Pulmonary Artery Catheterization

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Since its development more than 20 years ago as a research tool for the study of myocardial infarction (MI, the balloon-tipped pulmonary artery (PA) flotation catheter (Swan-Ganz catheter) has become one of the most important and valuable clinical tools for monitoring the critically ill patient. Recently, the indications for and clinical application of this monitoring modality have been reexamined; it remains an extremely useful tool for use in the perioperative period. In 1929, Werner Forstmann, a German surgical resident, used a mirror to catheterize his own right atrium via the left antecubital vein. Skill in cardiac catheterization increased markedly over the next several decades, until this procedure became common in the cardiac catheterization laboratory. However, the technique required fluoroscopic guidance and was time-consuming, often requiring 20 to 30 minutes for catheter passage. In addition, approximately 50% of all attempts at catheter placement were unsuccessful. Fortunately, in 1953, in conjunction with their experiments isolating each lung, Lategola and Rahn developed a catheter with an inflatable balloon at the tip. They reported that the catheter consistently and easily slipped into the PA without extensive manipulation. However, no clinical notice was taken of the accomplishment and it remained for the "rediscovery" of the principle 2 decades later by Jeremy Swan, William Ganz, and colleagues. Bedside monitoring of the critically ill became a reality because fluoroscopy was no longer needed and rapid passage to the PA was easily achieved. As originally designed, the catheter measured PA and pulmonary capillary wedge pressures. Subsequently, the catheter was modified to perform a wide variety of functions, including measurement of cardiac output by thermodilution, performance of angiography, intracavitary electrography and aural or ventricular pacing, calculation of ejection fraction, and detection of venous air embolism.

Catheter Design

The standard 7F thermodilution (TD) pulmonary artery catheter (PAC) consists of a single catheter 110 cm in length containing four lumina. It is constructed of flexible radiopaque polyvinyl chloride (PVC) (Fig. 14-1). Ten-centimeter increments are marked in black on the catheter beginning at the distal end. At the distal end of the catheter is a latex rubber balloon of 1.5 mL capacity. When inflated, the balloon extends slightly beyond the tip of the catheter but does not obstruct it. This feature prevents the tip of the catheter from contacting the right ventricular (RV) wall during passage and is responsible for the reduced incidence of arrhythmias during insertion. Not only does the balloon reduce the force of contact against the RV wall but it also acts to float the catheter into the PA. Balloon flotation in blood strongly influences PAC tip location, and this assists in preferentially directing its placement. Finally, inflation of the balloon allows measurement of the pulmonary capillary wedge pressure (PCWP). During inflation, the development of high intraballloon pressure may cause disruption of the PA, therefore, the duration of balloon inflation should be kept to a minimum.

Studies have implicated high peak intraballloon pressures, which are transmitted to the PA, as the main cause of this problem. Early studies evaluated the pressure-volume relationship of the balloon in four different PACs. A study by Ikedo et al. demonstrated that a slower rate of balloon inflation (over 2.5 to 6.0 seconds) resulted in a lower peak pressure and a lower balloon volume. Therefore, these authors suggested that to minimize the potential for excessive intraballloon pressure (and secondary increases in volume), air should be injected slowly, preferably over at least 5 seconds. In addition, initial reports suggested that the composition of the PAC balloon (particularly PVC) may also increase the risk of PA perforation. As a result, polyurethane has been suggested as an alternative material for balloon manufacture. A potential advantage of polyurethane is that the material softens at body temperature and does not stiffen over time (a trait of PVC catheters). Although theoretically attractive, the clinical advantage of polyurethane balloons remains to be elucidated.

Information Obtained With the Pulmonary Artery Catheter

Information provided by the PAC includes (1) right and left-sided intracardiac pressures; (2) cardiac output by the TD method; and (3) mixed venous blood for gas and chemical analysis. In addition, modifications of the "traditional" PAC provide data necessary for calculation of derived hemodynamic variables, facilitate diagnosis of complex arrhythmias, provide continuous measurement of mixed venous oxygen saturation, and allow for pacing of atrium or ventricle.

Intracardiac Pressure Measurements

PCWP is an indirect measurement of left ventricular end diastolic pressure (LVEDP) (Fig. 14-2). Traditionally, LVEDP measurement has been employed to assess left ventricular
Figure 14-1. A 7F thermocline Swan-Ganz catheter. Inset: Cross-section detailing lumen design. (Courtesy of Baxter Healthcare Corp., Edwards Division, Irvine, CA.)

(LV) function. However, a normal LVEDP (6 to 12 mmHg) does not ensure normal ventricular function. Conversely, an abnormal LVEDP (>15 mmHg) cannot directly measure the degree of LV impairment. LVEDP has also been used to assess preload.

Preload is classically derived from measurement of end-diastolic fiber length (or end-diastolic volume). However, due to logistic problems of routinely obtaining ventricular volume, a pressure measurement has been employed. Depending on the state of ventricular compliance, LVEDP may or may not have a linear relationship to LVEDV. In the absence of mitral valve disease, PCWP approximates left atrial pressure (LAP). Therefore, a more clinically available measurement of preload is the PCWP (normal, 8 to 12 mmHg).

PCWP correlates with LVEDP (LAP) over a wide range of filling pressures (5 to 25 mmHg). To avoid complications with PAC balloon inflation, pulmonary artery end-diastolic pressure (PAEDP) is frequently used as an estimate of PCWP. In the absence of increased pulmonary vascular resistance (PVR) (e.g., chronic mitral stenosis, chronic LV failure, pulmonary disease) the gradient between PAEDP and PCWP is approximately 1 to 4 mmHg. PAEDP may be greater than PCWP in a patient with tachycardia because end-diastolic filling time is decreased. The anatomic site of the PAC also influences the PCWP-LAP relationship. The ideal position for obtaining a PCWP is in a large branch of the PA. This will result in a good PCWP-LAP correlation. However, wedging in a small artery yields a PCWP higher than LAP. Occasionally the transition from PA to PCWP may not be evident by changes in the waveform. In these situations aspiration of pulmonary capillary blood will confirm the PAC location.

A number of additional factors alter the correlation between PCWP and LAP, including incorrect catheter placement, transducer-related artifacts, eccentric balloon occlusion, non-zone III PCWP, pulmonary venous obscurative disease, valvular heart disease, pericardial tamponade, and altered LV compliance and the presence of mitral regurgitation (y waves). In addition, depending on the state of ventricular compliance, LVEDP may or may not have a linear relationship to LVEDV. An elegant study by Richard et
Thermoclinical Cardiac Output

The ability to obtain accurate, rapid, and repetitive measurements of cardiac output is one of the principal advantages of thermoclinical techniques. The information gathered from serial measurements of cardiac output can be vital to diagnosis, evaluation of therapeutic interventions, and assessing prognosis. Estimation of cardiac output from physical diagnosis has been shown to be unreliable, therefore, direct measurement is essential.

The TD method of measuring cardiac output was first described in 1954 by Fick. Subsequent incorporation of a thermost in the PAC greatly enhanced the usefulness of the technique in clinical medicine. An excellent correlation has been reported between TD cardiac output and other techniques, including dye dilution techniques, the Fick method, Doppler method, and radionuclide and electromagnetic flowmeters. The noninvasive Doppler, Fick, and carbon dioxide rebreathing techniques tend to overestimate cardiac output compared to TD and the poor agreement has to be taken into consideration, especially in measurement of low cardiac output.

TD cardiac output is a variant of the indicator dilution technique, with "cold" used as the tracer indicator. Cooling of the blood is accomplished by injection of 5% dextrose and noting that the change in temperature at the downstream sampling site is proportional to cardiac output.

The TD principle is described by the Stewart-Hamilton equation:

\[ Q = \frac{V_i(T_a - T_i)K_1K_2}{T_a\Delta T dt} \]

where

- \( Q \) = cardiac output
- \( V_i \) = injectate volume
- \( T_a \) = blood temperature
- \( T_i \) = injectate temperature
- \( K_1 \) = density factor (specific heat/Gravitational injectate)
- \( K_2 \) = a computation constant that includes heat change in transit, dead space of the catheter, and injection rate, and adjusts the units to liters per minute
- \( T_a\Delta T dt \) = change in blood temperature as a function of time

Solution of this equation is accomplished by the cardiac
output computer, which integrates the area under the TD curve and displays a digital readout of cardiac output in liters per minute.\textsuperscript{63} Cardiac output is inversely proportional to the area under the curve \([T_q(\text{Qd})]\).

Volume of Inj e c t a t e

Standard cardiac output measurements are performed with 2.5, 5.0, or 10 mL of injectate \((D5W)\). The volume of injectate must be accurately measured as it will affect the total amount of thermal indicator injected. If careful attention is paid to filling syringes, the error introduced by variations in volume is small, amounting to 1%. If a separate injectate catheter is used, it should have the same volume as the proximal port of the PAC.\textsuperscript{64, 65} or the computation constant \((K_c)\) should be changed.

Blood Temperature

A stable baseline blood temperature is essential for computing an accurate TD curve. Currently available cardiac output computers utilize a thermistor to measure PA temperature. Even so, baseline temperatures can be seen to vary in phase with the respiratory cycle. These variations are small with normal respiration, amounting to 0.01\(^\circ\) to 0.02\(^\circ\)C, but are accentuated in dyspneic patients or patients being mechanically ventilated. To obviate or minimize the effect of these variations, each injection of the thermal indicator should be performed at the same time in the respiratory cycle.\textsuperscript{55}

Inj e c t a t e T e m p e r a t u r e

Of equal importance is the accurate measurement of injectate temperature. Temperatures ranging from 0\(^\circ\)C to room temperature \((15\%\to 24\%C)\) can be used. However, warm solutions require larger injectate volumes and higher thermistor sensitivities than do iced solutions.\textsuperscript{60} The use of iced solutions increases the signal-to-noise ratio by a factor of 2 to 3. In theory, this may lead to greater reproducibility of results. Commercial systems are now available for maintaining cold injectate syringes and accurately measuring injectate temperature at the proximal port. However, studies using an in vitro model failed to show any difference in accuracy or reproducibility between iced injectate and room temperature injectate. A potential hazard of cold injectate has been recently reported by Nishikawa and Dohl,\textsuperscript{69} who observed a transient bradycardia following injection of 10 mL of iced D5W.

The time between withdrawal of the injectate and injection should be as short as possible. Significant warming of the injectate can occur in handling and during prolonged injection phases. Little warming of room temperature injectate occurs between filling the syringe and injection. As a result, newer methods using in-line temperature probes have been developed that allow for measurement of injectate temperature as the injection proceeds. A 1\(^\circ\)C increase in the temperature of the injectate will cause an error of 3\% in cardiac output. Therefore, to create a smooth TD curve, injection should be made as rapidly and smoothly as possible and at the same point in the respiratory cycle. Most computation constants assume injection to have been made in less than 4 seconds. Rapid continuous infusion of fluid through the venous infusion port of the PAC significantly limits the accuracy of simultaneous intermittent bolus TD (STD) measurement.\textsuperscript{60} Optimally, measurements should be avoided during rapid volume infusion.

Density Factor

D5W and normal saline (NS) are the two most commonly used injectates. The choice of solutions does not significantly affect the computation of \(K_c\) because both yield nearly identical results \((\text{NS/blood } K_c = 1.08; \text{D5W/blood } K_c = 1.10)\). Although the specific gravity of blood changes with hematocrit, \(K_c\) shows little variation, decreasing only slightly from 1.13 to 1.07 as hematocrit is significantly changed from 52\% to 30\%.

Computation Constant

The computation constant combines several components of the Stewart-Hamilton equation. Calculation is based on the volume of injectate, temperature change of injectate, and the capacity of the injectate port of the cardiac output catheter.

Correction is required to allow for the warming of injectate as it passes through the intracavitary portion of the catheter.\textsuperscript{66, 67} The magnitude of this change may be appreciated by the fact that a 4°C injectate yields an effective temperature of 12°C at the point of entry into the circulation. It should be noted that each computer manufacturer determines \(K_c\) in a different manner. Therefore, the user should be aware of particular assumptions made by the manufacturer of a particular cardiac output computer.

Change in Blood Temperature With Time

When a bolus of thermal indicator is injected, a time-temperature plot is constructed. The computer then integrates the area under this curve \([T_q(\text{Qd})]\). Methods that employ this technique to calculate cardiac output include integrating to a point on the downslope equal to 10\% of the peak, integrating the entire curve, extrapolating the downslope to zero, or the use of a constant to multiply a certain portion of the curve.\textsuperscript{6, 54} The thermistor of the PAC is balanced through use of a wheatstone bridge. As a result, variations in temperature will alter resistance and current flow. To ensure correct calculations, it is important that a smooth TD curve be obtained. Low-amplitude curves may be caused by small injectate volumes, a high cardiac output, or an inadequate blood-to-injectate temperature differential. Irregular curves may result from poor mixing, changes in BP or heart rate, or contact between the thermistor and vessel wall.

Other Factors

The location of the thermistor is also important for the determination of an accurate cardiac output. A thermistor located at the catheter tip is likely to impinge upon the vessel wall, giving rise to irregular TD curves. Such curves are characterized by a prolonged upstroke, a reduced peak deflection, and an increased downslope. Early models of the TD catheters had the thermistor located in this position and were plagued by this problem. New modifications in PAC design locate the thermistor 4 cm from the catheter tip. With this change, abnormalities in cardiac output results from contact with the vessel wall have been minimized.\textsuperscript{13}

Room temperature TD cardiac output determinations from the venous infusion port can be used in place of the central venous port if the central port becomes nonfunctional.\textsuperscript{65, 66}

Technique

The clinical determination of cardiac output by the TD method is a simple technique, well suited to use during the perioperative period. However, to optimise accuracy and reproducibility, measurements should be obtained using care-
ful attention to technique. The following is a summary of key features that influence both the accuracy and reproducibility of TD measurements.

1. The correct computation constant (Kd) must be entered into the computer. This may vary with manufacturer and size of catheter, as well as with injectate volume and temperature.

2. The volume of injectate must be accurately measured. For example, an error of 0.5 mL in a 5-mL injection will cause a 10% error in the measurement.

3. The time between withdrawal of the sample and injection should be as short as possible, certainly less than 30 seconds, if possible. As previously described, a 1° increase in the temperature of the injectate will cause an error of 3% in cardiac output.

4. Each injection should be timed to occur at the same point in the respiratory cycle to ensure comparability of measurements. However, an average of multiple determinations with injections equally dispersed throughout the respiratory cycle has been shown to provide the best estimate of mean cardiac output. The results of this study suggest that the manual technique of determining cardiac output at end-expiration may not accurately reflect the average cardiac output.

In summary, to create a smooth TD curve, injection should be made as rapidly and smoothly as possible and at the same point in the respiratory cycle (Table 14-1).

Table 14-1. Guidelines for Best Results in Hemodynamic Monitoring

<table>
<thead>
<tr>
<th>Acquisition of Pressure Data</th>
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<tbody>
<tr>
<td>Completely eliminate any air or blood clots from the system</td>
</tr>
<tr>
<td>Discard catheters or tubes with kinks or bends</td>
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<tr>
<td>Do not depend on internal calibration alone; use a mercury manometer for external calibration</td>
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<tr>
<td>Check calibration routinely (3 or 4 times a day) or any time that unexpected pressures are recorded</td>
</tr>
<tr>
<td>Always recheck the zero reference and calibration before measuring pressures</td>
</tr>
<tr>
<td>Measure pressures at end-expiration, regardless of whether the patient is breathing spontaneously or is on mechanical ventilation</td>
</tr>
<tr>
<td>Determine pressures manually off hard copy when tracing artifact is present</td>
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Cardiac Output Measurements

Ensure proper positioning of the distal thermistor and right atrial lumen

Use 5 or 10 mL of cold injectate or 10 mL of room temperature injectate

Injections should be rapid and smooth, with minimal time wasted between picking up the injectate syringe, turning on the computer switch, and actually injecting the fluid

Adjust the computer constant according to the type, volume, and temperature of the injectate and the type of catheter used (predetermined constants are available)

...terminations, the potential for such contamination does exist. Inadvertent injection through a catheter containing potent cardiovascular drugs can occur. Fluid overload (due to repeated determinations) or hypothermia (if ice injectate is used) are additional possibilities for complications in pediatric patients. Bradycardia and arrhythmias have been reported following use of iced injectate. An occupational disease of caregivers ("Swan-Ganz elbow") has been described as the result of obtaining repetitive cardiac output injections.

Mixed Venous Oxygen Tension

Serial measurements of mixed venous oxygen tension (PvO₂) can provide valuable diagnostic and prognostic information. PvO₂ is also necessary for the calculation of several important derived respiratory and hemodynamic parameters such as arteriovenous oxygen content difference (Ca-aO₂), intrapulmonary shunt (Qs/Qt), and oxygen consumption (VO₂). Mixed venous carbon dioxide tension (PvCO₂) is used for calculating carbon dioxide production and respiratory quotient, and can be used for estimating changes in cardiac output. Continuous mixed venous oximetry is presently being used to supplement traditional hemodynamic monitoring in critically ill patients.

The technology which measures mixed venous oxygen saturation (by PAC) is based on the use of reflectance spectrophotometry. Using this technique, the determination of SvO₂ is based on the differential capacity of oxyhemoglobin and desaturated hemoglobin to absorb light. Of note, desaturated hemoglobin absorbs more light than saturated (oxy) hemoglobin. When SvO₂ monitoring was initially developed, the systems transmitted the different wavelengths of light along fiberoptic wires, which were incorporated into one of the lumina of the PAC. These fiberoptic components are used to measure hemoglobin oxygen saturation by the process of reflectance spectrophotometry. One of these wavelengths, identified as the indicator wavelength, is sensitive to changes in oxygen saturation. The second wavelength, or isosbestic wavelength, is relatively insensitive to changes in oxygen saturation but is quite sensitive to potential sources of interference such as temperature, pH, velocity, blood flow, and hematocrit. Light from either of these two wavelengths is reflected back along the catheter and then sensed by a photodetector connected to a microprocessor located within the monitor. The microprocessor then computes the ratio of the light reflection from wavelength 1 and wavelength 2 (in an attempt to minimize any effect of the interferences previously described). By doing this, the microprocessor theoretically determines the changes in light intensity due solely to changes in oxygenation. In practice, however, the relationship of light intensity to oxygenation is a nonlinear function. As a result, early prototypes of SvO₂ monitors often produced values that intermittently or variably correlated with in vitro data obtained by co-oximetry measurement. More recently, a third wavelength was incorporated into the SvO₂ monitoring system, which allows for the nonlinear computation of the relationship between light intensity and oxygen saturation and appears to have increased the clinical utility of this technology.

Clinical studies comparing three wavelength systems in vivo with in vitro (transmission spectrophotometry) techniques demonstrated an excellent correlation between these two techniques (r = .912 to .993). Hecker et al. demonstrated that a two-wavelength determination differed significantly from co-oximetry values (r =.762), but a three-wavelength system correlated more closely with co-oximetry...
values \( (r = .92) \) in patients undergoing cardiac surgery.\(^\text{117}\) Two other studies in cardiac surgery and intensive care unit (ICU) patients demonstrated acceptable agreement between two- and three-wavelength \( \text{SVO}_2 \) systems using reflectance spectrophotometry (PAT2 and OX3 respectively) and \( \text{SVO}_2 \) measured by co-oxymetry using transmission spectrophotometry.\(^\text{118, 119}\) The latter study demonstrated a strong correlation between \( \text{SVO}_2 \) and \( \text{SVO}_2 \) measured by co-oxymetry, with a correlation coefficient of .96. The latter group used a dual-electrode oximeter and co-oximeter catheter and had previously demonstrated an acceptable estimation of right ventricular-arterial fraction (RVEF).\(^\text{121}\) A relatively high coefficient of variation of 15% for the estimation of RVEF is due to a number of factors such as nonhomogenous mixing, respiratory artifacts, and small changes in injectate temperature.\(^\text{120}\)

Nelson\(^\text{122}\) reported a correlation between \( \text{SVO}_2 \) and the \( \text{O}_2 \) uptake coefficient reflecting the overall balance between \( \text{VO}_2 \) delivery and consumption. Subsequently, decreases in \( \text{SVO}_2 \) have been shown to correlate with decreases in cardiac output in a variety of clinical settings.\(^\text{106, 113, 131-134}\)

When arterial oxygen content and \( \text{VO}_2 \) are held constant, mixed venous oxygen content varies directly with cardiac output. Consequently, this value can be used to directly assess the adequacy of cardiac output in relation to tissue oxygen requirements.\(^\text{106}\) In a study assessing clinical usefulness, \( \text{SVO}_2 \) PAC monitoring was deemed useful in 57% of patients.\(^\text{136}\) Usefulness was defined as a change in therapy triggered solely by continuous \( \text{SVO}_2 \) data that would not have been obtained from other routine data or earlier recognition of significant adverse events. This study also defined independent factors associated with \( \text{SVO}_2 \) PAC monitoring and proposed a cutoff point above which \( \text{SVO}_2 \) may be useful.

The oxygen tension of venous blood varies according to the location from which the sample is obtained. Due to the large nonmetabolic blood flow (shunt) from the kidneys, blood from the inferior vena cava (IVC) usually has a higher oxygen tension than superior vena cava (SVC) blood. The high oxygen extraction ratio of the myocardium results in the low oxygen tension of the coronary sinus (CS). Use of blood from the right atrium (RA) for determination of oxygen tension may yield an inaccurate measurement, since streaming is present from the IVC, SVC, and CS. Numerous empirical formulas have been developed in an attempt to relate RA oxygen tension to true \( \text{FVO}_2 \).\(^\text{137}\) However, in critically ill patients, measurements of central venous oxygen tension correlate poorly with true \( \text{FVO}_2 \) obtained from the PA.\(^\text{138}\) It has been shown that mixing of the three streams of venous blood occurs in the RV; however, the risk of arrhythmias does not allow a catheter to be placed in the RV. A sample from the SVC is useful when a "true" mixed venous blood cannot be obtained, for example, in children with an intracardiac left-to-right shunt (ASD).

\( \text{FVO}_2 \) represents the final balance between total body oxygen supply and demand. The normal \( \text{FVO}_2 \) is 40 mmHg (\( \text{SVO}_2 \approx 75\% \)). Due to regional differences in blood flow, a normal \( \text{FVO}_2 \) does not necessarily indicate adequate perfusion in each organ system. Factors that reduce \( \text{FVO}_2 \) include:

1. Decreased \( \text{O}_2 \) delivery
   - Decreased arterial oxygen content (\( \text{CaO}_2 \))
   - Decreased \( \text{PaO}_2 \)
   - Decreased hemoglobin

2. Increased tissue requirements
   - Hypermetabolic states
   - Fever
   - Endocrinopathies

An elevated \( \text{FVO}_2 \) may be seen in patients who have a left-to-right shunt, for example, a ventricular septal defect (VSD) complicating an acute myocardial infarction (AMI).\(^\text{129, 130}\) Impairment of cellular respiration as seen with sepsis or cyanide poisoning also results in an elevated \( \text{PVO}_2 \). The latter is of particular importance to the anesthesiologist. Cyanide ion resulting from sodium nitroprusside administration may poison the cytochrome oxidase system. Significant cyanide poisoning can result from contamination of mixed venous blood by pulmonary capillary blood. This may occur with distal migration of the catheter to a wedge position or blood withdrawal with the balloon inflated. In these circumstances retrograde flow from pulmonary capillaries is the only possible source of blood. When the catheter tip is positioned more proximally, experimental results have been conflicting. Several studies demonstrate contamination accompanying rapid blood withdrawal, while several investigators could not support this observation.\(^\text{41, 131}\) Therefore, in light of current evidence, it is recommended that mixed venous blood samples be obtained only from properly positioned catheters and that a slow rate of withdrawal be used. Proponents of continuous mixed venous saturation monitoring claim it is associated with minimal risk and cost-effective.

**Pacing Catheter**

A multipurpose PAC composed of five pacing electrodes may be used for atrial, ventricular, or atrioventricular (AV) sequential pacing. An additional advantage provided by this catheter is its ability to record an intracardiac ECG.\(^\text{142, 143}\) Roth and Zuidan\(^\text{144}\) evaluated the ability of the pacing PAC to detect atrial and ventricular endocardial electrical activity during hypothermic cardioplegic arrest and compared it with the activity found on the standard ECG.\(^\text{145}\) These results demonstrated that the atrial electrodes detected activity that was noted also by visual inspection. However, the ventricular electrodes detected receiving electrical activity in 7 of 18 patients. Three of these 7 patients did not have simultaneous ECG activity, indicating that, in the usual monitoring circumstance, this ventricular electrical activity would have gone untreated. As a result of the ventricular activity seen with the pacing catheter, additional cardioplegia was administered. The authors therefore recommend that when a pacing Swan-Ganz catheter is used for clinical care, it can also be used to monitor myocardial electrical activity during cardioplegia arrest.\(^\text{146}\)

The multipurpose PAC that is presently available has two intraventricular electrodes situated 18.5 and 19.5 cm from the distal end and three intra-atrial electrodes situated 28.5, 31.0, and 33.5 cm further distal (Swan-Ganz flow-directing pacing catheter, Model 93-2000H-7F, Baxter Healthcare Corp., Irvine, CA). Incorporation of a third intra-atrial electrode enables proper positioning in hearts of varying chamber sizes. The ability of the catheter to provide successful pacing was evaluated in a series of 30 patients undergoing cardiac surgery.\(^\text{139}\) Atrial pacing was possible in 80% of patients, ventricular pacing in 93% and AV sequential pacing in 73%. Transmyocardial pacing is feasible using one temporary epicardial pacing lead and one endocardial lead of a pacing PAC.\(^\text{135}\)

In addition to the multipurpose PAC, a new modification of the PAC with an additional RV port placed 19 cm from the catheter tip has been introduced (Paceport, Baxter Healthcare Corp.). This additional lumen allows for the introduction of a pacing wire for emergency RV pacing (Fig. 14-4). With the Paceport system, the pacing wire is packaged separately from the PAC. This allows the flexibility of having
an adequate heart rate during minimally invasive cardiac surgery.\textsuperscript{140}

Suggested indications for the use of a PAC with pacing capability are as follows.\textsuperscript{141}

1. Intermittent third-degree heart block
2. Second-degree heart block (Mobitz II)
3. Left bundle branch block (LBBB)
4. Digitalis toxicity
5. Severe bradycardia
6. Need for A-V sequential pacing
7. Need for intracardiac ECG

In addition, the following preoperative diagnoses have been shown to significantly predict the need for pacing catheters: sinus node dysfunction or bradycardia, history of transient complete A-V block, aortic stenosis, aortic insufficiency, and reoperation.\textsuperscript{142}

**Right Ventricle Ejection Fraction**

Bing pioneered the technology responsible for our present ability to utilize indicator dilution techniques for the determination of ventricular volumes.\textsuperscript{49} He developed a method that attempted to estimate the residual end-diastolic blood volume of the RV in normal and diseased human hearts. Following catheterization of the RV and the PA with a double-lumen catheter, Evans blue was injected into the RV. The residual volumes were estimated from the slope of photometrically recorded dye dilution curves.

Using Bing's original concepts, technologic advances in PAC technology have facilitated the measurement of RV EF and RV volumes by use of TD techniques.\textsuperscript{120, 143, 144} This has occurred as a result of recent advances in the manufacture of thermistors for PACs that have a rapid response time of approximately 50 ms (normal, 200 to 1000 ms). The response time of these catheters is rapid enough to record beat-to-beat temperature variation and thus allow for calculation of RV EF. Kay and colleagues\textsuperscript{127} validated this technique with radionuclear studies both in animal models and in patients after open heart surgery. Subsequently, Jardim et al.\textsuperscript{167} and Rafferty\textsuperscript{172} also validated this technique using echocardiography.

Using this "rapid response" catheter (7.5F, Baxter Healthcare) and an accompanying computer system (Monarch REF-1, Baxter Healthcare), computation of RV EF is easily accomplished from an experimental decay process of the thermal washout curve.\textsuperscript{145} Normal RV EF (TD technique) is approximately 40%. RV stroke volume, RV end-diastolic volume, and RV end-systolic volume may be calculated as follows:

\[
\text{RV stroke volume} = \frac{\text{cardiac output}}{\text{heart rate}}
\]

\[
\text{RV end-diastolic volume} = \text{RV stroke volume} \times \text{RV EF}
\]

\[
\text{RV end-systolic volume} = \text{RV end-diastolic volume} - \text{RV stroke volume}
\]

Thus, from the standard RV EF catheter the following hemodynamic measurements may be obtained: cardiac output, RV EF, and right atrial, right ventricular, as well as pulmonary artery and capillary wedge pressures. Hines and Barash\textsuperscript{152} have demonstrated the ability to detect RV ischemia by monitoring RV EF and right ventricular end-diastolic pressure (RVEDP) in patients with right coronary artery disease. The
Continuous Cardiac Output: CCO
Modified Swan-Ganz® Catheter

A method to measure continuous TD cardiac outputs has been developed. Rather than a cold bolus injection to create a temperature signal, a filament is intermittently heated to provide a very small heat signal. To accomplish this, PACs have been modified such that a 10-cm thermal filament is located within the RV (Fig. 14–5). This filament is coiled over a portion of the PAC that lies in the RA and RV. The thermometer at the tip of the PAC detects changes in blood temperature, and the heat signal is then analyzed by stochastic techniques. Stochastic techniques differ from classic demonstrative techniques in that the statistical properties of the input and output signals are of more interest than the instantaneous values of the signals themselves. Once in place, this thermal filament continually transfers a safe level of heat directly into the blood according to a pseudorandom binary sequence. Any resulting temperature change is then detected downstream in the PA and is cross-correlated with an input sequence to produce a TD washout curve. This TD curve is then subsequently computed by the computer from the measured heat equation using the area under the curve.

With this technique the average heat infused is usually less than 7.5 W. This temperature was selected so that the catheter surface temperature remains below 44°C regardless of blood flow conditions. Earlier studies suggest that long-term exposure at this temperature (44°C) has no detrimental effects on red blood cells, the myocardium, or other blood components. In practice, the actual filament surface temperature is continually measured and the delivered power is either reduced or terminated when the average temperature exceeds 44°C.

Insertion of the PAC is performed by traditional methods allowing for placement of the thermistor in the PA outflow tract. Once the correct position of the PAC has been verified (using standard methods such as waveform or pressure form analysis), the catheter is connected to the monitor. Once this has been accomplished, the process of continuous cardiac output determination begins. The first cardiac output measurement is computed and displayed within several minutes. The heating sequence is repeated every 30 seconds; the displayed value is based on approximately six determinations and updated every 30 seconds. Thus, the monitor actually provides a time-averaged, continuously updated rather than "instantaneous" cardiac output.

This method of measuring cardiac output (i.e., volumetric fluid flow using stochastic techniques) has been evaluated in a laboratory bench model and in sheep. Clinically, Yelderman et al. have studied continuous cardiac output (CCO) as compared with BTD cardiac outputs in ICU patients. They found an acceptable correlation between TD (cardiac output) and CCO measurement (r = .94) in this patient population (range of cardiac output studied was 2.8 to 10.8 per minute). One potential advantage of this system is that it is user-friendly, requiring no calculations and no injection of volume. In addition, it is possible to perform routine bolus cardiac output determinations through the same catheter. Another study demonstrated that the CCO catheter adequately measured cardiac output and Svo2 in the clinical setting. In a study comparing intermittent BTD with CCO during liver transplantation, CCO demonstrated logistical advantages and challenged the accuracy of BTD.
Because BTD is not a true gold standard for cardiac output determination, new techniques compared with BTD may fail to achieve expected accuracy. However, good agreement has been found between CCO and BTD methods and between BTD and Fick methods with correlation coefficients on the order of $r = .94$ to $.97$ at steady state.\(^{155,156,158}\) The absolute measurement bias in one study was 0.02 L, and the 95% confidence limits were 1.07 and −1.03 L. In conclusion, CCO, compared with BTD, is accurate and reliable, especially when the cardiac index is less than or equal to 4.5 L/min\(^{-1}\) · m\(^{-2}\).\(^{156}\)

At present, increased cost is a major factor limiting the clinical application of this technology. In the setting of high cardiac output, the difference with BTD increases and the results must be cautiously interpreted.\(^{160}\) In addition, studies have demonstrated clinically important time delays in the response of the CCO catheter. This delay must be considered when there are rapid alterations of the hemodynamic state.\(^{161}\) The faster algorithm of stat CCO offers some advantage over trend CCO during an acute hemodynamic change. However, because of the averaging process for determining CCO, the response time of stat CCO is slower than that of mean arterial pressure and $SvO_2$.\(^{156}\)

Miyasaka et al.\(^{162}\) have advocated “thermoderivation” as yet another potential approach to the determination of CCO. This technique employs the measurement of flow velocity in the pulmonary artery using a continuous arterial thermoderivation system (KATS) catheter. This catheter is designed such that a continuously heated thermistor is incorporated into the tip of the PAC. The heated thermistor is surrounded by two streams of blood; the decrease in temperature is proportional to the velocity of blood. This system is then calibrated with a simultaneous TD cardiac output measurement and the velocity signal is subsequently converted into a quantitative flow value. The caveat here is that a constant blood vessel diameter (the vessel in which the PAC is placed) is assumed by the thermoderivation method. As a result, variations in PA diameter or changes in the diameter of PA during monitoring, (which may be seen with changes in volume status, positive end-expiratory pressure [PEEP], and so on) may prove to be a major limitation to the clinical usefulness of this technology. There has been one report of unsatisfactory continuous cardiac output measurement by thermoderivation in cardiac surgical patients.\(^{163}\) There was considerable error in the thermoderivation measurements compared with cardiac index measurements (2 SD of the bias ranged from 1.2 to 4.5 L/minute in the operating room [OR] and 1.8 to 5.8 L/minute in the ICU). The main sources of error are the assumptions that the rheology of blood, the position of the thermistor, and PA diameter all remain constant through the perioperative period.\(^{163}\)

A technique based on cyclic cooling of the blood in the RA and measurement of the temperature changes in the PA has been described.\(^{164}\) This study demonstrated the feasibility of the new method to monitor cardiac output, and to detect changes greater than 0.25 L/minute.\(^{164}\) Segal et al.\(^{165,166}\) recently evaluated a method for determining instantaneous and continuous cardiac output using a Doppler PAC. This method provides simultaneous measurements of blood flow velocity in the PA, coupled with continuous measurement of the diameter of the PA. In this model quantitative flow is calculated by the use of the instantaneous, spaced average velocity (obtained from the velocity profile) and the instantaneous area (obtained from the vessel diameter). Segal et al.\(^{161}\) compared the results obtained with this Doppler PAC with measurements made by electromagnetic flow. Their results demonstrated that Doppler catheter-determined flow was highly predictive of electromagnetic flow in both continuous and pulsatile pump models ($r^2 = .89$, $r^2 = .80$ respectively).\(^{161}\) This catheter system also provides instantaneous diameter measurements and mapping of instantaneous velocity profiles within the main PA. Although initial reports were encouraging, this technology failed for economic reasons and is not presently available.\(^{167}\)

**Indications**

As originally reported in 1970, the primary indication for PAC was for hemodynamic assessment of patients following complicated MI.\(^{166-170}\) Since these early reports, the potential benefits of the information gained from the PAC have extended its use to a variety of other clinical areas.\(^{171-174}\) This expansion is attested to by the fact that an estimated 2 million PACs are sold annually in the United States. Among patients with complicated AMI, use of PAC increased from 1975 through 1988 with a decline in use in 1990.\(^{175}\) However, the debate regarding the appropriate indications for PAC monitoring, which started over a decade ago, is still ongoing and is fueled by recent studies that have prompted a call for a moratorium in PAC use.\(^{176}\)

The fact that a physician's database is improved by PA catheterization is evidenced by several reports documenting the difficulty of correlating physical signs with the severity of myocardial dysfunction.\(^{154,156,168}\) Connors et al.\(^{173}\) prospectively analyzed 82 consecutive PA catheterizations. They found that less than half of a group of clinicians correctly predicted PCWP or cardiac output, and 43% made at least one change in therapy based on data from the PAC.\(^{173}\) Wal- ller et al.\(^{177}\) demonstrated that a group of experienced cardiac anesthesiologists and surgeons who were “blinded” to the results of PA catheterization during coronary artery bypass surgery were unaware of any problem during 65% of severe hemodynamic abnormalities. Similarly, Iberi and Fisher\(^{168}\) showed that a group of physicians were unable to accurately predict hemodynamic data on clinical grounds, that 60% made at least one change in therapy, and 33% changed their diagnosis based on PA catheterization data.

The clinical utility and value of the PAC depend largely on interpretation of the information obtained. Clinical interpretation of data is influenced by the level of understanding of the hemodynamic dynamics, clinical skills, and professional integrity of the physician.\(^{178}\) Clinician misinterpretation and misapplication of the data appear to be the greatest impediment to using PAC to alter pathophysiologic processes and improve outcome in critically ill patients.\(^{179}\) Iberi et al.\(^{180}\) have demonstrated an appalling lack of basic knowledge about information obtained from the PAC among ICU physicians. The development and maintenance of educational, credentialing, and continuous quality improvement policies involving the PAC is warranted and overdue.\(^{181}\) In addition, widespread use of the PAC has significant economic ramifications. Data regarding cost-effectiveness of the PAC is extremely limited in terms of methodology and scope. However, economic impact and cost-effectiveness are most prior to establishing clinical efficacy.\(^{182}\)

Intuitively, an enhanced understanding of pathophysiologic processes in severe acute disease states will lead to an improved ability to guide therapeutic decision making, for example, in severe preeclampsia.\(^{183}\) Whether enhanced understanding of patient hemodynamics translates into definitive benefits for patients has recently come into question.\(^{184}\) Although several studies have shown that PAC prompts changes in therapy in many patients, most data regarding
outcomes are retrospective. Some reviewers suggest that the evidence demonstrates an absence of risk of injury from PA catheterization and provision of important clinical data and that PA catheterization meets Food and Drug Administration (FDA) requirements for safety and effectiveness. Recent reports of patients cared for over 500 patients with PACs in situ reported that the catheter was "felt to be helpful" in the management of 80% of these patients. A number of meta-analyses have been performed. Sixteen randomized controlled trials were identified in this study. PAC-guided strategies revealed a modest risk reduction that did reach statistical significance. Risk reduction appears to be greatest in surgical series. Deficiencies of these trials regarding sample size calculations, unclear definition of concomitant therapies, blinding of physicians and patients, and outcome assessments have important implications for the proper design of future trials. Ethical difficulties have also hindered adequate trials. Competent physicians must be content to have their patients receive any of the various treatments in a randomized trial because, based on available data, none has proved preferable. If more than 70% of experts determine that PAC is indicated or contraindicated for a specific indication, a trial cannot ethically be performed for these indications. However, we must do appropriate prospective studies to determine who benefits from PAC and who does not.

In an attempt to address the issue of risk versus benefit of PACs, several organizations have published "guidelines" for the appropriate indications for PAC monitoring. In an attempt to provide practice guidelines for PAC catheterization, the American Society of Anesthesiologists (ASA) established a FA catheterization task force in 1991. The mission of this group was to develop guidelines for the appropriate indications for PAC use. To fulfill its purpose, the task force reviewed a total of 860 clinical trials, controlled observational studies, uncontrolled case reports, and individual case reports. In addition, the task force focused its review on evidence of effectiveness based on clinical outcome. In its report, the task force reported that their survey of the literature demonstrated that PAC data appeared to change therapy in 50% to 60% of all cases reviewed. Although these studies demonstrated no effect on mortality in patients whose therapy was changed (25% of adults, 10% of children), the task force concluded that one of the major deficiencies in these studies was the small sample size, and this may account for the lack of change in outcome in these patient groups. In summary, based on the available evidence and the preponderance of expert opinion, management with PAC improves outcome in a number of patient populations: (1) in patients with AMI complicated by cardiogenic shock, progressive hypotension, or associated with mechanical complications; (2) in patients with congestive heart failure (CHF) refractory to empiric therapy; (3) in patients with pulmonary hypertension; and (4) in patients with shock or hemodynamic instability. Even if a benefit in terms of mortality is undeniable, more rapid diagnosis and "achievement of therapeutic endpoints guided by PAC use can decrease morbidity and time needed for intensive care. If the patient is chosen carefully, the catheter inserted successfully and safely, the data obtained methodically and interpreted correctly, and this interpretation leads to a change in therapy to which the patient responds appropriately, the patient will experience an improved outcome based on PAC use. However, this does not occur often enough to significantly improve outcome in the general patient population.

To illustrate the potential clinical applications of PAC monitoring, its use in the following areas will be discussed:

1. Preoperative assessment
2. Perioperative monitoring
3. Hemodynamic monitoring
4. No-surgical indications

Preoperative Assessment

The preoperative use of the PAC provides physicians with data that may be used to guide patient therapy. Studies have suggested that this information gained from the PAC would often be undetected by clinical observation alone. In a retrospective study of 148 consecutive patients over 65 years of age cleared for surgery by standard clinical assessment, found that preoperative invasive hemodynamic monitoring resulted in 25% of patients being classified as having severe cardiopulmonary compromise. As a result, these patients were identified as being at extremely high risk for the planned surgical procedure. All eight of these patients who subsequently underwent surgery as originally planned died. Similarly, Babu et al. examined a series of 75 elderly patients (average age, 68 years) who underwent preoperative PAC placement. In this patient population, 30 (40%) patients were found to have abnormal LV function (by PAC data) which was not detected by clinical evaluation alone.

In a prospective study of elderly patients with hip fractures (N = 70; average age, 72 years), half of the patients (N = 35) were randomized for evaluation either by standard clinical examination combined with central venous pressure (CVP) placement, or PAC insertion. The patients in the PAC group went to surgery only after correction of all hemodynamic abnormalities. Mortality in this group was 2.9% versus 29% in the CVP group.

In an attempt to answer the question of the potential positive effect of preoperative hemodynamic optimization using PAC data on outcome, Berlauk et al. prospectively evaluated 89 patients scheduled for peripheral vascular surgery. In this study, patients were randomized into three groups: (1) preoperative optimization in the ICU 12 hours prior to surgery, (2) PAC insertion and hemodynamic manipulation 3 hours prior to surgery, or (3) control group (i.e., arterial line and CVP). Hemodynamic optimization was defined as a PCWP between 5 and 15 mmHg, a mean pulmonary artery wedge pressure (PAWP) less than 1500 dynes-sec-cm⁻², and a systemic vascular resistance (SVR) less than 1100 dynes-sec-cm⁻⁵. Patients in groups (1) and (2) were more hemodynamically stable intraoperatively and had a lower incidence of tachycardia, hypertension, and arrhythmias than group (3) patients. In addition, these groups had a lower incidence of postoperative cardiac morbidity and less early graft closure than did the control group (P < .05). However, PAC catheterization 12 hours before surgery did not result in any better outcome than catherization 3 hours before surgery.

In a recent retrospective study, patients who had normal initial preoperative hemodynamic values or abnormal initial values that were normalized preoperatively experienced significantly fewer perioperative cardiovascular complications than those with abnormal initial values that were not normalized preoperatively. These results suggest that there may be benefit to the practice of preoperative ICU admission, hemodynamic monitoring with a PAC, and "optimization" of cardiac function in selected patients undergoing major elective noncardiac surgery.

However, in a recent prospective study in which patients were randomized to receive preoperative monitoring and optimization with a PAC at the night before surgery or...
standard care prior to aortic surgery, the incidence of postoperative cardiac, renal, and other complications was similar in both groups. The authors suggested that routine use of PACs for perioperative monitoring during aortic surgery was not beneficial and may be associated with a higher rate of intraoperative complications. Variables such as cardiac risk factors and adenosine thallium scintigraphy may be more important predictors of cardiac events in such patients. Routine perioperative use of the PAC does not appear to be appropriate because of age alone.

An observational study was unable to demonstrate any difference in outcome between elderly patients who did not undergo preoperative catheterization and unmatched patients who were admitted to the hospital during the same time period for other diagnoses. The PAC task force of the ASA suggested that in this study, the similar outcomes may have been due to selection bias.

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**Perioperative Monitoring**

**High-Risk General Surgical Patients**

The presence of significant cardiac disease (defined as either a recent MI or clinical evidence of CHF) was one of the earliest indications for PAC insertion in noncardiac surgical patients. The presence of clinical CHF has been shown to place patients at increased risk for postoperative cardiac death following noncardiac surgery. In a 1972 report, Tarhan et al. evaluated patients with a history of recurrent MI who underwent noncardiac surgery. This study revealed a reinfarction rate of 37% within the first 3 months following infarction. In this study patients did not receive routine hemodynamic monitoring prior to their procedure. In a later study of 735 patients, Rao et al. studied the incidence of reinfarction in noncardiac surgical patients. In this study, PACs and arterial lines were inserted in all patients prior to surgery. Patients' hemodynamic status was optimized preoperatively using the information obtained from these monitors. Using this technique, Rao et al. reported a reinfarction rate (at 3 months) of only 5.8%. In spite of this study, implying that PAC monitoring can decrease mortality in critically ill patients, no scientific study has confirmed this impression. Recent studies have evaluated the impact of PAC monitoring on mortality with emphasis on how the information is used. Although a potential benefit from PAC monitoring has been noted, the limited sample size and selection criteria prevent definitive conclusions. Many reported studies are retrospective, nonrandomized, unblinded, limited in scope or size, and founded on subjective endpoints. Large multicentered randomized controlled trials are required.

**Major Vascular Surgery**

Perhaps the major difficulty with trying to interpret the impact of PAC use in major vascular surgery is the absence of a control group for comparison (i.e., patients who do not receive a PAC). Routine use of PACs in elective abdominal aortic reconstruction remains controversial.

In an early report utilizing controls, Hesdorfer et al. were able to demonstrate a reduction in mortality, perioperative hypertensive events, and renal failure in patients managed using an aggressive fluid loading protocol and a PAC who were undergoing aortic reconstruction. The main problem with this study is that the PAC was only a small part of the overall study design. Several other authors have suggested that utilizing PCWP measurements obtained from the PAC to optimize preoperative volume status may prove beneficial in this patient population. In a prospective study, 41 patients (13 abdominal aortic aneurysm repairs, 23 other peripheral vascular procedures) who maintained their postoperative PCWP within 3 mmHg of their best preoperative level had a decrease in overall complication rate (14% vs 79%). Berlauk et al. showed that optimization of hemodynamics in the ICU preoperatively reduced morbidity and mortality from 9.5% to 1.5%. Others believe that the preoperative "tune-up" can be done more quickly and safely intraoperatively. One recent prospective study demonstrated no change in postoperative cardiac, renal, and other complications following placement of the PAC the night before surgery and optimization of hemodynamic parameters. A high incidence of unsuspected cardiopulmonary abnormalities severe enough to defer surgery have been detected in the over-65-years age group with the PAC. If this would suggest that the PAC is necessary to truly predict increased risk and poor outcome. However, more recent studies by Joyce et al. and Isackson et al. reported different results. Using a randomized controlled protocol evaluation of patients without uncompensated renal disease or severe cardiac disease (left ventricular ejection fraction [LVEF] < 40%) undergoing abdominal aortic reconstruction, these authors were unable to show any difference in outcomes between patients monitored by PAC or CVP. In addition, it is likely that the general preparation of patients coming to the OR for vascular surgery has improved significantly over the last decade, particularly with regard to cardiac management and antihypertensive treatment.

In summary, the PAC may be useful in the management of some patients undergoing aortic surgery, although recent studies have identified patients who can be safely managed with arterial pressure and CVP monitoring alone. Use of the PAC may lead to fewer complications in high-risk patients undergoing peripheral vascular surgery.

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**Neurosurgery**

The main focus of all studies to date in the area of neurosurgery has been on the utility of PAC to detect air embolism. However, the use of the PAC to monitor and treat air embolism in neurosurgical patients does not appear to be appropriate. Its use as a monitor is less sensitive than other techniques and its efficacy as a treatment modality is questionable. Of note, none of the studies has evaluated the impact of PAC use on clinical outcome.

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**Obstetrics and Gynecology**

Once again, the major problems with studies performed using PAC in the obstetric and gynecologic patient population is the lack of historical controls. The major focus of PAC utilization has been in patients with severe preclampsia. Available scientific data do not support the use of the PAC in uncomplicated preclampsia; however, most experts believe that PAC use may be helpful in the management of selected patients with severe preclampsia. Severe preclampsia is characterized by elevated SVR, low or normal filling pressures, increased contractility (left ventricular stroke work index), and normal heart rate. The subsets of patients most likely to benefit from PAC monitoring were those with (1) refractory oliguria, (2) pulmonary edema, or (3) refractory hypertension. The first two are considered indications by the American College of Obstetricians and Gynecologists. Spaven et al. reported on the
potential of PAC monitoring to aid in the early recognition of an anamolous fluid embolus.

**Hemodynamic Disorders**

Historically, the use of PAC in ICUs has been widespread in both the medical and surgical settings. The data from the medical ICU has focused primarily on patients with MI. Once again, these uncontrolled studies have yielded inconsistent results.14, 167 Opponents of PAC use in this setting argue that patients with an MI who were monitored by PAC had a higher in-hospital mortality, longer hospital stay, and shorter short-term survival than patients who did not have PAC inserted.232, 233

Data from the surgical intensive care literature support the ability of data from PAC to aid in diagnosis and to guide therapy.121, 212, 265, 214, 215. However, the major question that remains is does routine placement of a PAC in selected surgical ICU (SICU) patients reduce morbidity and mortality? An attempt to answer this question, Scalea et al.219 studied a group of geriatric blunt trauma patients. The authors showed that using routine placement of the PAC identified a group of patients in clinically unrecognized shock (46%). They demonstrated a reduction in mortality from 58% to 40%.13 Shoemaker et al.171 preoperatively randomized a high-risk general surgical population to receive either PAC or CVP placement. For the purpose of this study, patients were randomized into one of two treatment groups: (1) normal values of healthy subjects were used as therapeutic goals or (2) a protocol group in which median values of patients who had survived life-threatening postoperative shock were the therapeutic goals.177 Controversy still exists about the result of this study (centering on whether the control and protocol groups were comparable), which revealed that the PAC protocol group had reduced mortality (4% versus 33%), fewer complications, fewer ICU hospital and ventilator days, and less total cost. Further research is required regarding goal-oriented use of the PAC to achieve supernormal oxygen delivery prior to high-risk surgery before a recommendation can be made.256

Other recent studies have demonstrated that in patients with sepsis and adult respiratory distress syndrome (ARDS) survival may be improved by therapy guided by the PAC. In a randomized prospective study, Tsuchschmidt et al.231 successfully employed the concept of achieving "supernormal" values in the treatment of 25 septic patients in the ICU. Similarly, Russell et al.172 documented (retrospectively) improved outcome in patients with ARDS who had an elevated cardiac output. There are now several other publications from different institutions validating these higher goals for cardiac output.271, 238 Each of the groups of investigators focused on oxygen delivery and changed the long-established concept that a CI of 2.2 L/minute/m² is sufficient in all clinical situations. Carefully designed, multicenter, randomized controlled trials are required to establish whether augmenting oxygen delivery improves organ-specific outcomes and survival in systemic inflammatory response syndrome (SIRS)- related organ dysfunction secondary to infection, trauma, or surgery.246 However, hyperdynamic resuscitation has been shown to improve survival rates in life-threatening burns.236 Unsustained or inadequate response to hyperdynamic resuscitation of burns has been associated with mortality.249 However, only 8% of burn units in the United Kingdom, United States, Canada, Australia, and New Zealand use PACs in over half of their patients and few centers describe the use of predetermined goals to direct therapy following PAC insertion.341 In conclusion, PAC use may be appropriate in septic shock unresponsive to early resuscitative measures.248 Maintenance of normal hemodynamics in this group of patients appears to be the appropriate goal. Further research is needed to determine the proper role of the PAC in sepsis and septic shock.

RV dysfunction has been identified in septic shock by the use of an Euvolemia PAC, and RV contractility was improved by epinephrine.246, 244 In a study of 27 septic shock patients, RV dysfunction was identified in 11 (41.9%).246 The value of RVEDV derived from the Euvolemia PAC as an index of LV preload has been investigated.246 RVEDV markedly overestimated LV preload with the conclusion that RVEDV should not be used as an absolute value for determining preload, as patients may be underresuscitated. The authors suggested use of transesophageal echocardiography (TEE) in conjunction with Euvolemia PAC to more accurately determine preload and cardiac performance in critically ill patients. In addition, Doppler ultrasound may be used as a screen to determine the need for PAC placement,247 acceleration less than 200 cm/s² correlates well with CI less than 3.0 L/minute/m².

Invasive hemodynamic monitoring has become standard in the management of aetrical or subarachnoid hemorrhage, facilitating the safe and effective use of hypervolemic, hypertensive therapy to treat or prevent cerebral vasospasm.250 This study documented a 13% incidence of catheter-related sepsis, a 2% incidence of CHF, a 1.3% incidence of subclavian vein thrombosis, and a 1.1% incidence of pneumothorax in this patient population. A novel indication for the PAC has been described: pulmonary wedge aspiration cytology, allowing the tissue diagnosis of malignancy and enabling prompt institution of chemotherapy. The diagnosis in the case reported was made as part of the workup of pulmonary arterial hypertension.249

A prospective cohort study of 5735 patients with adjustment for treatment selection bias was designed to examine the association between the use of the PAC during the first 24 hours in the ICU and subsequent survival, length of stay, intensity of care, and cost of care.216 The PAC was associated with increased mortality and increased utilization of resources. The cause of this apparent lack of benefit is unclear and the findings justify consideration of a randomized controlled trial of the PAC. Knowledge of the right heart PAC is not uniformly good among ICU physicians. Accreditation policies and teaching practices concerning this technique are undergoing urgent revision.246 In addition, less invasive means of cardiovascular assessment are growing in popularity. For example, training intensive therapy unit (ITU) physicians in limited TEE, using a pediatric monoplane probe to evaluate LV function, has been shown to be rapidly and safely achievable, and to yield data pertinent to patient management, even in the early stages of skill acquisition.246 Meta-analyses of clinical trials from 1979 to 1996 concluded that hemodynamic data obtained from the PAC appeared to be beneficial for the following indications:246 (1) defining the status of underlying cardiovascular performance or the need for improvement; (2) direction of therapy when non-invasive monitoring may be inadequate, misleading, or the endpoints of resuscitation are difficult to define; (3) assessment of response to resuscitation; (4) potential reduction of secondary head or spinal cord injury in multisystem trauma; (5) direction of management of major trauma complicated by severe ARDS, oliguria or anuria, myocardial ischemia, CHF, or major thermal injury; and (6) establishing futility of care. There are few data to identify a grade A indication for the PAC in the care of critically ill patients.251 Finding little evi-
Table 14-2. Guidelines for Safe Insertion of Pulmonary Artery (PA) Flow-Guided Catheters

1. Balance risk vs. benefit.
2. slowly inflate the balloon while continuously monitoring the PA waveform.
3. Upon transition from the PA to the pulmonary capillary wedge pressure (PCWP) trace, immediately stop infusion.
4. If an overwedge pattern is observed, the balloon should be immediately deflated, and the catheter immediately withdrawn 1-2 cm (see Fig. 14-5). The balloon is slowly reinflated and a normal wedge pressure waveform is noted.
5. Minimize duration of PCWP measurements.
6. If the balloon inflates with <1.5 mL of gas, the catheter should be withdrawn at least 1-2 cm.
7. Spontaneous tip migration may occur; therefore continuously monitor the PA trace for "spontaneous wedging." If this occurs, withdraw the catheter 1-2 cm or until a normal PA tracing reappears.
8. Minimize the number of PCWP measurements in patients who are elderly, uncoupled, or have pulmonary hypertension.
9. If PA diastolic pressure is <18 mmHg, use PA diastolic pressure rather than PCWP as an index of left ventricular filling pressure.

dence to support the use of PAC in the literature does not mean that it is neither efficacious nor effective. It may well be that information provided by PACs is important in the care process. However, there is little objective evidence to support this conclusion, and the challenge to clinicians is to design and conduct clinical trials capable of separating evidence from opinion.

Cardiac Surgery

Numerous uncontrolled observational studies have attempted to determine whether PACs change outcome in cardiac surgical patients. 177, 223, 225 Moore et al. 225 compared 20 consecutive patients with left main coronary artery stenosis undergoing coronary artery bypass grafting (CABG) without PAC monitoring with 28 patients undergoing surgery who had a preoperative PAC inserted. They demonstrated a decrease in mortality from 20% to 3.5% and concluded that this improvement was due to the use of vasodilators, inotropic agents, and propranolol. All of these modalities were facilitated by the information obtained using the PAC.

A more recent study by Tuman et al. 224 in 1094 patients undergoing cardiac surgery was unable to demonstrate any positive impact (i.e., a reduction in mortality, cardiac ischemia, or postoperative MI) in patients receiving elective or emergent PAC versus CVP placement. The lack of observed differences in outcome may have been due to patient demographics, as assignment to monitoring groups was made solely by the anesthesiologist assigned to the case. Similarly, a randomized controlled study by Pearson et al. 226 (N = 239) found no difference in depth, length of ICU stay, or use of vasopressors between cardiac surgical patients monitored by PAC or CVP. Once again, the anesthesiologist in charge of the case could remove patients from the control (CVP) group and place them into the monitored PAC group at discretion. On balance, low-risk patients undergoing surgery do not appear to benefit from PAC use. 224 Studies examining high-risk patients undergoing cardiac surgery are lacking, making accurate determination of patient benefit difficult.

Insertion

Successful PAC insertion begins with preparation of the site for venipuncture (see Chapter 15 for details) and appropriate balancing and calibration of pressure monitoring equipment. Following successful venipuncture (using the classic Selting technique), 227 a larger sheath and vessel dilator can be introduced into the vessel. After placement of the introducer, the dilator is removed and the larger intravascular sheath remains in place. 228 The PAC can then be inserted into the sheath and threaded into the central circulation. This method may be used whether the internal or external jugular, femoral, or antecubital veins are employed.

Selection of Insertion Site

A number of venous entry sites are employed for PA catheterization. 229-231 These include the internal and external jugular, subclavian, antecubital, and femoral veins. Ideally, the appropriate site should be easily accessible, a short distance from the RA, and be associated with minimal complications. Meticulous attention to detail is essential if complications are to be avoided (Table 14-2).

Based on these goals, most anesthesiologists inserting the PAC choose the internal jugular vein approach. 232 Advantages include simplicity, accessibility of the site during surgery, and a relatively short and direct pathway to the RA. Disadvantages include inadvertent carotid artery puncture with hematoma formation or dislodgment of atherosclerotic plaques, nerve injury, and, rarely, pneumomediastinum. 234-237 Insertion of the PAC through the femoral vein without the use of fluoroscopy has been shown to be safe and effective. 233

Insertion Technique

With the introducer sheath in place, the Swan-Ganz catheter is inserted carefully and advanced until the tip lies in a central vein. Approximate distances from various insertion sites and the advantages and disadvantages of different insertion sites are listed in Tables 14-3 and 14-4. Intracardiac knotting is a consequence of inserting the PAC too far distally without the appropriate pressure trace being displayed on the monitor.

Location of the tip of the catheter in a central vein can be confirmed by pressure changes related to respiration or coughing. With the catheter in the RA, the balloon is inflated with 1.5 mL of air (never more or less), and the catheter slowly advanced. When the RA is entered, typical venous s, a, c, and v waves will be noted (RAP = 0-8 mmHg) (Fig. 14-6). Further advancement of the catheter will produce a dramatic change in the pressure tracing as the tip of the catheter enters the RV. Within one cardiac cycle a pressure change from those characteristic of the atrium to a phasic pressure in the range of 25/0-5 mmHg, typical of the RV.

Table 14-3. Distances From Insertion Sites to Right Atrium, Pulmonary Artery, and Wedge Position

<table>
<thead>
<tr>
<th>Insertion Site</th>
<th>Right Atrium (cm)</th>
<th>Right Ventricle (cm)</th>
<th>Pulmonary Artery (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal jugular vein</td>
<td>Right 20</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>Left 20</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>Antecubital vein</td>
<td>Right 20</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>Left 20</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>Femoral vein</td>
<td>Right 20</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>Left 20</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>Subclavian vein</td>
<td>Right 20</td>
<td>30</td>
<td>45</td>
</tr>
</tbody>
</table>
Table 14-4. A Comparison of Venous Access Routes

<table>
<thead>
<tr>
<th>Route</th>
<th>Method of Cannulation</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peripheral external jugular</td>
<td>Percutaneous</td>
<td>Easy to learn</td>
<td>Valves may hinder catheter or guidewire insertion — Sustained, thrombosis, and phlebitis are more common</td>
</tr>
<tr>
<td>vein</td>
<td></td>
<td>Safe</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Does not interfere with cardiopulmonary resuscitation (CPR)</td>
<td></td>
</tr>
<tr>
<td>Antecubital vein</td>
<td>Percutaneous/cutdown</td>
<td>Easy to learn</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Safe</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Preferred route with anticoagulant or thrombolytic therapy, because the site is easily compressible should bleeding occur</td>
<td></td>
</tr>
<tr>
<td>Central internal jugular vein</td>
<td>Percutaneous</td>
<td>Rapidly accessible</td>
<td>Air embolism, carotid artery puncture, tracheal injury may occur</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Does not interfere with CPR</td>
<td>Pneumothorax (more common in the lower than the right internal jugular vein)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Provides a straight route to the heart</td>
<td>Thoracic duct injury (left internal jugular vein only)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Less restrictive to patient movement</td>
<td></td>
</tr>
<tr>
<td>Subclavian vein</td>
<td>Percutaneous</td>
<td>Rapidly accessible</td>
<td>Air embolism, more frequent pneumothorax and hemothorax; subclavian artery puncture; injury to nerve bundle may occur</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Allows free neck and arm movement</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Easier to keep sterile</td>
<td></td>
</tr>
<tr>
<td>Femoral vein</td>
<td>Percutaneous</td>
<td>Rapidly accessible</td>
<td>Sepsis, in situ thrombosis, pulmonary embolism may occur</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Does not interfere with CPR</td>
<td></td>
</tr>
</tbody>
</table>

should be observed. The catheter is then advanced through the RV (as quickly as possible to minimize the potential for dysrythmias until it enters the main PA). Location can be verified by an increase in the diastolic pressure of 25/12 mmHg and a change in the morphology of the waveform. Usually there is no change in the systolic pressure. The catheter is advanced farther until it wedges in a branch of the PA. At this point, the trace will have the appearance of an atrial pressure pattern with a, b, c, and v wave components transmitted retrograde from the left atrium (PCWP = 8 to 12 mmHg). In summary, pulmonary capillary wedge position is verified by (1) a characteristic waveform, (2) a mean pressure lower than the mean pulmonary artery pressure (PAP), and (3) the ability to withdraw arterialized blood.

Once the wedge position has been achieved, the balloon is deflated. This should produce a typical PAP tracing. Reinfation of the balloon should reproduce the wedge tracing with 1.5 mL of air. If less than 1.5 mL of air results in a wedge tracing, the catheter should be withdrawn to the point where a 1.5-mL balloon inflation is associated with a PCWP. At no time should more air be injected into the balloon than is necessary to obtain PCWP. This will result in distal migration of the catheter. By emphasizing the aforementioned technique, PA catheterization can be accomplished in an expeditious and efficient manner (<2 minutes in about 90% of patients). However, certain disease states such as low output, pulmonary hypertension, and congenital cardiac defects are commonly associated with difficult catheter insertions. In addition, unrecognized technical difficulties may also result in catheterization failure. These include air bubbles in the transducer or tubing that may dampen the pressure waves sufficiently to prevent recognition of the waveforms. Similarly, an improperly set calibration scale can also reduce the waveform deflection to such low levels that important pressure changes go unrecognized. Clotting within or at the tip of the catheter can prevent transmission of the characteristic waveform.

Interpretation of Hemodynamic Data

**Pressure Measurements**

The accurate interpretation of pressure measurements is central to defining the various subsets of patients with abnormal cardiovascular performance. Classically, intravascular pressures have been measured at end-exhalation because no airflow occurs and intrapleural pressure is considered static (Fig. 14-7). In those patients in whom the point of end-exhalation is difficult to discern, direct measurement of re-

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**Figure 14-6.** Pressure waveforms in relation to catheter position from right atrium to pulmonary capillary wedge position. RA, right atrial pressure; RV, right ventricular pressure; PA, pulmonary artery pressure; PCWP, pulmonary capillary wedge pressure.
piratory variables (airway pressure, end-tidal CO₂, and so on) may be necessary. Numerous reports have documented the effects of airway pressure on the correlation between LAP and PCWP. Spontaneous ventilation and non-compliant lungs do not alter the relationship. In contrast, increased airway pressure, as seen with positive PEEP, continuous positive airway pressure (CPAP), airway obstruction, PAC tip placement above the LA, hypovolemia, and obesity all serve to increase the gradient between PCWP and LAP. As a result, controversy exists as to whether PEEP should be temporarily removed in order to accurately measure PCWP. Disadvantages of this technique include a temporary increase in the alveolar-arterial O₂ gradient and potential destabilization of the hemodynamic state. Indeed, if a patient is receiving high levels of PEEP (>10 cm H₂O), spurious cardiovascular information may be obtained even with transient removal of PEEP. Errors in interpretation may also occur as a result of transmural pressure gradients across a vessel. Downes has suggested using direct measurement of intrapleural pressure as a means of more accurately assessing this transmural gradient. Finally, the relatively low resonant frequency of currently available clinical monitoring systems (catheter and tubing system) can be another significant cause of artifact.

Analysis of the pressure waveform may also yield information regarding cardiac pump function. Early reports by Kaplan and Wieland demonstrated in selected patients that abnormalities in the a, b, and c waves in the PCWP trace may be an early indicator of myocardial ischemia. In addition, acute papillary muscle dysfunction or rupture secondary to ischemia or infarction, respectively, may be detected by the onset of v waves in the PCWP trace. Large v waves may be seen in mitral regurgitation due to a dilated annulus, papillary muscle dysfunction, or ruptured chordae tendineae (Fig. 14-8). Unfortunately, the presence of v waves is not a clinically useful method for ischemia detection because it is not a specific marker. The pressure ratio of the v wave divided by the left ventricular systolic pressure has been found to correlate reasonably well with mitral regurgitant volume (r² = .75). The ratio is easily recorded during routine heart catheterization.

**Derived Cardiovascular Variables**

At present, the anesthesiologist is confronted with a data dilemma. On the one hand, it is possible to obtain extensive physiologic measurements in the critically ill patient. On the other, the volume of data, the organization of the data, and the subsequent calculations necessary for clinical management can be overwhelming. Nowhere is this more obvious than in cardiovascular monitoring. The use of the pulmonary artery TD catheter has facilitated the clinician's ability to perform extensive hemodynamic assessments. Using these data, various circulatory disease states can now be defined in terms of pump failure, hypovolemia, and high or low resistance states. Assessment of cardiac performance using the derived indices of cardiac performance such as CO, stroke work index, SVR, FVR, and the O₂ transport provide the foundation for sound physiologic management of the critically ill patient. (Table 14-5). To accommodate patients of varying body size, indexed systemic or pulmonary vascular resistance is often utilized. The sequential and repeated use of these measures provides the opportunity to use therapy aimed at treating specific hemodynamic abnormalities.

**Cardiac Work**

Although some estimation of ventricular function can be obtained by the shape of the ventricular pressure volume...
Table 14-5. Hemodynamic Calculations

Cardiac output (CO) L/min = heart rate × stroke volume

Cardiac index (CI) L/min/m² is calculated as follows:

\[ CI = \frac{CO}{BSA} \]

Stroke volume (SV) or stroke volume index (SVI) overcomes some of the difficulties inherent in the use of CO or CI.

\[ SV = \frac{CO}{Heart\ rate} \quad or \quad SVI = \frac{CI}{Heart\ rate} \]

SV = End-diastolic volume - end-systolic volume

Systemic vascular resistance (SVR) or systemic vascular resistance index (SVRI) is defined as:

\[ SVR\ (RU) = \frac{MBP - RAP}{CO} \]

\[ SVRI\ (RU/m²) = \frac{MBP - RAP}{CI} \]

Pulmonary vascular resistance (PVR) or pulmonary vascular resistance index (PVRI) is defined as:

\[ PVR\ (RU) = \frac{PAP - PCWP}{CO} \]

\[ PVRI\ (RU/m²) = \frac{PAP - PCWP}{CI} \]

Measurement of resistance is reported in one of two methods.

1. Absolute resistance units (ARU) = dynes-sec · m⁻²
2. Hydraulic resistance units (HERU) = RU

To convert HRU to ARU, multiply by 79.9

BSA, body surface area; RU, resistance units; MAP, mean blood pressure; RAP, right atrial pressure; PAP, pulmonary artery pressure; PCWP, pulmonary capillary wedge pressure.

Ventricular Function Curve

The ventricular function curve (VFC) defines the relationship between ventricular filling pressure and ventricular stroke work and is a unifying concept to explain the performance characteristics of a given ventricle. The LV function curves possess certain characteristics. Each has a steep ascending limb, which plateaus at higher filling pressures. Because the RV empties into a lower pressure system (PA), right VFCs have lower values for stroke work and may not possess a plateau. However, with either ventricle, the larger the input (end-diastolic volume), the greater the output (work)(within the limits of normal contractile performance).

Although more sophisticated indices of cardiac performance have been advocated, the VFC serves as one of the best clinical means of physiologically describing the performance of the intact heart. This is due, in part, to the fact that both ordinate (LVSWI) and abscissa (LVEDP, LAF, FPCWP, and the like) are related qualitatively to the two major symptom complexes of patients with heart disease.

The graphic representation of the VFC is based on the work of Ross and Braunwald. They constructed VFCs relating LV filling pressures and LVSWI. These curves were derived from data obtained under controlled conditions during cardiac catheterization. From these data the authors described three curves of ventricular function: normal function, mildly depressed ventricular function, and grossly depressed ventricular function.

The use of LVSWI rather than cardiac output or stroke volume has several advantages:

1. LVSWI defines the area within a pressure volume loop.
2. LVSWI includes measurements of both systolic and diastolic performance.
3. LVSWI contains the major variables that alter cardiac performance (e.g., heart rate, preload, afterload).

An upward shift to the left has been interpreted as an improvement in ventricular performance. A shift downward and to the right has been considered as a deteriorating ventricular performance. In addition to changes in contractility, many interventions, including alternations in preload, afterload, heart rate, and ventricular compliance, can produce shifts in the VFC. On this basis, some authorities have held that the use of LVSWI is too global to be informative. However, the directional changes of the VFC allow qualitative assessment of overall cardiac performance.

Derived Indices of Respiratory Performance

Derived indices, especially those concerning oxygen delivery, can play an important role in optimizing respiratory evaluation and support of critically ill patients. Nowhere is the interplay of respiratory and circulatory function more frequently assessed than in the selection of the optimal level of PEEP. Just as there is no one perfect measure of cardiac function, no single parameter will define the optimal level of respiratory performance for all patients. The optimal level of PEEP has been variously defined as follows:

The best PaO₂ does not necessarily infer the optimal level of PEEP. As PaO₂ is increased by higher levels of PEEP, transport of oxygen to the tissues may actually decrease (secondary to decreased cardiac output). Similarly, the lowest alveolar-arterial oxygen gradient may be a function of an improvement in PaO₂ regardless of the effect on cardiac output. A reduction in intrapulmonary shunt to less than
Table 14-6. Complications (Case Reports) Associated With the Use of Pulmonary Artery (PA) Catheters

<table>
<thead>
<tr>
<th>Venous Cannulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air emboziation</td>
</tr>
<tr>
<td>Arterial puncture</td>
</tr>
<tr>
<td>Homer's syndrome</td>
</tr>
<tr>
<td>Hematoma</td>
</tr>
<tr>
<td>Nerve injury</td>
</tr>
<tr>
<td>Phrenic nerve block</td>
</tr>
<tr>
<td>Pneumothorax</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Catheter Passage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrhythmias</td>
</tr>
<tr>
<td>Knotting</td>
</tr>
<tr>
<td>Knotting on papillary muscle</td>
</tr>
<tr>
<td>Pneumoperitoneum</td>
</tr>
<tr>
<td>Separation of introducer from hub</td>
</tr>
<tr>
<td>Bundle branch block</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Catheter In Situ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aberrant waveform due to balloon rupture</td>
</tr>
<tr>
<td>Bradycardia secondary to thermodilution cardiac output measurement</td>
</tr>
<tr>
<td>Cardiac valve injury</td>
</tr>
<tr>
<td>Catheter fracture</td>
</tr>
<tr>
<td>Deep venous thrombosis</td>
</tr>
<tr>
<td>Endobronchial hemorrhage</td>
</tr>
<tr>
<td>Endocarditis</td>
</tr>
<tr>
<td>False-positive lung imaging</td>
</tr>
<tr>
<td>False-positive echocardiography</td>
</tr>
<tr>
<td>Hemoptysis</td>
</tr>
<tr>
<td>Intraoperative transaction of a catheter</td>
</tr>
<tr>
<td>Migration of pediatric PA catheter</td>
</tr>
<tr>
<td>PA perforation</td>
</tr>
<tr>
<td>Pulmonary infarction</td>
</tr>
</tbody>
</table>

15% has been thought to be a therapeutic goal that is consistent with adequate respiratory performance. Other reports emphasize that the best compliance coincides with optimal PEEP. Finally, an optimal level of PEEP has been defined as that which promotes the highest oxygen transport to the peripheral tissues.

Complications

Experience gained with more than a decade of use of the PAC in a wide variety of clinical situations has revealed a large variety of complications which can, and do, occur (Table 14-6). These range from minor sequelae of catheter use, without clinical significance, to those with a fatal outcome. As a matter of fact, Alschuler notes that there are complications of vascular catheters—a new branch of medicine.

Swan, in his initial report describing 100 patients, noted only transient premature ventricular contractions, 2 cases of intravascular thrombosis, and 10 cases of balloon failure. The last may have been related to the fact that catheters were reused. Despite numerous case reports that have detailed, the occurrence of specific complications resulting from PAC insertion, few large series exist that quantify complication rates. More recent reports have focused on specific complications resulting from PAC insertion (Table 14-7).

For the purpose of this discussion, the complications arising from the use of a Swan-Ganz catheter can be usefully grouped in three categories:

1. Those associated with venous cannulation
2. Those associated with passing the catheter
3. Those occurring after the catheter is in place

Table 14-6 lists the variety of complications associated with the use of a Swan-Ganz catheter. Most complications are avoidable by meticulous attention to technique. Table 14-8 outlines associated factors and prevention and treatment.

### Venous Cannulation

Arterial Puncture

The complications occurring during venous cannulation are, with a few exceptions, the same as those which may occur during insertion of any central venous catheter (CVC). The frequency of arterial puncture depends on several variables such as operator skill and experience, site of insertion, and the urgency of the situation. However, it should be noted that arterial puncture has been reported in conjunction with all insertion sites. The carotid artery can be punctured during attempts at cannulating the internal jugular vein. Shah et al. reported a 1.9% incidence of carotid artery puncture in more than 6000 patients receiving PACs. Another report reported an incidence of 4 perforations in 1500 cannulations. Methods to confirm that the insertion site is venous and not arterial include pressure waveform analysis, the usual comparison with blood in the arterial tubing, and blood gas laboratory measurements of Pao2. Although most arterial punctures result in minimal morbidity, on occasion it has resulted in dissection of the right common carotid, subclavian, and innominate arteries and, rarely, death has been reported. Early recognition followed by pressure over the puncture site will lead to immediate cessation of

### Table 14-7. Reported Incidence of Adverse Effects Resulting From Pulmonary Artery (PA) Catheter Insertion

<table>
<thead>
<tr>
<th>Complication</th>
<th>Reported Incidence (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Central Venous Access</strong></td>
<td></td>
</tr>
<tr>
<td>Arterial puncture</td>
<td>1.1-13</td>
</tr>
<tr>
<td>Bleeding at cutdown site (children)</td>
<td>5.5</td>
</tr>
<tr>
<td>Postoperative neuropathy</td>
<td>0.3-1.1</td>
</tr>
<tr>
<td>Pneumothorax</td>
<td>0.3-4.5</td>
</tr>
<tr>
<td>Air embolism</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Catheterization</strong></td>
<td></td>
</tr>
<tr>
<td>Minor dysrhythmia*</td>
<td>4.7-68.9</td>
</tr>
<tr>
<td>Severe dysrhythmia (ventricular tachycardia or fibrillation)*</td>
<td>0.3-62.7</td>
</tr>
<tr>
<td>Right bundle branch block*</td>
<td>0.1-4.5</td>
</tr>
<tr>
<td>Complete heart block (in patients with prior left bundle branch block)*</td>
<td>8.0-8.5</td>
</tr>
<tr>
<td><strong>Catheter Residence</strong></td>
<td></td>
</tr>
<tr>
<td>PA rupture*</td>
<td>0.1-1.5</td>
</tr>
<tr>
<td>Positive catheter tip cultures</td>
<td>1.4-34.8</td>
</tr>
<tr>
<td>Catheter-related sepsis</td>
<td>0.1-14.4</td>
</tr>
<tr>
<td>Thrombophlebitis</td>
<td>6.5</td>
</tr>
<tr>
<td>Venous thrombosis</td>
<td>0.5-66.7</td>
</tr>
<tr>
<td>Pulmonary infarction*</td>
<td>0.1-5.8</td>
</tr>
<tr>
<td>Mural thrombus*</td>
<td>28-61</td>
</tr>
<tr>
<td>Valvular/endothelial vegetations or endocarditis*</td>
<td>2.2-100</td>
</tr>
<tr>
<td>Deaths (attributed to PA catheter)*</td>
<td>0.02-1.5</td>
</tr>
</tbody>
</table>

*Complications thought to be more common or exclusively associated with PA catheterization than with central venous catheterization.

Table 14-8. Pulmonary Artery Catheter Complications, Associated Factors, and Prevention and Treatment

<table>
<thead>
<tr>
<th>Complications</th>
<th>Associated or Causative Factors</th>
<th>Prevention/Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balloon rupture</td>
<td>Repeated infusions</td>
<td>Do not inflate the balloon if a rupture is suspected</td>
</tr>
<tr>
<td></td>
<td>Excessive inflation volumes</td>
<td>Use pulmonary artery diastolic pressure whenever possible, because diastolic pressure</td>
</tr>
<tr>
<td></td>
<td>Prolonged catheterization</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Prolonged shelf life or absorption of lipoproteins resulting in weakened structural integrity of the balloon</td>
<td></td>
</tr>
<tr>
<td>Less Common Complications</td>
<td>Intensive occlusion of the pulmonary artery</td>
<td>Inflate the balloon slowly under continuous pulmonary arterial monitoring</td>
</tr>
<tr>
<td>Pulmonary artery rupture</td>
<td>Balloon inflation with fluid</td>
<td>Discourage inflation once pulmonary capillary wedge pressure is obtained</td>
</tr>
<tr>
<td></td>
<td>Excess catheter looping</td>
<td>Keep wedge time to a minimum (&lt;8-15 s)</td>
</tr>
<tr>
<td></td>
<td>Pulmonary hypertension</td>
<td>Prophylactic pacemaker</td>
</tr>
<tr>
<td>Complete heart block</td>
<td>Preexisting left bundle branch block</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Loop tightening (exerts direct pressure on the conduction system)</td>
<td></td>
</tr>
<tr>
<td>Cardiac tissue injury</td>
<td>Forceful catheter withdrawal without deflated balloon</td>
<td>Always deflate the balloon when withdrawing the catheter</td>
</tr>
<tr>
<td>Catheter knotting</td>
<td>Inadequate balloon inflation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Repeated catheter manipulation</td>
<td>Argid-catheter redundancy</td>
</tr>
<tr>
<td></td>
<td>Catheter insertion with deflated balloon</td>
<td>Use estimates of average insertion lengths when catheterizing a patient without fluoroscopic guidance</td>
</tr>
</tbody>
</table>

Bleeding without further consequence. However, large hematomas can occur leading to respiratory compromise, arterial compression, or exsanguination. The more serious sequelae are much more likely to occur if the large bore-introducer has been inserted into the artery. The incidence of this complication has been reported as 0.0995% in one series. Arterial perforation in patients who are, or are subsequently to be, given heparin may result in cancellation of surgical procedures. Another possibility is that atherosclerotic plaques may be dislodged and embolized to the cerebral circulation. Puncture of the subclavian artery may be more insidious. Evidence of bleeding is not readily visible, nor can pressure be easily applied. The first evidence of subclavian artery puncture may be the appearance of a hematoma on chest radiograph.

Presently, insertion techniques are aimed at increasing the ease of finding the vein and minimizing the risk of arterial injury. Techniques that result in engagement of the internal jugular and subclavian veins such as use of Trendelenburg's position, coughing, Valsalva's maneuver, or the inspiratory phase of mechanical ventilation all contribute to a successful cannulation. Similarly, the use of a 20-gauge "finder" needle as a preliminary to locating the vein will produce a smaller hole in the event of an inadvertent arterial perforation. Once the vein has been located, this small needle can be left in place to serve as a visual guide for insertion of the larger needle. Unfortunately, arterial puncture can still occur with the second needle, although much less frequently. The technique described by Civetta and Gobelet uses a 20-gauge spinal needle as the finder with a 16-gauge over-the-needle catheter threaded on the spinal needle prior to insertion. Schwartz and colleagues have emphasized the importance of transducing the IV catheter or needle before the guide wire is passed. In their series, a number of patients sustained unrecognized carotid artery puncture with passage of an 8F sheath into the artery. In a subsequent group of patients in whom pressures were transduced, no sheaths were inserted in the carotid artery.

Previous arterial puncture often precludes subsequent use of the vein in the same location. Following the development of a hematoma, attempts at cannulation yield blood from the hematoma that cannot be distinguished from that of ventricle. If arterial puncture occurs and a hematoma develops, we recommend use of another venous access site when feasible. If the carotid artery is entered prior to cardiac surgery, we recommend postponement due to heparinization and possible expansion of the hematoma. This may not be possible in urgent or emergent situations. In these cases, the neck is prepared and draped into the surgical field where the hematoma may be observed. Following heparinization, if the hematoma is enlarging, surgical exploration may be necessary before CPB.

Pneumothorax

Violation of the pleural space during attempts at venous cannulation is a well-recognized complication of both the subclavian and internal jugular vein approaches. The incidence of pneumothorax depends on both operator experience and cannulation site. In patients being mechanically ventilated, a simple pneumothorax may be converted into a tension pneumothorax, resulting in serious respiratory and circulatory compromise. In these patients, the insertion of a chest tube is indicated, with more urgency being demanded for a tension pneumothorax. If a chest tube is not immediately available, needle aspiration of the pleural space will relieve symptoms temporarily. If possible, a chest film should be obtained following PAC insertion, not only to confirm catheter position but to exclude the presence of pneumothorax. However, intraoperatively this is not routinely feasible. Because of differences in solubilities of gases, nitrogen oxide will diffuse into any pneumothorax much faster than nitrogen can diffuse out. This can lead to a doubling or tripling of the size of the pneumothorax in a very few minutes, leading to the development of cardiovascular compromise. Clinically, unexpected rises in PCWP and pulmonary artery diastolic pressure (PADP) are the earliest signs of pneumothorax. For this reason, attempts at subclavian cannulation are not advised intraoperatively or preoperatively when chest films cannot be obtained on a regular basis. In addition, hemotherax or hemothorax or pneumothorax can occur rarely when the subclavian or low internal jugular approach is used.
Air Embolism

Despite the theoretical likelihood of air embolus occurring with some frequency during venous cannulation (especially through the large-bore introducers), very few reports have appeared in the literature documenting its occurrence.523-534 Fatal air embolism has been reported to occur through smaller-bore CVCs connected to continuous flush systems.456 Only three cases of clinically significant embolism have appeared in the literature that were associated with the insertion of a Swan-Ganz catheter.318-319 Two of these were in conjunction with an introducer that had no provision for a self-sealing valve following removal of the catheter. The third was detected in a study in which Doppler monitors were placed over the right parasternal area specifically to study the occurrence of air embolism.412 No clinical changes were noted at the time of embolization. Had it not been for the presence of the Doppler monitor, no suspicion of air embolus would have arisen. The utilization of Trendelenburg's position is probably responsible for preventing many air emboli. Nonetheless, air embolus probably occurs more frequently than we are aware of, but insufficient air enters the venous circulation to cause clinical symptoms. A recent report by Moorthy and colleagues946 illustrates that venous air embolism can also occur during removal of the PAC.

Neurologic Deficit

Nerve injury during percutaneous venous catheterization is rare. Traumatic injury during attempts at venous cutoff has been reported.317 As a result of trauma to the subclavian, Horner's syndrome has been described during internal jugular catheterization.346-319 In a series examining neurologic deficits following open heart surgery, 4.1% of internal jugular vein catheterizations were associated with ipsilateral nerve deficit.520 One report has emphasized the fact that complications of mediastinal hematoma may also result in a similar neurologic presentation as that observed in venous cannulation.521,522 This makes identifying the precise cause of neurologic deficit difficult. However, when a peripheral neurologic deficit is observed, extensive workup is indicated. Both transient and permanent phrenic nerve injury has been reported with internal jugular and subclavian approaches.524,525 Brown890 reported ten patients in whom an ETT introducer was inserted into the right common carotid artery. Cerebral embolization, rather than prolonged catheterization of the artery, led to a left hemiparesis.503

__Passage of the Pulmonary Artery Catheter__

Arrhythmias

The most common complication during catheter passage is the development of cardiac arrhythmias. Swan and Ganz528 reported a 13% incidence of transient premature ventricular contractions in their original report. Since then, numerous studies have documented an incidence of isolated premature ventricular contractions ranging from 12% to 48%.24,257 Those studies reporting the lower incidence relied on visual observation of an oscilloscopic ECG monitor during insertion, while investigators reporting the higher incidence of this complication (46% and 48%) relied on continuous ECG tracings for their data collection. As a result, the true incidence of premature ventricular contractions is probably closer to the latter. Ventricular tachycardia has been noted in as many as 33% of patients.529 VF has been reported as well. The incidence of arrhythmias may be related to the time required to float the catheter into the PA.328 In a study by Lopez-Sendon51 the presence of a recent right ventricular infarction (RVI) increased the incidence of VF during passage of the PAC (4.2% with RVI vs. 0.28%). In this same study, the incidence of VF was also higher during PAC insertion in patients suffering from AMI (1.07% versus a 0.85% overall rate of VF).

PAC-induced ventricular arrhythmias are most frequently characterized by right bundle branch block (RBBB) morphology and inferior frontal plane axis.539 In a large series of insertions analyzed for new and complex arrhythmias, 5% of patients sustained a new RBBB.456 Casellas et al.331 theorize that damage to the bundle of His may occur during passage of the PAC through the RV resulting in RBBB. In the majority of patients, this conduction abnormality has no significance. In one patient RBBB was only seen during balloon inflation.532 However, in patients with preexisting LBBB, complete heart block may result with passage of the catheter through the RV chamber.533 If catheterization is required for these patients, a pacing electrode should be available. Alternatively, transcutaneous pacing could be used in these situations. Using this approach, should complete heart block develop during insertion, the patient can be transcutaneously paced. A multipurpose (pacing) Swan-Ganz catheter may be placed in this situation. Parenthetically, the RV section of the pacing catheter shaft is stiffer and may actually predispose to RBBB. Left fascicular block or LBBB has also been reported with PAC insertion.

Clinically significant arrhythmias, including ventricular tachycardia and asystole, have also been reported on removal of PAC (65% incidence).24,532 The mechanism of production of these arrhythmias is the result of mechanical stimulation of the cardiac conduction pathways. Theoretically, the design of the catheter balloon prevents the tip of the catheter from contacting the ventricular surface. It was originally believed that this feature would eliminate arrhythmias during insertion. No doubt, it has reduced the incidence of serious arrhythmias. Nonetheless, sufficient force is generated when the balloon or free portion of the catheter contacts the ventricular wall to simulate the conduction system in a high percentage of patients. Production of arrhythmias can be minimized by passing the catheter rapidly once the RV is reached. Lidocaine 1.0 to 1.5 mg/kg IV, has been shown to be effective in reducing the incidence of ventricular arrhythmias.544-537 We use lidocaine when previous catheter passage has resulted in hemodynamically significant arrhythmias. However, Salmenpera et al.537 have shown that prophylactic use of lidocaine is ineffective.

In addition to the development of arrhythmias, a recent report demonstrates that the PAC may lodge in the coronary sinus during insertion.318 Resistance to passage from RA to RV in conjunction with an observation of the systemic pressure trace should alert the clinician to this possibility. Similarly, Alyn et al.338 reported the inadvertent passage of a PAC from the SVC through the LA and LV. Close observation of acute change in the waveform of the PAC should have alerted these authors to a potential change in PAC location.338 Electrode separation from a multipurpose pacing PAC has been reported. As a result, the manufacturer has made specific recommendations for removal of this type of catheter.

__Intracardiac Knotting__

Several reports of intracardiac knotting of a PAC have appeared.539 Most knots probably occur during insertion when coiling in the RA or RV can occur.246 These knots may
take the form of free, single, or double knots in the catheter, or more ominously, may incorporate intracardiac structures such as a papillary muscle and chordae tendineae, or the lead from a cardiac pacemaker. Knots may be diagnosed from postinsertion radiographs, or during attempts to remove the catheter, when resistance to withdrawal is felt.26,27

The knot may be withdrawn through the original venotomy site.269 More often, it becomes necessary to utilize one of a number of fluoroscopic techniques in the cardiac catheter laboratory in which the knot can be either tightened or untied or the catheter cut.558-559 Many successful nonsurgical techniques for removal of the knot have been described.263,264 Occasionally operative intervention becomes necessary.

The suspicion of a coil during insertion should be raised whenever an undue length of catheter has been inserted without achieving the expected Intracardiac pressure tracing. Normal distances from insertion site to RA, RV, PA, and wedge position are shown in Table 14-3. When these reference points are exceeded by about 10 cm without the tip of the catheter reaching the appropriate location, the balloon should be deflated and the catheter withdrawn to the RA. If resistance is encountered, all attempts at withdrawal should cease and a chest film should be immediately obtained. Another sign suggestive of coil is the occurrence of ventricular arrhythmias at a time when pressure tracings indicate the tip is still in the RA. Use of TEE to guide PAC placement in difficult cases has been described.315

Patients with a transvenous pacemaker in place who also require PAC monitoring are at risk of having the catheter become entrained around the pacing lead. Insertion of a PAC in such a patient should be performed under fluoroscopy. Venous cannula obstruction by the PAC during CPB has been described.265

Isolated complications occurring during PAC insertion include torn chordae tendineae, probably caused by multiple attempts at insertion and withdrawal of the catheter while the balloon was still inflated.267 Aberrant catheter locations have been reported, including the pleural space, the peritoneal cavity, the renal vein, the aorta, and the vertebral artery.358 Most, if not all, of these complications probably could have been prevented by strict adherence to the previously described insertion techniques (see Table 14-2). Severe pulmonary hypertension secondary to embolization of a PAC fragment into the right PA has been described, which resolved with migration of the fragment to the lung periphery.299

The right PA was injured in 93% of cases. Several significant risk factors for the development of PAC perforation have been identified. Advanced age, hypothermia, and pulmonary hypertension place the patient at greater risk for perforation.380,381 Furthermore, as noted, females have a higher incidence of perforation. Of 24 patients who had a PA perforation and in whom PA pressures were reported, 22 had pulmonary hypertension. In addition, deviations from standard insertion techniques have been noted in at least 10 of 56 reported cases as well.382-389

The presenting sign of PA perforation in most cases is the sudden appearance of hemoptysis. Characteristically the blood is bright red and may vary in amount from less than 5 mL to massive bleeding.398-399 Usually this episode of bleeding is related to balloon inflation on catheter manipulation. However, hemoptysis may also be caused by flushing the catheter in the wedge position.397 Acute pulmonary hypertension after wedging of a PAC may be a clue to PA perforation.396 Use of an external balloon can limit balloon pressures within the PA and identify when excessive volumes are being forced into the PA balloon.391

Treatment of PAC perforation is largely supportive. If bleeding is massive, the patient must be intubated. If a double-lumen endotracheal tube is not available, an ordinary single-lumen endotracheal tube should be advanced into the mainstem bronchus of the noninvolved lung, usually the left. If the patient has received heparin, it should be reversed if possible. Massive blood and fluid replacement may be necessary, as well as operative intervention. The mortality rate is 70% in patients with hemoptysis, and urgent thoracotomy is essential to survival in this setting.92,93 Conservative management strategies are associated with a high incidence of secondary, often fatal, hemorrhage. PEEP has been used, as well, in an attempt to compress the bleeding site.392-394 PA perforation has been described as a complication following CPB. Rice et al.395 reported a patient who sustained a PA perforation following CPB. In this situation, reversal of heparinization with protamine resulted in a resolution of the hemorrhage.

Controversy exists about what to do with the PAC once a PA perforation is suspected (i.e., do you have the balloon up, put more air in the balloon, or take the PAC out?). Barasch et al.99 commenting on the early reports of PA perforation, suggested that pulling the PAC back with the balloon down about 5 to 10 cm was appropriate. The authors suggested that by doing this one could then inject some contrast media into the PAC to radiographically identify the precise location of the PA perforation. This could then be used to guide surgical interventions (i.e., wedge resection vs. pneumonectomy) if necessary.11 Resnick et al.96 recently reported on the ability of angiography to aid in the diagnosis and localization of PA perforation.

The common feature of PA perforation in most patients is distal location of the tip of the PAC (although it has been reported with a more central location as well).300 (Fig. 14-9). When the tip is located too far distal, balloon inflation can distend the vessel wall, subjecting it to large transmural pressures.97 Distal catheter placement can occur as a result of failure to follow currently accepted insertion techniques or in the presence of pulmonary hypertension. The most frequently observed technical error is the use of less than 1.5 mL of air to inflate the balloon during PAC insertion. This allows the tip of the catheter to pass into smaller, more distal vessels. Subsequent balloon inflation with the full 1.5 mL will then overdistend the vessel, increasing the risk of PA perforation. The original description of the PA insertion technique of PA perforation by Swan and Ganz and colleagues suggested advancing the tip of the catheter...
1 to 3 cm with the balloon deflated after the initial wedge pressure was obtained. However, this can also lead to distal placement. Pulmonary hypertension may lead to distal placement by distending smaller pulmonary arteries, thus allowing the catheter to wedge in a more distal location. PA hypertension can also lead to degenerative changes in the vessel wall such as sclerosis and aneurysmal dilation, which may further predispose the vessel to rupture. A case of PA perforation has been reported secondary to pneumothorax, which caused mediastinal shift to the right, elevated PA pressures, and distal migration of the PAC. RV perforation by a PAC during coronary artery bypass surgery has been described. The fact that the catheter tip is in a distal location may be identified by the phenomenon of overwedgeing (Fig. 14-10). Overwedgeing results from impingement of the tip of the catheter against the vessel wall or herniation of the balloon over the catheter tip. The continuously rising pressure trace seen with this phenomenon results from the high-pressure flush system. Therefore, if overwedgeing is observed, the catheter should be withdrawn until a normal wedge tracing is obtained.

Several mechanisms that may be responsible for PA perforation have been described (Fig. 14-11). Inflation of the balloon with a distally located catheter tip can lead to direct tearing of the vessel. Eccentric balloon inflation, as demonstrated by several investigators, can expose the catheter tip and actually propel it through the arterial wall. This mechanism can be aggravated by the gradient existing with pulmonary hypertension. The tip of the catheter may become lodged in a small vascular branch and may erode or perforate directly. Direct perforation may also occur during insertion: Migration of the catheter tip to more distal location during cardiac surgery has also been postulated as a potential mechanism.

One safeguard that can clearly reduce the potential of PA perforation is to minimize the number of balloon inflations. In view of the fact that PAPD agrees very well with PCWP (in the absence of pulmonary hypertension), we recommend that the PAPD be used, whenever possible, as an indirect measurement of LAP. If this is done the tip of the catheter can be left in a very proximal location, 4 to 5 cm beyond the pulmonic valve. If a true wedge pressure is required, the catheter can be floated into position through an external sheath which protects the catheter. Faber et al. also reported a patient who not only had PA perforation but also pneumothorax upon removal of the PAC. Culpepper and colleagues also reported a patient who had massive hemoptysis and tension pneumothorax following insertion of a fiberoptic PAC. They hypothesized that perforation of a small artery and visceral pleura occurred following persistent wedging of the catheter. Since these early reports, several authors have demonstrated that the development of hemoptysis in patients with PAC in place should alert the clinician to the possibility of PA perforation. These authors also suggest that patients who survive the PA rupture (mortality rate of 40% to 70%) should undergo further studies.

Figure 14-9. Postmortem helium gel studies showing extravasation of gel at the site of pulmonary artery perforation. The distal migration of the catheter presumably occurred with cardiac manipulation during cardiopulmonary bypass. (From Ikeda S, Yagi K, Schweiss JF, et al: In vitro reappraisal of the pulmonary artery catheter balloon volume-pressure relationship: Comparison of four different catheters. Can J Anaesth 1991; 38:648-653.)

Figure 14-10. Intracorporeal pulmonary artery pressure tracing demonstrating overwedgeing patterns observed with balloon inflation. This pattern results from the catheter tip impaling against the vessel wall, or balloon herniation over the catheter tip. The pulmonary artery catheter is withdrawn 3 cm and a normal transition from pulmonary artery to pulmonary capillary wedge pressure is obtained. (From Ikeda S, Yagi K, Schweiss JF, et al: In vitro reappraisal of the pulmonary artery catheter balloon volume-pressure relationship: Comparison of four different catheters. Can J Anaesth 1991; 38:648-653.)
aimed at diagnosing a possible catheter-induced pseudoaneurysm.\textsuperscript{210, 217} If such a pseudoaneurysm is found, it must be obliterated to prevent further bleeding.\textsuperscript{602} Recently, immediate transcatheter steel coil embolization of a PAC-induced FA pseudoaneurysm has been described.\textsuperscript{604, 605} In a recent series, seven false aneurysms of the FA were diagnosed in five patients (four women, one man) age 67 to 81. All five patients underwent PAC placement to monitor cardiac surgery.\textsuperscript{493}

Pulmonary Infarction

Early reports indicated that pulmonary infarction also resulted from distal placement of the catheter.\textsuperscript{607, 608, 499} The mechanism responsible for distal placement has been described in the previous section. The sequelae of PA infarction may include deep venous thrombosis (DVT) with embolization, endothelial damage, or permanent wedging of the catheter tip in a distal PA. Clinical states characterized by low cardiac output may further predispose to this complication. Usually the diagnosis of pulmonary infarction is made by chest film.

As with PA perforation, prevention is directed at avoiding distal placement of the catheter, avoiding persistent balloon inflation, and use of a continuous high-pressure flush system with heparinized saline.

Thrombosis and Coagulopathies

Several studies have documented the fact that PACs are thrombogenic. Substantial thrombi (several hundred milligrams) will form on virtually 100% of catheters in vivo within 1 to 2 hours of insertion.\textsuperscript{268, 217, 410, 412} These thrombi are capable of causing both damped pressure tracings and yielding inaccurately low cardiac output measurements.

Connors et al.\textsuperscript{270, 36} performed detailed postmortem examination on 32 consecutive patients brought to autopsy with a PAC in place. Thrombosis or hemorrhage related to PAC was found in 29 (91%) patients.\textsuperscript{270, 363} The incidence of thrombosis was higher after 36 hours of catheterization.

In addition, massive thromboses of the subclavian vein\textsuperscript{217} and the SVC\textsuperscript{413} have been reported. Devitt et al.\textsuperscript{357} reported a case in which catheter thrombus was apparently stripped off the PAC during removal and embolized across a VSD to the cerebral and coronary circulations.

One hypothesis for the occurrence of pulmonary infarction or embolus is the development of thrombus on the catheter body. Although no report has directly shown embolization from such thrombi, much circumstantial evidence exists.\textsuperscript{404, 412, 414} In addition to the potential damage to the pulmonary parenchyma, Devitt et al. reported embolization across a VSD: the origin of which was thought to be from the PAC.\textsuperscript{357} Early reports by Brunswick and Gondis\textsuperscript{413} stated that stanch crystals were seen on microscopic examination of the PAC clot. As a result, stanch has been abolished in the subsequent manufacture of PACs. In an attempt to reduce thrombotic complications, heparin bonding of the catheters is now routine. Heparin bonding prevents thrombosis in a canine model and in humans.\textsuperscript{412} A meta-analysis of randomized controlled trials has shown that heparin administration effectively reduces thrombus formation and may reduce PAC-related infection.\textsuperscript{414} However, at present, no published study shows a lower mortality when heparin-bonded catheters are inserted and one study suggested that the failure rate of PACs was not increased by the use of nonheparinized solutions, unlike arterial catheters.\textsuperscript{417} Comparisons of cost-effectiveness of unfractionated heparin, low-molecular-weight heparin, and warfarin are also needed.\textsuperscript{416} One study demonstrated an association between 8.5F femoral vein catheters and an increased incidence of DVT, and the authors concluded that this technique should not be routine.\textsuperscript{418} In addition, thrombosis has also been reported at insertion sites, such as the internal jugular vein.\textsuperscript{419}

At the other end of the spectrum is the possibility of coagulopathies in patients with a PAC. Kim et al.\textsuperscript{426} originally presented data to show thrombocytopenia related to PAC in
Infection

Septic complications of PACs have been documented by many investigators. While evaluating these studies, it is important to remember that patients with PACs have other sources of infection present, for example, urinary catheters, IV catheters, and so on. While their occurrence is clearly demonstrated, the incidence and significance of these complications is less well known. It is difficult to separate colonization, contamination, and infection in published studies. Fortunately, reports of serious sequelae of positive catheter cultures are rare. The fortuitous surface antimicrobial activity of heparin-bonded catheters may account for the low incidence of catheter-related bacteremia (mean, 1.06%) compared with PACs of the same materials but not coated with benzalkonium-heparin (mean, 2.8%). Elliott et al. have provided a useful classification for the study of catheter sepsis. They defined colonization as a positive culture of the catheter tip without evidence of local or systemic infection. Contamination is defined as one of multiple blood cultures yielding a typical nonpathogenic and culture of the catheter tip failing to grow any organisms. Infection can be (1) definite—positive blood and catheter cultures yielding the same organism; (2) probable—the same organism cultured from blood and catheter with no other probable source of infection; or (3) unrelated—if the same organism had been previously recovered from another source.

The reported incidence of catheter-related sepsis varies widely from 2% to 3.6%. Earlier reports disagreed on the impact of the duration of catheterization on rates of infection. The skin insertion wound is the major source of catheter contamination. Sensitivity in diagnosis of PAC colonization can be improved by evaluating both the tip and intradural segments. In the presence of an indwelling introducer, the introducer tip should be used. Studies by Mermel et al. and Raad et al. have provided new evidence for the role of duration of placement as a predictor of PAC-related infections. Mermel et al. demonstrated an overall rate of local infection of 22% (65 of 297 catheters). The authors further subdivided these PAC-related infections into those which occurred as a result of local infection of the insertion site (20/297) or the intradural portion of the PAC catheter (20/297); only two catheters (0.7%) caused bacteremia. Eighty percent of infected catheters (the introducer or the PAC itself) showed concordance with organisms cultured from skin of the insertion site. Of these, 17% were the result of a contaminated hub and 18% were organisms contaminating the extravascular portion of the catheter beneath the sleeve. The following were identified as increasing the relative risk (RR) of PA infection: (1) cutaneous colonization of the insertion site with more than 100 CFU (RR 5.5, P < .001), (2) insertion into an internal jugular vein (RR 4.3, P < .001), and (3) insertion in the OR using less stringent barrier precautions (RR 2.1, P = .05). Similarly, Raad et al. found that 17% (5/71) of PACs in their study produced local infections and 5.5% (5/71) led to sepsis. These episodes of septicemia were directly related to the duration of PAC placement. Catheter-related septicemia occurred at rates of 2% and 16%, before and after 7 days of catheter placement, respectively. Further analysis of their data (life table analysis) showed that the cumulative risk of developing a catheter infection increased from 9% to 18% after 4 days of placement of the PAC. As a result of the data from these studies we recommend that the PAC be changed to a new site every 4 to 7 days. It is recommended that the use of a guidewire technique for catheter replacement (PAC to CVC) is a safe alternative to de novo insertion of a CVC within 48 hours after initial insertion of the PAC.

Recently, the use of sterile sleeves has been advocated for repositioning the PAC in a sterile fashion. However, the precise benefit of these devices in substantially reducing PAC infections remains to be elucidated. A recent randomized study using a PAC that is completely shielded during balloon testing, preparation, and insertion (Arrow Hands-Off thermolubrication catheter) has demonstrated a reduced incidence of systemic infections associated with prolonged PAC catheterization.

Not only are localized and systemic infections of concern, but PACs may also be associated with an increased incidence of cardiac valve injury and endocarditis. Smith and coworkers reported ruptured chordae tendineae of the tricuspid valve as a result of withdrawing the PAC with the balloon inflated. Isolated case reports of erosion of the pulmonary and tricuspid valves were followed by several series documenting an increased incidence of aseptic endocarditis. In a retrospective analysis Pace and Horton noted three cases of aseptic endocarditis in 88 catheterized patients compared with 1 in 205 unchattened patients. Greene and Cummings found four cases in 24 autopsies. An additional four cases occurred in the 270 nonchattened patients. Subsequently, Greene et al. reported that 1 in 493 patients dying prior to introduction of the PAC developed septic endocarditis, whereas 10 of 483 patients with PAC developed this condition. Routine PAC hemodynamic monitoring is not associated with an increased rate of prosthetic aortic graft infection.

Earle et al. noted that all six burn patients studied developed endocarditis and Sasaki et al. documented a statistically significant increase in the incidence of this complication in 1105 burn patients following introduction of the PAC. In contrast, Katz et al. were unable to find evidence of valvular damage.

Limitations

In addition to the complications associated with invasive monitoring, a major limitation of PACs is the assumption that intracardiac pressure measurements (PCWP) are a good approximation of the volume status of the ventricle. Preload can be clinically defined as being equal to end-diastolic volume. The use of PCWP to directly or indirectly assess preload assumes a linear relationship between ventricular end-diastolic volume and ventricular end-diastolic pressure. However, alterations in ventricular compliance can affect this pressure-volume relationship. Hansen et al. demonstrated this poor correlation between FAP and LVEDV following CABG surgery. In this study, LVEDV was determined using concomitant determinations of ejection fraction, gated blood pool scintigraphy, and stroke volume (determined from TD cardiac output). The authors postulated that an altered ventricular pressure-volume relationship may reflect acute changes in ventricular compliance in the first few hours following bypass surgery. Reductions in ventricular compliance (upward shift to the left) can be seen with myocardial ischemia, shock, RV overload, and pericardial effusion. Ventricular compliance is increased with vasodilators such as nitroglycerin and sodium nitroprusside.

Cain et al. made simultaneous pressure and volume measurements using radionuclide angiography in patients with sepsis and in another group with acute cardiac illnesses. They found no relationship between LV end-diastolic pressure and PCWP in either group (r = .58). The correlation decreased further when PEEP was employed (r = .30). Beauve
et al.,69 using 2-D echocardiography, reported similar findings in a group of anesthetized patients. They concluded that using PCWP as a guide to fluid therapy may be misleading.69

This was further emphasized by Marmasa and colleagues,31 who examined the relationship of PCWP and LAP in patients undergoing coronary artery bypass surgery. In this study, PCWP was a poor predictor of LAP in the early postoperative period. They hypothesized that pulmonary venous constriction resulting from increased pulmonary extravascular water (due to hemodilution of CBF) accounted for the difference between LAP and PCWP.31

Ellis and colleagues,46 also using intraoperative radionuclide monitoring (gated pool), found alterations in ventricular diastolic and systolic performance that were not appreciated on routine hemodynamic monitoring. In patients with an LVEF less than 50% undergoing coronary artery bypass, a decreased ventricular compliance suggested that this group of patients required closer observation and increased cardiovascular support in the postbypass period. On the basis of additional radionuclide data showing a decline in LVEF from 70% to 49%, they also concluded that volume loading following CPB may be detrimental.

Significant diagnostic errors may result when PCWP is assumed to be directly related to LVEDV. For example, an elevated PCWP and a decreased cardiac output can be interpreted as LV failure. However, these hemodynamic findings may also reflect ventricular interdependence.27 Ventricular interdependence occurs when the interventricular septum encroaches on the LV cavity. This can occur in acute respiratory failure, with high levels of PEEP, and so forth.464 The differential is made on the basis of knowledge of LVEDV. LVEDV is increased in LV failure, while it is decreased when ventricular interdependence is present (Table 14-9).

### Future Directions

Noninvasive assessment of cardiovascular function by perioperative 2-D TEE offers the anesthesiologist monitoring techniques that overcome these limitations. These techniques will assume greater importance for the clinician in terms of patient care, research, and education. The potential appeal of these methods is a more precise physiologic definition of the patient's cardiac reserve without the risks associated with invasive tests. Just as invasive monitoring with the Swan-Ganz catheter has raised our awareness of cardiovascular physiology, these noninvasive procedures offer a unique method of supplementing our knowledge of the cardiovascular system. A satisfactory echocardiographic technique to monitor cardiac output has been difficult to develop.464 PAC bolus TD remains the gold standard used for assessment of duct oxygenation with carbon dioxide production (VCO2) and oxygen consumption (Vo2) measured by a new metabolic monitor.465

Clinically, 2-D TEE is frequently being utilized in combination with the PAC. This combination provides the most sensitive and specific methods for cardiac monitoring. In a 1990, Rafferty highlighted the ability of the PAC and TEE to complement each other in the management of critically ill patients. In another study, there was complete agreement between PAC and TEE data in 36 (69%) of 42 patients in the diagnosis of acute cardiogenic pulmonary edema.61 The time taken from admission for PAC placement was 63 ± 45 minutes vs. 19 ± 7 minutes for TEE, which is clinically significant in the ICU setting.

PA catheterization has transformed the care of critically ill patients. It permits the direct measurement of vital hemodynamic and respiratory variables and permits rational application of therapeutic modalities. The existence of significant complications, however, mandates care in patient selection and in insertion and maintenance of the catheter. The age-old question of risk-benefit and the debate regarding the appropriate indications for PAC monitoring continue. The debate has been fueled by recent studies already alluded to. However, although precise data are lacking, all of us who rely on the information obtained from the PAC are convinced that it will continue to be an important tool in the management of the critically ill patient. It should not be forgotten that it is a tool only and that the ultimate monitoring system remains the clinician.

### REFERENCES


