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VIDEOS IN CLINICAL MEDICINE

SUMMARY POINTS

# Pulmonary-Artery Catheterization

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*The following text summarizes information provided in the video.*

## OVERVIEW

The modern flow-directed pulmonary-artery catheter, also known as the Swan–Ganz catheter, was first described in the *Journal* 43 years ago.[1] The inflatable balloon at its tip permitted catheterization at the bedside, and the subsequent addition of a thermistor and infusion ports permitted measurement of cardiac output with the use of thermodilution.[2]

## INDICATIONS

Pulmonary-artery catheterization aids the diagnosis and management of numerous cardiovascular illnesses, including pulmonary hypertension, cardiogenic shock, mixed shock states, cardiac tamponade, and mechanical complications of ST-segment elevation myocardial infarction (e.g., right ventricular infarction, ventricular septal rupture, and papillary-muscle rupture). It is also part of the standard evaluation of patients being considered for heart or lung transplantation.

Although pulmonary-artery catheterization had historically been the standard of care for all critically ill patients, data from randomized, controlled trials have shown that it offers no clear benefits to patients with septic shock,[3] acute respiratory distress syndrome,[3,4] or acute decompensated heart failure.[5] Similarly, pulmonary-artery catheterization offers no clear benefits in the routine treatment of patients undergoing high-risk surgery.[6] In such populations, cardiac function and volume status should instead be assessed through noninvasive means when possible, including physical examination, measurement of B-type natriuretic peptide levels, echocardiography, measurement of variations in pulse pressure during respiration, and sonographic assessment of the diameter of the inferior vena cava during respiration. In patients with acute respiratory distress syndrome, treatment determined on the basis of central venous pressure, which can be obtained with a simple central venous catheter, yields outcomes equivalent to those of treatment determined on the basis of pulmonary-capillary wedge pressure.[4]

## CONTRAINDICATIONS

Absolute contraindications include right-sided endocarditis, tumors, or masses, since the catheter may dislodge tissue into the pulmonary artery. Relative contraindications include severe coagulopathy and thrombocytopenia, either of which may complicate sheath insertion. Caution should be exercised in patients with left bundle-branch block, in whom catheter passage may induce complete heart block, and in patients with right-sided valve disease (e.g., tricuspid regurgitation), which makes catheter passage more difficult.

## EQUIPMENT

To create a sterile field, you will need chlorhexidine applicators, a fenestrated sterile drape, a surgical cap, a surgical mask with an eye shield, a sterile gown, and sterile gloves.

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To insert the introducer sheath, you will need gauze, sterile saline flushes, lidocaine, a 10-cc syringe, a 25-gauge needle, an 18-gauge introducer needle, a guidewire, a scalpel with a number 11 blade, the introducer sheath itself with an internal obturator, sutures, a needle driver, scissors, and an antibiotic-impregnated adhesive dressing. The use of ultrasonography greatly facilitates location of a central vein and is recommended. To use the probe during cannulation, you will need a sterile sleeve for the probe and conduction jelly.

To insert the pulmonary-artery catheter, you will need the catheter itself, a plastic sleeve, sterile saline flushes, appropriate tubing with stopcocks, and an electronic pressure monitor, preferably one capable of displaying multiple tracings at the same time.

The pulmonary-artery catheter (Fig. 1) is 110 cm long and 5 to 8 French in diameter, depending on the features and design. All catheters have a distal port, typically yellow, that connects to the catheter tip. Most catheters also have a proximal port, typically blue, that connects to a lumen 30 cm from the tip. Larger catheters usually have an accessory infusion port, typically clear or white, that also terminates approximately 30 cm from the tip.

The balloon at the catheter tip can be inflated by injecting air into the pink (or, in some cases, red) port; use only the syringe that is supplied with the catheter, since it will fill only to the balloon's capacity. To reduce mechanical trauma during insertion, the inflated balloon should completely encircle the catheter tip. Make sure that the balloon is fully inflated whenever the catheter is advanced and fully deflated whenever it is withdrawn.

Most catheters contain a thermistor wire that terminates near the tip and permits measurement of cardiac output with the thermodilution technique. Some catheters also have additional features, such as oximeters and pacing wires, with their own specialized ports.

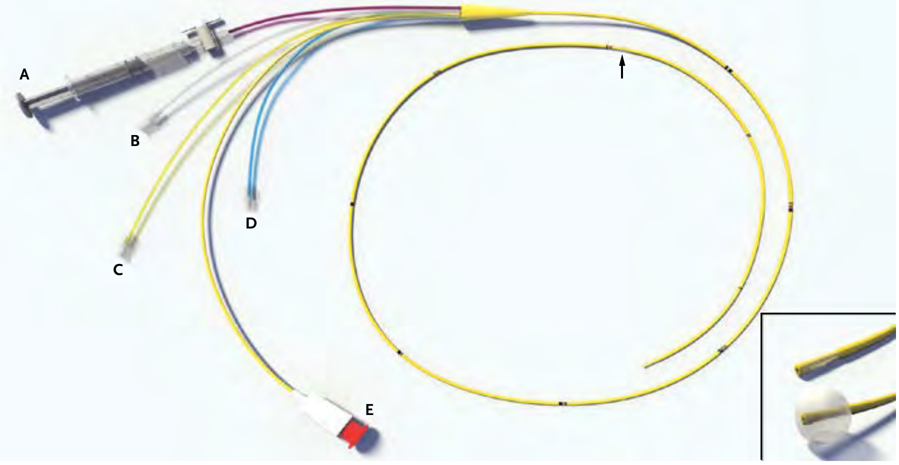

**Figure 1. Standard Pulmonary-Artery Catheter.**

The pulmonary-artery catheter is generally 110 cm long and 7 to 8 French in diameter. An air-filled syringe (A) is used to inflate the balloon at the catheter tip (inset). An accessory infusion port (B) is present in most catheters and connects to a lumen 30 cm from the catheter tip (arrow). The distal port (C) connects to a lumen at the catheter tip and is used to measure all pressures during catheter insertion. The proximal port (D) connects to an additional lumen 30 cm from the catheter tip and is used to monitor right atrial pressures once the catheter tip is in the pulmonary artery. A thermistor wire extends from the catheter tip to an electronic connector (E) and is used to measure cardiac output by means of thermodilution.

Because the catheter tip may induce ventricular arrhythmias, a defibrillator and transvenous pacemaker should be available at all times. If fluoroscopy is used, each operator must wear a lead apron and thyroid guard. The patient should be shielded in such a way that the chest is not covered and sheath insertion is not hindered.

### PREPARATION

After obtaining informed consent from the patient, review a preoperative checklist to confirm the identity and condition of the patient, the procedure to be performed, and the availability of all required equipment.

Place the patient in the supine position, and select a central vein for cannulation. The right internal jugular and left subclavian veins are preferred because the curvature of the catheter facilitates passage from these sites to the pulmonary artery. When cannulating an internal jugular or femoral vein, use ultrasonography to confirm the location and patency of the vein. (Cannulation of the subclavian vein generally relies on anatomical landmarks, although techniques incorporating ultrasound guidance have recently been described.[7])

Wash your hands with antimicrobial solution and don the sterile garments and sterile gloves. Sterilize the patient's skin with chlorhexidine, and then place the drape. Insert the ultrasound probe into the sterile sleeve. Flush the introducer sheath and pulmonary-artery catheter with sterile saline, and inflate the balloon to confirm that there are no air leaks. Slide the pulmonary-artery catheter through its plastic sleeve.

### PROCEDURE

Insert the introducer sheath using the modified Seldinger technique (Fig. 2). Use the 25-gauge needle to infiltrate the skin and subcutaneous tissue with lidocaine. Next, advance the 18-gauge needle into the vein while applying negative pressure to the syringe. Use ultrasonography to directly visualize needle entry.

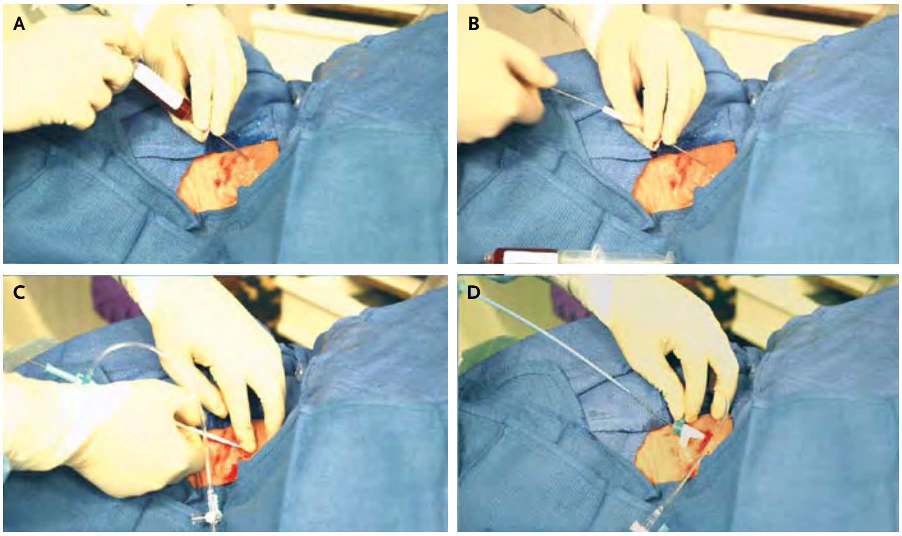

**Figure 2. Sheath Insertion with the Modified Seldinger Technique.**

The central vein is accessed with a large-bore needle while negative pressure is applied to a syringe (Panel A). The syringe is removed. Dark-red, nonpulsatile blood should continue to drip from the needle. A guidewire is inserted through the needle (Panel B). The needle is removed, and the sheath and internal obturator are advanced over the wire until the hub fills the wound (Panel C). The obturator and guidewire are removed (Panel D).

Once dark-red, nonpulsatile blood is aspirated, remove the syringe and insert the guidewire through the needle. Use the scalpel to stab the skin adjacent to the needle, and then remove the needle. While holding the guidewire to ensure that it remains accessible and does not embolize, insert the sheath and internal obturator over the guidewire until the hub fills the wound. Remove the obturator and guidewire from the sheath, and then attach a sterile flush to the port to ensure brisk flow.

Attach the distal port of the pulmonary-artery catheter to the main pressure monitor. Place the catheter tip level with the patient's heart, and set the pressure to zero. Orient the catheter so that its curvature follows its expected path, and then insert it into the sheath. Advance the catheter to 15 cm (i.e., halfway between the first two thin marks), at which point its tip will lie outside the sheath, and then inflate the balloon.

Continue to advance the catheter until a right-atrial-pressure waveform is transduced. The distance to the right atrium is typically 15 to 20 cm from an internal jugular or subclavian vein, and approximately 40 to 50 cm from a femoral vein. The right atrial waveform has several identifiable components (Fig. 3): an *a* wave, which indicates atrial contraction; an *x* descent, which indicates atrial relaxation; a small *c* wave, which indicates closure of the tricuspid valve; a *v* wave, which indicates passive atrial filling during right ventricular systole; and a *y* descent, which indicates passive atrial emptying following the opening of the tricuspid valve. Instruct an assistant to write down the mean right atrial pressure.

Advance the catheter another 5 to 10 cm until a right-ventricular-pressure waveform is transduced (Fig. 3). This sinusoidal waveform contains a swift upstroke and downstroke, representing ventricular systole, and a slower upstroke, representing passive ventricular filling during diastole followed by right atrial contrac-

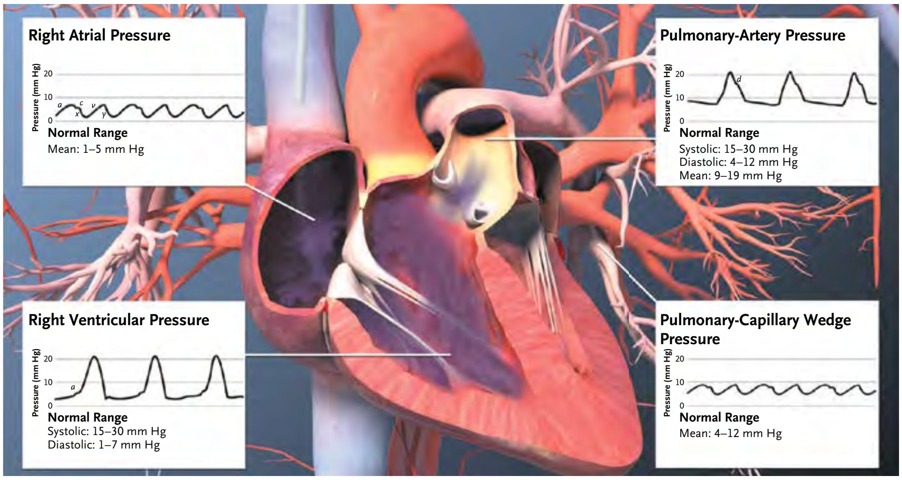

**Figure 3. Pressure Waveforms in the Right Heart and Pulmonary Artery.**

The right-atrial-pressure waveform is notable for an *a* wave, which represents atrial contraction; an *x* descent, which represents atrial relaxation and contains a small *c* wave, corresponding to tricuspid valve closure; a *v* wave, which represents passive atrial filling during ventricular systole; and a *y* descent, which represents passive atrial emptying during ventricular diastole. The right-ventricular-pressure waveform is notable for an *a* wave, which represents atrial systole, followed by a large upstroke and a large downstroke, which represent ventricular contraction and relaxation, respectively. During diastole, the pressure slowly increases as the ventricle passively fills. The pulmonary-artery-pressure waveform features a swift upstroke and downstroke, with the addition of a dicrotic notch (*d*), representing pulmonic-valve closure; an overall increase in diastolic pressure as compared with the right ventricle; and a progressive decrease in pressure during diastole. The pulmonary-capillary wedge pressure waveform is similar in appearance to the right-atrial-pressure waveform.

tion. Instruct an assistant to write down the systolic and diastolic right ventricular pressures.

Advance the catheter another 5 to 10 cm until a pulmonary-artery-pressure waveform is transduced (Fig. 3). This waveform also contains a systolic-pressure waveform, but it is distinguished from the right ventricular waveform by a progressive decrease rather than an increase in pressure during diastole, an overall increase in diastolic pressure (so long as the pulmonic valve is functional), and a dicrotic notch (representing closure of the pulmonic valve). Instruct an assistant to write down the systolic, diastolic, and mean pulmonary-artery pressures.

Advance the catheter until the waveform indicating pulmonary-capillary wedge pressure is transduced (Fig. 3). This waveform is similar to the right atrial waveform, except that greater variation may be noted during respiration. Instruct your assistant to write down the mean pressure at the end of expiration, whether the patient is breathing spontaneously or receiving mechanical ventilation. Although positive end-expiratory pressure may affect measurements of pulmonary-capillary wedge pressure, the effect is typically negligible when the positive end-expiratory pressure is less than 10 cm of water.

Once all measurements have been completed, deflate the balloon and confirm the reappearance of a pulmonary-artery-pressure waveform. If this waveform does not reappear, slowly withdraw the catheter until it does.

Aspirate blood from the distal port to measure the mixed venous oxygen saturation ($MvO_2$, also known as the pulmonary-artery saturation [$SvO_2$]). Record the cardiac output by connecting the thermistor to a computer and then injecting a saline bolus through the proximal port into the right atrium. On a plot of temperature against time, the area under the curve is inversely proportional to the cardiac output. Repeat the measurement of cardiac output until at least three consistent results have been obtained, and then calculate the average of the results.

Note the final position of the catheter. Confirm that the balloon has deflated. Fasten the plastic sleeve to the sheath, which will secure the catheter and may reduce the risk of infection. Suture the sheath to the skin and apply adhesive dressing.

### AFTERCARE

Obtain a portable chest radiograph to evaluate the position of the catheter and to rule out a pneumothorax. To minimize the risk of perforation or infarction, make sure that the catheter tip does not extend more than 4 or 5 cm beyond the midline.

With the catheter in place, the right atrial and pulmonary-artery pressures can be monitored continuously from the proximal and distal ports, respectively. The balloon can be periodically reinflated to reassess pulmonary-capillary wedge pressure but should always be deflated afterward. If you are able to measure the pulmonary-capillary wedge pressure when the balloon is only partially inflated, then the catheter has been inserted too far distally in the pulmonary artery. Withdraw the catheter until full balloon inflation is needed to measure the pulmonary-capillary wedge pressure.

### PROBLEMS AND COMPLICATIONS

If a right ventricular waveform cannot be obtained, the catheter may be exiting the right atrium through the opposite vena cava, the catheter may be coiling in the right atrium, or tricuspid regurgitation may be preventing the catheter from crossing the valve. The latter problem is suggested by large *v* waves on the right atrial tracing that represent retrograde atrial filling during ventricular systole. If a pulmonary-artery waveform cannot be obtained, the catheter may be coiling in the right ventricle.

In each instance, the balloon should be deflated and the catheter withdrawn approximately 10 cm. The balloon can then be reinflated and the catheter readvanced. If repeated attempts prove fruitless, the procedure should be attempted again with fluoroscopic guidance.

Common early complications include ventricular arrhythmias and right bundle-branch block, which are generally self-limiting. Complete heart block may occur in patients with preexisting left bundle-branch block. In rare cases, the guidewire may embolize and become inaccessible, or the catheter may become knotted in one of the cardiac chambers, preventing withdrawal. In either instance, a vascular surgeon or interventional radiologist must be consulted to ensure safe extraction.

Air embolism may occur if the catheter ports are not properly flushed with saline before the procedure or if the saline-filled tubing becomes disrupted. Manifestations include dyspnea, chest pain, tachycardia, hypotension, and in some cases, an acute increase in right heart pressures. In cases of air embolism, place the patient in the Trendelenburg position to limit the outflow of air from the right ventricle, and administer high-flow supplemental oxygen to reduce the nitrogen content of the blood and thereby promote the reabsorption of air. In severe cases, hyperbaric oxygen therapy is required.

Pulmonary-artery perforation is a rare but dangerous event that occurs in approximately 1 in 3000 patients.[8] Risk factors include older patient age, prolonged balloon inflation, pulmonary hypertension, and systemic anticoagulation. Symptoms include hemoptysis, hypoxemia, and shock. If immediate action is not taken, the risk of death is high. Keep the balloon inflated to limit further bleeding. Intubate the patient with a dual-lumen endotracheal tube, and then place the patient in the lateral decubitus position, with the affected side down. Immediately consult a thoracic surgeon and an interventional radiologist.

Later complications include pulmonary infarction, catheter-related infection, and thrombosis. To reduce the risk of pulmonary infarction, make sure that the catheter tip is positioned such that full inflation of the balloon is required to measure pulmonary-capillary wedge pressure and that the balloon is deflated after pulmonary-capillary wedge pressure measurements have been completed.

## INTERPRETATION

Normal pressures and waveforms are shown in Figure 3. The measured pressures can be used to calculate cardiac output, systemic vascular resistance, and pulmonary vascular resistance, as shown in Table 1.

Specific changes in chamber pressures and waveforms are typical of various conditions.[9] In pericardial tamponade, for example, high pericardial pressures equalize diastolic pressure throughout the heart, and the pressure waveforms appear abnormal. In the right atrium, the *x* descent appears exaggerated because of the drop in pericardial pressure during ventricular systole, whereas the *y* descent appears blunted because the pericardial pressure remains constant during ventricular diastole.

Hemodynamic data can also help to clarify the cause of shock. A patient with cardiogenic shock has a low cardiac output, which raises filling pressures in the left atrium (creating high pulmonary-capillary wedge pressure). The systemic vascular resistance rises to offset the changes in mean arterial pressure, and $M\text{v}O_2$ declines as tissues increase their oxygen extraction to compensate for decreased oxygen delivery.

A patient in the early stages of distributive shock (e.g., septic shock) has a pathologic reduction in systemic vascular resistance that results in functional ar-

**Table 1. Calculation of Cardiac Output and Vascular Resistance with the Use of Fick's Method.***

| Value | Equation | Normal Values |
|---|---|---|
| Cardiac output (liters/min) | $CO = \frac{\dot{V}O_2}{C_a - C_v}$<br>which can be simplified to<br>$CO = \frac{\dot{V}O_2}{1.36 \times Hgb \times (Sao_2 - Svo_2) \times 10}$ | 4.8–7.3 for an average adult |
| Cardiac index (liters/min/m²) | $CI = \frac{CO}{BSA}$ | 2.8–4.2 |
| Systemic vascular resistance (dyn·sec·cm⁻⁵) | $SVR = \frac{MAP - RA}{CO} \times 80$ | 700–1600 |
| Pulmonary vascular resistance (dyn·sec·cm⁻⁵) | $PVR = \frac{PA - PCWP}{CO} \times 80$ | 20–130 |

* In the equation for cardiac output (CO), $\dot{V}O_2$ denotes oxygen consumption (ml/min), $C_a$ the oxygen content of arterial blood, $C_v$ the oxygen content of venous blood, 1.36 the oxygen-carrying capacity of hemoglobin (ml/g), Hgb hemoglobin (g/dl); $Sao_2$ arterial oxygen saturation (fraction), and $Svo_2$ mixed venous oxygen saturation (fraction); 10 is a conversion factor (10 dl in 1 liter). In the equation for the cardiac index (CI), BSA denotes body-surface area. In the equation for systemic vascular resistance (SVR), MAP denotes mean systemic arterial pressure, and RA right atrial mean pressure. In the equation for pulmonary vascular resistance (PVR), PA denotes pulmonary-artery mean pressure, and PCWP pulmonary-capillary wedge pressure. Although $Vo_2$ may be directly measured with the use of specialized equipment, an estimate of 125 ml per minute per square meter of body-surface area is often used. This estimate, however, may be inaccurate in critically ill patients.

teriovenous shunting, which, in combination with sepsis-induced mitochondrial dysfunction, causes a high $Mvo_2$. Cardiac output increases to offset the changes in mean arterial pressure. Pulmonary-capillary wedge pressure may initially be normal, but if adequate fluid resuscitation does not occur, pulmonary-capillary wedge pressure and cardiac output will fall.

A patient with a normal heart in hypovolemic shock (e.g., massive hemorrhage) has inadequate ventricular filling, which results in low pulmonary-capillary wedge pressure and cardiac output. As in cardiogenic shock, there are compensatory changes in systemic vascular resistance and in $Mvo_2$.

## SUMMARY

Pulmonary-artery catheterization can be safely performed at the bedside and yields a wealth of hemodynamic data. Although recent studies indicate that this procedure should not be performed routinely in critically ill patients, it remains invaluable in the diagnosis and management of a wide range of cardiovascular illnesses. Because fatal complications can occur, however, the procedure should be performed only when its results are expected to aid clinical management.

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Disclosure forms provided by the authors are available with the full text of this article at NEJM.org.

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