venous triple-lumen catheters impregnated with antibacterial agents may have lower rates of infection and should be considered for patients at high risk for infection. CVP, PA, and arterial catheters should be changed only when there is evidence of infection. Although the incidence of infection increases dramatically after 3 days, routine catheter exchange has been shown in randomized, prospective trials not to reduce the risk for infection. This applies to catheter exchange over a guidewire and to catheter replacement at a new site.

Thrombosis

All catheter materials are thrombogenic to varying degrees and can result in thrombosis of the vessel in which the catheter is inserted. The incidence of thrombosis with subclavian CVP catheters is reported to be as high as 67%, whereas the incidence with internal jugular CVP catheters is lower, approximately 10% [32]. The clinical importance of thrombosis associated with CVP catheters is not really clear. Although upper extremity venous thrombosis has generally not been associated with pulmonary thromboembolism, a recent study [33] suggested that upper extremity venous thrombosis might pose a greater risk

for pulmonary thromboembolism than previously thought. Fontes and Barash [32] recently reviewed the problem of venous thrombosis associated with CVP catheters and suggested that anticoagulant drugs of various types might be considered to reduce the incidence of thrombosis. PA catheters are also susceptible to thrombus formation. Hoar [34] reported that non-heparin–bonded PA catheters are associated with thrombus extending from the insertion site to the right side of the heart and pulmonary artery, with an incidence approaching 100%. Heparin bonding of PA catheters appears to retard the thrombotic process [35], but little heparin may remain after 24 hours [36]. Incidentally, care should be taken to avoid placing a heparin-bonded PA catheter in a patient with heparin-induced thrombocytopenia. Factors affecting thrombus formation on PA catheters have been reviewed [37].

Pulmonary artery catheters

Unique complications associated with the PA catheter are arrhythmias, knotting of the PA catheter, pulmonary infarction, and pulmonary artery perforation. Of these, pulmonary artery perforation is by far the most serious; the reported fatality rate is approximately 50% [38].

Arrhythmias

Transient atrial and ventricular arrhythmias are expected during placement of a PA catheter because of the mechanical irritation caused by the catheter. Entry of the catheter into the right ventricular outflow tract is particularly likely to produce ventricular ectopy that typically disappears when the catheter enters the pulmonary artery. These transient arrhythmias, though unnerving at times, are usually harmless. However, sustained ventricular tachycardia or ventricular fibrillation occurs rarely, especially in patients with ischemic myocardium. Accordingly, facilities for cardioversion or defibrillation should be immediately available. Some anesthesiologists administer lidocaine before placement of a PA catheter in patients at particular risk for ventricular arrhythmias, but the efficacy of this is unknown. Transient right bundle branch block can occur, presumably from mechanical effects of the catheter on the conduction system. In the presence of preexisting left bundle branch block, passage of a PA catheter can produce transient complete heart block. This is a relatively rare event, but the author has observed this on one occasion. Before placing a PA catheter in a patient with left bundle branch block, thought should be given to the availability of a method to pace the heart in the event of complete heart block. The simplest approach is usually transcutaneous pacing.

Pulmonary artery perforation

Injury to the pulmonary artery is the most feared complication associated with the PA catheter. Pulmonary artery perforation appears to occur sporadically, with

an incidence of less than 1%. In their retrospective study of 6245 patients receiving PA catheters for cardiac and noncardiac surgery, Shah et al found pulmonary artery rupture in 4 (0.064%) patients; one of these died from uncontrolled hemorrhage [39]. Boyd et al [40] reviewed PA catheter placement in 500 surgical and nonsurgical patients and found one (0.2%) nonfatal case of pulmonary artery injury. Advanced age and pulmonary hypertension are said to be risk factors; however, this is of little practical use because these are just the patients in whom pulmonary artery catheters are frequently useful. Hypothermia causes stiffening of polyvinylchloride catheters and may make pulmonary artery injury more likely [37,41]; the practical implication of this would be to avoid manipulation of a PA catheter during hypothermic cardiopulmonary bypass. Balloon inflation has been associated with arterial rupture in some patients, leading to the suggestion that the balloon be inflated for measurement of pulmonary artery wedge pressure only when absolutely necessary. Other than balloon inflation, no particular operator- or technique-related factors seem to be implicated in pulmonary artery perforation, suggesting that bad luck may override skill level. Of course, this provides little comfort to those who place these devices.

Consideration of the anatomy and pathology of pulmonary artery injury is useful for understanding the various clinical presentations. After laceration of the vessel wall, hemorrhage into the pulmonary parenchyma occurs. Typically, blood enters the airway and hemoptysis develops. Rupture of the visceral pleura may result in hemothorax, which may also be accompanied by pneumothorax. Interestingly, a case of retrograde dissection and rupture of the pulmonary artery into the contralateral lung has been reported [42]. Pulmonary artery pseudoaneurysms may develop as layers of thrombus compress adjacent lung parenchyma [43]. These pseudoaneurysms are unstable and prone to rupture. Rupture of a pseudoaneurysm may be delayed, with reported cases ranging from 33 hours to 7 months [43]. A high index of suspicion may be required to make the diagnosis of a pseudoaneurysm after an episode of self-limited hemoptysis in a patient with a PA catheter. Chest radiographs may contain the only clue to the presence of a pseudoaneurysm in patients without hemoptysis or other signs of hemorrhage. Yellin et al [44] recommended that contrast-enhanced computed tomography or pulmonary angiography be performed in all cases of self-limited hemoptysis possibly related to a PA catheter [44]. Coil embolization may be the best treatment of pulmonary artery pseudoaneurysm [45,46].

Urschel and Myerowitz [38] reviewed 30 published cases of pulmonary artery rupture associated with PA catheters in patients undergoing cardiac surgery. The right pulmonary artery was injured in 93% of patients. The presenting sign was airway hemorrhage in 29 of 30 patients. In 19 patients, hemorrhage presented during weaning from bypass. Overall mortality rate was 41%. The authors recommended aggressive treatment with surgery or radiologic intervention because conservative treatment was associated with a high incidence of recurrent, fatal hemorrhage. A treatment protocol was presented that began with isolation of the lung by a double lumen tube and bronchoscopy. The pleura were then opened for evaluation of the injury. Central arterial injury was repaired directly. Extensive

parenchymal hemorrhage with visceral pleural rupture was treated by lobectomy, if pulmonary reserve was adequate. Patients with minimal parenchymal hemorrhage and intact visceral pleura or with inadequate pulmonary reserve for lobectomy were treated by continued lung isolation, PEEP, and angiography with embolization.

Avoidance of pulmonary artery injury probably revolves around placing pulmonary artery catheters as infrequently as possible, exercising caution not to float the catheter into a distal position in the pulmonary artery, and minimizing balloon inflation after the catheter is in place. In the author's practice of cardiac anesthesia, the key information gained from the PA catheter is often the pulmonary artery systolic pressure, diastolic pressure, CVP, and cardiac output. Pulmonary artery wedge pressure is usually similar to pulmonary artery diastolic pressure (in patients with high pulmonary vascular resistance, there may be a large gradient between the pulmonary artery diastolic and the pulmonary artery wedge pressure). Therefore, we do not always float the catheters into a wedge position, and we avoid inflating the balloon unless we specifically find the wedge pressure to be of value in a particular patient.

Rupture of the pulmonary artery usually results in hemoptysis; rarely, rupture into the pleural space may not produce obvious pulmonary parenchymal bleeding. A prompt response is necessary to minimize the chance of catastrophe. Therapeutic measures to be considered include placement of a double lumen tube to protect the lung opposite the hemorrhage, inflation of the balloon of the PA catheter to obstruct blood flow to the ruptured artery, and application of positive end expiratory pressure to tamponade the bleeding site. Definitive therapy may be surgical, requiring thoracotomy and repair of the bleeding site, or radiologic, with placement of the various transvascular hemostatic devices available to the interventional radiologist [47].

Catheter knotting

PA catheters can become knotted around papillary muscle, chordae tendineae, and pacing leads. PA catheters may also be accidentally ensnared in sutures during cardiac surgery, particularly at the venous cannulation site. Removal of the knotted or sutured PA catheter may require interventional radiology or even surgery in extreme cases. The author does not regard the presence of pacing leads as necessarily a contraindication to placement of a PA catheter. Permanent pacer leads are typically firmly attached to the myocardium after they have been in place for a period of time and are unlikely to be dislodged by a PA catheter. However, knotting is a rare problem, and occasionally pacer leads may cause passage of a PA catheter to be technically difficult. Fluoroscopy may be useful in maneuvering a PA catheter around a pacer lead.

Pulmonary artery catheters and outcome

Clinicians have debated the appropriate indications for the use of PA catheters for many years. Generally the evidence for the effectiveness of PA catheter

monitoring is weak and is based on retrospective studies or relatively small prospective studies that lack randomized controls [47–52]. Accordingly, proposals for strictly limiting the use of PA catheters have existed for at least 2 decades. For example, in the case of coronary artery bypass surgery, Loop [53] proposed in 1983 that PA catheter use be limited to patients with severely impaired left ventricular function. Bashein [47] reported in 1985 on a retrospective analysis of 698 consecutive patients with preserved ventricular function undergoing coronary artery bypass surgery with CVP monitoring instead of PA catheter monitoring. Outcomes in these patients did not appear to be adversely affected by the omission of a PA catheter [43,47]. Tuman et al [52] studied 1094 patients in a prospective but nonrandomized study of coronary artery bypass and found little difference between outcome with a CVP catheter and outcome with a PA catheter. These authors all focused on the question of the usefulness of PA catheters and weighed usefulness against known mechanical complications of PA catheters and financial cost.

More recently, the discussion has taken an unexpected turn because of studies suggesting that pulmonary artery catheters somehow result in worse outcomes for patients, independent of the mechanical complications directly related to PA catheters [54,55]. The mechanism by which PA catheters would negatively affect the overall outcome of critically ill patients is unclear. Misinterpretation of data from PA catheters, resulting in inappropriate therapies, is a hypothetical possibility. Connors et al [50] reported in 1996 on 5735 patients in an intensive care unit using a case-matching analysis with adjustment for treatment selection bias. They found increased mortality and increased use of resources when patients were monitored with PA catheters [50]. Connors' article was accompanied by a dramatic editorial by Dalen and Bone [52], who called for the FDA to issue a moratorium on the use of PA catheters until suitable randomized clinical trials could be carried out to confirm or refute the findings of Connors et al [54]. Ramsey et al [55] subsequently reported a retrospective analysis of 13,907 patients undergoing coronary artery surgery, with risk adjustment, again finding an apparently worsened outcomes for patients monitored with PA catheters [55].

Several major organizations issued consensus statements on pulmonary artery catheterization in response to the articles by Connors et al [54] and Dalen and Bone [56], including the Society of Critical Care Medicine [57], the American College of Cardiology [58], and the National Heart, Lung, and Blood Institute (NHLBI) with the FDA [59]. These documents are valuable resources for anyone interested in PA catheter monitoring. They did not support a moratorium on the use of PA catheters; however, the NHLBI/FDA statement does advocate prospective, randomized clinical trials to further evaluate the safety and efficacy of PA catheters. Interestingly, the NHLBI/FDA statement gave "urgent" priority to the development of a standardized educational program to improve the skill level of health care providers in using PA catheters. This was in response to studies showing deficiencies in the performance of physicians and nurses using PA catheters. A recent report of the failure of an educational program to improve

the interpretation of pulmonary artery occlusion pressure tracings suggests that raising the skill level of health care providers may not be easy [60].

Arterial catheterization

Arterial catheterization is the most common form of invasive monitoring, and it appears to be safe, especially in comparison with CVP and PA catheter monitoring. However, studies related to vascular insufficiency have appeared repeatedly in the literature. In general, review of these studies suggests that vascular insufficiency is a rare complication, at least in patients without peripheral vascular disease such as Raynaud or thromboangiitis obliterans, which affect small arteries.

Vascular insufficiency

The most common site of arterial catheterization by anesthesiologists is the radial artery. Several large series have demonstrated that vascular insufficiency from radial artery catheterization is extremely rare. The classic paper in this area, published in 1983 by Slogoff and Keats [61], prospectively documented the experience with radial artery catheterization in 1699 patients at the Texas Heart Institute. Despite partial or complete radial artery occlusion after decatheterization in more than 25% of patients, there was no ischemia or disability of the hand. The modified Allen's test was performed on 411 (24%) patients, and results were considered abnormal (greater than 15 seconds for return of perfusion) in 16. The radial artery was cannulated regardless of the results of the Allen's test, and none of the 16 had adverse sequelae. Interestingly, the ulnar artery was cannulated in 22 patients after multiple punctures of the ipsilateral radial artery, again with no adverse sequelae. Slogoff and Keats [61] concluded that radial artery catheterization was safe and that the Allen's test was not useful. The description of their clinical experience is instructive:

> In our own experience of more than 20 years, ischemia of the hand during or after radial artery cannulation occurred only in patients who had multiple emboli or prolonged circulatory failure with high-dose vasopressor therapy, and ischemia was always present in more than one extremity. . .It is significant that in no report of tissue necrosis after radial artery cannulation did the area of necrosis arise from or remain limited to the tissue uniquely dependent on radial artery blood flow.

Other reports with combined results from several thousand patients support Slogoff and Keats [62,63]. Interestingly, despite the lack of evidence for adverse outcomes, debate continues regarding the advisability of performing the Allen's test or other tests to characterize ulnar circulation before radial catheterization. Dr. Edgar V. Allen devised the Allen's test in 1929 as a method for diagnosing thromboangiitis obliterans [64,65]. With various modifications, the Allen's test has been used subsequently to evaluate the quality of the circulation to the hand

during temporary occlusion of the radial artery to predict whether vascular insufficiency will occur if the circulation from the radial artery is permanently interrupted. Aside from the relevance of this for radial artery catheterization, surgeons are interested in the blood supply to the hand because of operations during which the radial artery is surgically interrupted, as in radial artery harvest for coronary grafting or radial forearm free flaps.

According to Ciria-Llorens and Gomez-Cia [66] there is only one report [67] of acute ischemia of the hand resulting from elevation of a radial forearm flap. Based on this and other evidence, they conclude that "vascular morbidity by reducing the blood supply to the hand is not proven" [66]. They also performed Doppler ultrasound examination of the distal forearm in patients who underwent radial forearm flap surgery. Flow in the anterior interosseous artery increased after surgery, suggesting that the anterior interosseous artery is significant collateral in the absence of the radial artery [66].

Recently, cardiac surgeons have shown renewed interest in the circulation of the hand because of the use of radial artery grafts for coronary artery bypass. A remarkable array of studies have made conflicting claims about the usefulness of various techniques for assessing the circulation of the hand, including the Allen test, Doppler ultrasound, pulse oximetry, digit blood pressure, and color-flow Doppler [68–73]. The authors of these studies have made an implicit assumption that a test with adequate sensitivity and specificity can predict in which patients vascular insufficiency of the hand will develop when the radial artery is harvested. Interestingly, there do not appear to be any outcome studies showing that patients undergoing radial artery harvest actually experience adverse sequelae because of the absence of the radial artery. One case report discusses a patient who had acute ischemia of the hand 2 days after coronary artery bypass with a radial graft [70]. This occurred at the time of onset of atrial fibrillation, and the symptoms and signs of ischemia improved after the restoration of sinus rhythm. Angiography revealed congenital absence of the left ulnar artery, with a large interosseous apparently taking its place. Despite improvement in symptoms and signs, it was elected to revascularize the radial artery with a venous graft [70]. Parenthetically, this patient had normal results of a modified Allen's test before surgery. A discussion appended to report [73] reveals the disconnection between the tests that are used to assess circulation and the clinical outcomes. Part of that discussion follows:

> Surgeon A: Do we have any notion of what the reported incidence of hand ischemia is with radial artery removal? Is this a problem that we need to be concerned about, or is it something that is of minimal consequence?
> Surgeon B: Actually, on my literature search, I have found no cases of reported hand ischemia after radial artery harvesting [the case cited above was probably published after the literature search was done]. . .With the experience we have had with the Allen's test over the many years of using it, we have shown that it has significant false-positive and false-negative rates. I think with the increasing use of the radial artery as a conduit, it is just a matter of time before we see that complication in this population. . .So it is important to have a more objective test. . .

> Surgeon C: Our approach has been simplistic and pragmatic; I personally have done the Allen's test on 731 patients. . .Seven hundred patients did have harvesting of their radial artery based on the Allen's test, and we did not see or experience hand ischemia. . .I am concerned that an excessive number of your patients were denied radial artery harvest on the basis of your screening methods.

Despite the apparent safety of radial catheterization, as described above, the anesthesiologist wanting to hedge bets against rare ischemic or infectious problems is well advised to catheterize the radial artery of the nondominant hand.

Little is known about the safety of radial artery catheterization in patients with peripheral vascular disease, such as Raynaud's or thromboangiitis obliterans, involving the small arteries of the hand. Because these patients may be at greater risk for ischemic complications of radial catheterization, avoidance of arterial catheterization or use of a large artery such as the femoral artery should be considered.

Femoral and brachial arterial lines

Femoral and brachial arterial catheterization are also performed commonly by anesthesiologists. Available evidence suggests that both these routes have a degree of safety similar to radial artery catheterization. Cannulating these larger arteries has a specific advantage for patients undergoing cardiopulmonary bypass because they tend to give more accurate blood pressure measurement after bypass, whereas radial artery catheters, for unknown reasons (often presumed to be vasospasm), frequently are damped and give falsely low blood pressure values [74,75]. Some anesthesiologists believe that brachial catheterization is more likely to produce ischemia than radial catheterization, apparently because of the notion that the collateral circulation at the elbow is poor. However, available evidence does not support this viewpoint. Barnes et al [76] reported that at the University of Iowa, "all patients undergoing open heart surgery [they specifically comment on more than 1000 cases] are monitored during and after operation with brachial arterial percutaneous cannulas. . .Clinically there has been no significant complication as a result of such catheterizations. . ." Frezza and Mezghebe [58] reported on 2119 patients in the ICU with arterial lines. Radial catheterization was most common, followed closely by femoral catheterization, with brachial catheterization accounting for approximately 2%. They found no cases of permanent ischemic injury and an infection rate of less than 1% that did not differ by site of catheterization.

Radial artery pseudoaneurysm

At least 16 cases of pseudoaneurysm formation at the site of an infected radial artery catheter have been reported. These pseudoaneurysms may rupture, so surgical repair is recommended. The most common operation appears to be ligation of the radial artery [77].

Summary

Invasive monitoring in anesthesiology is relatively safe. Arterial catheterization in particular has an extremely low rate of serious complications. Radial, brachial, and femoral artery catheterization sites appear to have similar and low complication rates. CVP and PA catheters are more dangerous and entail potentially fatal complications. The most troublesome complication with CVP catheters is perforation of the heart or cava, which should be avoidable under most circumstances if care is taken to position the catheter properly, outside the heart. Chest radiography should be used to specifically ascertain that the catheter is not in a dangerous location. The most troublesome complication with PA catheters is perforation of the pulmonary artery. This is probably a sporadic problem, and it is not necessarily avoidable by adherence to particular techniques. It should be assumed that hemoptysis in a patient with a PA catheter is caused by perforation of the pulmonary artery until proven otherwise, and it should be treated aggressively.

References

[1] Rosen M, Latto IP, Ng WS. Handbook of percutaneous central venous catheterization. London: WB Saunders; 1981.
[2] Welliver MD, Masoud PJ. Thoracic duct cannulation during central venous catheterization: a case report. Am J Anesthesiol 2001;28:199–202.
[3] Sarodia BD, Stoller JK. Persistent left superior vena cava: case report and literature review. Respir Care 2000;454:411–6.
[4] Martin-Hirsch DP, Newbegin CJ. Right vocal fold paralysis as a result of central venous catheterization. J Laryngol Otol 1995;109:1107–8.
[5] Eckhardt WF, Iaconetti J, Kwon JS, et al. Inadvertent carotid artery cannulation during pulmonary artery catheter insertion. J Cardiothorac Vasc Anesth 1996;10:283–90.
[6] Golden LR. Incidence and management of large-bore introducer sheath puncture of the carotid artery. J Cardiothorac Vasc Anesth 1995;9:425–8.
[7] Applebaum RM, Adelman MA, Kanshuger MS, et al. Transesophageal echocardiographic identification of a retrograde dissection of the ascending aorta caused by inadvertent cannulation of the common carotid artery. J Am Soc Echocardiogr 1997;10:749–51.
[8] Jobes DR, Schwartz AJ, Greenhow DE et al. Safer jugular vein cannulation: recognition of arterial puncture and preferential use of the external jugular route. Anesthesiology 1983;59: 353–5.
[9] Troianos CA, Jobes DR, Ellison N. Ultrasound-guided cannulation of the internal jugular vein. A prospective, randomized study. Anesth Analg 1991;72:823–6.
[10] Randolph AG, Cook DJ, Gonzales CA et al. Ultrasound guidance for placement of central venius catheters: A meta-analysis of the literature. Crit Care Med 1996;24:2053–8.
[11] Cheney FW. The American Society of Anesthesiologists Closed Claims Project: what have we learned, how has it affected practice, and how will it affect practice in the future? Anesthesiology 1999:552–6.
[12] Bowdle TA. Complications from placement of central venous catheters: importance of the chest x-ray. American Society of Anesthesiologists Newletter 1996;60:22–5.
[13] Scott WL. Central venous catheters: an overview of Food and Drug Administration activities. Surg Oncol Clin North Am 1995;4:377–93.
[14] Bar-Joseph G, Galvis AG. Perforation of the heart by central venous catheters in infants: guidelines to diagnosis and management. J Ped Surg 1983;18:284–7.

[15] Brandt RL, Foley WJ, Fink GH, et al. Mechanism of perforation of the heart with production of hydropericardium by a venous catheter and its prevention. Am J Surg 1970;119: 311–6.
[16] Collier PE, Ryan JJ, Diamond DL. Cardiac tamponade from central venous catheters: a report of a case and review of English literature. Angiology 1984;35:595–600.
[17] Jiha JG, Weinberg GL, Laurito CE. Intraoperative cardiac tamponade after central venous cannulation. Anesth Analg 1996;82:664–5.
[18] Maschke SP, Rogove HJ. Cardiac tamponade associated with a multilumen central venous catheter. Crit Care Med 1984;12:611–2.
[19] Scott WL. Complications associated with central venous catheters. Chest 1988;94:1221–4.
[20] Sheep RE, Guiney WB. Fatal cardiac tamponade: occurrence with other complications after left internal jugular vein catheterization. JAMA 1982;248:1632–5.
[21] Langston CH. The aberrant central venous catheter and its complications. Radiology 1971;100: 55–9.
[22] Trigaux JP, Goncette L, Van Beers B, et al. Radiologic findings of normal and compromised thoracic venous catheters. J Thorac Imaging 1994;9:246–54.
[23] Tocino IM, Watanabe A. Impending catheter perforation of superior vena cava: radiographic recognition. Am J Roentgenol 1986;146:487–90.
[24] Heckmann JG, Lang CJ, Kindler K, et al. Neurologic manifestations of cerebral air embolism as a complication of central venous catheterization. Crit Care Med 2000;28:1621–5.
[25] Cohen MB, Mark JB, Morris RW, et al. Introducer sheath malfunction producing insidious air embolism. Anesthesiology 1987;67:573–5.
[26] Hartung EJ, Ender J, Sgouropoulou S, et al. Severe air embolism caused by a pulmonary artery introducer sheath. Anesthesiology 1994;80:1402–3.
[27] Guidelines for prevention of intravascular device-related infections. Am J Infect Control 1996; 24:261–93.
[28] Raad II, Bodey GP. Infectious complications of indwelling cascular catheters. Clin Infect Dis 1992;15:197–208.
[29] Hampton AA, Sheretz RJ. Vascular-access infections in hospitalized patients. Surg Clin North Am 1988;68:57–71.
[30] Mermel LA, Maki DG. Infectious complications of Swan-Ganz pulmonary artery catheters. pathogenesis, epidemiology, prevention and management. Am J Respir Crit Care Med 1994; 149:1020–36.
[31] Saint S, Matthay MA. Risk reduction in the intensive care unit. Am J Med 1998;105:515–23.
[32] Fontes MF, Barash PG. "AAA" to the rescue? Crit Care Med 1999;27:2827–9.
[33] Hingorani A, Ascher E, Lorenson E, et al. Upper extremity deep venous thrombosis and its impact on morbidity and mortality rates in a hospital-based population. J Vasc Surg 1996;26: 853–60.
[34] Hoar PF, Stone JG, Wicks AE, et al. Thrombogenesis associated with Swan-Ganz catheters. Anesthesiology 1978;48:445–7.
[35] Hoar PF, Stone JG, Wicks AE, et al. Heparin bonding reduces thrombogenicity of pulmonary artery catheters. N Engl J Med 1981;305:993–5.
[36] Hofbauer R, Moser D, Kaye AD, et al. Thrombus formation on the balloon of heparin-bonded pulmonary artery catheters: an ultrastructural scanning electron microscope study. Crit Care Med 2000;28:727–35.
[37] Fontes M, Barash PG. Pulmonary artery catheter under the microscope. Crit Care Med 2000; 28:891–2.
[38] Urschel JD, Myerowitz D. Catheter-induced pulmonary artery rupture in the setting of cardiopulmonary bypass. Ann Thorac Surg 1993;56:585–9.
[39] Shah KB, Rao TL, Laughlin S, et al. A review of pulmonary artery catheterization in 6,245 patients. Anesthesiology 1984;61:271–5.
[40] Boyd KD, Thomas SJ, Gold J, et al. A prospective study of complications of pulmonary artery catheterizations in 500 consecutive patients. Chest 1983;84:245–6.

[41] Cohen JA, Blackshear RH, Gravenstein H, et al. Increased PA perforating potential of PA catheters during hypothermia. J Cardiothorac Vasc Anesth 1991;5:234–6.
[42] Gomez-Arnau J, Montero CG, Luengo C, et al. Retrograde dissection and rupture of PA after catheter use in pulmonary hypertension. Crit Care Med 1982;10:694–5.
[43] DeLima LG, Wynanads JE, Bourke ME, et al. Catheter-induced pulmonary artery false aneurysm and rupture: case report and review. J Cardiothorac Vasc Anesth 1994;8:70–5.
[44] Yellin LB, Filler JJ, Barnette RE. Nominal hemoptysis heralds pseudoaneurysm induced by a pulmonary artery catheter. Anesthesiology 1991;74:370–3.
[45] Gottwalles Y, Wunschel-Joseph ME, Hanssen M. Coil embolization treatment in pulmonary artery branch rupture during Swan-Ganz catheterization. Cardiovasc Intervent Radiol 2001;23: 477–9.
[46] Kirton OC, Varon AJ, Henry RP, et al. Flow-directed, pulmonary artery catheter-induced pseudoaneurysm: urgent diagnosis and endovascular obliteration. Crit Care Med 1992;20:1178–80.
[47] Bashein G, Johnson PW, Davis KB, et al. Elective coronary bypass surgery without pulmonary artery catheter monitoring. Anesthesiology 1985;63:451–4.
[48] Bender JS, Smith-Meek MA, Jones CE. Routine pulmonary artery catheterization does not reduce morbidity and mortality of elective vascular surgery: results of a prospective, randomized trial. Ann Surg 1997;226:229–36.
[49] Coles NA, Hibberd M, Russell M, et al. Potential impact of pulmonary artery catheter placement on short-term management decisions in the medical intensive care unit. Am Heart J 1993;126: 815–9.
[50] Isaacson IJ, Lowdon JD, Berry AJ, et al. The value of pulmonary artery and central venous monitoring in patients undergoing abdominal aortic reconstructive surgery: a comparative study of two selected, randomized groups. J Vasc Surg 1990;12:754–60.
[51] Mimoz O, Rauss A, Rekik N, et al. Pulmonary artery catheterization in critically ill patients: a prospective analysis of outcome changes associated with catheter-prompted changes in therapy. Crit Care Med 1994;22:573–9.
[52] Tuman KJ, McCarthy RJ, Spiess BD, et al. Effect of pulmonary artery catheterization on outcome in patients undergoing coronary artery surgery. Anesthesiology 1989;70:199–206.
[53] Loop FD, Christiansen EK, Lester JL, et al. A strategy for cost containments in coronary artery surgery. JAMA 1983;250:76–7.
[54] Connors AF, Speroff T, Dawson NV, et al. The effectiveness of right heart catheterization in the initial care of critically ill patients. JAMA 1996;276:889–97.
[55] Ramsey SD, Saint S, Sullivan SD, et al. Clinical and economic effects of pulmonary artery catheterization in non-emergent coronary artery bypass graft surgery. J Cardiothorac Vasc Anesth 2000;14:113–8.
[56] Dalen JE, Bone RC. Is it time to pull the pulmonary catheter? JAMA 1996;276:916–8.
[57] Pulmonary artery catheter consensus conference: consensus statement. Crit Care Med 1997;25: 910–25.
[58] Mueller HS, Chatterjee K, Davis KB, et al. Present use of bedside right heart catheterization in patients with cardiac disease. JACC 1998;32:840–64.
[59] Bernard GR, Sopko G, Cerra F, et al. Pulmonary artery catheterization and clinical outcomes: National Heart, Lung and Blood Institute and Food and Drug Administration Workshop Report: consensus statement. JAMA 2000;283:2577–8.
[60] Zarich S, Pust-Marcone J, Amoateng-Adjepong Y, et al. Failure of a brief educational program to improve interpretation of pulmonary artery occlusion pressure tracings. Intensive Care Med 2000;26:698–703.
[61] Slogoff S, Keats SS, Arlund C. On the safety of radial artery cannulation. Anesthesiology 1983;59:42–7.
[62] Frezza EE, Mezghebe H. Indications and complications of arterial catheter use in surgical or medical intensive care units: analysis of 4932 patients. Am Surg 1998;64:127–31.
[63] Sellden H, Nilsson K, Larsson L, et al. Radial arterial catheters in children and neonates: a prospective study. Crit Care Med 1987;15:1106–9.

[64] Allen EV. Thromboangiitis obliterans: methods of diagnosis of chronic occlusive arterial lesions distal to the wrist with illustrative cases. Am J Med Sci 1929;2:1–8.
[65] Cable DG, Mullany CJ, Schaff HV. The Allen Test. Ann Thorac Surg 1999;67:876–7.
[66] Ciria-Llorens G, Gomez-Cia T. Hand blood supply in radial forearm flap donor extremities: a qualitative analysis using doppler examination. J Hand Surg 2001;26B:125–8.
[67] Jones B, O'Brien C. Acute ischemia of the hand resulting from elevation of a radial forearm flap. Br J Plast Surg 1985;38:396–7.
[68] Jarvis M, Jarvis C, Jones PR, et al. Reliability of Allen's test in selection of patients for radial artery harvest. Ann Thorac Surg 2000;70:1362–5.
[69] Kochi K, Sueda T, Orihashi K, et al. New noninvasive test alternative to Allen's test: snuff-box technique. J Thorac Cardiovasc Surg 1999;118:756–8.
[70] Nunoo-Mensah J. An unexpected complication after harvesting of the radial artery for coronary artery bypass grafting. Ann Thorac Surg 1998;66:929–31.
[71] Pola P, Serricchio M, Flore R, et al. Safe removal of the radial artery for myocardial revascularization: a Doppler study to prevent ischemic complications to the hand. J Thorac Cardiovasc Surg 1996;112:737–44.
[72] Ruengsakulrach P, Brooks M, Hare DL, et al. Preoperative assessment of hand circulation by means of doppler ultrasonography and the modified Allen test. J Thorac Cardiovasc Surg 2001; 121:526–31.
[73] Starnes SL, Wolk SW, Lampman RM, et al. Noninvasive evaluation of hand circulation before radial artery harvest for coronary bypass grafting. J Thorac Cardiovasc Surg 1999;117:261–6.
[74] Bazaral MG, Welch M, Golding LA, et al. Comparison of brachial and radial arterial pressure monitoring in patients undergoing coronary artery bypass surgery. Anesthesiology 1990;73: 38–45.
[75] Gravlee GP, Wong AB, Adkins TG, et al. A comparison of radial, brachial, and aortic pressures after cardiopulmonary bypass. J Cardiothorac Anesth 1989;3:20–6.
[76] Barnes RW, Foster EJ, Janssen A, et al. Safety of brachial arterial catheters as monitors in the intensive care unit–prospective evaluation with the Doppler ultrasonic velocity detector. Anesthesiology 1976;44:260–4.
[77] Ganchi PA, Wilhelmi BJ, Fujita BS, et al. Ruptured pseudoaneurysm complicating an infected radial artery catheter: case report and review of the literature. Ann Plast Surg 2000;46:647–50.