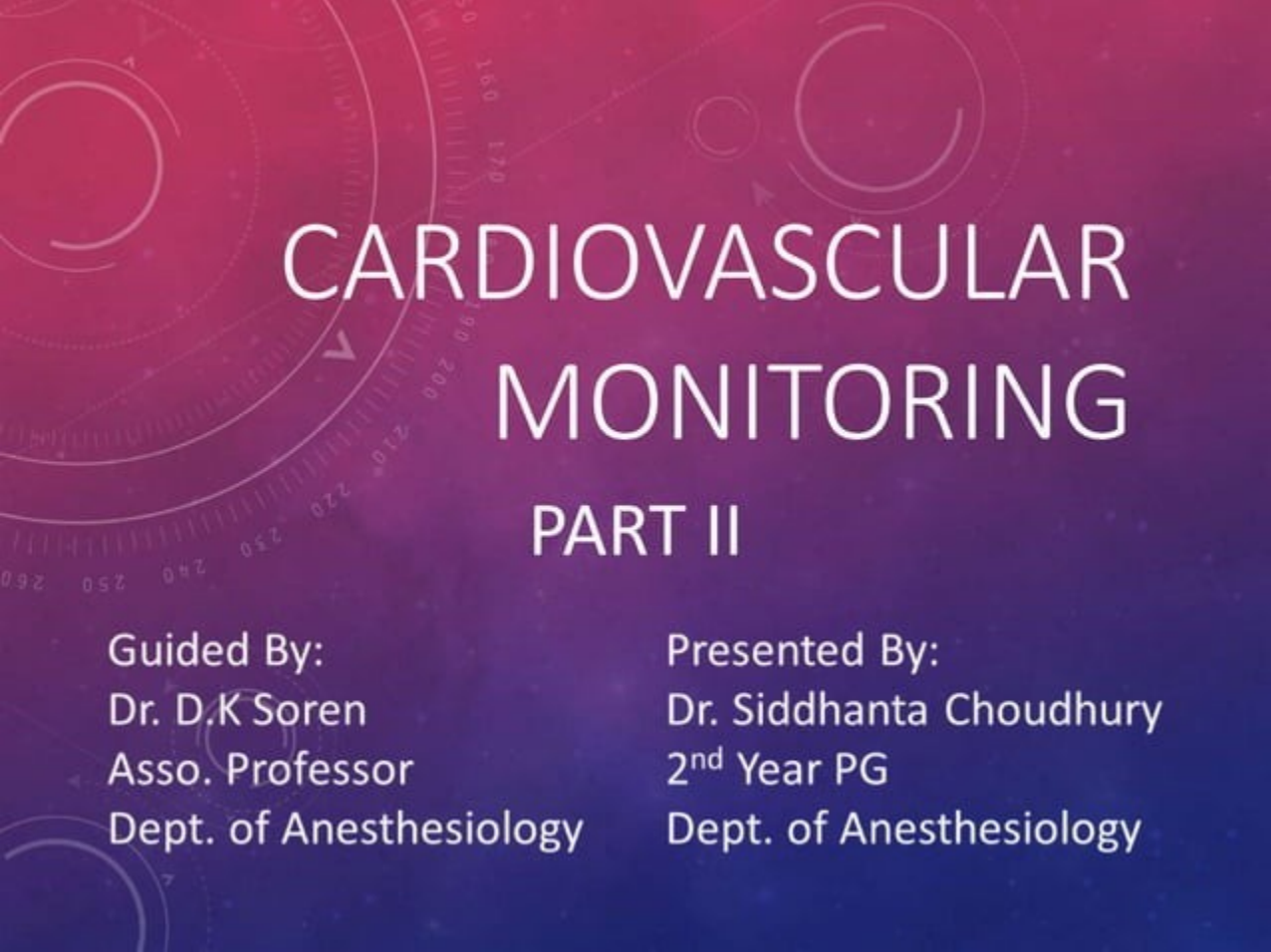




CARDIOVASCULAR MONITORING

PART II

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PULMONARY ARTERY CATHETER MONITORING

- In 1970, Swan, Ganz, and colleagues introduced pulmonary artery catheterization into clinical practice for the hemodynamic assessment of patients with acute myocardial infarction.
- It quickly became common for patients undergoing major surgery to be managed with PA catheterization.
- The PAC provides measurements of several hemodynamic variables that many clinicians, including experts in intensive care, cannot predict accurately from standard clinical signs and symptoms.
- However, it remains uncertain whether PAC monitoring improves patient outcome.

PHYSIOLOGICAL MEASUREMENTS

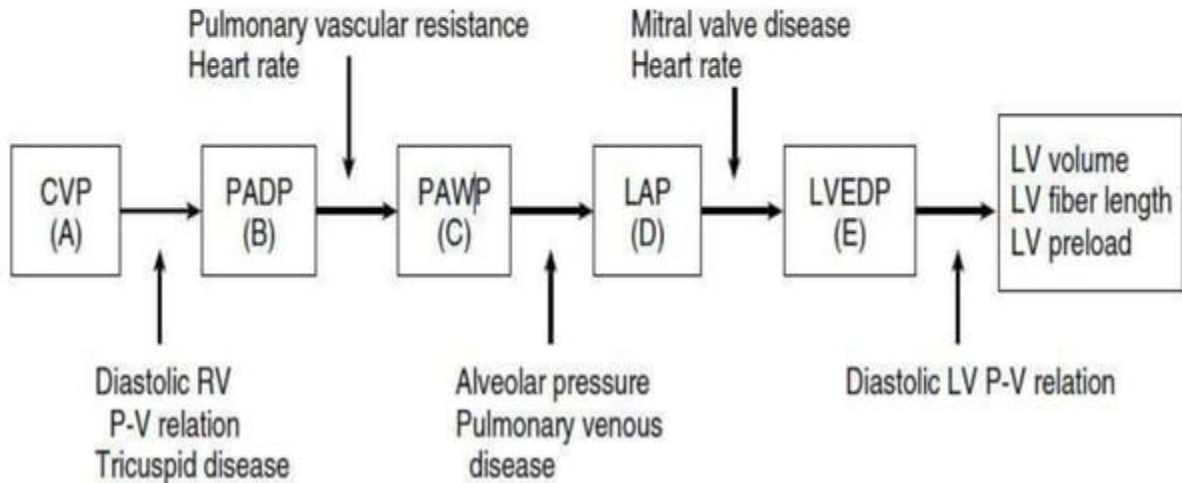
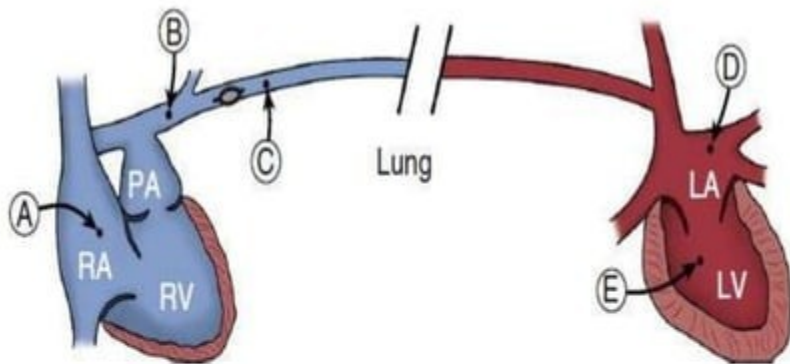
- Direct measurements of the following can be obtained from an accurately placed pulmonary artery catheter (PAC)
 - Central Venous Pressure(CVP)
 - Right sided intracardiac pressures(RA/V)
 - Pulmonary artery pressure(Pap)
 - Pulmonary artery occlusion pressure (PAOP)
 - Cardiac Output
 - Mixed Venous Oxygen Saturation(SvO₂)

- Indirect measurements that are possible:
 - Systemic Vascular Resistance
 - Pulmonary Vascular Resistance
 - Cardiac Index
 - Stroke volume index
 - Oxygen delivery
 - Oxygen uptake

WHY PAOP?

- The filling pressure of the right and left ventricle depends on the blood volume, venous tone, ventricular compliance, contractility and afterload. The left ventricle (LV) is less compliant with greater afterload than the right ventricle (RV) and the left sided filling pressure is normally higher than the right.
- Under normal circumstances, the right side of the heart and lungs are merely passive conduits for blood and it is possible to discern a relationship between the central venous pressure (CVP) and the left atrial pressure (LAP).

- In health, it is possible to make reasonable assumptions about the relationship between the CVP and the LAP and manipulate the circulation according to the measurements of the CVP.
- However, in a critically ill patient and a patient with cardiovascular disease, no such assumptions can be made and conclusions about left heart based on measurements of CVP may be invalid.
- Since there are no valves between the pulmonary capillaries and the left atrium, PAOP is a reflection of the LAP. During diastole, when mitral valve is open, the PAOP reflects LVEDP. LVEDP is an index of left ventricular end-diastolic volume.



Indications For PAP & PCWP Monitoring:

A. Cardiac surgery:

- i) Poor LV function ($EF < 0.4$; $LVEDP > 18$ mm Hg)
- ii) Recent MI
- iii) Complications of MI eg. MR, VSD, ventricular aneurysm.
- iv) Combined lesions eg. CAD+MR or CAD+AS
- v) Complicated lesions eg. IHSS
- vi) IABP

B. Non-cardiac situations:

- i) Shock of any cause
- ii) Severe pulmonary disease
- iii) Bleomycin toxicity
- iv) Complicated surgical procedure
- v) Massive trauma
- vi) Hepatic transplantation

CONTRAINDICATIONS

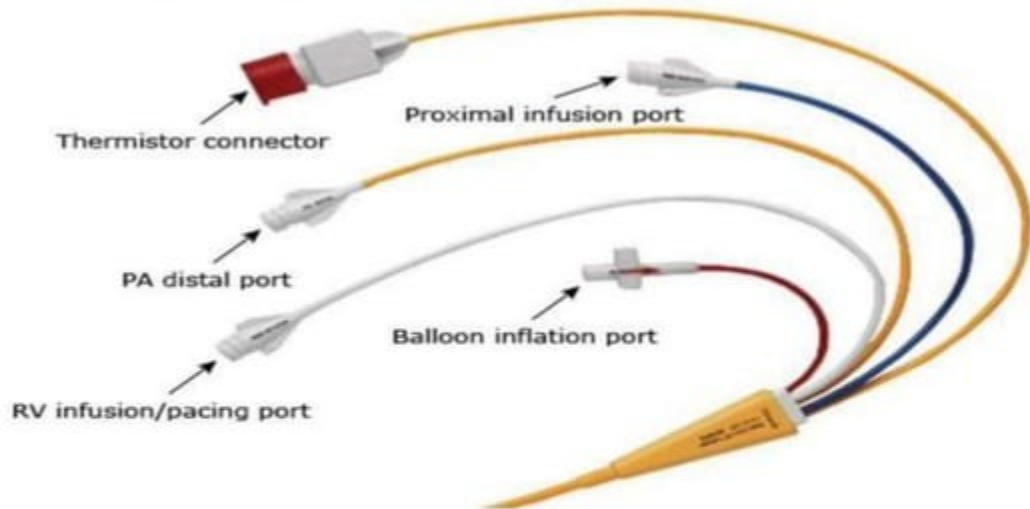
- Absolute:

- Infection at insertion site
- Presence of RV assist device
- Insertion during CPB
- Lack of consent

- Relative:

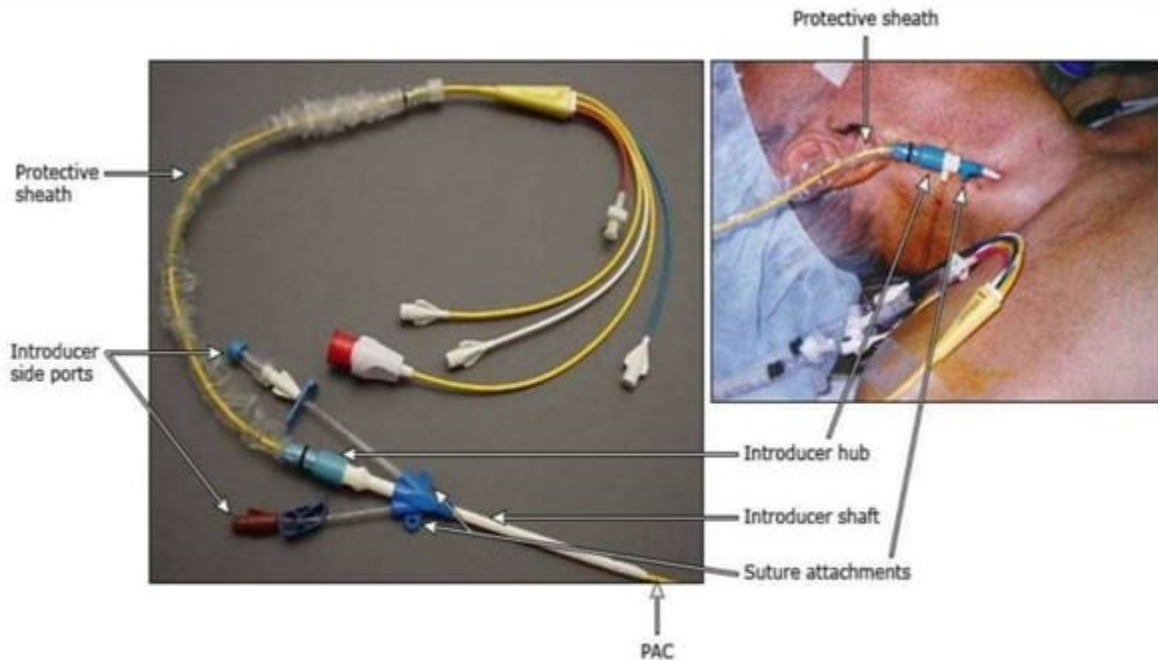
- Coagulopathy
- Thrombocytopenia
- Electrolyte disturbances (K/Mg/Na/Ca)
- Severe Pulmonary HTN

Pulmonary artery catheter ports



Five pulmonary artery catheter (PAC) ports are shown. The thermistor port contains fine wires that lead to a temperature thermistor just proximal to the balloon. It is used to monitor pulmonary artery blood temperature as part of the thermodilution method for cardiac output monitoring. The pulmonary artery (PA) distal pressure monitoring port connects to the distal tip of the PAC and is used to transduce pressure. The proximal drug infusion port, usually 30 cm from the catheter tip, is intended for central venous pressure monitoring as well as for intravenous fluid and drug administration. The balloon inflation port leads to the balloon at the catheter tip and allows the balloon to be inflated and deflated during catheter placement. The right ventricle (RV) infusion port is a fifth port that is available on some catheters. It can be used for infusions and occasionally for pacing the RV.

Pulmonary artery catheter with protective sleeve and introducer



The left panel shows a pulmonary artery catheter (PAC) that is inserted through the introducer *ex vivo*. The right panel shows the PAC inserted *in vivo*. *In vivo*, the introducer shaft is located intravenously and the hub is external to the skin. A protective sheath is shown; it is attached to the hub of the introducer and serves to reduce infectious complications. The introducer has one or two side ports that can also be used for the administration of medications and fluids; side attachments can be used to suture it to the skin. The distal portion of the PAC can be seen in the left panel projecting beyond the introducer.

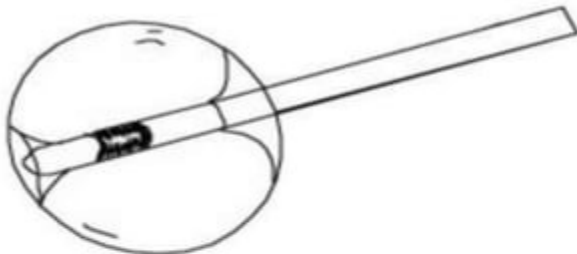
TECHNIQUE

- PACs can be inserted from any of the central venous cannulation sites, but the right internal jugular vein provides the most direct route to the right heart chambers.
- A large-bore introducer sheath with a hemostasis valve at its outer end is inserted in a manner similar to that for central venous cannulation.
- The PAC is passed through a sterile sheath to allow for later sterile manipulation of the PAC position, its distal lumen is connected to a pressure transducer, and then the catheter is inserted through the introducer's hemostatic valve to a depth of 20 cm.

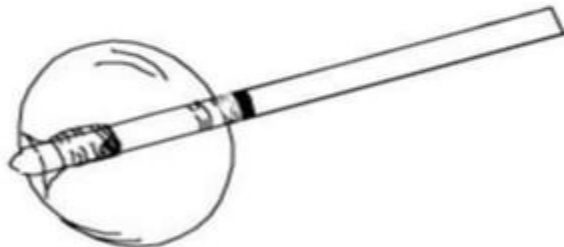
- The balloon at the tip of the catheter is inflated with air (1.5 ml), and the catheter is advanced into the right atrium, through the tricuspid valve, the right ventricle, the pulmonic valve, into the pulmonary artery, and finally into the wedge position.
- Characteristic waveforms from each of these locations confirm proper catheter passage and placement.
- After the pulmonary artery wedge pressure is measured, the balloon is deflated, and the pulmonary artery pressure waveform should reappear.
- Wedge pressure may be obtained as needed by reinflating the balloon and allowing the catheter to float distally until pulmonary artery occlusion again occurs.

Balloon inflation of pulmonary artery catheter

Balloon at Full Inflation Volume

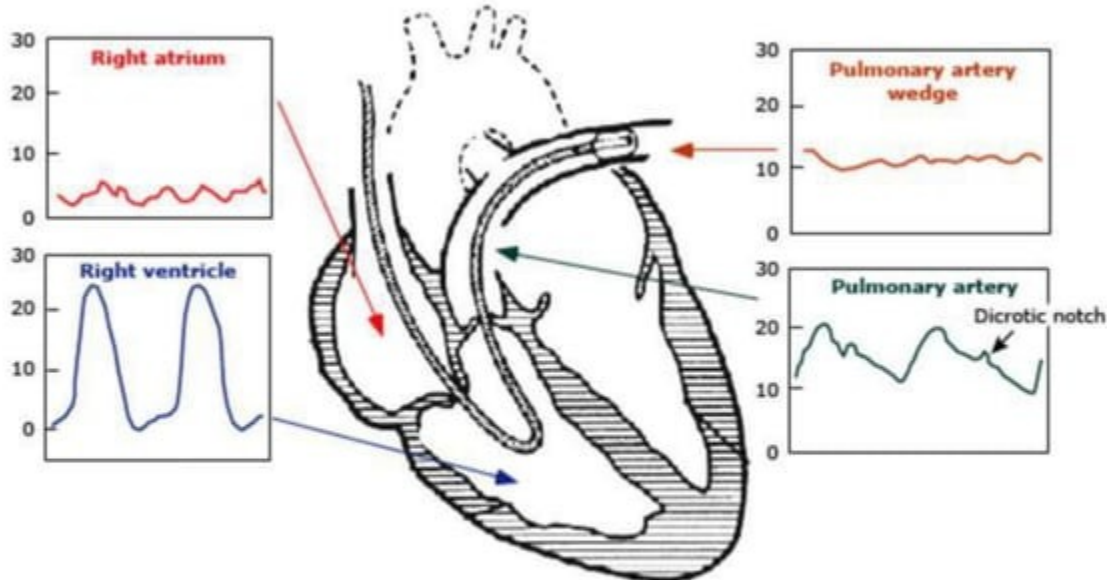


Balloon at Less Than Full Inflation Volume



This schematic diagram shows the appearance of a pulmonary artery (Swan-Ganz) catheter tip with the balloon at full inflation (top) and at less than full inflation (bottom). The tip of the catheter protrudes beyond the balloon when the balloon is less than fully inflated.

Waveforms by location of the pulmonary artery (PA) catheter tip



Tracings obtained in the right atrium or pulmonary capillary wedge position share similar morphology. The transition from the right ventricle to the pulmonary artery tracing can be identified by the increase in diastolic pressure and the presence of a dicrotic notch. The diastolic "step-up" results from the transducer crossing the pulmonic valve; the dicrotic notch reflects closing of the pulmonic valve.

ADDITIONAL GUIDELINES FOR PULMONARY ARTERY CATHETER INSERTION

- From a right internal jugular vein puncture site, the right atrium should be reached when the PAC is inserted 20 to 25 cm, the right ventricle at 30 to 35 cm, the pulmonary artery at 40 to 45 cm, and the wedge position at 45 to 55 cm.
- When other sites are chosen for catheter placement, additional distance is required, typically an additional 5 to 10 cm from the left internal jugular and left and right external jugular veins, 15 cm from the femoral veins, and 30 to 35 cm from the antecubital veins.

- These distances serve only as a rough guide; waveform morphology must always be verified and catheter position confirmed with a chest radiograph as soon as practical.
- The tip of the PAC should be within 2 cm of the cardiac silhouette on a standard anteroposterior chest film.

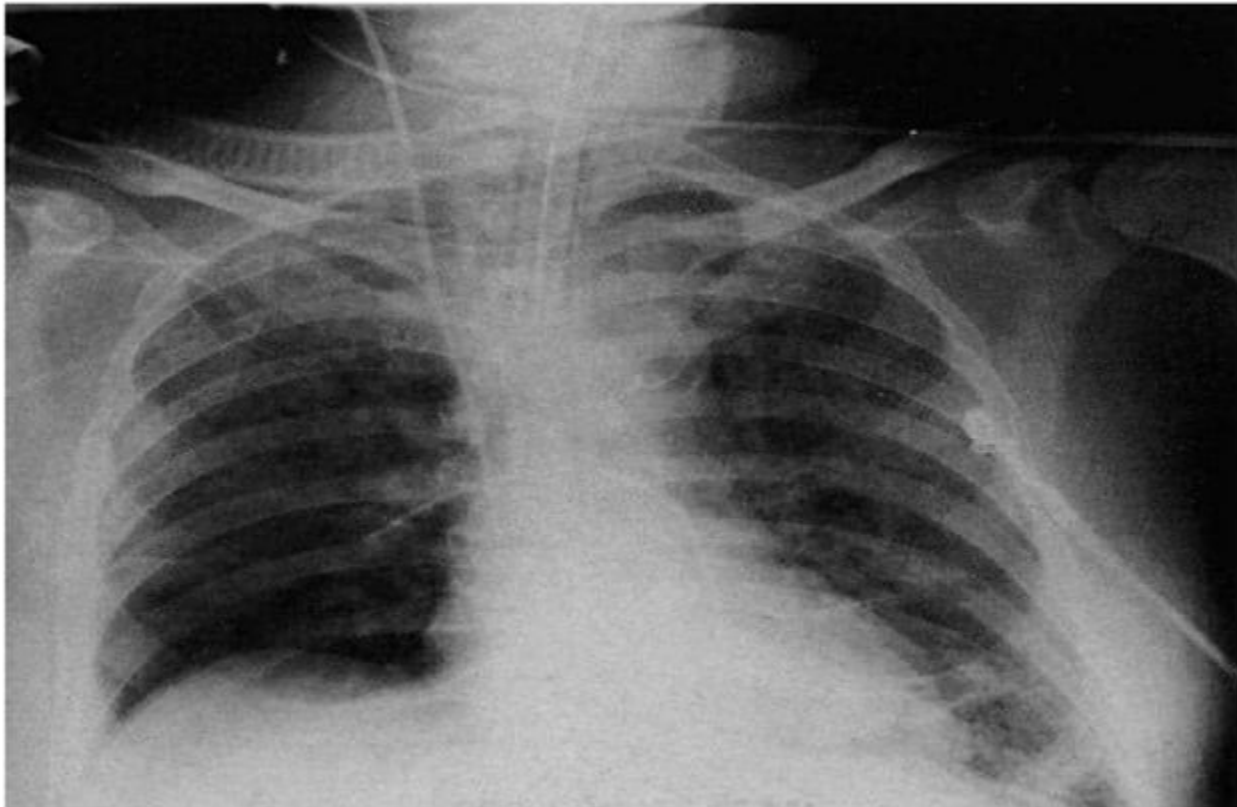


Fig. 4.10 Pulmonary artery flotation catheter correctly positioned in a patient with acute respiratory distress syndrome.

- Use of these typical distances helps avoid complications caused by unintended catheter loops and knots within the heart. If a right ventricular waveform is not observed after inserting the catheter 40 cm, coiling in the right atrium is likely.
- Similarly, if a pulmonary artery waveform is not observed after inserting the catheter 50 cm, coiling in the right ventricle has probably occurred.
- The balloon should be deflated, the catheter withdrawn to 20 cm, and the PAC floating sequence repeated.

- A few additional points might aid successful positioning of the PAC. The air-filled balloon tends to float to nondependent regions as it passes through the heart into the pulmonary vasculature.
- Consequently, positioning the patient head down will aid flotation past the tricuspid valve, and tilting the patient onto the right side and placing the head up will encourage flotation out of the right ventricle, as well as reduce the incidence of arrhythmias.

- Important tip:
 - When advancing catheter- always inflate tip
 - When withdrawing catheter- always deflate
 - Once in pulmonary artery - NEVER INFLATE AGAINST RESISTANCE - RISK OF PULMONARY ARTERY RUPTURE

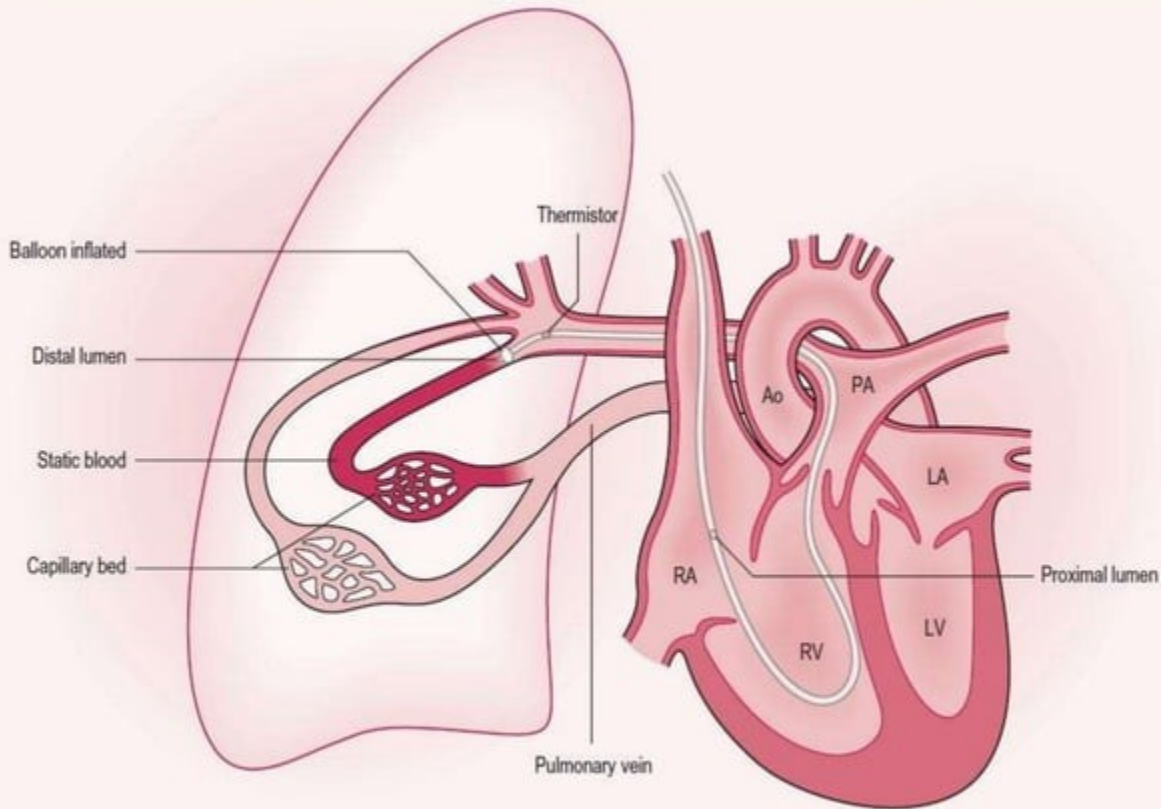
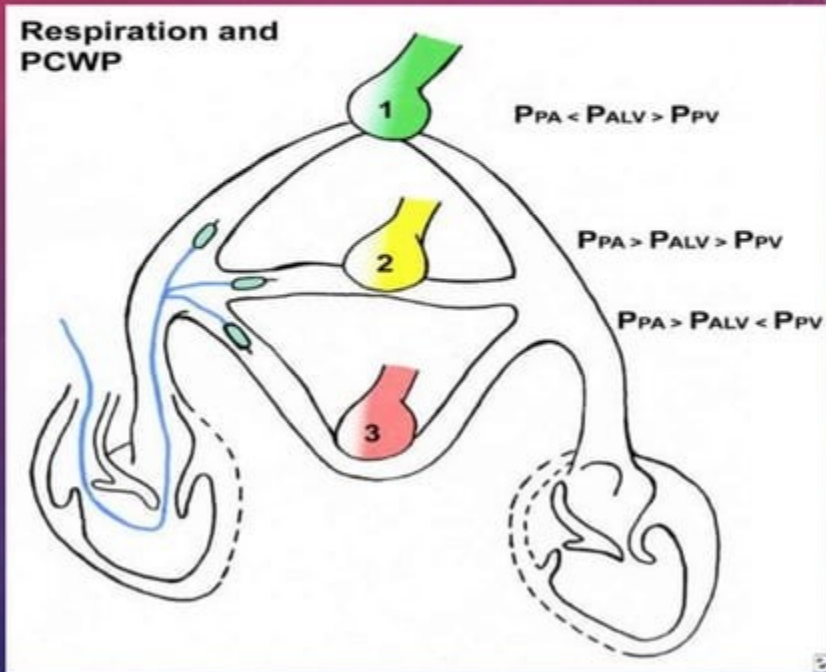


Fig. 4.11 Balloon flotation pulmonary artery catheter in the wedged position. There is now a continuous column of static blood between the tip of the catheter and the left atrium; pulmonary artery occlusion pressure (PAOP) is therefore usually closely related to left atrial pressure. LA, left atrium; LV, left ventricle; PA, pulmonary artery; RA, right atrium; RV, right ventricle.

THE 3 LUNG ZONES OF WEST



ENSURING ACCURATE MEASUREMENTS

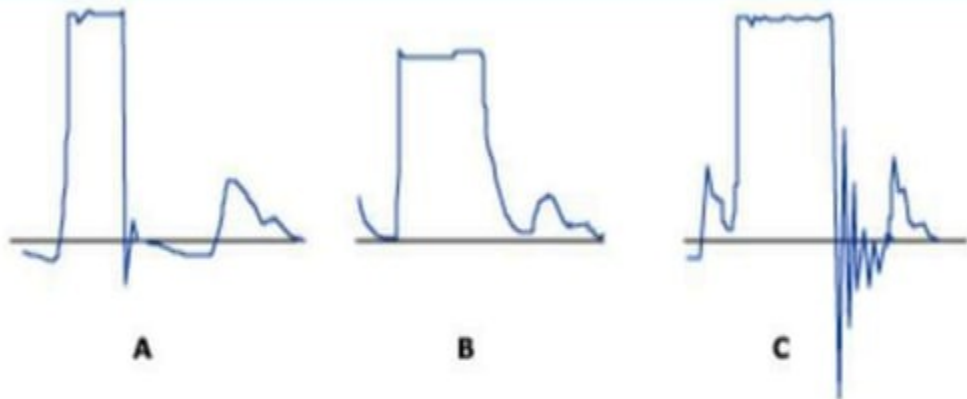
Zero reference

- Any independent vertical movement of the transducer or the patient will affect the hydrostatic column of this fluid-filled system and thus alter the pressure measurements. The system must therefore be zeroed to ambient air pressure.
- The reference point for this is the midpoint of the left atrium (LA), estimated as the fourth intercostal space in the midaxillary line with the patient in the supine position. With the transducer at this height, the membrane is exposed to atmospheric pressure, and the monitor is then adjusted to zero.

Calibration

- Once zeroed, the monitoring system must be calibrated for accuracy. Currently, most monitors perform an automated electronic calibration.
- Two methods are used to manually calibrate and check the system, as follows:
 - If the catheter has not been inserted, the distal tip of the PAC is raised to a specified height above the LA. For example, raising the tip 20 cm above the LA should produce a reading of approximately 15 mm Hg if the system is working properly (1 mm Hg equals 1.36 cm H₂O).
 - Alternatively, pressure can be applied externally to the transducer and adjusted to a known level using a mercury or aneroid manometer. The monitor then is adjusted to read this pressure, and the system is calibrated.

Arterial catheter rapid flush test



Intravascular pressure tracings obtained during the rapid flushing of a monitoring catheter. A. Optimal damping in which rapid flushing produces a rapid upstroke in pressure followed by recovery characterized by a fall in pressure to below baseline with less than three beats of ringing. B. Overdamped system in which no ringing is seen. C. Underdamped system in which there is excessive ringing.

MEASUREMENTS

- Important information provided by a PAC catheter includes the CO, mixed venous oxygen saturation (SaO_2), and oxygen saturations in the right heart chambers to assess for the presence of an intracardiac shunt.
- Using these measurements, other variables can be derived, including pulmonary or systemic vascular resistance and the difference between arterial and venous oxygen content.
- Obtaining CO and PCWP measurements is the primary reason for inserting most PACs; therefore, understanding how they are obtained and what factors alter their values is of prime importance.

TABLE 45-2 NORMAL CARDIOVASCULAR PRESSURES

Pressures	Average (mm Hg)	Range (mm Hg)
Right Atrium		
a wave	6	2-7
v wave	5	2-7
Mean	3	1-5
Right Ventricle		
Peak systolic	25	15-30
End-diastolic	6	1-7
Pulmonary Artery		
Peak systolic	25	15-30
End-diastolic	9	4-12
Mean	15	9-19
Pulmonary Artery Wedge		
Mean	9	4-12
Left Atrium		
a wave	10	4-16
v wave	12	6-21
Mean	8	2-12
Left Ventricle		
Peak systolic	130	90-140
End-diastolic	8	5-12
Central aorta		
Peak systolic	130	90-140
End-diastolic	70	60-90
Mean	90	70-105

Derived Hemodynamic Parameters

FORMULA	NORMAL VALUE
$CI = CO / BSA$	2.8 – 4.2 L / min / m ²
$SV = CO. 1000 / HR$	50-110 mL/beat
$SI = SV/BSA$	30-65 mL/beat/ m ²
$LVSWI = 1.36. (MAP - PCWP). SI / 100$	45-60 g.m / m ²
$RVSWI = 1.36. (PAP - CVP). SI/ 100$	5-10 g.m / m ²
$SVR = (MAP-CVP). 80 / CO$	900-1400 dyne. sec. cm ⁻⁵
$SVRI = (MAP-CVP). 80 / CI$	1500-2400 dyne.sec.cm ⁻⁵
$PVR= (PAP-PCWP). 80 / CO$	150-250 dyne.sec. cm ⁻⁵
$PVRI= (PAP-PCWP). 80 / CI$	250-400 dyne.sec. cm ⁻⁵

CI=Cardiac index; CO=cardiac output; BSA=body surface area; SV=stroke volume; HR=heart rate; MAP=mean arterial pressure; PCWP=pulmonary capillary wedge pressure; PAP=pulmonary arterial pressure; CVP=central venous pressure; SVR=systemic vascular resistance; PVR=pulmonary vascular resistance; SI=stroke index; LVSWI=left ventricular stroke work index; RVSWI=right ventricular stroke work index; SVRI= systemic vascular resistance index; PVRI=pulmonary vascular resistance index.

Oxygen Delivery Parameters

FORMULA	NORMAL VALUES
Arterial O ₂ content Ca O ₂ = (1.39. Hb. Sa O ₂) + (0.0031. PaO ₂)	18-20 mL/dl
Mixed venous O ₂ content Cv O ₂ = 1.39. Hb. Sv O ₂ + 0.0031. PvO ₂	13-16 mL / dl
Atreriovenous O ₂ content difference av DO ₂ = Ca O ₂ - Cv O ₂	4-5.5 mL/ dl
Pulmonary capillary O ₂ content Cc O ₂ = 1.39. Hb. Sc O ₂ + 0.0031. Pc O ₂	19-21 mL/dl
Pulmonary shunt fraction $Q_s / Q_t = 100. (Cc O_2 - Ca O_2) / (CcO_2 - Cv O_2)$	2-8 percent
O ₂ delivery DO ₂ = 10. CO. Ca O ₂	800-1100 mL/ min
O ₂ consumption V O ₂ = 10. CO. (Ca O ₂ - Cv O ₂)	150-300 mL/ min

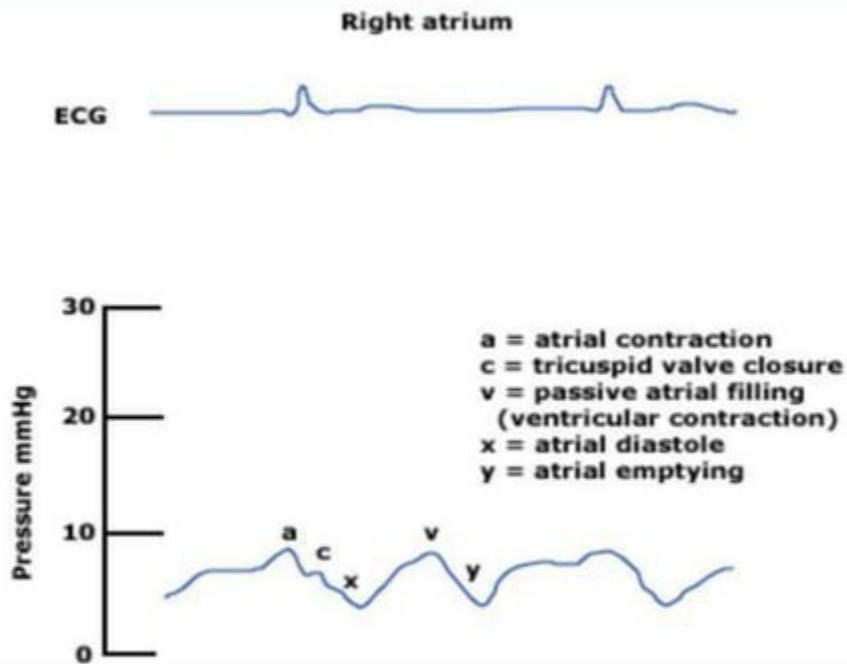
Hb=Hemoglobin; SvO₂=venous oxygen saturation; PvO₂=venous oxygen tension; ScO₂=pulmonary capillary oxygen saturation; PcO₂=pulmonary capillary oxygen tension.

CATHETER WAVEFORMS AND PRESSURES

- Pressure waveforms can be obtained from
 - Right atrium
 - Right ventricle
 - Pulmonary artery

- In presence of a competent tricuspid valve, RA pressure waveform reflect both
 - Venous return to RA during ventricular systole
 - RV End Diastolic Pressure
- Normal RA pressure: 2-7 mmHg.
- At this point, the PAC balloon is inflated, and the catheter is advanced until it crosses the tricuspid valve to record right ventricular pressure

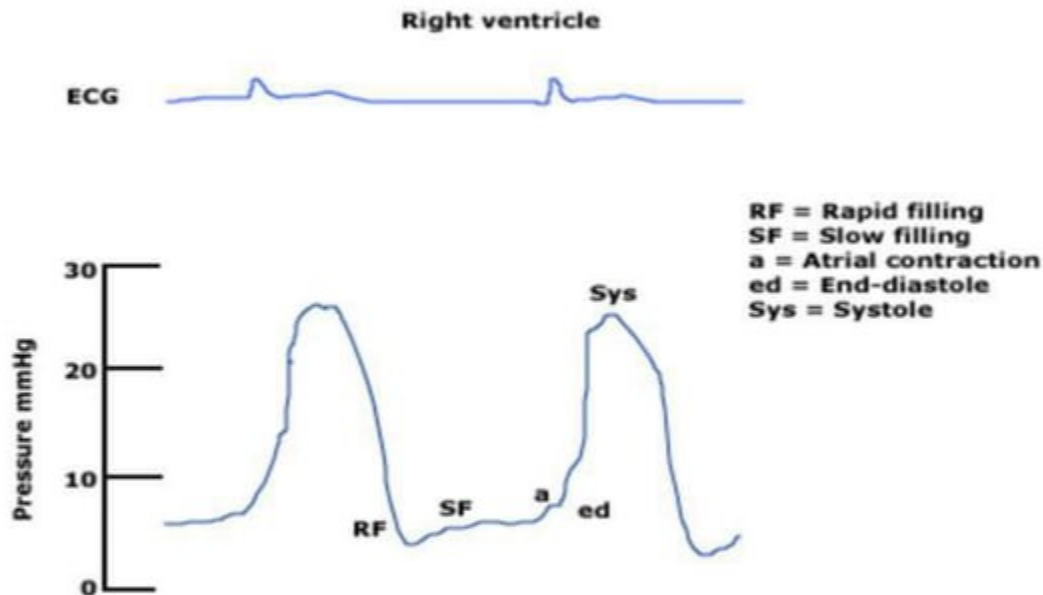
Right atrial pressure tracing



This schematic diagram shows the different components of the right atrial pressure tracing. A simultaneous ECG is shown to demonstrate the timing of the different components.

- When catheter tip is across tricuspid valve, pressure waveform changes and is characterized by a rapid systolic upstroke, a wide pulse pressure, and low diastolic pressure.
- 2 pressures are typically measured in right ventricular pressure waveform
- Peak RV systolic pressure : 15-30mmHg
- RV end diastolic pressure : 1-7 mmHg.

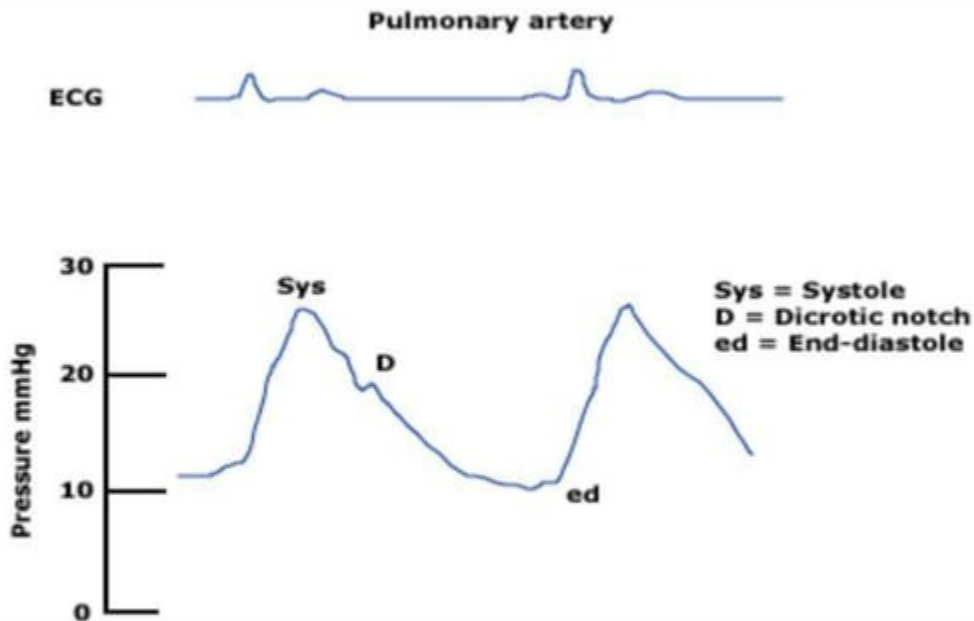
Right ventricular pressure tracing



This schematic diagram shows the different components of the right ventricular pressure tracing. A simultaneous ECG is shown to demonstrate the timing of the different components. Right ventricular end diastolic pressure is measured after the a wave, just prior to the systolic upstroke.

- Next, the PAC enters the right ventricular outflow tract and floats past the pulmonic valve into the main pulmonary artery. Premature ventricular beats are common during this period as the balloon-tipped catheter strikes the right ventricular infundibular wall. Entry into the pulmonary artery is heralded by a step-up in diastolic pressure and a change in waveform morphology.
- When catheter tip passes pulmonary valve, diastolic pressure increases and characteristic dichrotic notch appears in waveform. This is due to the pulmonic valve closure.
- Normal pulmonary artery pressures:
 - Peak systolic 15-30mmHg
 - End Diastolic 4-12 mmHg
 - Mean 9-19 mmHg

Pulmonary artery pressure tracing



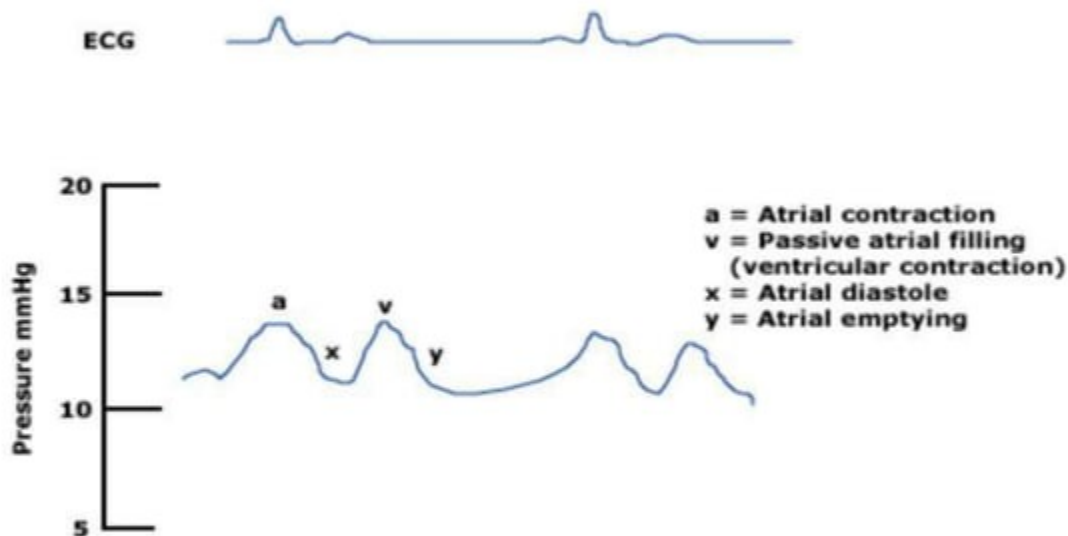
This schematic diagram shows the demonstrates key features of the pulmonary artery pressure tracing. A simultaneous ECG is shown to demonstrate the timing of the different components. The peak systolic pressure falls within the electrocardiographic T wave.

PULMONARY ARTERIAL OCCLUSION PRESSURE

- Once catheter tip has reached PA, it should be advanced until PAOP is identified by decrease in pressure and change in waveform.
- The balloon should then be deflated and PA tracing should reappear.
- If PCOP tracing persists catheter should be withdrawn with definitive PA tracing obtained

Pulmonary artery wedge pressure tracing

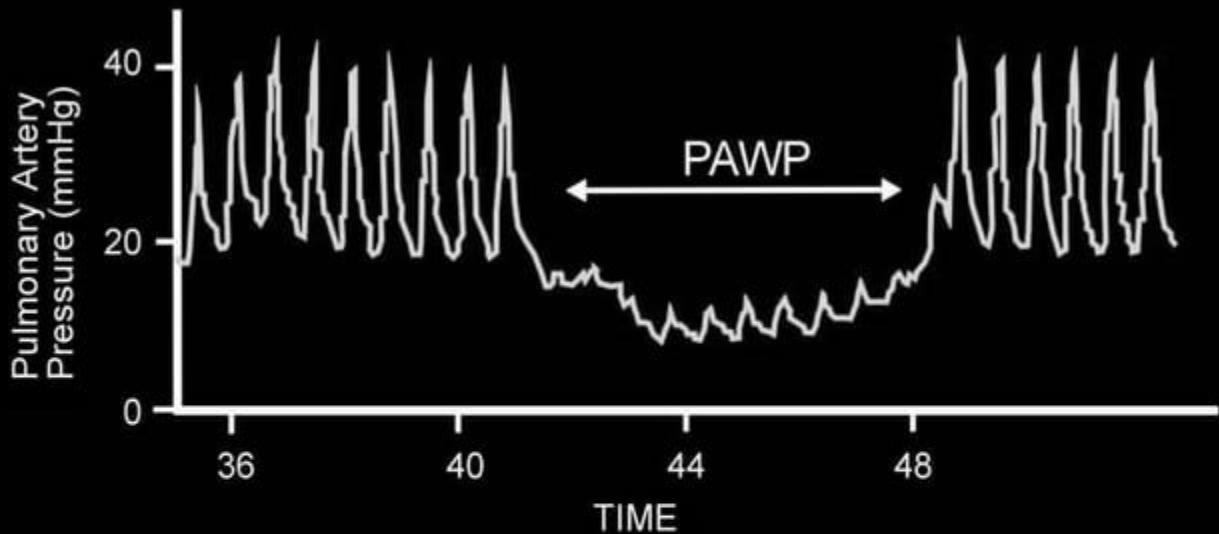
Pulmonary artery wedge



This schematic diagram shows the different components of the pulmonary artery wedge pressure tracing. A simultaneous ECG is shown to demonstrate the timing of the different components. The peak of the 'v' wave falls outside the peak of the electrocardiographic T wave.

- Final position of the catheter within PA must be such that PCOP tracing is obtained whenever 75-100% of 1.5ml maximum volume of balloon is insufflated
 - If < 1 ml of air is injected and PAOP is seen then it is overwedged : needs to be withdrawn
 - If after maximal inflation fails to result in PCOP tracing or after 2-3 seconds delay : too proximal -advanced with balloon inflated

- PCWP/PAOP interprets Left atrial pressures; more importantly – LVEDP
- Best measured in
 - Supine position
 - At end of expiration
 - Zone 3 (most dependent region)
- Normal PCWP- 4-12 mmHg ; Mean :9mmHg



When the PAC tip is positioned properly and the balloon is inflated, the PAP tracing disappears. This occurs because inflation of the balloon causes distal migration (approximately 2 cm) of the tip into a smaller branch of the PA, where it occludes blood flow. The resulting non-pulsatile pressure tracing is called the PCWP

UTILITY OF PAOP

Preload (left ventricular end-diastolic pressure)

- PCWP is a reflection of LAP, which, in the absence of mitral valve disease, is an indication of LV diastolic pressure. Often, the inference is made that PCWP reflects left ventricular end-diastolic volume (LVEDV) or end-diastolic pressure (LVEDP). Numerous conditions in critically ill patients preclude this assumption.

Effect of respiration

- The timing of PCWP measurement is critical because intrathoracic pressures can vary widely with inspiration and expiration and are transmitted to the pulmonary vasculature.
- During spontaneous inspiration, the intrathoracic pressures decrease (more negative); during expiration, intrathoracic pressures increase (more positive). Positive pressure ventilation (eg, in an intubated patient) reverses this situation.
- To minimize the effect of the respiratory cycle on intrathoracic pressures, measurements are obtained at end-expiration, when intrathoracic pressure is closest to zero.

Positive end-expiratory pressure

- Debate exists over how to correct PCWP in the presence of PEEP. Although previously advocated, temporary discontinuation of PEEP may have adverse effects, such as cardiovascular collapse or hypoxemia, that are difficult to reverse.
- For PEEP greater than 10 cm H₂O, the following general rule can be applied:
 - Corrected PCWP equals measured PCWP minus one half the quotient of PEEP divided by 1.36. If available, an intra-esophageal balloon can be used. Esophageal pressure equals pleural pressure, so corrected PCWP equals measured PCWP minus esophageal pressure.

ABNORMAL PULMONARY ARTERY AND WEDGE PRESSURE WAVEFORMS

SHOCK

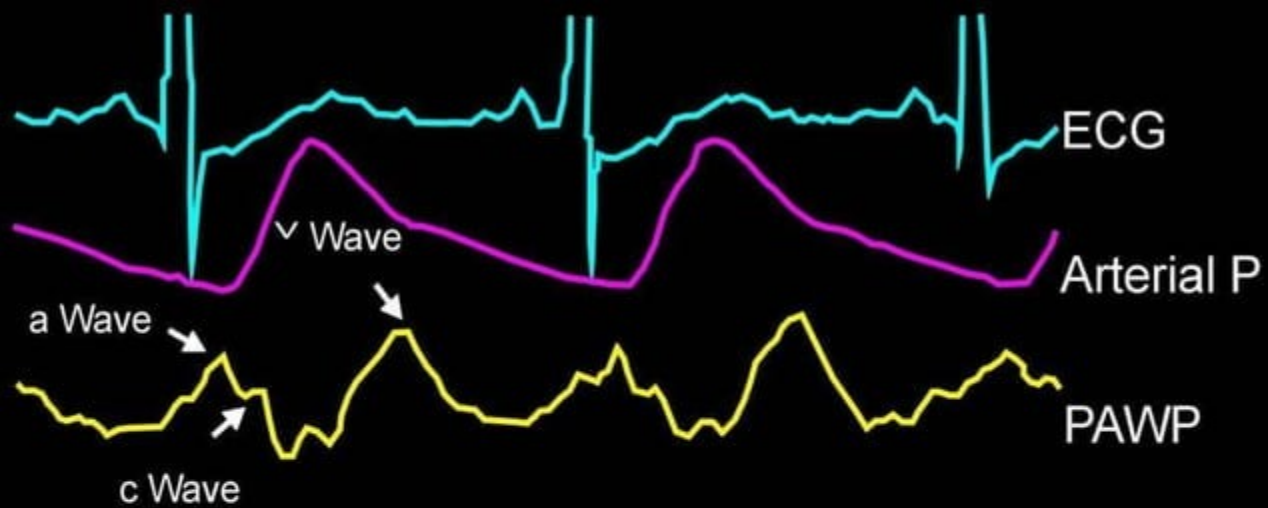
PACs are used frequently in the management of various forms of shock.

Hypovolemic shock

- Preload is markedly decreased, leading to inadequate ventricular filling.
- Systemic, venous, and intracardiac pressures are abnormally low.
- The overall PAC pressure tracing has a damped appearance.

Cardiogenic shock

- Cardiogenic shock is characterized by systolic blood pressure less than 80 mm Hg, cardiac index less than 1.8 L/min/m², and PCWP greater than 18 mm Hg.
- This form of shock can occur from a direct insult to the myocardium (eg, large AMI, severe cardiomyopathy) or from a mechanical problem that overwhelms the functional capacity of the myocardium (eg, acute severe mitral regurgitation, acute ventricular septal defect).
- With acute mitral regurgitation, large volumes of blood regurgitate into a poorly compliant LA, raising Ppv and causing pulmonary edema.
- Large V waves usually are observed in the PCWP pressure tracing



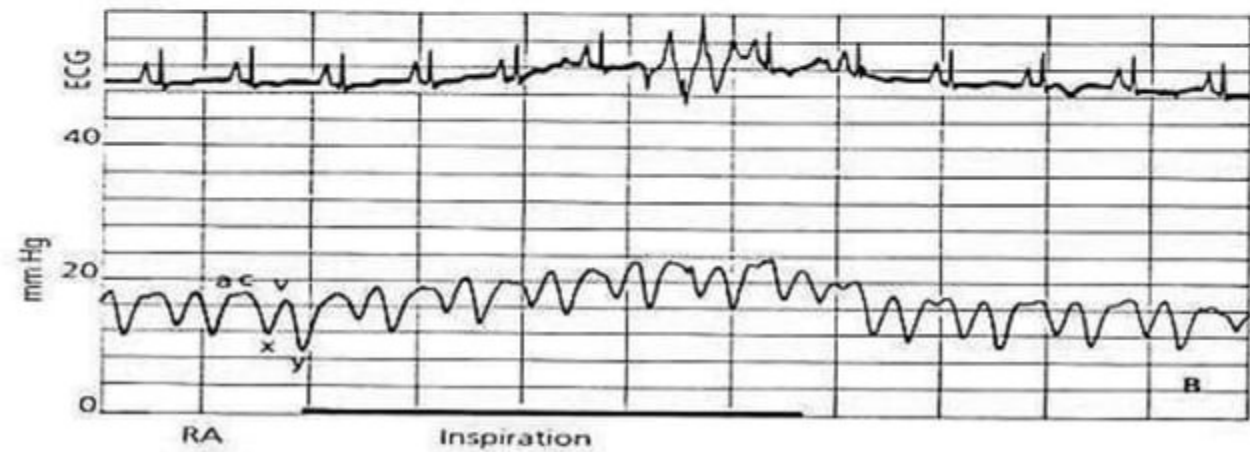
Tall V waves presented here on pulmonary arterial and wedge pressure waveforms are characteristic of severe mitral regurgitation.

Septic shock

- Septic shock is an example of distributive shock, a form of shock characterized by profound peripheral vasodilation.
- Swan-Ganz catheter measurements frequently demonstrate low filling pressures.

Extracardiac obstructive shock

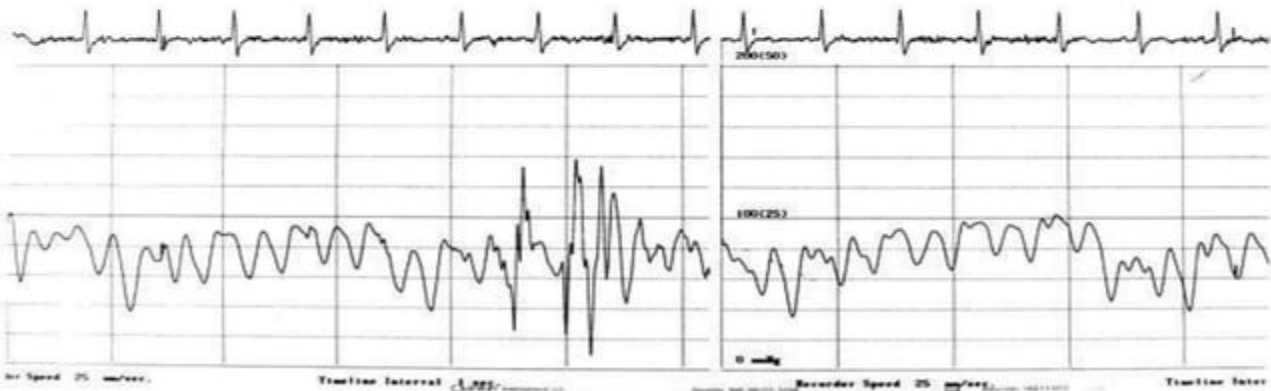
- Pericardial tamponade is an example of this form of shock
- The increased pericardial pressure impairs ventricular diastolic filling, decreasing preload, stroke volume, and CO.
- The RAP approximates the RV diastolic pressure, which approximates the PA diastolic pressure, and also approximates PCWP



- The RA waveform shows a minimal X and small and/or absent Y descent, and the mean RAP is elevated.
- Ppa loses its usual respiratory variation.
- In pericardial tamponade, the systemic arterial pressure shows evidence of pulsus paradoxus.
- Other causes of extracardiac shock include massive PE and tension pneumothorax.

Constrictive pericarditis

- Once this occurs, ventricular filling is stopped abruptly, creating a plateau in the RV pressure, which is typical of constrictive pericarditis. This is called the "dip and plateau" pattern or square root sign.
- The RAP waveform has a characteristic configuration suggestive of an M or W. A and V waves are accentuated with rapid X and Y descents,
- PCWP may be as high as 20-25 mm Hg, and usually appears similar to the RA waveform.
- Pulsus paradoxus is present much less commonly with constrictive pericarditis than with pericardial tamponade.



Mitral stenosis

- LAP, and thus PAWP, is elevated
- Pulmonary hypertension also develops as the severity of the valve lesion progresses. This leads to increase in RV systolic pressure and in the RA A wave.
- Atrial fibrillation is a common complication in mitral stenosis and results in loss of A waves in both the RA and PCWP pressure tracings.

Aortic stenosis

- The RA, RV, and PA waveforms usually are normal unless congestive heart failure is present.
- PCWP may show large A waves in severe cases because of poor LV compliance.

Aortic regurgitation

- The hemodynamics in acute aortic regurgitation include modestly elevated RAP and elevated RV systolic and diastolic pressures. PA systolic and diastolic pressures also are elevated, as is PCWP.
- A widened and elevated systemic arterial pressure without a diastolic notch is sometimes observed.
- A wide pulse pressure usually is not observed in acute regurgitation.

COMPLICATIONS

General

- Immediate:
 - Bleeding
 - Arterial Puncture
 - Air embolism
 - Thoracic duct injury (L side)
 - Pneumothorax / hemothorax
- Delayed:
 - Infections
 - Thrombosis

Related to insertion of PAC:

- Arrhythmias (most common- Ventricular/ RBBB)
- Misplacement
- Knotting
- Myocardial/valve/vessel rupture

Related to maintenance and use of PAC:

- Pulmonary artery perforation
- Thromboembolism
- Infection

CARDIAC OUTPUT MONITORING

- Cardiac output is the total blood flow generated by the heart, and in a normal adult at rest, it ranges from 4.0 to 6.5 L/min.
- Measurement of cardiac output provides a global assessment of the circulation, and in combination with other hemodynamic measurements, it allows calculation of additional important circulatory variables, such as systemic and pulmonary vascular resistance and ventricular stroke work.
- $CO = HR \times SV$

Indications for monitoring cardiac output

Diagnostic

- Differential diagnosis of shock
 - Cardiogenic
 - Septic
 - Hypovolemic
- Evaluation of pulmonary oedema
 - Cardiogenic from non cardiogenic
- Evaluation of cardiac failure
 - Tamponade
- Evaluation of cardiac structures
 - Valvular disease and intracardiac shunts
- Others
 - Shock in acute myocardial infarction
 - Pulmonary hypertension

Therapeutic

- Guide therapy in shock
 - Fluid management
 - Vasopressor / inotropes
- Guide therapy peri-operatively
- Guide therapy in cardiac failure
- Ventilator management
- Multi - organ failure

- The ideal system for cardiac output monitoring would be non-invasive, easy to use, accurate, reliable, consistent and compatible in patients.
- At present, no single technique meets all these criteria.
- Methods may be :
 - Invasive
 - Non-Invasive

INVASIVE METHODS

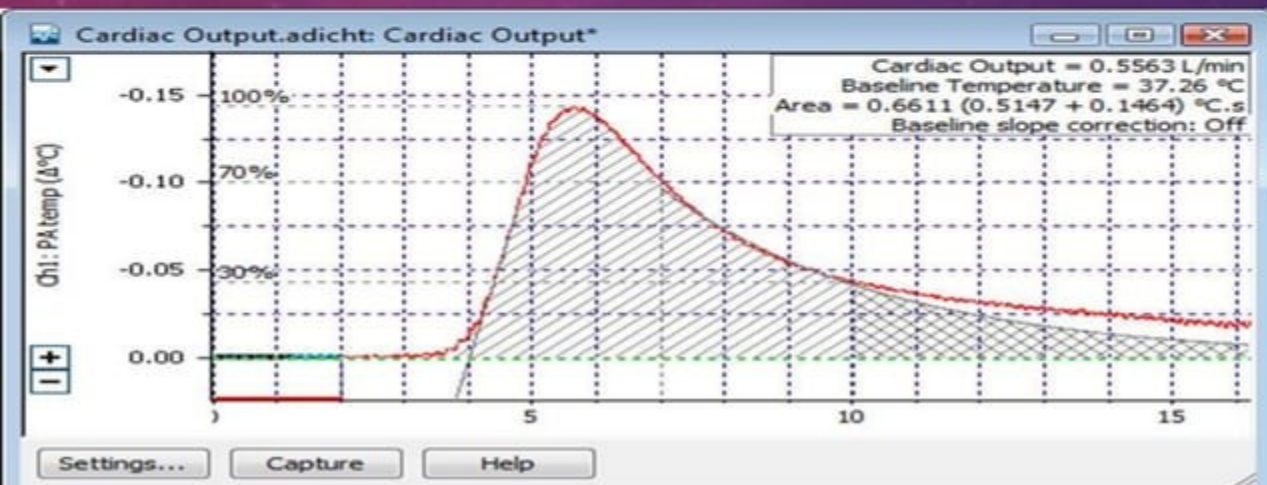
Fick method

- This method is based on the principle described by Adolfo Fick in 1870.
- Amount of a substance taken up by an organ per unit time is equal to the arterial minus the venous concentration multiplied by blood flow
- $CO = VO_2 / CaO_2 - CvO_2$
- The arteriovenous difference is computed by receiving samples of arterial blood, and mixed venous blood by receiving blood from the pulmonary artery.

Thermodilution method

- This method uses a special thermistor – tipped catheter inserted from a central vein into the pulmonary artery. A cold solution of D/W 5% or normal saline (temperature 0°C) is injected into the right atrium from a proximal catheter port.
- This solution causes a decrease in blood temperature, which is measured by a thermistor placed in the pulmonary artery catheter.
- The decrease in temperature is inversely proportional to the dilution of the injectate. The cardiac output can be derived from the modified Stewart-Hamilton conservation of heat equation.
- The pulmonary artery catheter is attached to the cardiac output computer, which displays a curve and calculates output and derived indices automatically

$$\dot{Q} = \frac{n}{\int c dt} = \frac{k(T_{\text{core}} - T_{\text{indicator}}) V_{\text{indicator}}}{\int_{t_1}^{t_2} -\Delta T dt}$$



- Thermodilution technique remain the most common approach in use today and is considered as the golden standard approach to cardiac output monitoring.
- Factors that may compromise this technique are shunts, tricuspid regurgitation, cardiac arrhythmias, abnormal respiratory patterns and low cardiac output

NON-INVASIVE METHODS

Lithium dilution cardiac output (LiDCO)

- This technique was first described in 1993 and is minimally invasive. It requires a venous line and an arterial catheter.
- A bolus of isotonic lithium chloride solution is injected via the venous line. Arterial plasma concentration is measured by withdrawing blood across a selective lithium electrode at a rate of 4 mL/min.
- Cardiac output is calculated based on the lithium dose and the area subject to the concentration– time circulation. This technique is contra-indicated in patients on lithium therapy and atracurium.
- The technique is simple to perform, safe and accurate.

Pulse index Contour Continuous Cardiac Output (PiCCO)

- This technique calls for the insertion of an arterial catheter, and hence is considered a minimally invasive procedure. A long arterial catheter (with a thermistor) placed in the femoral axillary, or brachial artery, and connected to a pulse contour device.
- With this catheter, a continuous pulse waveform contour analysis is obtained. The calculation is made by analysis of the area under the systolic portion of the arterial pressures waveform, from the end-diastole to the end of the ejection phase; this corresponds to stroke volume.
- Also, by virtue of a pulse contour analysis device, a beat-to-beat analysis of cardiac output, averaged at 30 seconds, is displayed.
- Calibration requires a central venous cannulation, using a transpulmonary thermodilution technique.
- This method offers a level of accuracy comparable to thermodilution

PiCCO plus

PULSON
Medical Systems



Thoracic electrical bioimpedance

- This technique employs four pairs of electrodes. Two pairs are applied to the neck base on opposite sides and two pairs are placed at the level of the xiphoid junction. Each pair of electrodes comprises transmitting and sensing electrodes.
- With these electrodes, low-level electricity conducted by body fluid is transmitted. Another set of two electrodes is used to monitor a single ECG signal. This electricity is harmless and not felt by the patient.
- The first derivative dZ/dt of the impedance waveform is related linearly to aortic blood flow.

- Changes in impedance correlate with stroke volume, calculated using the following formula

$$SV = \rho \frac{L^2}{Z_0^2} (dZ/dt)_{\max} \times T$$

where SV=stroke volume

ρ =resistivity of blood (Ω/cm)

L=mean distance between the inner electrodes (the thoracic length)

Z_0 =basal thoracic impedance

$(dZ/dt)_{\max}$ =the maximum value of the first derivative during systole (Ohms/second)

T=ventricular ejection time (sec)

- Cardiac output is calculated from the stroke volume and heart rate
- Cardiac output is easier to measure by impedance cardiography than by thermodilution with a pulmonary artery catheter, can be applied quickly, and does not pose a risk of infection, blood loss or other complications associated with arterial catheters
- This method can be used to calculate various other parameters, such as cardiac index, stroke index, end-diastolic index and other hemodynamic parameters including systemic vascular resistance

Esophageal Doppler

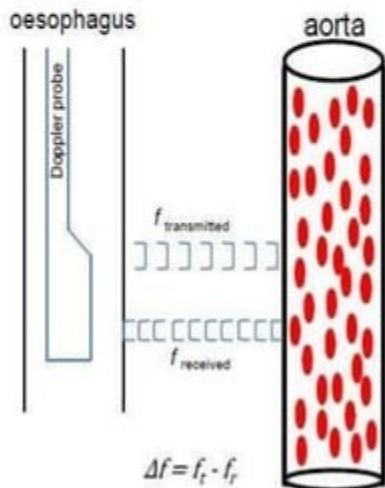
- Relies upon the Doppler principle to measure the velocity of blood flow in the descending thoracic aorta.
- By using the Doppler equation, it is possible to determine the velocity of blood flow in the aorta.
- The equation is:

$$V = \frac{\Delta f c}{2 f_t \cos \theta}$$

f_t = transmitted frequency

c = velocity of sound in tissue (1540 m/s)

$\cos \theta$ = incident angle between the ultrasound beam and blood flow direction (if the probe is parallel to the aorta, $\theta = 0$ and $\cos \theta = 1$)



- The monitor thus calculates both the distance the blood travels, as well as the area: $\text{area} \times \text{length} = \text{volume}$.
- Consequently, the SV of blood in the descending aorta is calculated. Knowing the HR allows calculation of that portion of the CO flowing through the descending thoracic aorta, which is approximately 70% of total CO. Correcting for this 30% allows the monitor to estimate the patient's total CO.
- For Doppler to provide a reliable estimate of velocity, the angle of incidence should be as close to zero as possible, since the cosine of 0 is 1.

Echocardiography

- There are no more powerful tools to diagnose and assess cardiac function perioperatively than transthoracic echocardiography (TTE) and transesophageal echocardiography (TEE).
- Echocardiography employs ultrasound from 2 to 10 MHz.
- In the heart, both the blood flowing through the heart and the heart tissue move relative to the echo probe in the esophagus or on the chest wall.
- By using the Doppler effect, it is possible for echocardiographers to determine both the direction and the velocity of blood flow and tissue movement.

- The Bernoulli equation (pressure change = $4V^2$) allows echocardiographers to determine the pressure gradient between areas of different velocity, where v represents the area of maximal velocity.
- Likewise, the Bernoulli equation permits echocardiographers to estimate PA and other intracavitary pressures, if assumptions are made.
- TTE and TEE can be used to estimate CO.
- Provides accurate assessment of stroke volume and chamber pressures
- Also enables estimation of myocardial function / dysfunction including diastolic dysfunction
- Severity of valvular dysfunction can be assessed

- Disadvantages:
 - Requires trained personnel
 - Equipment costs
 - Operator dependent
 - Body habitus, ventilation and position of the patient may preclude obtaining good images
 - Examination takes considerable time; real time imaging is not possible – can be overcome to a certain extent by limiting assessment to fixed protocols



THANK YOU