

UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

Abiomed, Inc., Abiomed R&D, Inc., and Abiomed Europe GmbH
Petitioners

v.

Maquet Cardiovascular, LLC
Patent Owner

Case IPR2017-02151
U.S. Patent No. 9,327,068

PATENT OWNER'S EXHIBIT 2007

Hemodynamic Principles

The Fundamentals

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Maquet, Ex. 2007-1

IPR2017-02151

Hemodynamic Principles

An Overview

- **Pressure measurement**
- **Right and left heart catheterization**
- **Cardiac output measurement**
 - **Fick-oxygen method**
 - Arterial-venous oxygen difference
 - **Indicator-dilution methods**
 - Indocyanine green
 - Thermodilution
- **Vascular resistance**
- **Shunt detection and measurement**
- **Gradients and valve stenoses**

Pressure Measurement Terminology

- Natural frequency
 - Frequency at which fluid oscillates in a catheter when it is tapped
 - Frequency of an input pressure wave at which the ratio of output/input amplitude of an undamaged system is maximal

$$\text{Natural frequency} = \frac{\text{catheter radius}}{\text{Volume elasticity of transducer membrane}} \times \sqrt{\frac{\text{Catheter length} \times \text{fluid density} \times \pi}{\text{Volume elasticity of transducer membrane}}}$$

SHORTER catheter
LARGER catheter lumen
LIGHTER fluid

} HIGHER natural frequency

Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

Pressure Measurement Terminology

- Damping
 - Dissipation of the energy of oscillation of a pressure management system, due to friction

$$\text{Damping} = \frac{4 \times \text{viscosity of fluid}}{\text{Fluid density} \times (\text{catheter radius})^2}$$

GREATER fluid viscosity
SMALLER catheter radius
LESS dense fluid

} GREATER damping

Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

Pressure Measurement Terminology

- Damped natural frequency
 - Frequency of oscillation in catheter system when the friction losses are taken into account

$$\text{Damped natural frequency} = \sqrt{(\text{Natural frequency})^2 - (\text{Damping})^2}$$

Natural frequency = Damping → System critically damped

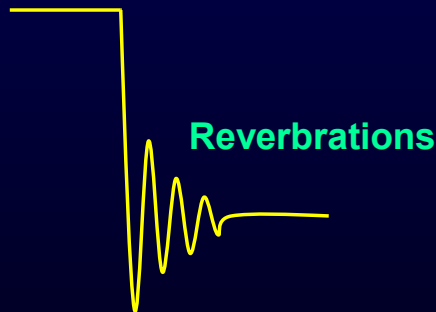
Natural frequency < Damping → OVERdamped

Natural frequency > Damping → UNDERdamped

Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

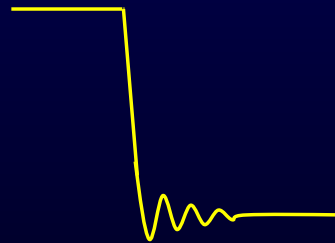
Pressure Measurement Terminology

UNDER damped

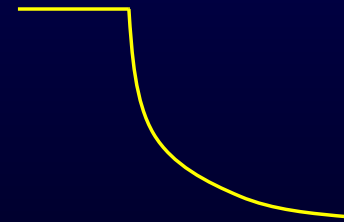


Less damping → greater
artifactual recorded pressure
overshoot above true
pressure when pressure
changes suddenly

OPTIMALLY damped



OVER damped



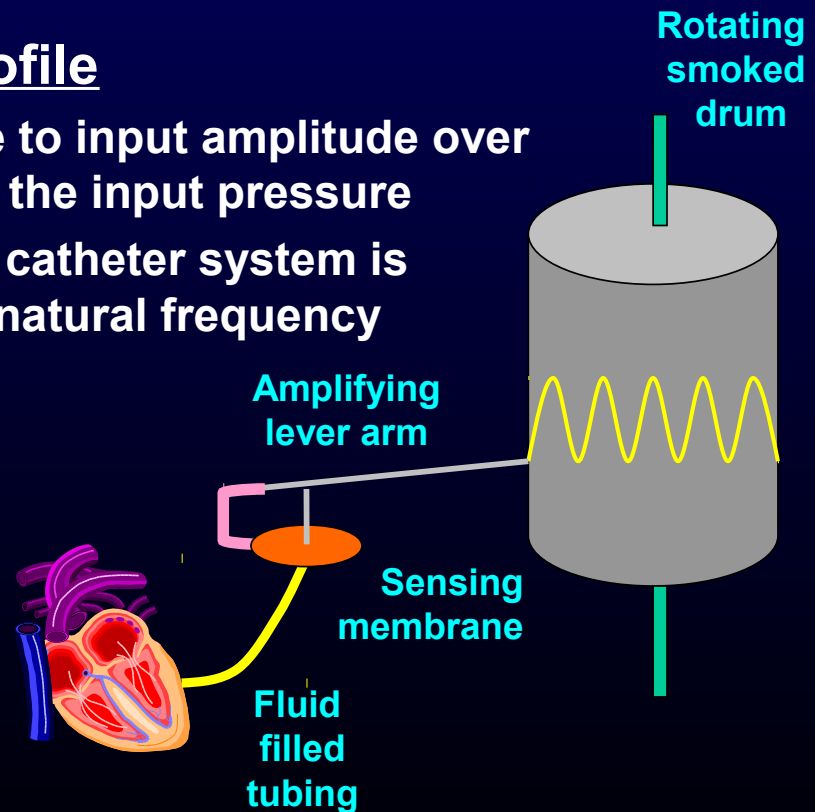
More damping → less
responsive to rapid
alterations in pressure

Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

Pressure Measurement

Hürthle Manometer

- Frequency response profile
 - Ratio of output amplitude to input amplitude over a range of frequencies of the input pressure
 - Frequency response of a catheter system is dependent on catheter's natural frequency and amount of damping
 - The higher the natural frequency of the system, the more accurate the pressure measurement at lower physiologic frequencies

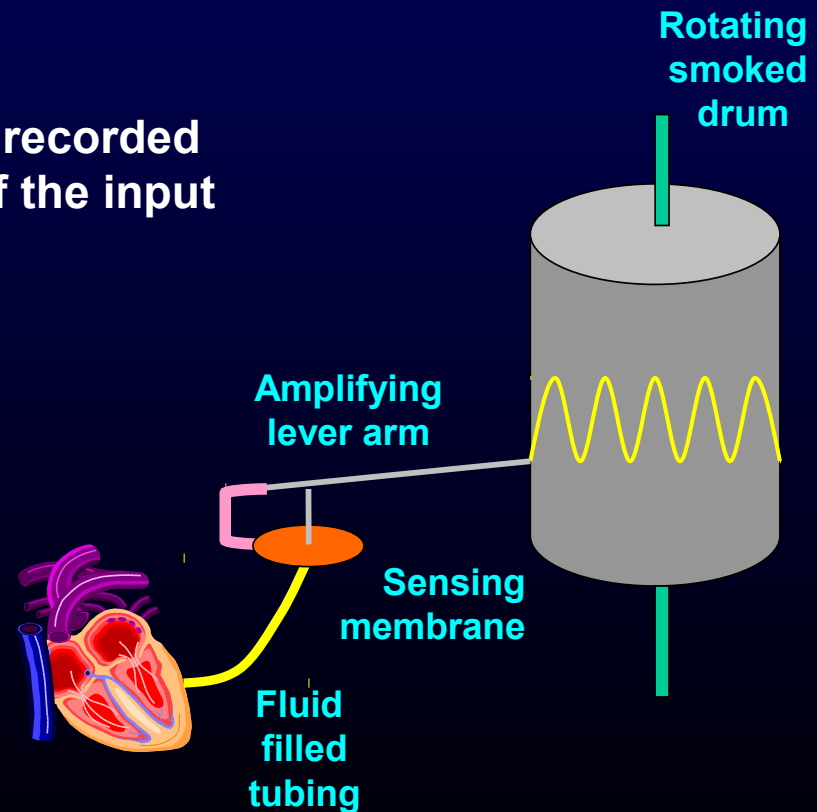


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Pressure Measurement

Hürthle Manometer

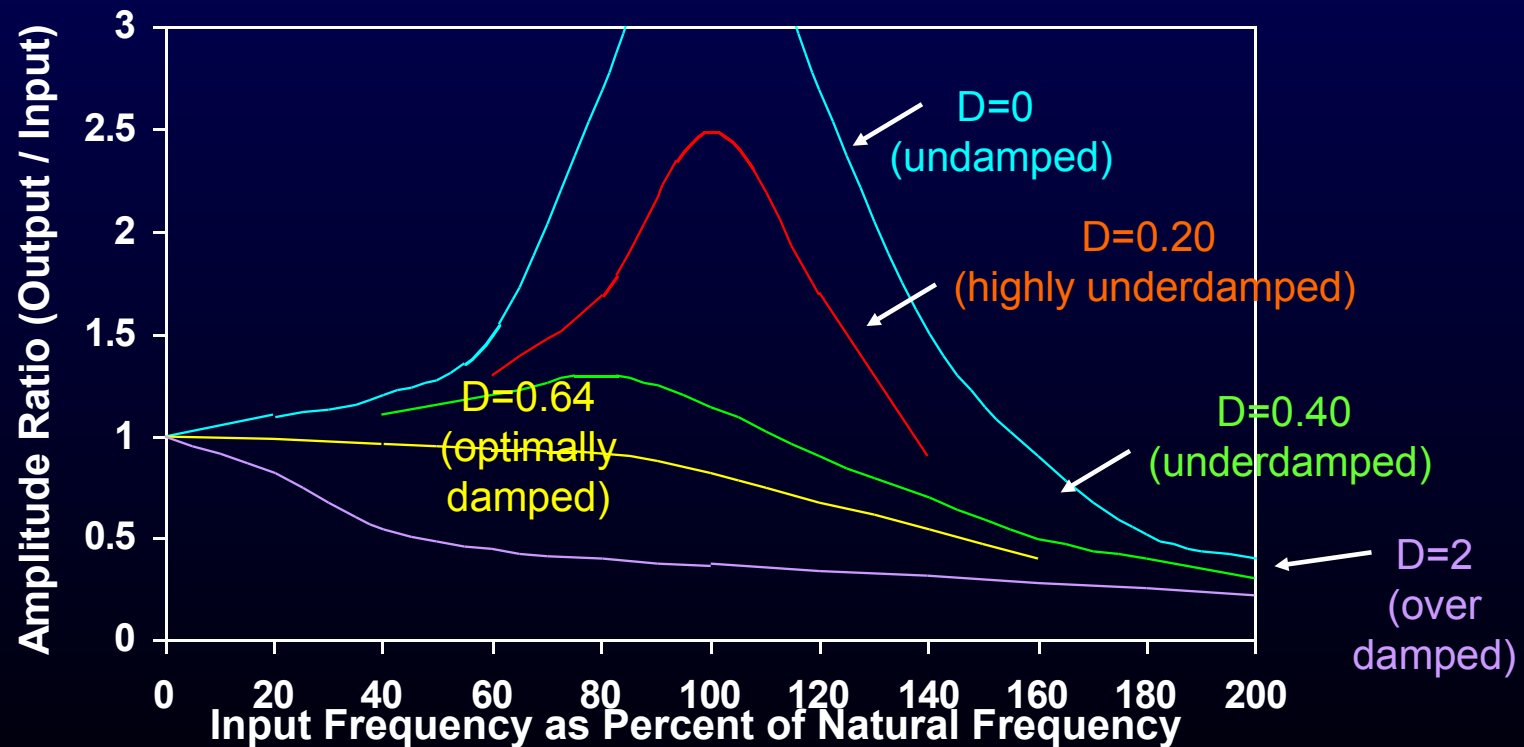
- Sensitivity
 - Ratio of amplitude of the recorded signal to the amplitude of the input signal



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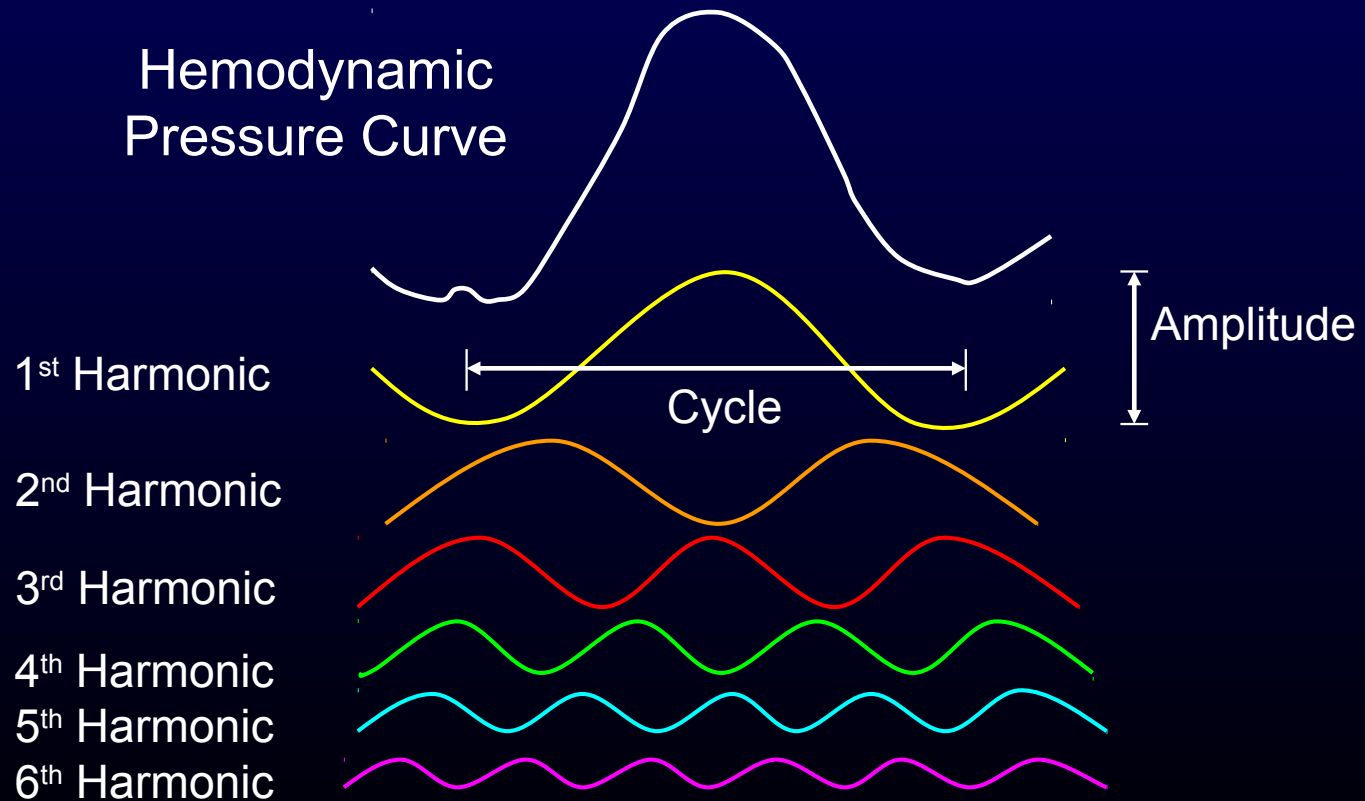
Pressure Measurement

Optimal Damping



Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

Pressure Measurement Harmonics



Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

Pressure Measurement

Terminology

- Pressure wave: Complex periodic fluctuation in force per unit area
- Fundamental frequency: number of times the pressure wave cycles in 1 second
- Harmonic: multiple of fundamental frequency
- Fourier analysis: resolution of any complex periodic wave into a series of simple sine waves of differing amplitude and frequency

Pressure Measurement Terminology

- **Essential physiologic information is contained within the first 10 harmonics**
 - **At pulse of 120, the fundamental frequency is 2 cycles/sec, and 10th harmonic is 20 cycles/sec. A pressure response system with a frequency response range that is flat to 20 cycles/sec will be adequate.**
 - **Natural frequency should be 3 times as fast as the 10th harmonic of the pressure measured.**
 - **Fidelity of the recording drops with increasing HR.**

Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

Pressure Measurement Devices

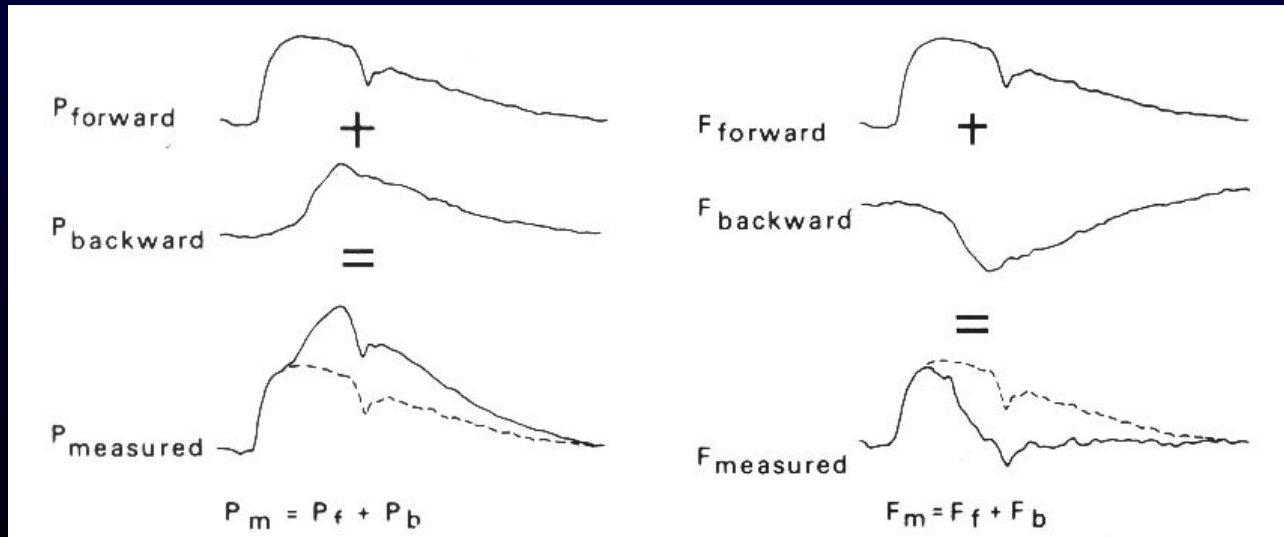
- **Fluid-filled catheter manometer**
- **Micromanometer (Catheter-tip pressure manometer)**
 - **High fidelity transducer catheter with miniaturized transducer placed at tip (Millar Instruments)**
 - **Improved frequency response characteristics and reduced artifact**
 - **Measurement of myocardial mechanics (dP/dt of LV)**

Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

Pressure Measurement

Reflected Waves

- **Reflected waves:** Both pressure and flow at any given location are the geometric sum of the forward and backward waves



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Pressure Measurement

Reflected Waves

- **Augmented pressure wave reflections**
 - Vasoconstriction
 - Heart failure
 - Hypertension
 - Aortic / iliofemoral obstruction
 - Post-valsalva release
- **Diminished pressure wave reflections**
 - Vasodilation (physiologic / pharmacologic)
 - Hypovolemia
 - Hypotension
 - Valsalva maneuver strain phase

Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

Pressure Measurement

Wedge Pressure

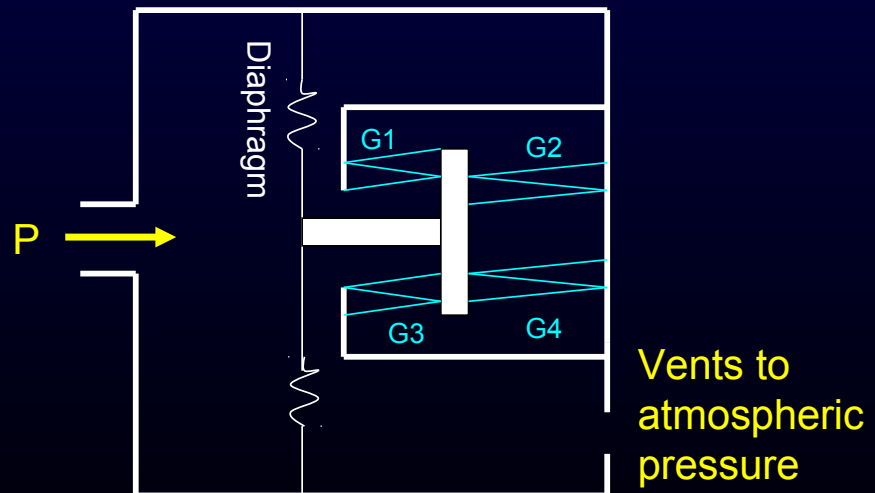
- **Wedge Pressure**
 - Pressure obtained when an end-hole catheter is positioned in a “designated” blood vessel with its open end-hole facing a capillary bed, with no connecting vessels conducting flow into or away from the “designated” blood vessel between the catheter’s tip and the capillary bed
 - True wedge pressure can be measured only in the absence of flow, allowing pressure to equilibrate across the capillary bed

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Pressure Measurement

Wheatstone Bridge

- Strain-gauge pressure transducer
- Increased pressure on diaphragm stretches, and increases resistance of G1 & G3 wires, while relaxing G2 & G4 wires
- Voltage is applied across the wires and unbalanced resistance leads to current flow across Wheatstone bridge



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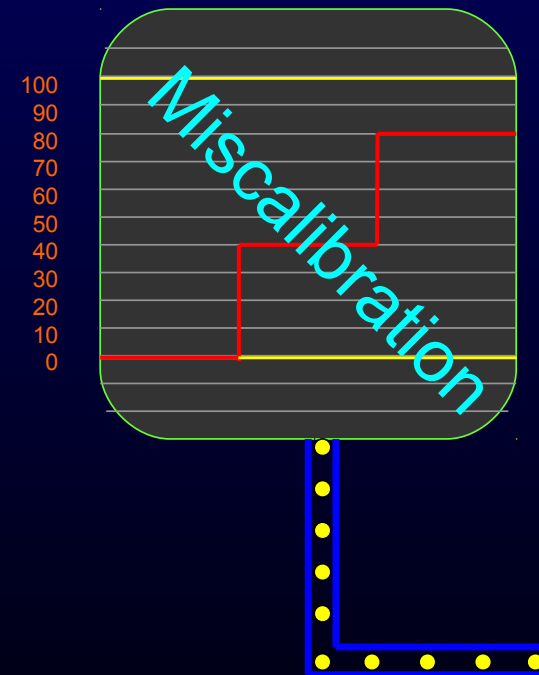
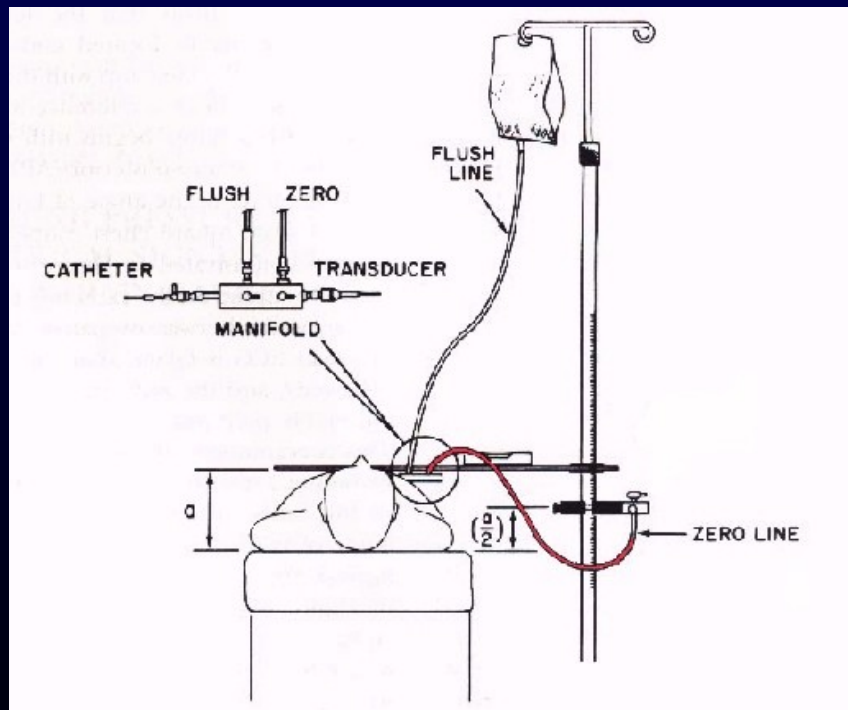
Pressure Measurement

Balancing and Calibration

- **Balancing a transducer**
 - Variable resistance is interpolated into circuit so that at an arbitrary baseline pressure the voltage across the output terminal can be reduced to zero
 - Zero reference
 - Midchest level
 - Measure antero-posterior thoracic diameter at angle of Louis
- **Calibration**
 - Mercury manometer attached to free port with 100 mm Hg of pressure transmitted through fluid-filled line
 - Provides accurate scaling of pressure measurement

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Pressure Measurement Calibration

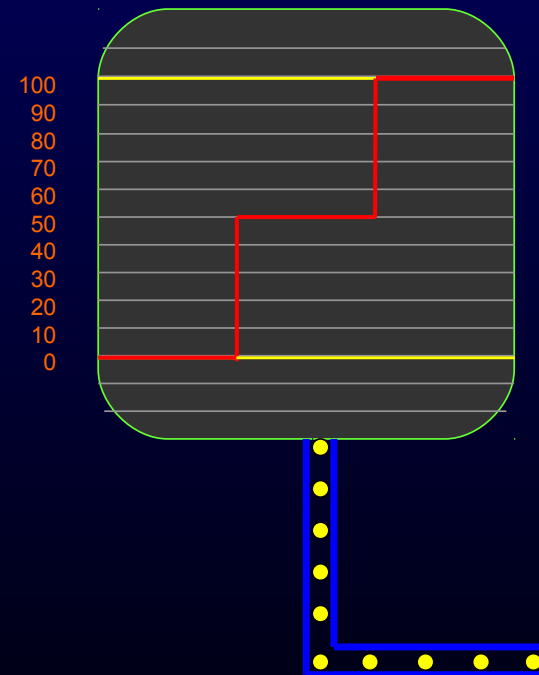
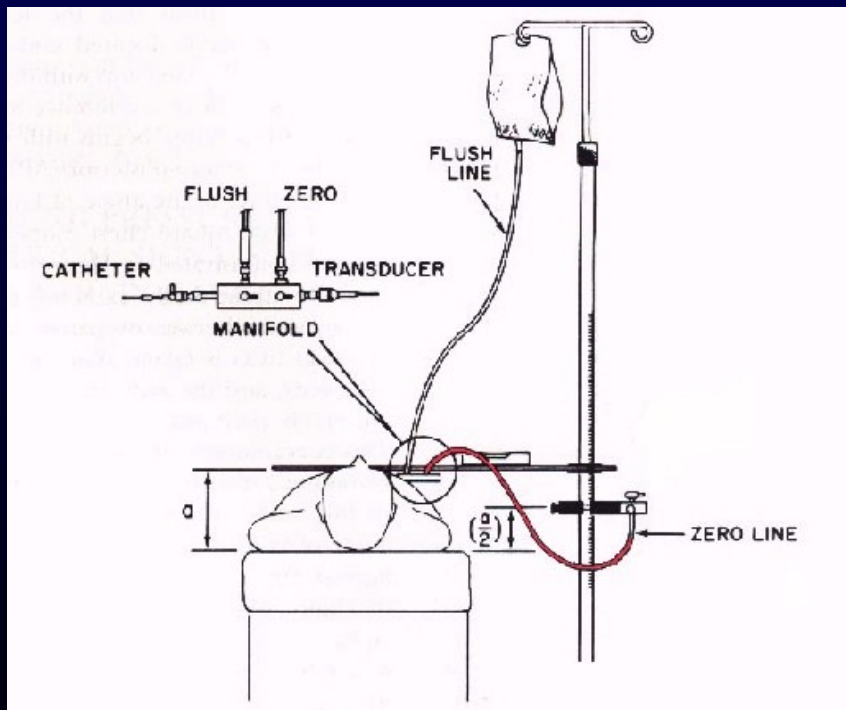


Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

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Pressure Measurement Calibration

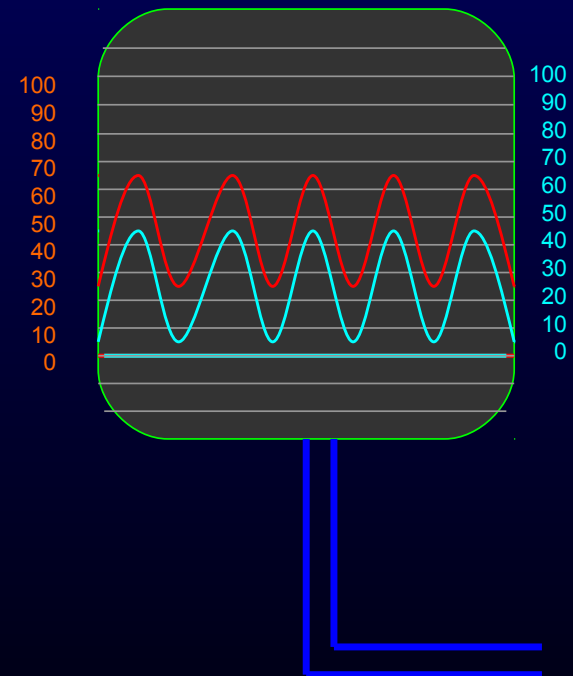
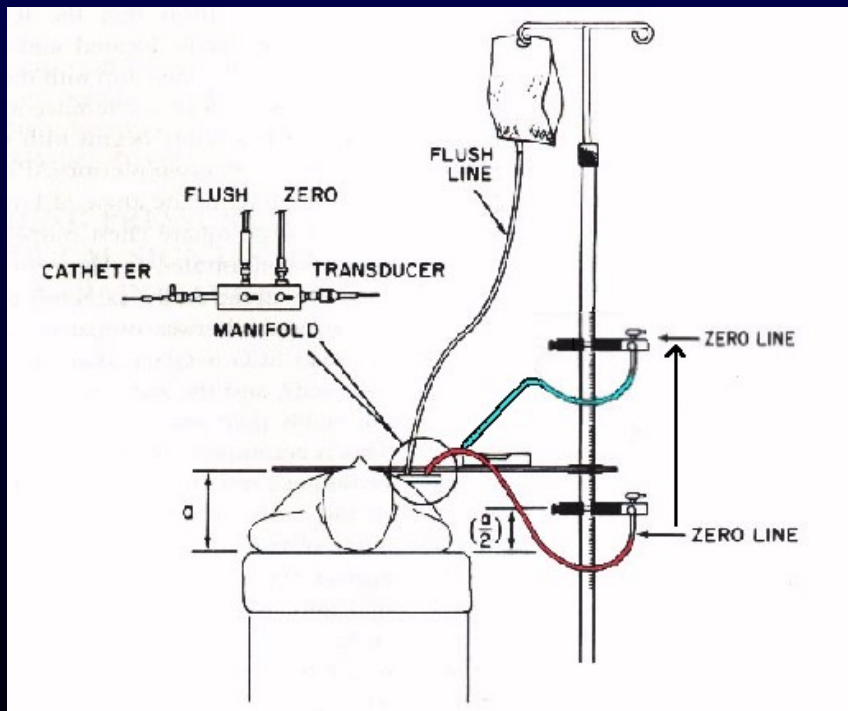


Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

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Pressure Measurement Balancing



Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

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Pressure Measurement

Sources of Error

- **Tachycardia**
 - If pulse is too fast for natural frequency of system, the fidelity of the recording will drop.
 - Pulse = 120 → 10th harmonic = 20 Hz → Damped natural frequency should be at least 60 Hz
- Deterioration in frequency response
- Catheter whip artifact
- End-pressure artifact
- Catheter impact artifact
- Systolic pressure amplification in the periphery
- Errors in zero level, balancing, calibration

Pressure Measurement

Sources of Error

- Tachycardia
- **Sudden changes in pressure**
 - Peak LV systole, trough early diastole, catheter bumping against wall of valve
 - Artifact seen due to underdamping
- Deterioration in frequency response
- Catheter whip artifact
- End-pressure artifact
- Catheter impact artifact
- Systolic pressure amplification in the periphery
- Errors in zero level, balancing, calibration

Pressure Measurement

Sources of Error

- Tachycardia
- Sudden changes in pressure
- **Deterioration in frequency response**
 - Introduction of air or stopcocks permits damping and reduces natural frequency by serving as added compliance
 - When natural frequency of pressure system falls, high frequency components of the pressure waveform (intraventricular pressure rise and fall) may set the system into oscillation, producing “pressure overshoots”
- Catheter whip artifact
- End-pressure artifact
- Catheter impact artifact
- Systolic pressure amplification in the periphery
- Errors in zero level, balancing, calibration

Pressure Measurement

Sources of Error

- Tachycardia
- Sudden changes in pressure
- Deterioration in frequency response
- **Catheter whip artifact**
 - Motion of the catheter within heart or large vessels accelerates fluid in catheter and produces superimposed waves of ± 10 mm Hg
- End-pressure artifact
- Catheter impact artifact
- Systolic pressure amplification in the periphery
- Errors in zero level, balancing, calibration

Pressure Measurement

Sources of Error

- Tachycardia
- Sudden changes in pressure
- Deterioration in frequency response
- Catheter whip artifact
- **End-pressure artifact**
 - Pressure from endhole catheter pointing upstream is artifactually elevated. When blood flow is halted at tip of catheter, kinetic energy is converted in part to pressure. Added pressure may range 2-10 mm Hg.
 - When endhole catheter is oriented into the stream of flow, the “suction” can lower pressure by up to 5%
- Catheter impact artifact
- Systolic pressure amplification in the periphery
- Errors in zero level, balancing, calibration

Pressure Measurement

Sources of Error

- Tachycardia
- Sudden changes in pressure
- Deterioration in frequency response
- Catheter whip artifact
- End-pressure artifact
- **Catheter impact artifact**
 - Pressure transient produced by impact on the fluid-filled catheter by an adjacent structure (i.e. heart valve)
 - Any frequency component of this transient that coincides with the natural frequency of the catheter manometer system will cause a superimposed oscillation on the recorded pressure wave
- **Systolic pressure** amplification in the periphery
- Errors in zero level, balancing, calibration

Pressure Measurement

Sources of Error

- Tachycardia
- Sudden changes in pressure
- Deterioration in frequency response
- Catheter whip artifact
- End-pressure artifact
- Catheter impact artifact
- **Systolic pressure amplification in the periphery**
 - Consequence of reflected wave
 - Peripheral arterial systolic pressure commonly 20 mm Hg higher than central aortic pressure (mean pressure same or slightly lower)
 - Masks pressure gradients in LV or across aortic valve
- Errors in zero level, balancing, calibration

Pressure Measurement

Sources of Error

- Tachycardia
- Sudden changes in pressure
- Deterioration in frequency response
- Catheter whip artifact
- End-pressure artifact
- Catheter impact artifact
- Systolic pressure amplification in the periphery
- **Errors in zero level, balancing, calibration**
 - Zero level must be at mid chest level
 - All manometers must be zeroed at same point
 - Zero reference point must be changed if patient repositioned
 - Transducers should be calibrated against standard mercury reference (rather than electrical calibration signal) and linearity of response should be verified using 25, 50, and 100 mm Hg

Hemodynamic Principles

An Overview

- Pressure measurement
- Right and left heart catheterization
- Cardiac output measurement
 - Fick-oxygen method
 - Arterial-venous oxygen difference
 - Indicator-dilution methods
 - Indocyanine green
 - Thermodilution
- Vascular resistance
- Shunt detection and measurement
- Gradients and valve stenoses

Right Heart Catheterization

Indications

- **Heart failure**
- **Acute MI**
- **Acute or chronic pulmonary disease**
- **Screening for unspecified respiratory disease**
- **Hypotension**
- **Valvular heart disease**
- **Mechanical complications**
- **Endomyocardial fibrosis**
- **Congenital heart disease**
- **Complications of transplanted heart**

Right Heart Catheterization

Indications for Bedside Placement

- **Heart failure**
- **Myocardial infarction**
- **Preoperative use**
- **Primary pulmonary hypertension**

Right Heart Catheterization

Indications for Bedside Placement

- **Heart Failure**
 - Differentiating between hemodynamic and permeability pulmonary edema or dyspnea when trial of diuretic or vasodilator has failed or is associated with high risk
 - Differentiating between cardiogenic and noncardiogenic shock when trial of intravascular volume expansion has failed or is associated with high risk; guidance of pharmacologic or mechanical therapy
 - Guidance of therapy in patients with features of both “forward” and “backward” heart failure
 - Determination of pericardial tamponade when clinical exam and echocardiography are inconclusive
 - Perioperative management of patients with heart failure undergoing intermediate or high risk surgery
 - Detection of pulmonary HTN and guidance of therapy

ACC Expert Consensus Document. JACC 1998; 32: 840-64.

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Right Heart Catheterization

Indications for Bedside Placement

- **Myocardial Infarction**
 - Differentiating between cardiogenic and hypovolemic shock when initial therapy with trial of intravascular volume and low-dose inotropes has failed
 - Management of cardiogenic shock with pharmacologic and/or mechanical therapy
 - Pharmacologic and/or mechanical management of acute mitral regurgitation
 - Pre-op assessment left-to-right shunt severity in VSD
 - Management of RV infarction associated with hypotension and/or signs of low cardiac output, not responsive to intravascular volume, low dose inotropes, and restoration of heart rate and AV synchrony
 - Management of pulmonary edema not responsive to diuretics, vasodilators, and low-dose inotropes

Right Heart Catheterization

Indications for Bedside Placement

- **Pre-operative Use**
 - Differentiating between causes of low cardiac output (hypotension vs. LV dysfunction) when clinical and/or echocardiographic assessment is inconclusive
 - Differentiating between right and left ventricular dysfunction and pericardial tamponade when clinical and echocardiographic assessment is inconclusive
 - Management of severe low cardiac output syndrome
 - Management of pulmonary HTN in patients with systemic hypotension and evidence of inadequate organ perfusion

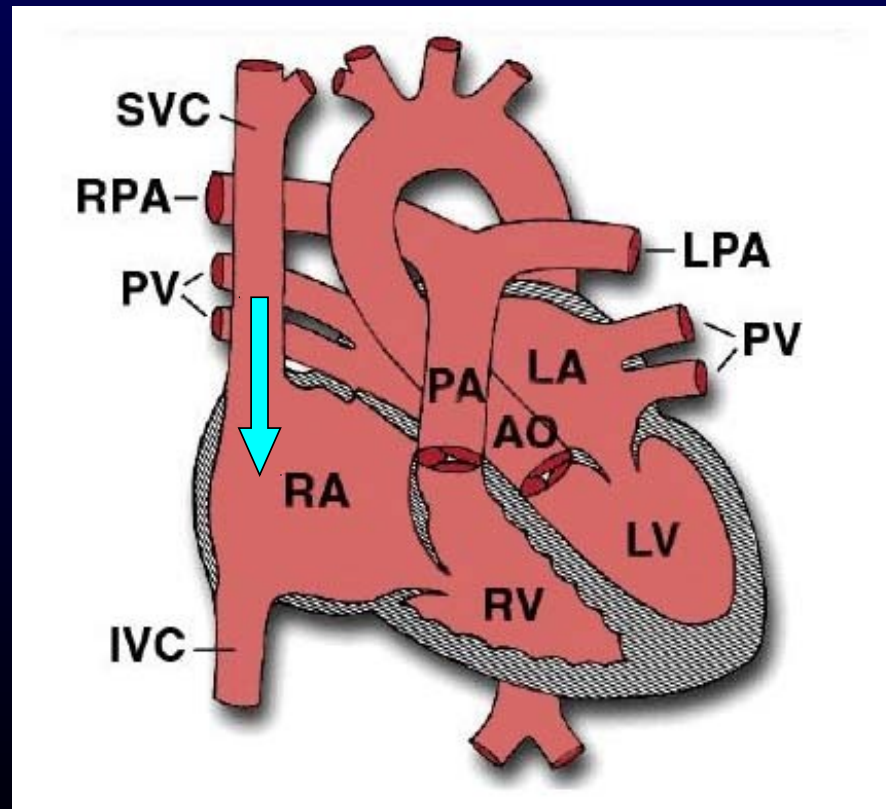
Right Heart Catheterization

Indications for Bedside Placement

- **Primary Pulmonary Hypertension**
 - Exclusion of post-capillary (elevated PAOP) causes of pulmonary hypertension
 - Diagnosis and assessment of severity of precapillary (normal PAOP) pulmonary hypertension
 - Selection of long-term vasodilator therapy based on acute hemodynamic response
 - Assessment of hemodynamic variables prior to lung transplantation

Right Heart Catheterization

Swan Ganz Catheter

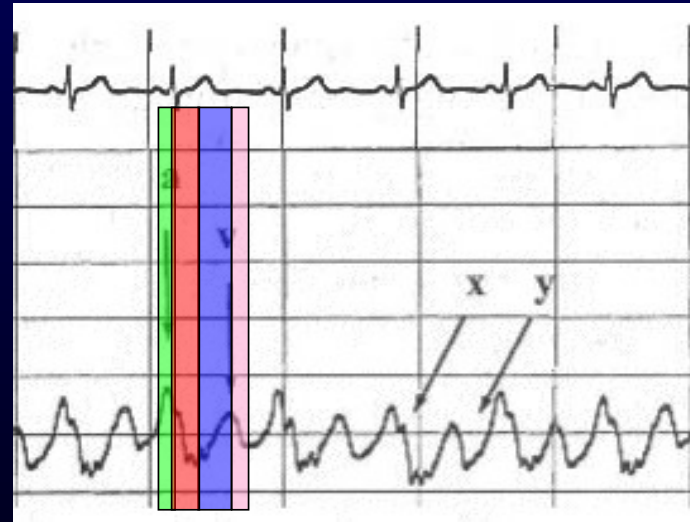


Kern MJ. Right Heart Catheterization. CATHSAP II CD-ROM. Bethesda, American College of Cardiology, 2001.

Right Heart Catheterization

Right Atrial Pressure

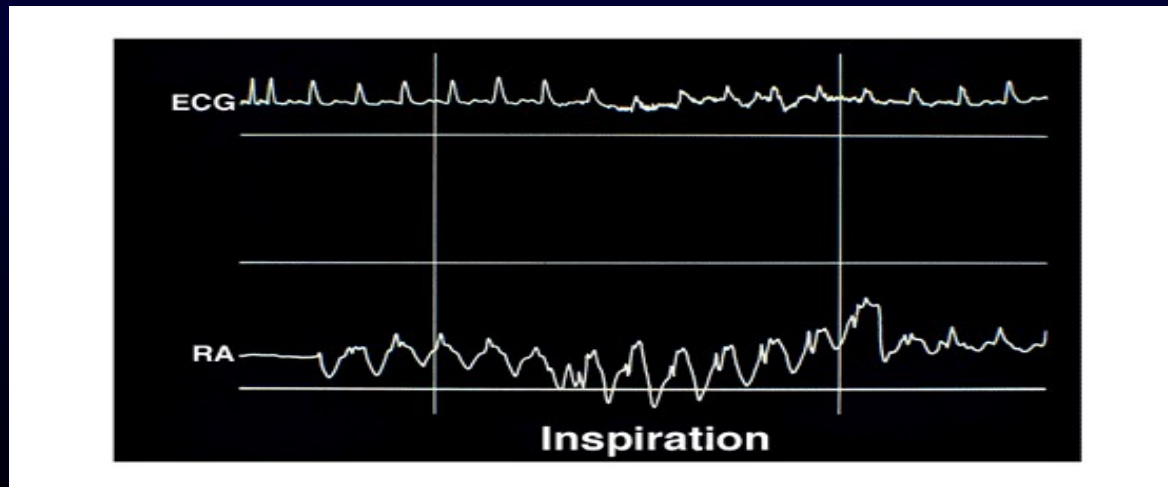
- **“a” wave**
 - Atrial systole
- **“c” wave**
 - Protrusion of TV into RA
- **“x” descent**
 - Relaxation of RA
 - Downward pulling of tricuspid annulus by RV contraction
- **“v” wave**
 - RV contraction
 - Height related to atrial compliance & amount of blood return
 - Smaller than a wave
- **“y” descent**
 - TV opening and RA emptying into RV



Right Heart Catheterization

Inspiratory Effect on Right Atrial Pressure

- Normal physiology
 - Inhalation: Intrathoracic pressure falls → RA pressure falls
 - Exhalation: Intrathoracic pressure increases → RA pressure increases



Kern MJ. Right Heart Catheterization. CATHSAP II CD-ROM. Bethesda, American College of Cardiology, 2001.

Right Heart Catheterization

Abnormalities in RA Tracing

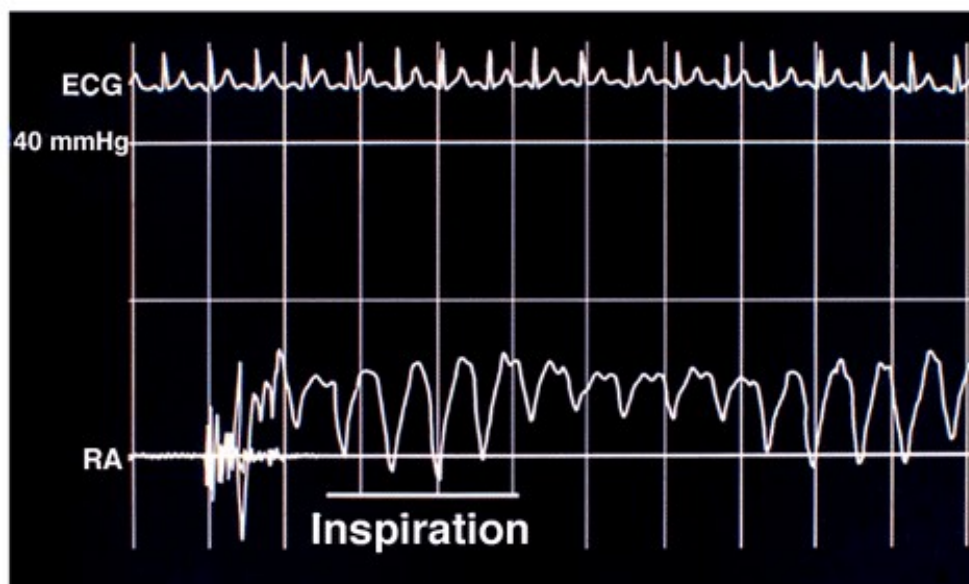
- **Low mean atrial pressure**
 - Hypovolemia
 - Improper zeroing of the transducer
- **Elevated mean atrial pressure**
 - Intravascular volume overload
 - Right ventricular failure
 - Valvular disease (TS, TR, PS, PR)
 - Myocardial disease (RV ischemia, cardiomyopathy)
 - Left heart failure (MS, MR, AS, AI, cardiomyopathy)
 - Increased pulmonary vascular resistance (PE, COPD, primary pulmonary HTN)
 - Pericardial effusion with tamponade physiology
 - Atrial myxoma

Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Right Heart Catheterization

Abnormalities in RA Tracing

- Elevated mean atrial pressure



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Right Heart Catheterization

Abnormalities in RA Tracing

- **Elevated a wave**
 - Tricuspid stenosis
 - Decreased RV compliance due to RV failure
- **Cannon a wave**
 - A-V asynchrony (3rd degree AVB, VT, V-pacer)
- **Absent a wave**
 - Atrial flutter or fibrillation
- **Elevated v wave**
 - TR
 - RV failure
 - Reduced atrial compliance (restrictive myopathy)
- **Equal a and v waves**
 - Tamponade
 - Constrictive physiology

Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Right Heart Catheterization

Abnormalities in RA Tracing

- **Prominent x descent**
 - Tamponade
 - Subacute/chronic constriction
 - RV ischemia
- **Prominent y descent**
 - TR
 - Constrictive pericarditis
 - Restrictive myopathy
- **Blunted x descent**
 - Atrial fibrillation
 - RA ischemia
- **Blunted y descent**
 - TS
 - RV ischemia
 - Tamponade

Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Right Heart Catheterization

Abnormalities in RA Tracing

- **M or W waves**
 - Diagnostic for RV ischemia, pericardial constriction or CHF

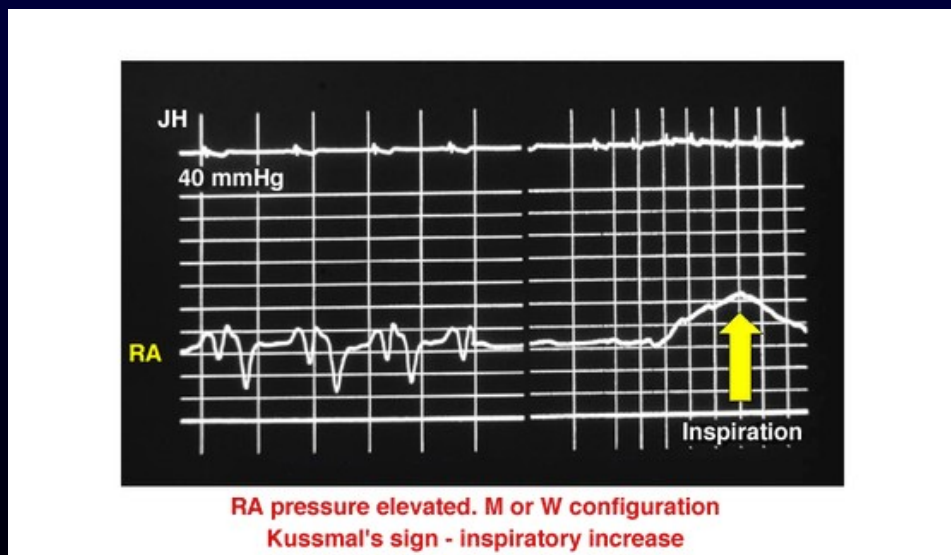


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Right Heart Catheterization

Abnormalities in RA Tracing

- **Kussmaul's Sign**
 - Inspiratory rise or lack of decline in RA pressure
 - Diagnostic for constrictive pericarditis or RV ischemia

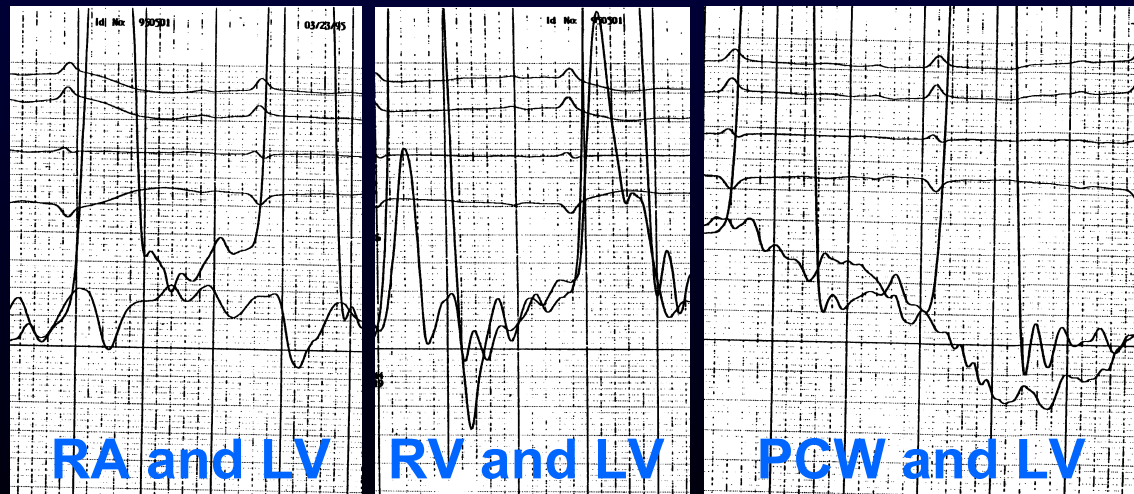


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Right Heart Catheterization

Abnormalities in RA Tracing

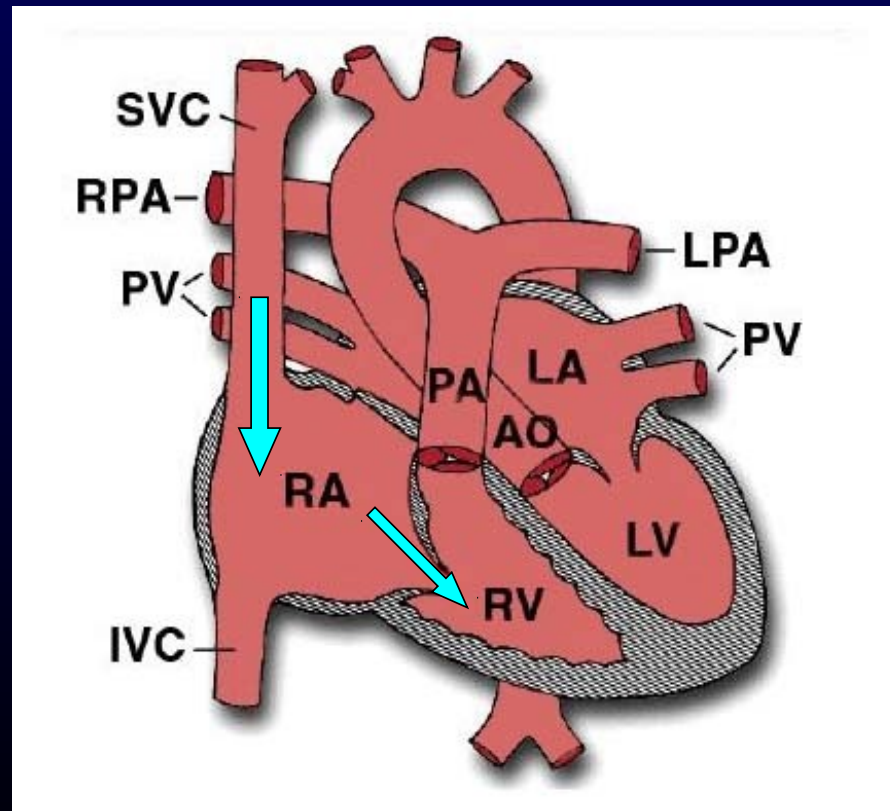
- **Equalization of pressures**
 - < 5 mm Hg difference between mean RA, RV diastolic, PA diastolic, PCWP, and pericardial pressures
 - Diagnostic for tamponade



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Right Heart Catheterization

Swan Ganz Catheter

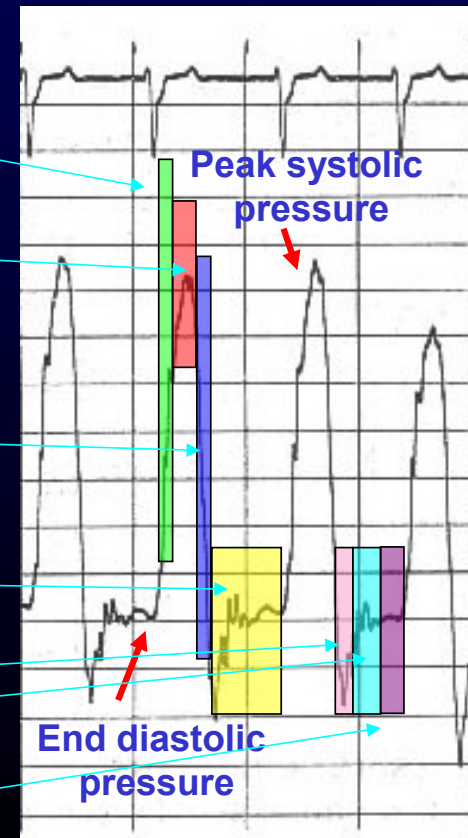


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Right Heart Catheterization

Right Ventricular Pressure

- **Systole**
 - **Isovolumetric contraction**
 - From TV closure to PV opening
 - **Ejection**
 - From PV opening to PV closure
- **Diastole**
 - **Isovolumetric relaxation**
 - From PV closure to TV opening
 - **Filling**
 - From TV opening to TV closure
 - Early Rapid Phase
 - Slow Phase
 - Atrial Contraction (“a” wave”)



Right & Left Heart Catheterization

Abnormalities in RV Tracing

- **Systolic pressure overload**
 - Pulmonary HTN
 - Pulmonary valve stenosis
 - Right ventricular outflow obstruction
 - Supravalvular obstruction
 - Significant ASD or VSD
 - Increased pulmonary vascular resistance

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Right & Left Heart Catheterization

Abnormalities in RV Tracing

- **Systolic pressure overload**
 - Pulmonary HTN
 - Pulmonary valve stenosis
 - Right ventricular outflow obstruction
 - Supravalvular obstruction
 - Significant ASD or VSD
 - Increased pulmonary vascular resistance
- **Systolic pressure reduced**
 - Hypovolemia
 - Cardiogenic shock
 - Tamponade

Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Right & Left Heart Catheterization

Abnormalities in RV Tracing

- **End-diastolic pressure overload**
 - Hypervolemia
 - CHF
 - Diminished compliance
 - Hypertrophy
 - Tamponade
 - Tricuspid regurgitation
 - Pericardial constriction

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Right & Left Heart Catheterization

Abnormalities in RV Tracing

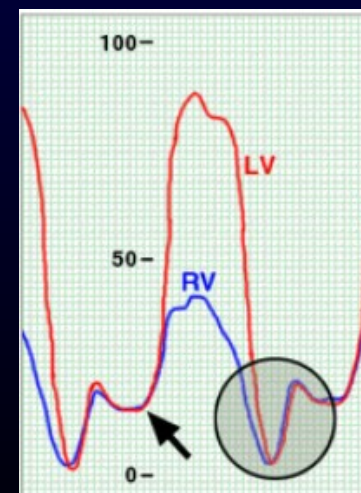
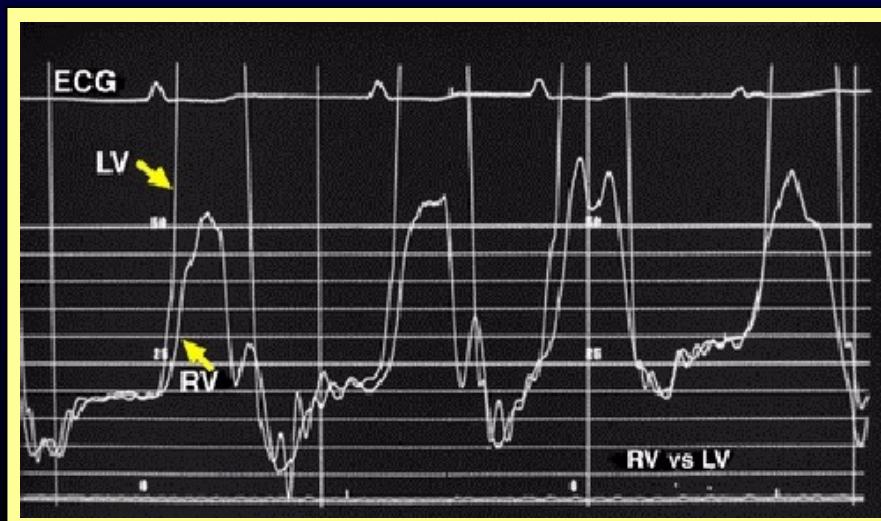
- **End-diastolic pressure overload**
 - Hypervolemia
 - CHF
 - Diminished compliance
 - Hypertrophy
 - Tamponade
 - Tricuspid regurgitation
 - Pericardial constriction
- **End-diastolic pressure reduced**
 - Hypovolemia
 - Tricuspid stenosis

Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Right & Left Heart Catheterization

Abnormalities in RV Tracing

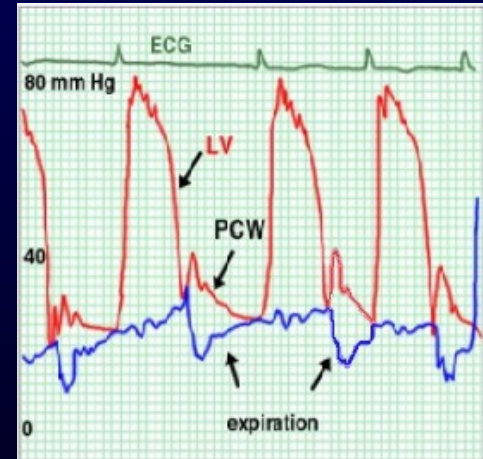
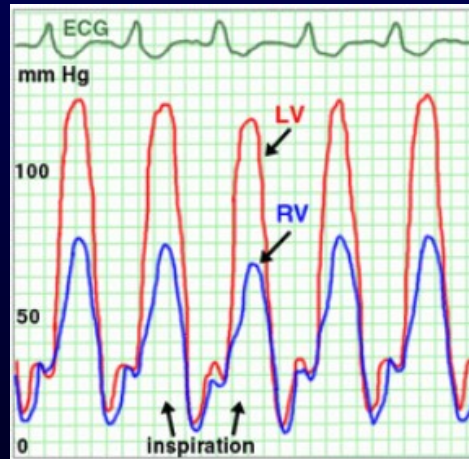
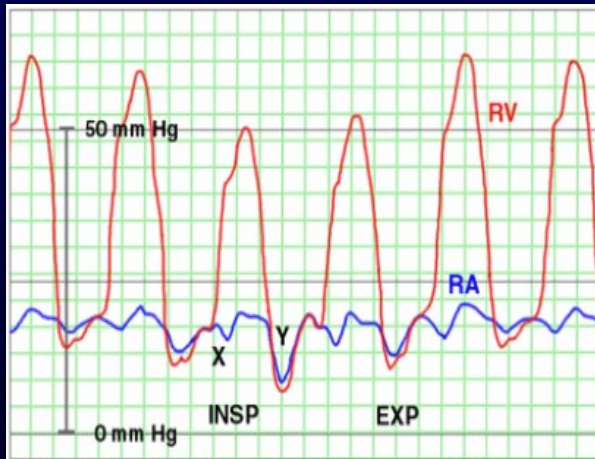
- **Dip and plateau in diastolic waveform**
 - Constrictive pericarditis
 - Restrictive cardiomyopathy
 - RV ischemia



Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Right Heart Catheterization

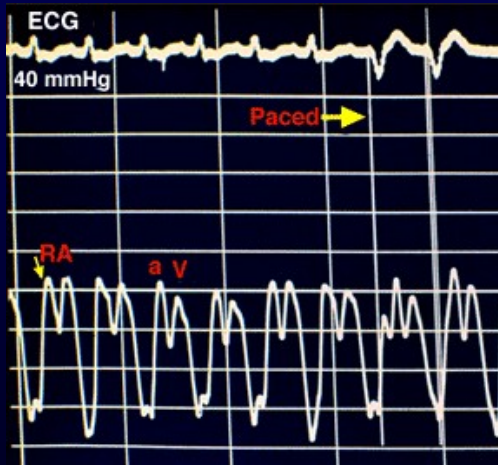
Restrictive Cardiomyopathy



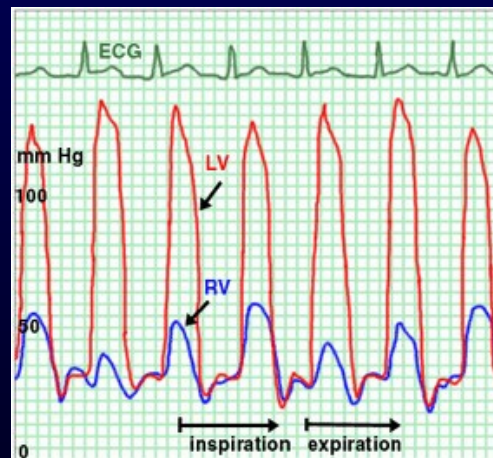
- Prominent y descent
- Normal respiratory variation
- Square root sign
- RVSP > 55 mm Hg
- RVEDP / RVSP < 1/3
- LVED-RVED > 5 mm Hg
- **RV-LV interdependence absent**
- Prominent y descent
- Lack of variation in early PCW-LV gradient

Right Heart Catheterization

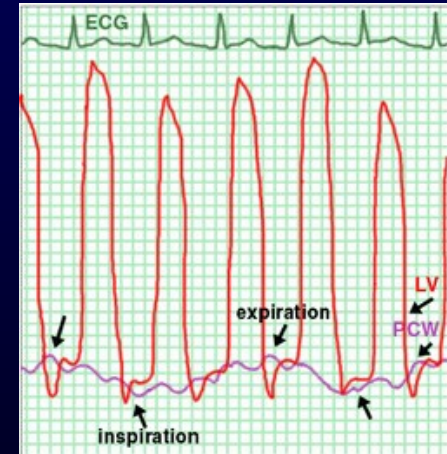
Constrictive Pericarditis



- Prominent x and y descents
- Equal a and v waves
- M wave morphology



- Square root sign
- $RVSP < 55 \text{ mm Hg}$
- $RVEDP / RVSP > 1/3$
- $LVED - RVED < 5 \text{ mm Hg}$
- **RV-LV interdependence**



- Prominent y descent
- Variation in early PCW-LV gradient

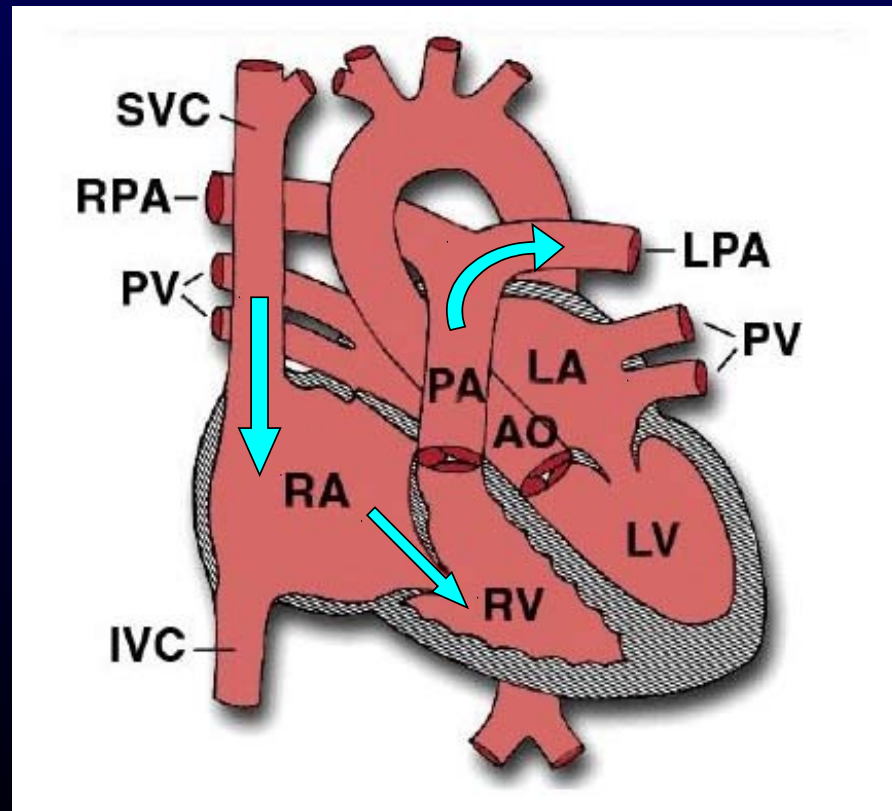
Right Heart Catheterization

Right vs Left Ventricular Pressure

	Constrictive Pericarditis	Restrictive Cardiomyopathy
End diastolic pressure equalization (LVED-RVED)	≤ 5 mm Hg	> 5 mm Hg
Pulmonary artery pressure	< 55 mm Hg	> 55 mm Hg
RVEDP / RVSP	$> 1/3$	$\leq 1/3$
Dip-plateau morphology	LV rapid filling wave > 7 mm Hg	LV rapid filling wave ≤ 7 mm Hg
Kussmaul's sign	No respiratory variation in mean RAP	Normal respiratory variation in mean RAP

Right Heart Catheterization

Swan Ganz Catheter

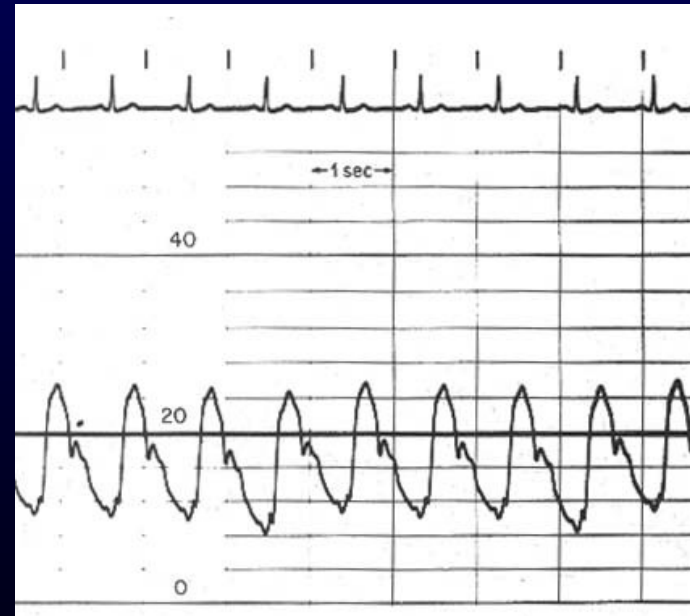


Kern MJ. Right Heart Catheterization. CATHSAP II CD-ROM. Bethesda, American College of Cardiology, 2001.

Right Heart Catheterization

Pulmonary Artery Pressure

- **Biphasic tracing**
 - Systole
 - Diastole
- **Pulmonary HTN**
 - Mild: **PAP** > 20 mm Hg
 - Moderate: **PAP** > 35 mm Hg
 - Severe: **PAP** > 45 mm Hg



Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

Right Heart Catheterization

Abnormalities in PA Tracing

- **Elevated systolic pressure**
 - Primary pulmonary HTN
 - MS
 - MR
 - CHF
 - Restrictive myopathy
 - Left-to-right shunt
 - Pulmonary disease

Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Right Heart Catheterization

Abnormalities in PA Tracing

- **Elevated systolic pressure**
 - Primary pulmonary HTN
 - MS
 - MR
 - CHF
 - Restrictive myopathy
 - Left-to-right shunt
 - Pulmonary disease
- **Reduced systolic pressure**
 - Hypotension
 - Pulmonary artery stenosis
 - Pulmonic stenosis
 - Supra or subvalvular stenosis
 - Ebstein's anomaly
 - Tricuspid stenosis
 - Tricuspid atresia

Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Right Heart Catheterization

Abnormalities in PA Tracing

- **Reduced pulse pressure**
 - Right heart ischemia
 - RV infarction
 - Pulmonary embolism
 - Tamponade

Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Right Heart Catheterization

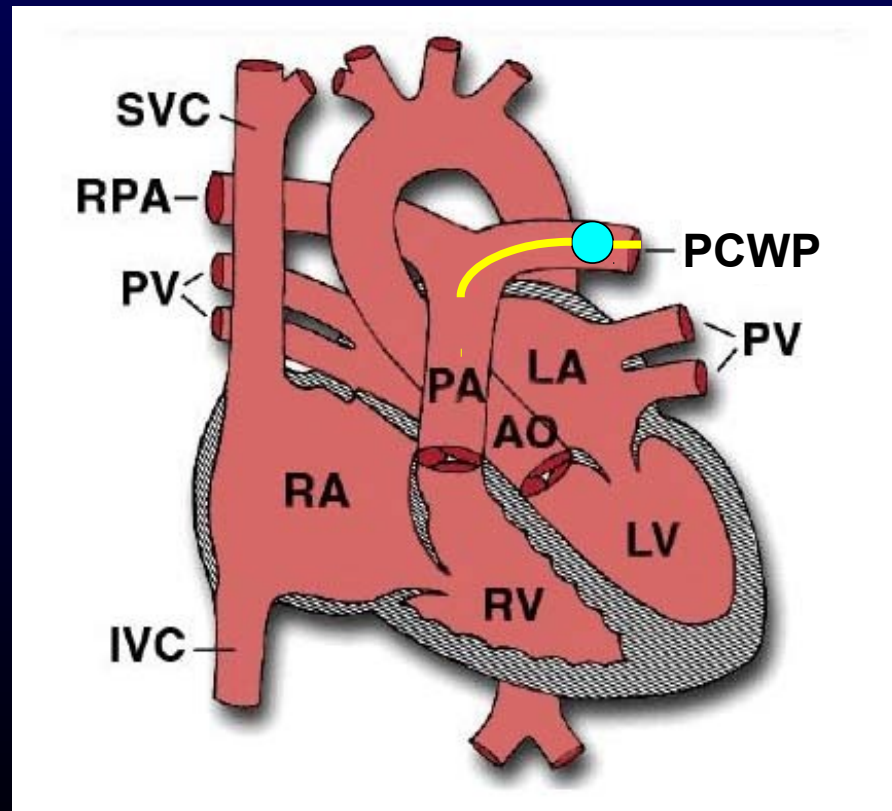
Abnormalities in PA Tracing

- **Reduced pulse pressure**
 - Right heart ischemia
 - RV infarction
 - Pulmonary embolism
 - Tamponade
- **PA diastolic pressure > PCW pressure**
 - Pulmonary disease
 - Pulmonary embolus
 - Tachycardia

Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Right Heart Catheterization

Swan Ganz Catheter

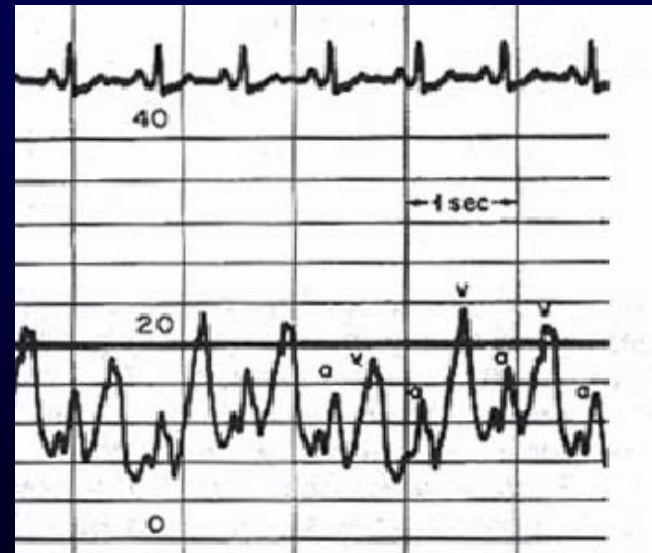


Kern MJ. Right Heart Catheterization. CATHSAP II CD-ROM. Bethesda, American College of Cardiology, 2001.

Right Heart Catheterization

Pulmonary Capillary Wedge Pressure

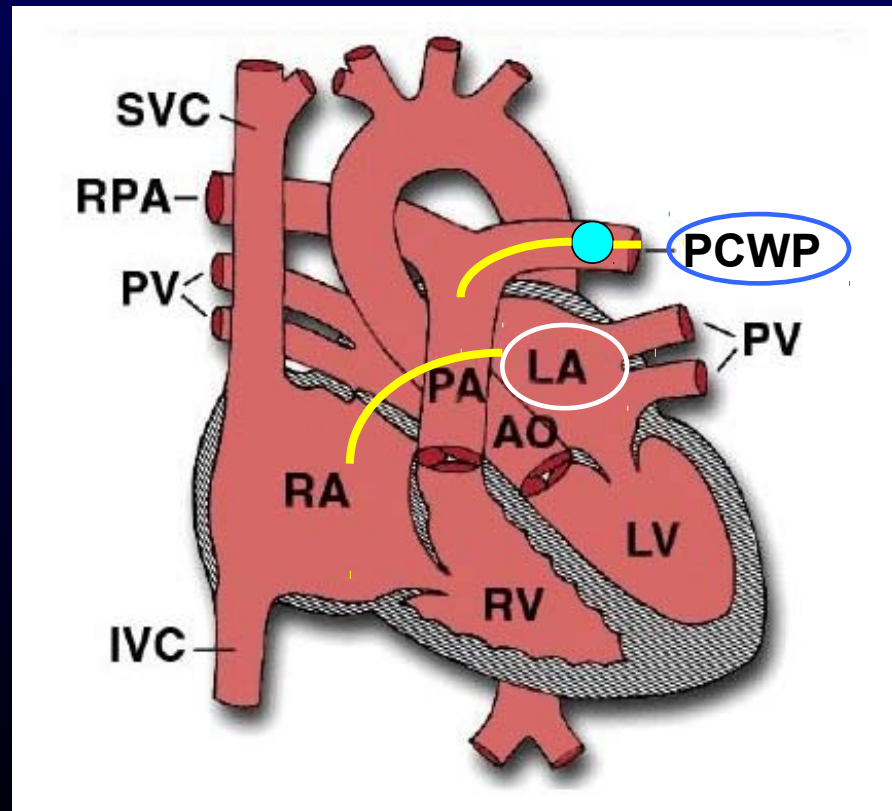
- **“a” wave**
 - Atrial systole
- **“c” wave**
 - Protrusion of MV into LA
- **“x” descent**
 - Relaxation of LA
 - Downward pulling of mitral annulus by LV contraction
- **“v” wave**
 - LV contraction
 - Height related to atrial compliance & amount of blood return
 - Higher than a wave
- **“y” descent**
 - MV opening and LA emptying into LV



Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

Right Heart Catheterization

Inspiratory Effect on Right Atrial Pressure

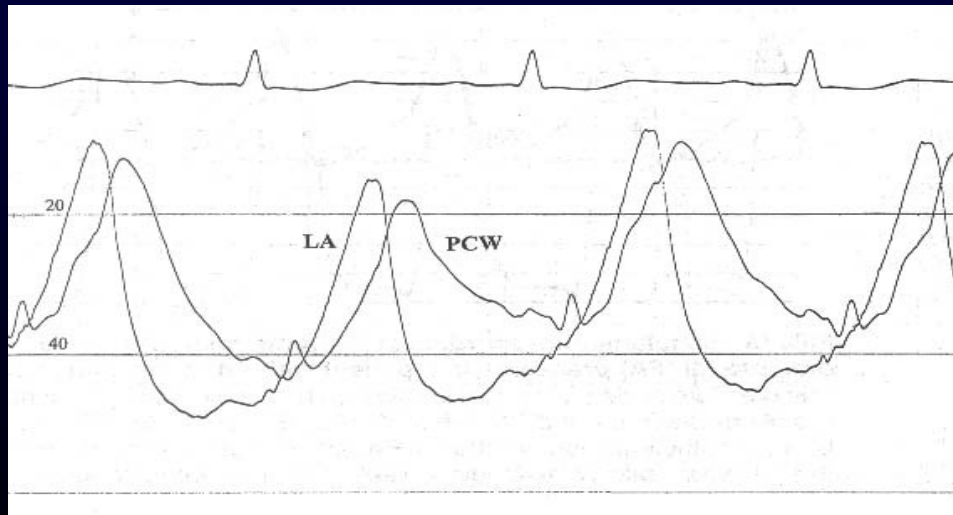


Kern MJ. Right Heart Catheterization. CATHSAP II CD-ROM. Bethesda, American College of Cardiology, 2001.

Right Heart Catheterization

Left Atrial and PCW Pressure

- PCW tracing “approximates” actual LA tracing but is slightly delayed since pressure wave is transmitted retrograde through pulmonary veins

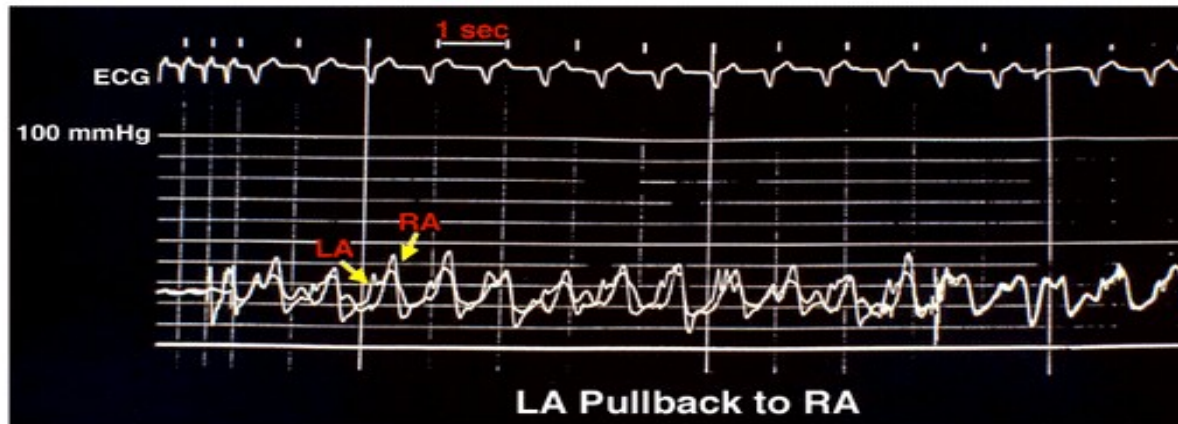


Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

Right Heart Catheterization

Right vs Left Atrial Pressure

- Normal LA pressure slightly higher than RA pressure



Kern MJ. Right Heart Catheterization. CATHSAP II CD-ROM. Bethesda, American College of Cardiology, 2001.

Right Heart Catheterization

Abnormalities in PCWP Tracing

- **Low mean pressure**
 - Hypovolemia
 - Improper zeroing of the transducer
- **Elevated mean pressure**
 - Intravascular volume overload
 - Left ventricular failure
 - Valvular disease (MS, MR, AS, AR)
 - Myocardial disease (LV ischemia, cardiomyopathy)
 - Left heart failure secondary to HTN
 - Pericardial effusion with tamponade
 - Atrial myxoma

Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Right Heart Catheterization

Abnormalities in PCWP Tracing

- **Elevated a wave**
 - Mitral stenosis
 - Decreased LV compliance due to LV failure / valve disease
- **Cannon a wave**
 - A-V asynchrony (3rd degree AVB, VT, V-pacer)
- **Absent a wave**
 - Atrial flutter or fibrillation
- **Elevated v wave**
 - MR
 - LRV failure
 - Ventricular septal defect
- **Equal a and v waves**
 - Tamponade
 - Constrictive physiology

Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Right Heart Catheterization

Abnormalities in PCWP Tracing

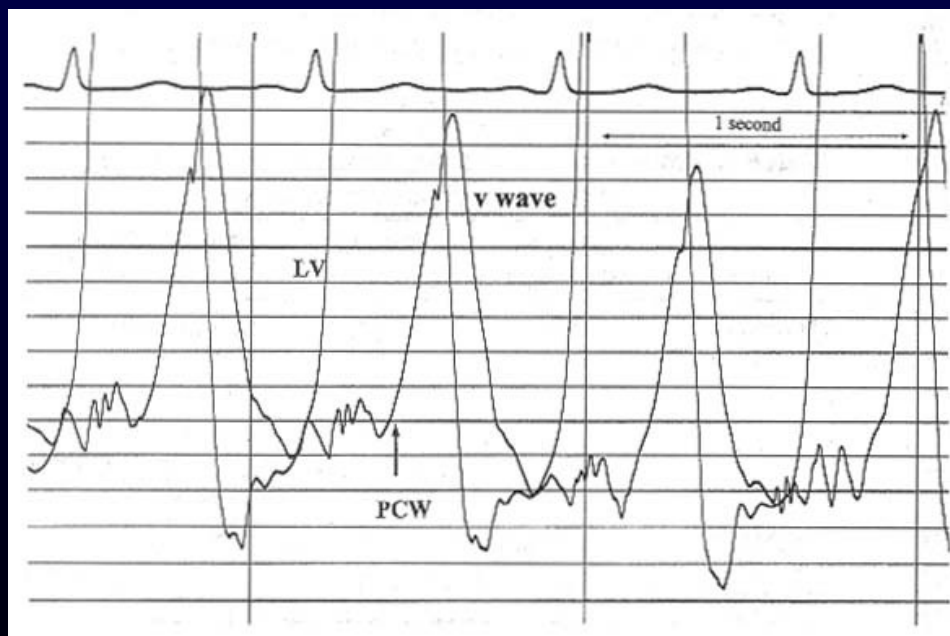
- **Prominent x descent**
 - Tamponade
 - Subacute/chronic constriction
- **Prominent y descent**
 - MR
 - Constrictive pericarditis
 - Restrictive myopathy
- **Blunted x descent**
 - Atrial fibrillation
 - LA ischemia
- **Blunted y descent**
 - MS
 - LV ischemia
 - Tamponade

Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Right Heart Catheterization

Abnormalities in PCWP Tracing

- Severe Mitral Regurgitation



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Right Heart Catheterization

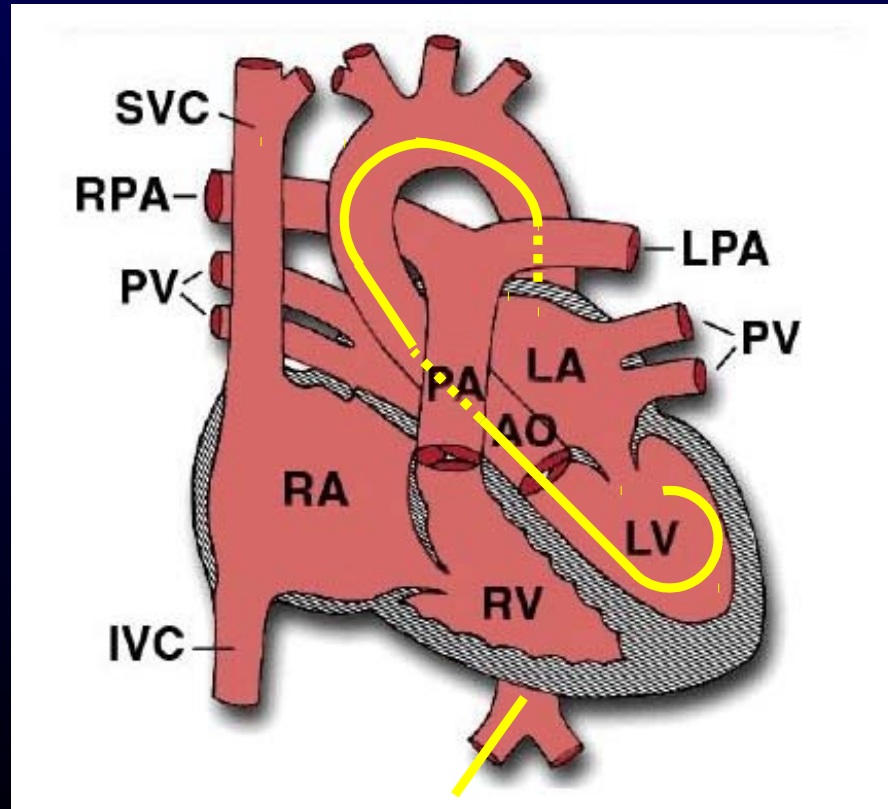
Abnormalities in PCWP Tracing

- **PCWP not equal to LV end diastolic pressure**
 - Mitral stenosis
 - Atrial myxoma
 - Cor triatriatum
 - Pulmonary venous obstruction
 - Decreased ventricular compliance
 - Increased pleural pressure

Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Left Heart Catheterization

Pigtail Catheter



Kern MJ. Right Heart Catheterization. CATHSAP II CD-ROM. Bethesda, American College of Cardiology, 2001.

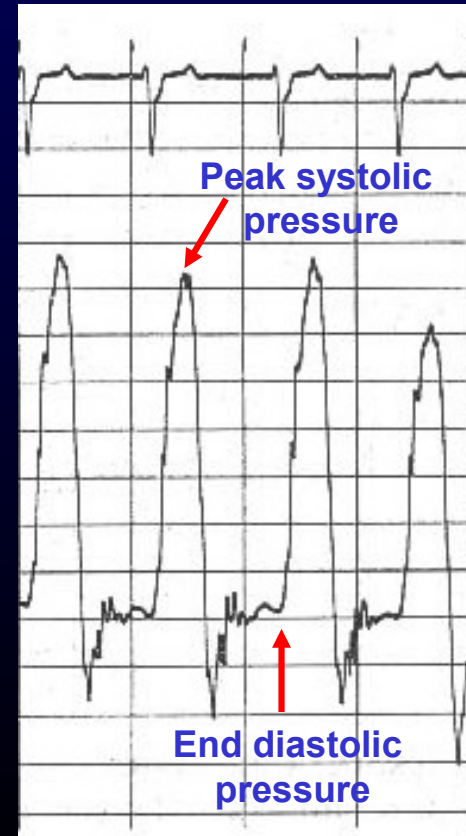
Maquet, Ex. 2007-73

IPR2017-02151

Right Heart Catheterization

Left Ventricular Pressure

- **Systole**
 - **Isovolumetric contraction**
 - From MV closure to AoV opening
 - **Ejection**
 - From AoV opening to AoV closure
- **Diastole**
 - **Isovolumetric relaxation**
 - From AoV closure to MV opening
 - **Filling**
 - From MV opening to MV closure
 - Early Rapid Phase
 - Slow Phase
 - Atrial Contraction (“a” wave”)



Right Heart Catheterization

Right vs Left Ventricular Pressure

- **Diastolic amplitude similar between RV and LV tracings**
- **Systolic amplitude higher for LV than RV**
- **Duration of systole, isovolumetric contraction, and isovolumetric relaxation is are longer for LV compared to RV**
- **Duration of ejection is shorter for LV than RV**

Right & Left Heart Catheterization

Abnormalities in LV Tracing

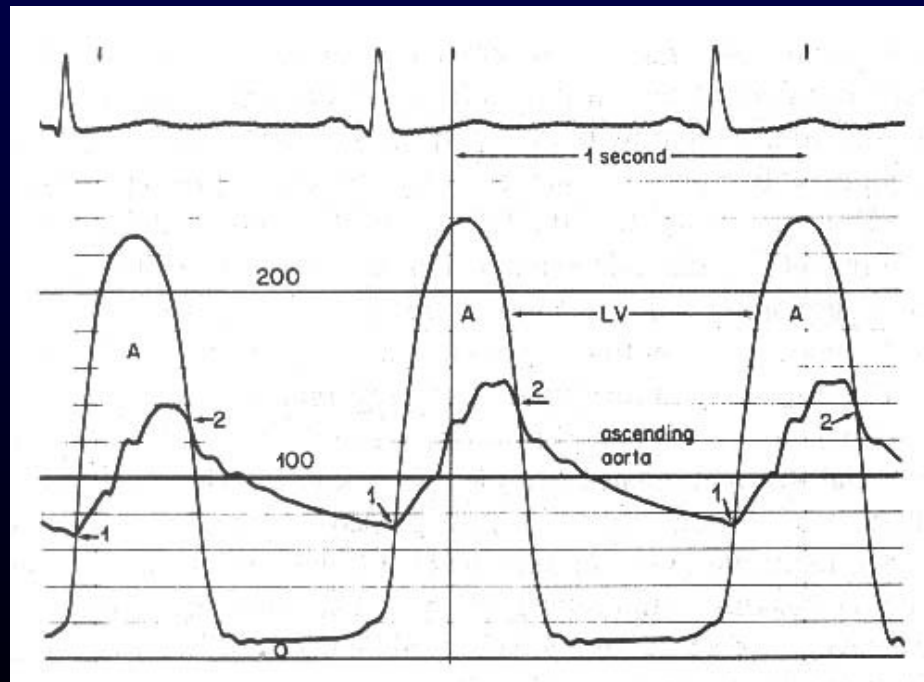
- **Systolic pressure overload**
 - Systemic HTN
 - Aortic valve stenosis
 - Left ventricular outflow obstruction
 - Supravalvular obstruction
 - Significant ASD or VSD
- **Systolic pressure reduced**
 - Hypovolemia
 - Cardiogenic shock
 - Tamponade

Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Right & Left Heart Catheterization

Abnormalities in LV Tracing

- Severe Aortic Stenosis



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Right & Left Heart Catheterization

Abnormalities in LV Tracing

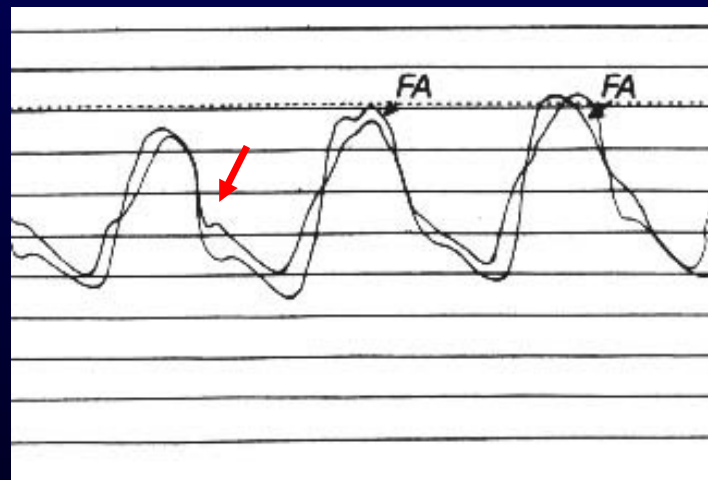
- **End-diastolic pressure overload**
 - Hypervolemia
 - CHF
 - Diminished compliance
 - Hypertrophy
 - Tamponade
 - Mitral regurgitation
 - Pericardial constriction
- **End-diastolic pressure reduced**
 - Hypovolemia
 - Mitral stenosis

Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Arterial Pressure Monitoring

Central Aortic and Peripheral Tracings

- **Pulse pressure = Systolic – Diastolic**
- **Mean aortic pressure typically < 5 mm Hg higher than mean peripheral pressure**
- **Aortic waveform varies along length of the aorta**
 - Systolic wave increases in amplitude while diastolic wave decreases
 - Mean aortic pressure constant
 - Dicrotic notch less apparent in peripheral tracing



Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Arterial Pressure Monitoring

Abnormalities in Central Aortic Tracing

- **Systolic pressure elevated**
 - Systemic hypertension
 - Atherosclerosis
 - Aortic insufficiency
- **Systemic pressure reduced**
 - Hypovolemia
 - Aortic stenosis
 - Heart failure

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Arterial Pressure Monitoring

Abnormalities in Central Aortic Tracing

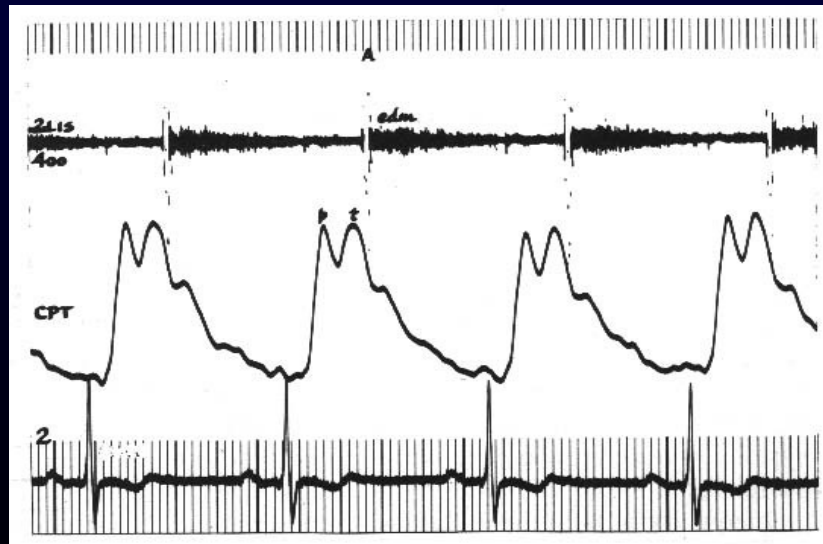
- **Widened pulse pressure**
 - Systemic hypertension
 - Aortic insufficiency
 - Significant patent ductus arteriosus
 - Ruptured sinus of valsalva aneurysm
- **Reduced pulse pressure**
 - Tamponade
 - Heart failure
 - Cardiogenic shock
 - Aortic stenosis

Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Arterial Pressure Monitoring

Abnormalities in Central Aortic Tracing

- **Pulsus bisferiens**
 - Hypertrophic obstructive cardiomyopathy
 - Aortic insufficiency



Marriott HJL. Bedside Cardiac Diagnosis. Philadelphia: JB Lippincott Company, 1993.

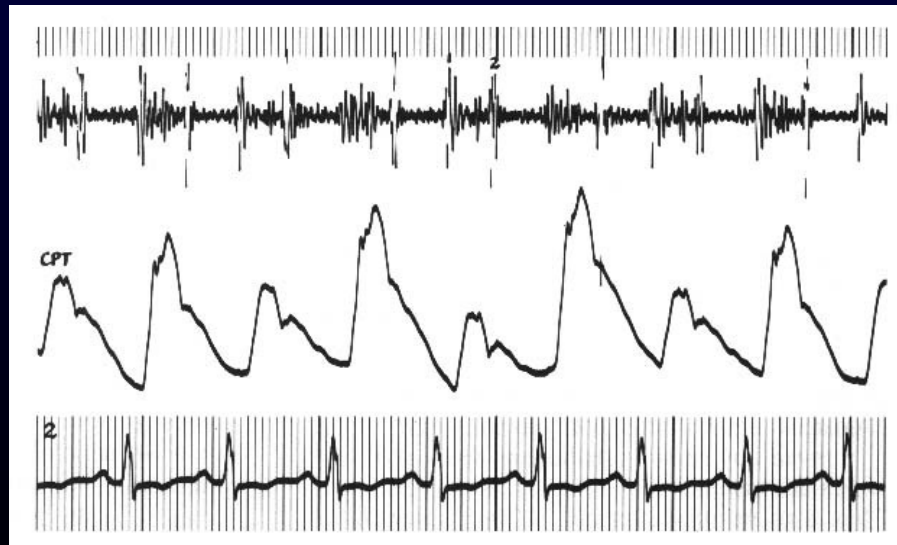
Maquet, Ex. 2007-82

IPR2017-02151

Arterial Pressure Monitoring

Abnormalities in Central Aortic Tracing

- **Pulsus alternans**
 - Pericardial effusion
 - Cardiomyopathy
 - CHF



Marriott HJL. Bedside Cardiac Diagnosis. Philadelphia: JB Lippincott Company, 1993.

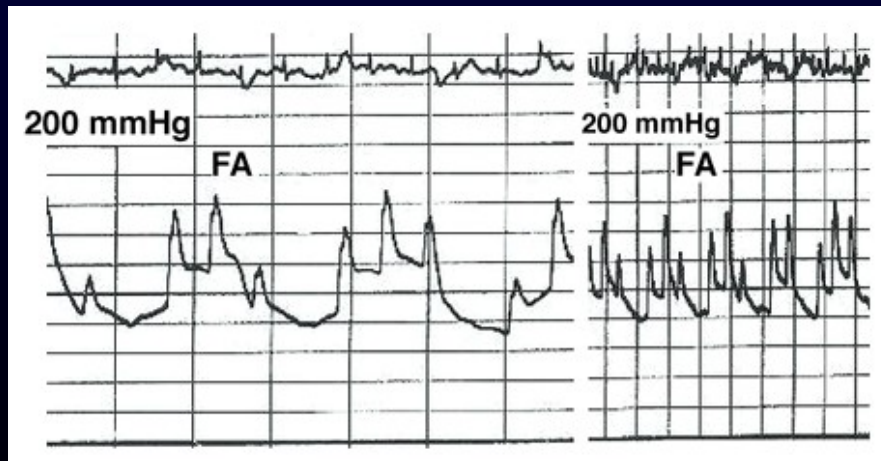
Maquet, Ex. 2007-83

IPR2017-02151

Arterial Pressure Monitoring

Abnormalities in Central Aortic Tracing

- Pulsus paradoxus
 - Tamponade
 - COPD
 - Pulmonary embolism

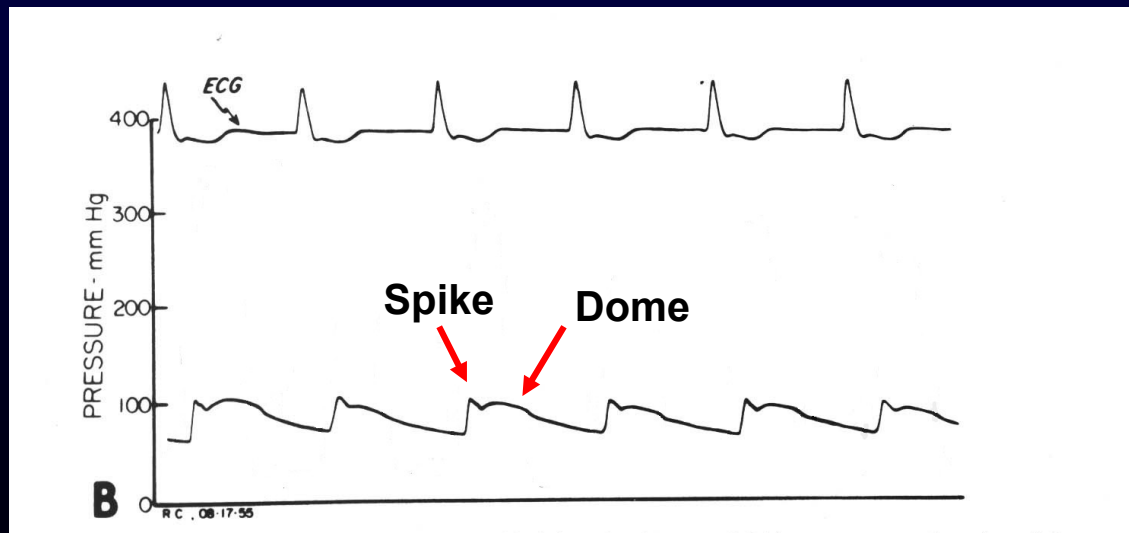


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Arterial Pressure Monitoring

Abnormalities in Central Aortic Tracing

- **Spike and dome configuration**
 - Hypertrophic obstructive cardiomyopathy



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Arterial Pressure Monitoring

Abnormalities in Central Aortic Tracing

- **Pulsus parvus and tardus**
 - Aortic stenosis

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Hemodynamic Parameters

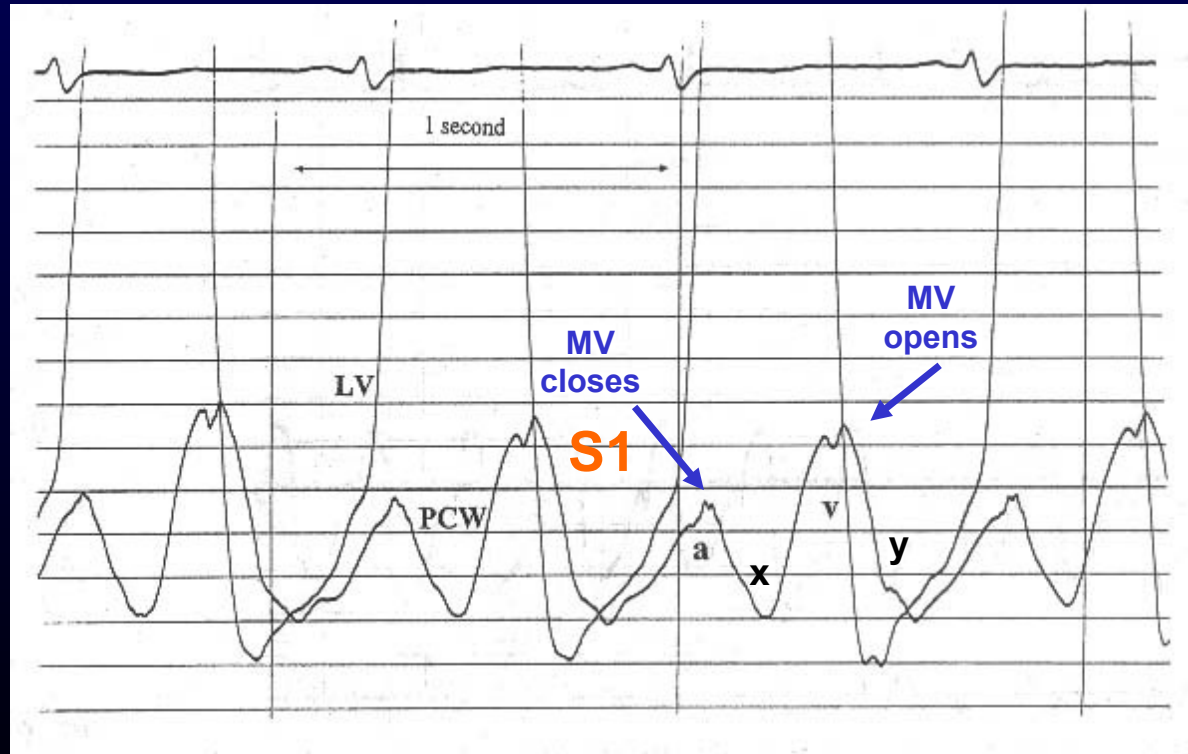
Reference Values

	<u>Average</u>	<u>Range</u>		<u>Average</u>	<u>Range</u>
Right atrium			PCWP		
a wave	6	2 - 7	mean	9	4 - 12
v wave	5	2 - 7	Left atrium		
mean	3	1 - 5	a wave	10	4 - 16
Right ventricle			v wave	12	6 - 21
peak systolic	25	15 - 30	mean	8	2 - 12
end diastolic	4	1 - 7	Left ventricle		
Pulmonary artery			peak systolic	130	90 - 140
peak systolic	25	15-30	end diastolic	8	5 - 12
end diastolic	9	4-12	Central aorta		
mean	15	9-19	peak systolic	130	90 - 140
			end diastolic	70	60 - 90
			mean	85	70 -105

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Left Heart Catheterization

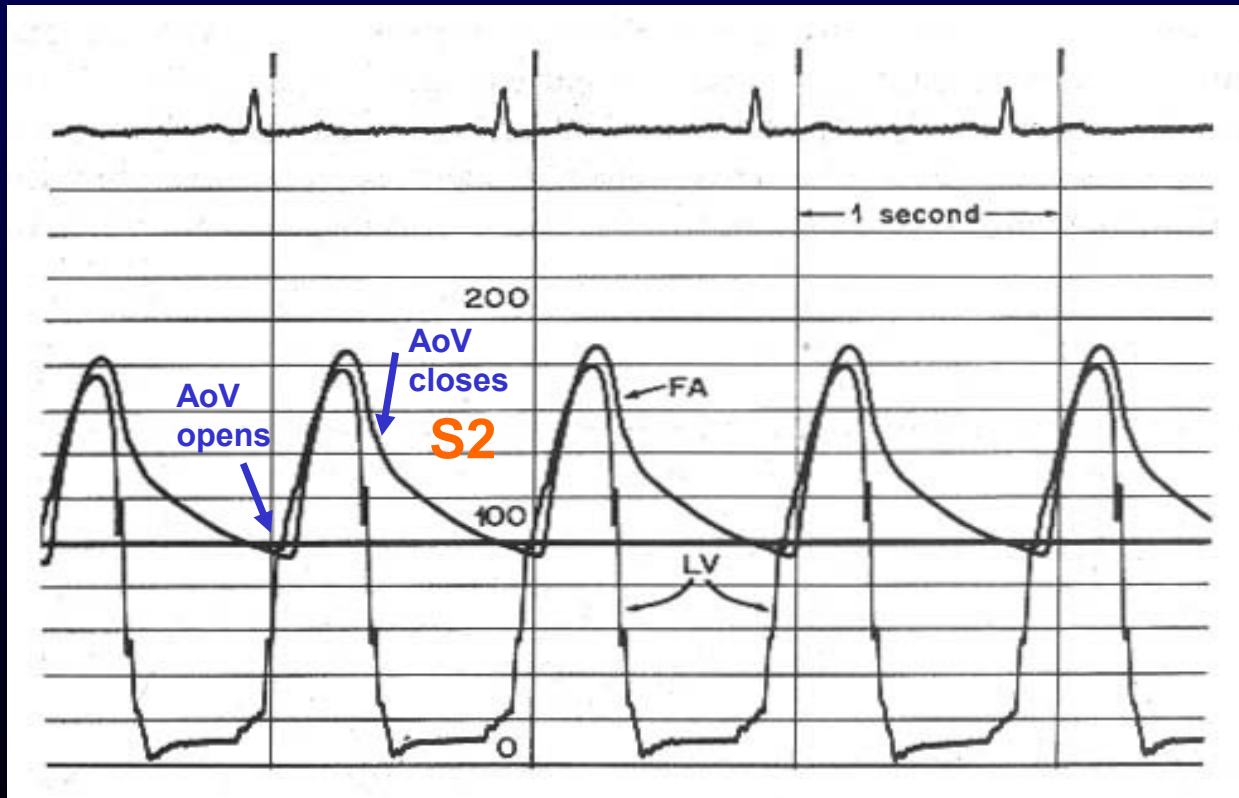
Left Ventricular Diastole



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Left Heart Catheterization

Left Ventricular Systole



Davidson CJ, et al. Cardiac Catheterization. In: Heart Disease: A Textbook of Cardiovascular Medicine, Edited by E. Braunwald, 5th ed. Philadelphia: WB Saunders Company, 1997

Hemodynamic Principles

1. A 76-year-old woman with shortness of breath and pulmonary edema is admitted to the Coronary Care Unit. Blood pressure on admission was 280/130 mmHg. With treatment, pulmonary edema has resolved and the patient is stable. For which of the following is right heart catheterization an indication?
 - A. Routine management of pulmonary edema even if endotracheal intubation and mechanical ventilation has been necessary.
 - B. To differentiate cardiogenic from noncardiogenic shock before a trial of intravascular volume expansion.
 - C. To treat patients with marked hemodynamic instability in whom pericardial tamponade is probable by echo criteria.
 - D. To be used in the perioperative-managed patients with compensated CHF undergoing low-risk, noncardiac surgery.
 - E. To facilitate titration of diuretic, vasodilator, or inotropic therapy in patients with severe heart failure.



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Hemodynamic Principles

2. A patient with a chest pain syndrome comes to cardiac catheterization. Previous history includes angina pectoris, cigarette smoking, and emphysema. Which of the following would be an indication for right heart catheterization?
- A. First-degree AV block.
 - B. Left bundle branch block.
 - C. Positive stress test.
 - D. Dyspnea at rest.
 - E. Right axis deviation on electrocardiogram.



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 - B. Left bundle branch block.
 - C. Positive stress test.
 - D. Dyspnea at rest.**
 - E. Right axis deviation on electrocardiogram.

Hemodynamic Principles

3. You are performing a cardiac catheterization procedure and need to be certain your pulmonary capillary wedge pressure is correct. Which of the following is the most reliable way to confirm that a presumed wedge pressure is a correct wedge pressure?
- A. The catheter tip does not move with cardiac motion.
 - B. The waveform has classic A and V deflections.
 - C. Obtain a blood sample for oximetry from the catheter tip when wedged.
 - D. The mean PA pressure exceeds mean PCW pressure.
 - E. The T wave on the electrocardiogram follows the V wave on the wedge pressure tracing.



Hemodynamic Principles

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Hemodynamic Principles

4. A 48 yo man is referred to you because of progressive edema, ascites, and dyspnea developing over the past 6 months. He had been previously healthy, but was treated recently for chronic venous insufficiency. In retrospect, he has also noticed fatigue during the past 2 years. On exam, his BP was 105/85 mmHg without a pulsus paradoxus and his heart rate was 95 bpm and regular. His JVP was elevated to the mandible while sitting upright with a prominent y-descent. The 1st and 2nd heart sounds were normal, and an early diastolic sound was heard at the apex. His lungs were clear, ascites was present without hepatosplenomegaly, and there was severe peripheral edema. Mild cardiomegaly and small bilateral pleural effusions were present on his CXR. Blood chemistry revealed the following: hemoglobin 13.9 mg/dl, serum creatinine 1.7 mg/dl, AST 40IU, total bilirubin 1.6 mg/dl, alkaline phosphatase 403 IU. His EKG showed NSR with nonspecific ST and T-wave changes. An echocardiogram demonstrated normal LV size and function with an EF of 50% to 55%. There was abnormal septal motion and mild MR and TR. Figure 4-1 and Figure 4-2 show hemodynamic results from his cardiac catheterization. Coronary angiography showed no atherosclerosis in the major epicardial arteries. Which of the following is the most likely explanation for these findings?

Hemodynamic Principles

PAW and LV Tracings during Inspiration and Expiration



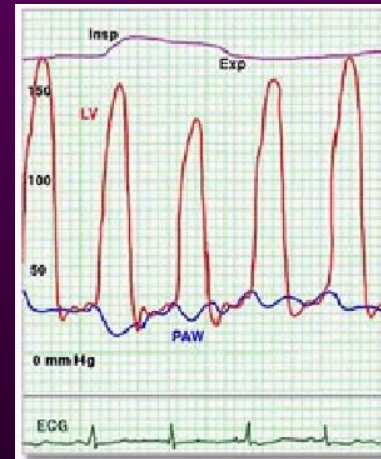
RV and LV Tracings during Inspiration and Expiration



Hemodynamic Principles

Which of the following is the most likely explanation for these findings?

- A. Chronic recurrent PE.
- B. Constrictive pericarditis.
- C. Atrial septal defect with a large shunt and right heart failure.
- D. Chronic pericarditis now presenting with tamponade.
- E. Chronic hepatitis with cirrhosis.



PAW and LV
Tracings during
Inspiration and
Expiration



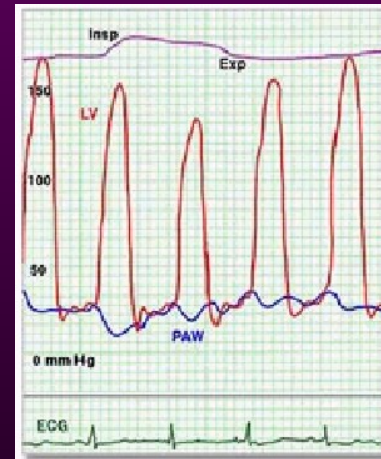
RV and LV
Tracings during
Inspiration and
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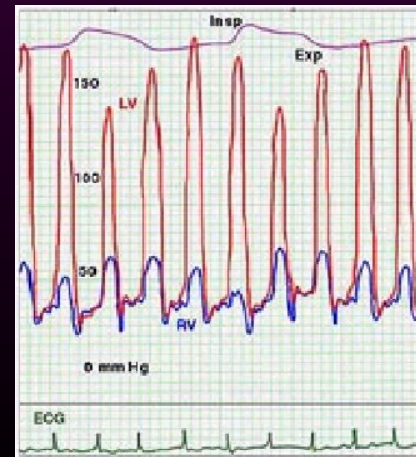
Hemodynamic Principles

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- E. Chronic hepatitis with cirrhosis.



PAW and LV
Tracings during
Inspiration and
Expiration



RV and LV
Tracings during
Inspiration and
Expiration

Hemodynamic Principles

5. A 37-year-old man is referred for the evaluation of aortic regurgitation. He has known of his condition since he was rejected from military service at age 20. His only symptom is mild, but now over the past year has been suffering from a progressive decline in his ability to work as a brick mason. His physical examination, chest x-ray, and echocardiogram are all consistent with important aortic regurgitation. Cardiac catheterization is performed. Which of the following is not seen in severe aortic insufficiency?
- A. Femoral artery systolic pressure exceeds central aortic systolic pressure by 60 mmHg.
 - B. An early rapid rise in the left ventricular diastolic pressure.
 - C. Diastasis of left ventricular and aortic diastolic pressures.
 - D. A regurgitant fraction of 0.35.
 - E. An LV end-diastolic volume index of 230ml/m².



Hemodynamic Principles

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Hemodynamic Principles

6. Which of the following is the best method of differentiating constrictive pericarditis from restrictive cardiomyopathy in patients undergoing cardiac catheterization?
- A. Enhanced ventricular interaction between left ventricle and right ventricle.
 - B. End diastolic equalization of pressures less than 5 mmHg.
 - C. Pulmonary artery pressure less than 50 mmHg.
 - D. A different plateau pattern in the right ventricular and left ventricular pressure curve.
 - E. Right ventricular diastolic pressure greater than one-third of the right ventricular systolic pressure.



Hemodynamic Principles

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Hemodynamic Principles

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 - E. Right ventricular diastolic pressure greater than one-third of the right ventricular systolic pressure.

Hemodynamic Principles

8. A patient comes to the cardiac catheterization laboratory for possible constrictive pericarditis. This patient has had progressive edema and ascites for the past year. The patient is currently taking large dosages of diuretics to control his symptoms. When the patient comes to the catheterization laboratory, the RA pressure is 5 mmHg, the RV pressure is 30/5 mmHg, and the PA pressure is 30/10 mmHg. The PCWP is 10 mmHg. The aortic pressure is 100/70 mmHg. Which of the following is true about the work-up for this patient?
- A. This patient does not have constrictive pericarditis or restrictive cardiomyopathy and no further evaluation is necessary.
 - B. This patient has a restrictive cardiomyopathy rather than constrictive pericarditis due to the end equalization of PA and RA pressures.
 - C. This patient should undergo fluid loading and have another measurement of pressures.
 - D. This patient should receive nitroprusside infusion and have remeasurement of pressures.
 - E. This patient should have a RA angiogram to look for pericardial thickening.



Hemodynamic Principles

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Hemodynamic Principles

9. A 32-year-old obese man with a dilated cardiomyopathy is referred for hemodynamic assessment to determine if he is a candidate for cardiac transplantation. His mean pulmonary artery pressure is 45 mmHg, mean pulmonary capillary wedge pressure is 30 mmHg, and cardiac output is 5.0 L/min. Which of the following is the next step in management?
- A. Based on the PVR, he can be listed for cardiac transplantation.
 - B. He should undergo further hemodynamic evaluations during the infusion of nitroprusside.
 - C. Based on the pulmonary vascular resistance, he is not a candidate for cardiac transplantation.
 - D. He should be considered for combination heart-lung transplantation.
 - E. More information is required to determine the pulmonary vascular resistance.



Hemodynamic Principles

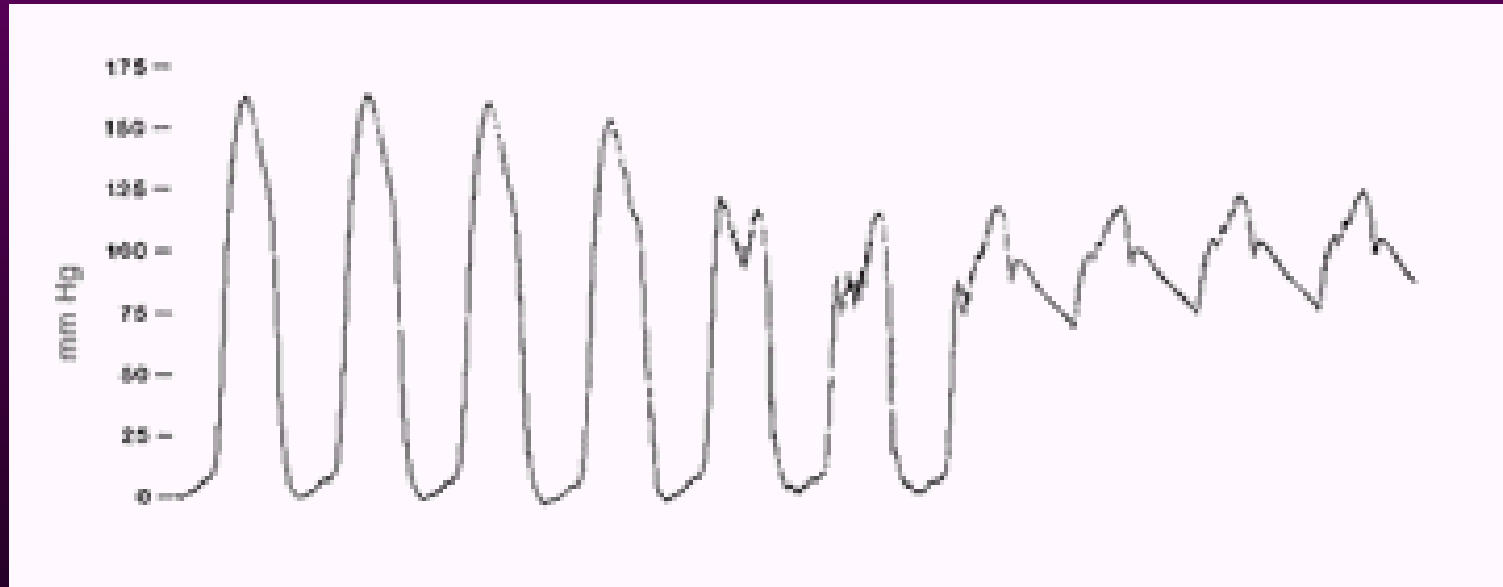
9. A 32-year-old obese man with a dilated cardiomyopathy is referred for hemodynamic assessment to determine if he is a candidate for cardiac transplantation. His mean pulmonary artery pressure is 45 mmHg, mean pulmonary capillary wedge pressure is 30 mmHg, and cardiac output is 5.0 L/min. Which of the following is the next step in management?

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- B. He should undergo further hemodynamic evaluations during the infusion of nitroprusside.
- C. Based on the pulmonary vascular resistance, he is not a candidate for cardiac transplantation.
- D. He should be considered for combination heart-lung transplantation.
- E. More information is required to determine the pulmonary vascular resistance.

Hemodynamic Principles

10. An obese 30-year-old woman with a murmur is referred for evaluation. An echocardiogram was of poor-quality but is interpreted as showing important aortic stenosis. Your exam confirms the presence of a systolic ejection murmur with radiation to the base but the exam is limited by her obesity. Cardiac catheterization is performed and the pullback pressure (shown in Figure 1-1) is recorded. Which of the following is the correct interpretation of this pressure recording?
- A. She has valvular aortic stenosis.
 - B. She has hypertrophic cardiomyopathy with obstruction.
 - C. She has an intraventricular pressure gradient.
 - D. She has a bicuspid aortic valve with mild stenosis.
 - E. She has a pressure gradient but it is likely an artifact.

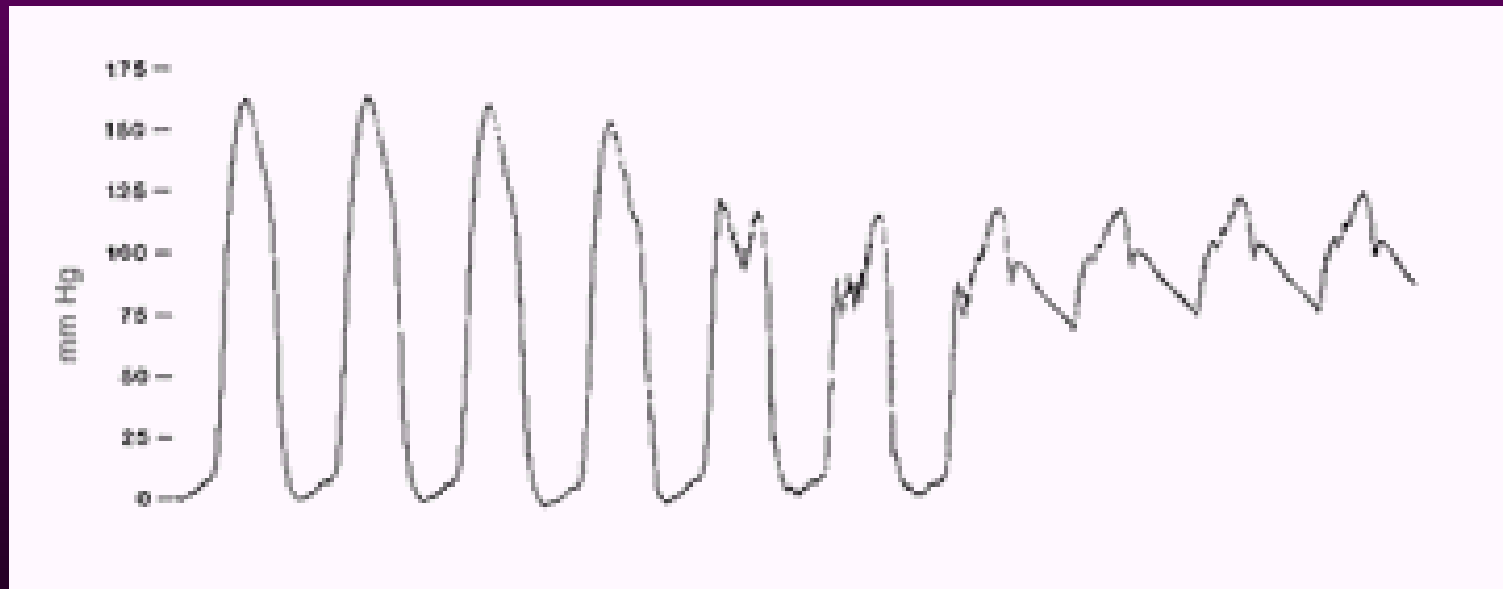
Hemodynamic Principles



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Hemodynamic Principles



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Hemodynamic Principles

11. Of the following criteria, which has the greatest positive predictive value for diagnosing constrictive pericarditis?
- A. Left ventricular end-diastolic pressure minus right ventricular end-diastolic pressure < 5 mmHg.
 - B. Right ventricular end-diastolic pressure divided by right ventricular systolic pressure $> 1/3$.
 - C. Respiratory change in right atrial pressure < 3 mmHg.
 - D. Left ventricular/right ventricular interdependence.
 - E. Dip and plateau of left ventricular diastolic pressure.



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Hemodynamic Principles

12. In the diagnosis of restrictive physiology, what are the criteria with the highest sensitivity?

- A. Parallel increase in left and right ventricular end-diastolic pressures.**
- B. Concordance of left and right ventricular systolic pressures during normal respiration.**
- C. Dyssynchronous increase in right ventricular systolic pressure with left ventricular pressure at end inspiration.**
- D. Simultaneous increase in left ventricular, pulmonary capillary wedge, and left ventricular systolic pressures.**
- E. Dip and plateau of LV diastolic pressure.**



Hemodynamic Principles

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Hemodynamic Principles

13. A 65-year-old man presents with progressive dyspnea on exertion, edema, and ascites. A history of coronary artery disease was present and coronary artery bypass surgery had been performed several years earlier. Echocardiography revealed normal left ventricular function with small-to-moderate pericardial and pleural effusions. On examination, there was jugular venous distention with rapid 'Y' descent, bilateral lower extremity, and distant heart sounds. The electrocardiogram showed sinus tachycardia. In examination of the hemodynamics of this patient, which findings are most diagnostic of constrictive physiology?
- A. Abrupt cessation of ventricular filling with simultaneous right and left ventricular diastolic pressures.
 - B. Respiratory discordance of simultaneous right and left ventricular systolic pressures.
 - C. Respiratory concordance of simultaneous right atrial and left ventricular pressures.
 - D. Respiratory discordance of simultaneous pulmonary capillary wedge and right atrial pressures.
 - E. Dip and plateau of left ventricular diastolic pressure.



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- A. Abrupt cessation of ventricular filling with simultaneous right and left ventricular diastolic pressures.
 - B. Respiratory disconcordance of simultaneous right and left ventricular systolic pressures.**
 - C. Respiratory concordance of simultaneous right atrial and left ventricular pressures.
 - D. Respiratory disconcordance of simultaneous pulmonary capillary wedge and right atrial pressures.
 - E. Dip and plateau of left ventricular diastolic pressure.

Hemodynamic Principles

14. A 70 yo woman with signs and symptoms of right and left heart failure undergoes cardiac catheterization. Her study shows no underlying coronary artery disease, but elevations of her right and left ventricular diastolic pressures in the range of 22-25 mmHg. Which of the following is more commonly seen in patients with restrictive cardiomyopathy than in patients with constrictive pericarditis?
- A. Elevation and equilibration of right and left ventricular end diastolic pressures.
 - B. Absence of rapid early diastolic filling (no dip and plateau ventricular waveform).
 - C. Lower pulmonary artery systolic pressures typically in the range of 35-45 mm Hg.
 - D. An increase in mean right atrial pressure with inspiration.
 - E. A normal left ventricular ejection fraction.



Hemodynamic Principles

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Hemodynamic Principles

An Overview

- Pressure measurement
- Right and left heart catheterization
- Cardiac output measurement
 - Fick-oxygen method
 - Arterial-venous oxygen difference
 - Indicator-dilution methods
 - Indocyanine green
 - Thermodilution
- Vascular resistance
- Shunt detection and measurement
- Gradients and valve stenoses

Cardiac Output Measurement

- **Definition: Quantity of blood delivered to the systemic circulation per unit time**
- **Techniques**
 - **Fick-Oxygen Method**
 - **Indicator-Dilution Methods**
 - **Indocyanine Green**
 - **Thermodilution**

Cardiac Output Measurement

Fick Oxygen Method

- **Fick Principle:** The total uptake or release of any substance by an organ is the product of blood flow to the organ and the arteriovenous concentration difference of the substance.
- As applied to lungs, the substance released to the blood is oxygen, oxygen consumption is the product of arteriovenous difference of oxygen across the lungs and pulmonary blood flow.

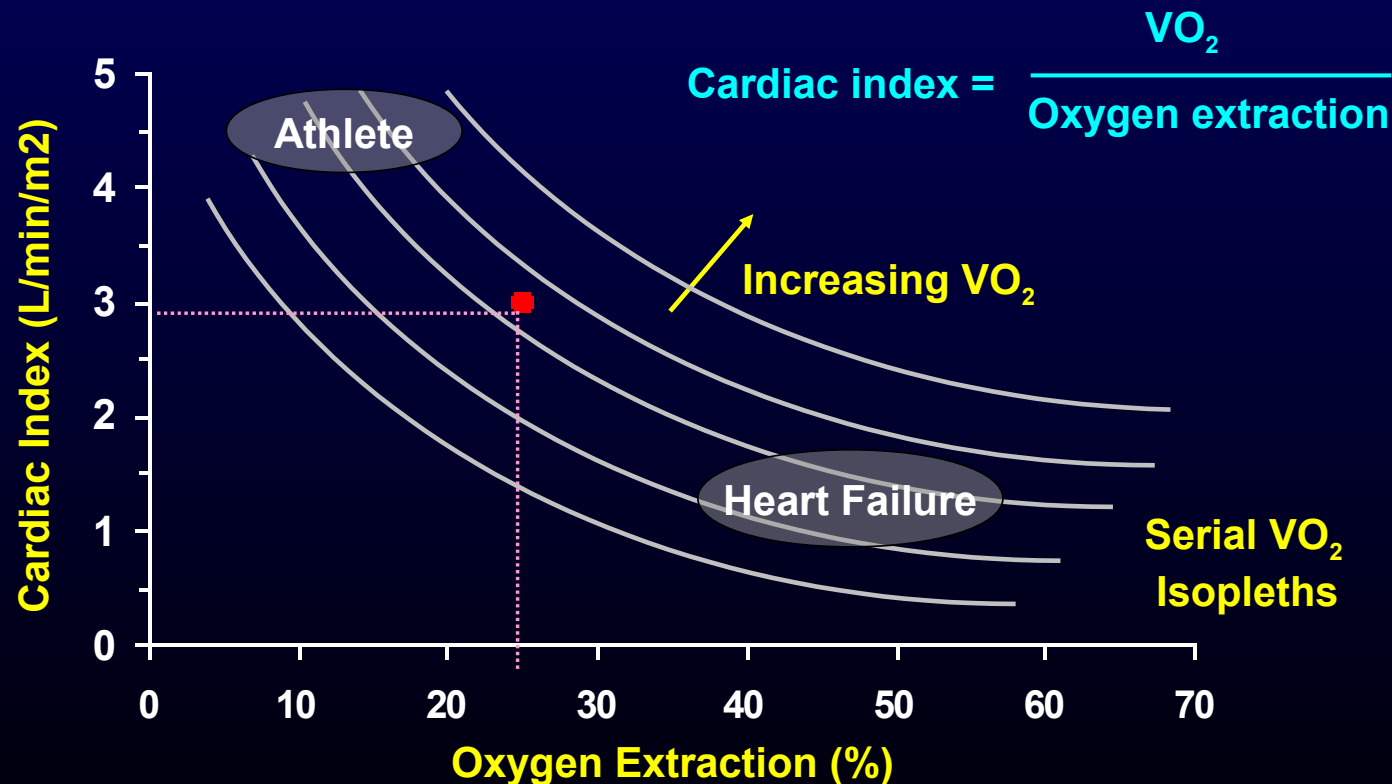
$$Q_p = \frac{\text{Oxygen consumption}}{\text{Arteriovenous O}_2 \text{ difference}}$$

- In the absence of a shunt, systemic blood flow (Q_s) is estimated by pulmonary blood flow (Q_p).

Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

Cardiac Output Measurement

O₂ Consumption



Vincent JL. Hemodynamic Monitoring, Pharmacologic Therapy, and Arrhythmia Management in Acute Congestive Heart Failure. In: Congestive Heart Failure. Edited by Hosenpud JD and Greenberg BH. New York: Springer-Verlag, 1994.

Cardiac Output Measurement

Fick Oxygen Method: O₂ Consumption

- **Polarographic O₂ Method**
 - Metabolic rate meter
 - Device contains a polarographic oxygen sensor cell, a hood, and a blower of variable speed connected to a servocontrol loop with an oxygen sensor.
 - The MRM adjusts the variable-speed blower to maintain a unidirectional flow of air from the room through the hood and via a connecting hose to the polarographic oxygen-sensing cell.

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Cardiac Output Measurement

Fick Oxygen Method: O₂ Consumption

- **Polarographic O₂ Method**

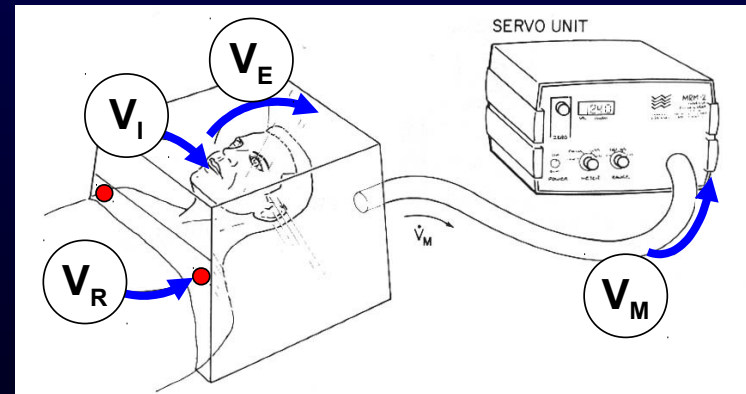
$$V_M = V_R + V_E - V_I$$

V_M = Blower Discharge Rate

V_R = Room Air Entry Rate

V_I = Patient Inhalation Rate

V_E = Patient Exhalation Rate



$$V_{O_2} = (F_R O_2 \times V_R) - (F_M O_2 \times V_M)$$

$F_R O_2$ = Fractional room air O₂ content = 0.209

$F_M O_2$ = Fractional content of O₂ flowing past polarographic cell

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Cardiac Output Measurement

Fick Oxygen Method: O₂ Consumption

- **Polarographic O₂ Method**

$$V_{O_2} = (F_R O_2 \times V_R) - (F_M O_2 \times V_M)$$

$$V_{O_2} = V_M (0.209 - F_M O_2) + 0.209 (V_I - V_E)$$

Constant if
steady state

Servocontrolled system adjusts VM to keep
fractional O₂ content of air moving past
polarographic sensor (FMO₂) at 0.199

$$V_{O_2} = 0.01 (V_M) + 0.209 (V_I - V_E)$$

Respiratory quotient
RQ = V_I / V_E = 1.0

$$V_{O_2} = 0.01 (V_M)$$

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Cardiac Output Measurement

Fick Oxygen Method: O₂ Consumption

- **Douglas Bag Method**
 - Volumetric technique for measuring O₂
 - Analyzes the collection of expired air
 - Utilizes a special mouthpiece and nose clip so that patient breathes only through mouth
 - A 2-way valve permits entry of room air while causing all expired air to be collected in the Douglas bag
 - Volume of air expired in a timed sample (3 min) is measured with a Tissot spirometer

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Cardiac Output Measurement

Fick Oxygen Method: O₂ Consumption

- **Douglas Bag Method**

Barometric pressure =	_____	mm Hg
Barometric temperature =	_____	° C
Corrected barometric pressure =	_____	mm Hg
pO ₂ room air =	_____	mm Hg
pO ₂ expired air =	_____	mm Hg
Tissot: initial =	_____	cm
Tissot: final =	_____	cm
Sample volume (oxygen analysis)	_____	L
Correction factor	_____	(standard tables)
Collection time	_____	min

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Cardiac Output Measurement

Fick Oxygen Method: O₂ Consumption

- **Douglas Bag Method**

Step 1: Calculate oxygen difference

$$\text{O}_2 \text{ content room air} = \frac{\text{pO}_2 \text{ room air} \times 100}{\text{Corrected barometric pressure}}$$

$$\text{O}_2 \text{ content expired air} = \frac{\text{pO}_2 \text{ expired air} \times 100}{\text{Corrected barometric pressure}}$$

Oxygen difference =

$$\text{O}_2 \text{ room air} - \text{O}_2 \text{ expired air} = \text{_____ mL O}_2 \text{ consumed / L air}$$

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Cardiac Output Measurement

Fick Oxygen Method: O₂ Consumption

- **Douglas Bag Method**

Step 2: Calculate minute ventilation

Tissot difference = Tissot initial – Tissot final = _____ cm

Tissot volume = Tissot difference x correction factor = _____ L

Total volume = Tissot volume + sample volume = _____ L

Ventilation volume (corrected to STP) =

Total volume expired air x correction factor = _____ L

Minute ventilation =
$$\frac{\text{Ventilation volume}}{\text{Collection time}}$$

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Cardiac Output Measurement

Fick Oxygen Method: O₂ Consumption

- **Douglas Bag Method**

Step 3: Calculate oxygen consumption

O₂ consumption = O₂ difference x minute ventilation

$$\text{O}_2 \text{ consumption index} = \frac{\text{O}_2 \text{ consumption}}{\text{Body surface area}}$$

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Cardiac Output Measurement

Fick Oxygen Method: AV O₂ Difference

- **Sampling technique**
 - **Mixed venous sample**
 - Collect from pulmonary artery
 - Collection from more proximal site may result in error with left-right shunting
 - **Arterial sample**
 - Ideal source: pulmonary vein
 - Alternative sites: LV, peripheral arterial
 - If arterial desaturation (SaO₂ < 95%) present, right-to-left shunt must be excluded
- **Measurement**
 - **Reflectance (optical absorbance) oximetry**

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Cardiac Output Measurement

Fick Oxygen Method: AV O₂ Difference

Step 1: Theoretical oxygen carrying capacity

$$\text{O}_2 \text{ carrying capacity (mL O}_2 \text{ / L blood)} = \\ 1.36 \text{ mL O}_2 \text{ / gm Hgb} \times 10 \text{ mL/dL} \times \text{Hgb (gm/dL)}$$

Step 2: Determine arterial oxygen content

$$\text{Arterial O}_2 \text{ content} = \text{Arterial saturation} \times \text{O}_2 \text{ carrying capacity}$$

Step 3: Determine mixed venous oxygen content

$$\text{Mixed venous O}_2 \text{ content} = \text{MV saturation} \times \text{O}_2 \text{ carrying capacity}$$

Step 3: Determine A-V O₂ oxygen difference

$$\text{AV O}_2 \text{ difference} = \text{Arterial O}_2 \text{ content} - \text{Mixed venous O}_2 \text{ content}$$

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Cardiac Output Measurement

Fick Oxygen Method

- **Fick oxygen method total error $\approx 10\%$**
 - Error in O₂ consumption $\approx 6\%$
 - Error in AV O₂ difference $\approx 5\%$. Narrow AV O₂ differences more subject to error, and therefore Fick method is most accurate in low cardiac output states
- **Sources of Error**
 - Incomplete collection of expired air (Douglas bag)
 - Underestimate O₂ consumption and CO
 - Respiratory quotient = 1
 - Volume of CO₂ expired is not equal to O₂ inspired
 - Leads to underestimation of O₂ consumption and CO
 - Incorrect timing of expired air collection (Douglas bag)

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Cardiac Output Measurement

Fick Oxygen Method

- **Sources of Error**
 - Spectrophotometric determination of blood oxygen saturation
 - Changes in mean pulmonary volume
 - Douglas bag and MRM measure amount of O₂ entering lungs, not actual oxygen consumption
 - Patient may progressively increase or decrease pulmonary volume during sample collection. If patient relaxes and breathes smaller volumes, CO is underestimated
 - Improper collection of mixed venous blood sample
 - Contamination with PCW blood
 - Sampling from more proximal site

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Cardiac Output Measurement Indicator Dilution Methods

- **Requirements**
 - **Bolus of indicator substance which mixes completely with blood and whose concentration can be measured**
 - **Indicator is neither added nor subtracted from blood during passage between injection and sampling sites**
 - **Most of sample must pass the sampling site before recirculation occurs**
 - **Indicator must go through a portion of circulation where all the blood of the body becomes mixed**

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Cardiac Output Measurement

Indicator Dilution Methods

Stewart-Hamilton Equation

$$CO = \int_0^{\infty} \frac{\text{Indicator amount}}{C(t) dt} \quad C = \text{concentration of indicator}$$

$$CO = \frac{\text{Indicator amount (mg)} \times 60 \text{ sec/min}}{\text{mean indicator concentration (mg/mL)} \times \text{curve duration}}$$

- Indicators
 - Indocyanine Green
 - Thermodilution (Indicator = Cold)

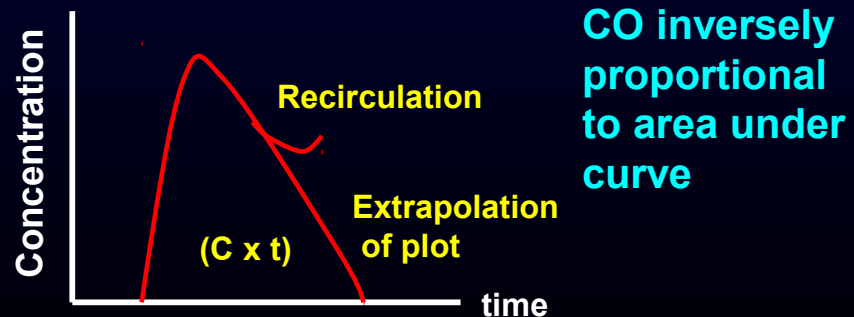
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Cardiac Output Measurement

Indocyanine Green Method

- Indocyanine green (volume and concentration fixed) injected as a bolus into right side of circulation (pulmonary artery)
- Samples taken from peripheral artery, withdrawing continuously at a fixed rate
- Indocyanine green concentration measured by densitometry

$$CO = \frac{I}{(C \times t)}$$



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Cardiac Output Measurement

Indocyanine Green Method

- **Sources of Error**
 - Indocyanine green unstable over time and with exposure to light
 - Sample must be introduced rapidly as single bolus
 - Bolus size must be exact
 - Indicator must mix thoroughly with blood, and should be injected just proximal or into cardiac chamber
 - Dilution curve must have exponential downslope of sufficient length to extrapolate curve. Invalid in Low cardiac output states and shunts that lead to early recirculation
 - Withdrawal rate of arterial sample must be constant

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Cardiac Output Measurement

Thermodilution Method

$$CO = \frac{V_i (T_B - T_i) (S_i \times C_i / S_B \times C_B) \times 60}{\int_0^{\infty} \Delta T_B dt}$$

V_i = volume of injectate

S_i, S_B = specific gravity of injectate and blood

C_i, C_B = specific heat of injectate and blood

T_i = temperature of injectate

ΔT_B = change in temperature measured downstream

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Cardiac Output Measurement

Thermodilution Method

- **Advantages**
 - **Withdrawal of blood not necessary**
 - **Arterial puncture not required**
 - **Indicator (saline or D5W)**
 - **Virtually no recirculation, simplifying computer analysis of primary curve sample**

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Cardiac Output Measurement

Thermodilution Method

- **Sources of Error ($\pm 15\%$)**
 - Unreliable in tricuspid regurgitation
 - Baseline temperature of blood in pulmonary artery may fluctuate with respiratory and cardiac cycles
 - Loss of injectate with low cardiac output states ($CO < 3.5 \text{ L/min}$) due to warming of blood by walls of cardiac chambers and surrounding tissues. The reduction in ΔT_b at pulmonary arterial sampling site will result in overestimation of cardiac output
 - Empirical correction factor (0.825) corrects for catheter warming but will not account for warming of injectate in syringe by the hand

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Cardiac Output Measurement

Stroke Volume

- **Stroke Volume**

- Volume of blood ejected in a single contraction
- Volumetric analysis requires 3-dimensional analysis to calculate end-diastolic and end-systolic volume

Stroke volume = End-diastolic volume – End-systolic volume

- Estimation based on cardiac output

$$\text{Stroke volume} = \frac{\text{Cardiac output}}{\text{Heart rate}}$$

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Hemodynamic Principles

1. In the cardiac catheterization laboratory, cardiac output is measured using the Fick principle or thermodilution technique. Which of the following statements is correct?
 - A. Using an assumed O_2 consumption of 125 ml/m^2 is acceptable and results in minimal variability in cardiac output compared with direct measurements of O_2 consumption.
 - B. The thermodilution method underestimates cardiac output in patients with low forward flows (cardiac outputs $<3.5 \text{ L/min}$).
 - C. The thermodilution method underestimates cardiac output in the presence of important tricuspid regurgitation.
 - D. O_2 saturation measured in blood collected from a central line in the right atrium is an acceptable substitute for a pulmonary artery sample when calculating the AV O_2 difference.
 - E. A high cardiac output will produce a large area under the temperature-time curve in thermodilution determinations.



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Hemodynamic Principles

An Overview

- Pressure measurement
- Right and left heart catheterization
- Cardiac output measurement
 - Fick-oxygen method
 - Arterial-venous oxygen difference
 - Indicator-dilution methods
 - Indocyanine green
 - Thermodilution
- Vascular resistance
- Shunt detection and measurement
- Gradients and valve stenoses

Vascular Resistance

Poiseuille's Law

$$Q = \frac{\pi (P_i - P_o) r^4}{8 \eta L}$$

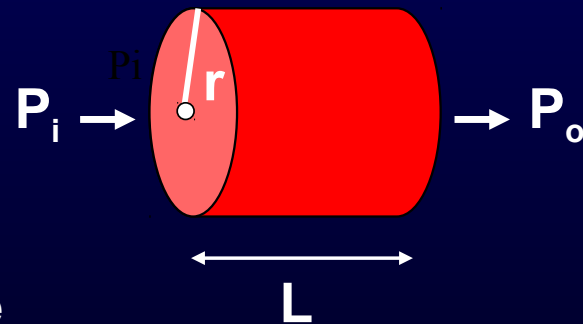
Q = volume flow

P_i – P_o = inflow – outflow pressure

r = radius of tube

L = length of tube

η = viscosity of the fluid



$$\text{Resistance} = \frac{\Delta P}{Q} = \frac{8 \eta L}{\pi r^4}$$

In vascular system,
key factor is radius
of vessel

Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

Vascular Resistance

Definitions

Normal reference values		
	<u>Woods Units</u>	<u>Metric Units</u>
Systemic vascular resistance		
$SVR = \frac{\overline{Ao} - \overline{RA}}{Q_s}$	10 – 20	770 – 1500
Pulmonary vascular resistance		
$PVR = \frac{\overline{PA} - \overline{LA}}{Q_p}$	0.25 – 1.5	20 – 120

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Vascular Resistance

Systemic Vascular Resistance

- **Increased**
 - **Systemic HTN**
 - **Cardiogenic shock with compensatory arteriolar constriction**
- **Decreased**
 - **Inappropriately high cardiac output**
 - **Arteriovenous fistula**
 - **Severe anemia**
 - **High fever**
 - **Sepsis**
 - **Thyrotoxicosis**

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Vascular Resistance

Pulmonary Vascular Resistance

- **Increased**
 - Primary lung disease
 - Eisenmenger syndrome
 - Elevated pulmonary venous pressure
 - Left-sided myocardial dysfunction
 - Mitral / Aortic valve disease
- **Decreased**

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Hemodynamic Principles

1. An obese patient with a dilated cardiomyopathy comes to the cardiac catheterization laboratory to determine whether or not he might be a candidate for cardiac transplantation. The pulmonary artery pressure is 40 mmHg, the pulmonary artery wedge pressure is 25 mmHg, and the cardiac output is 5 L/min. Which of the following statements is true?
 - A. He would be a candidate for cardiac transplantation based upon the calculated pulmonary arteriolar resistance.
 - B. He should undergo further evaluation with infusion of nitroprusside.
 - C. He would not be a candidate for cardiac transplantation based upon pulmonary arteriolar resistance.
 - D. He should be considered for combination heart-lung transplantation.
 - E. More information is required to determine the pulmonary arteriolar resistance.




Hemodynamic Principles

1. An obese patient with a dilated cardiomyopathy comes to the cardiac catheterization laboratory to determine whether or not he might be a candidate for cardiac transplantation. The pulmonary artery pressure is 40 mmHg, the pulmonary artery wedge pressure is 25 mmHg, and the cardiac output is 5 L/min. Which of the following statements is true?
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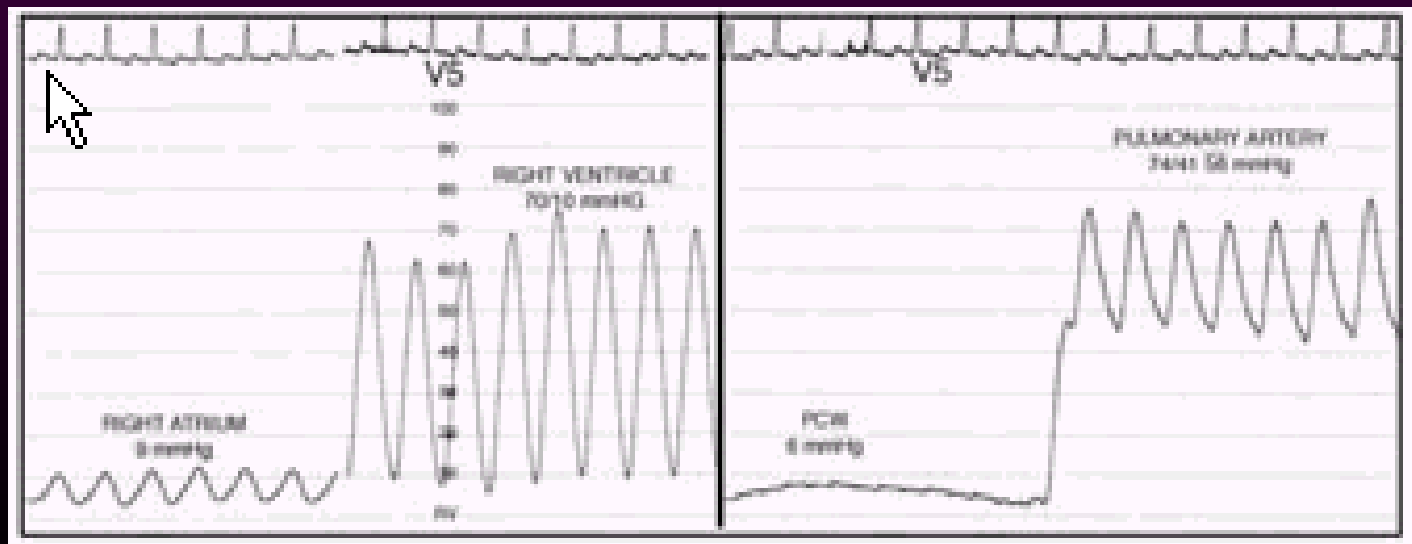
Hemodynamic Principles

2. The patient is a 55-yo woman who was diagnosed with severe pulmonary hypertension 2 months ago. She has had evidence of RVH by ECG dating back 6 years, but remained asymptomatic until recently. A daughter died at the age of 8 years from primary pulmonary hypertension. She was referred for right heart catheterization to exclude an intracardiac shunt and to perform an intravenous prostacyclin challenge to assess her pulmonary vasoreactivity. Her pulmonary artery hydrogen curve appearance time was 12 seconds.

The hydrogen curve technique is performed by having the patient inhale one breath of hydrogen and record the time to downward drift of the electrocardiographic baseline recorded from the tip of an electrode catheter placed in the main pulmonary artery. A short appearance time of the ECG drift (1-2 seconds) confirms the presence of a left-to-right intracardiac shunt. The 12 second recorded in this patient is normal and excludes a left-to-right shunt. The hydrogen curve technique is very sensitive compared to oximetry, but is not useful in quantifying the magnitude of the shunt nor in detecting a  to left shunt.

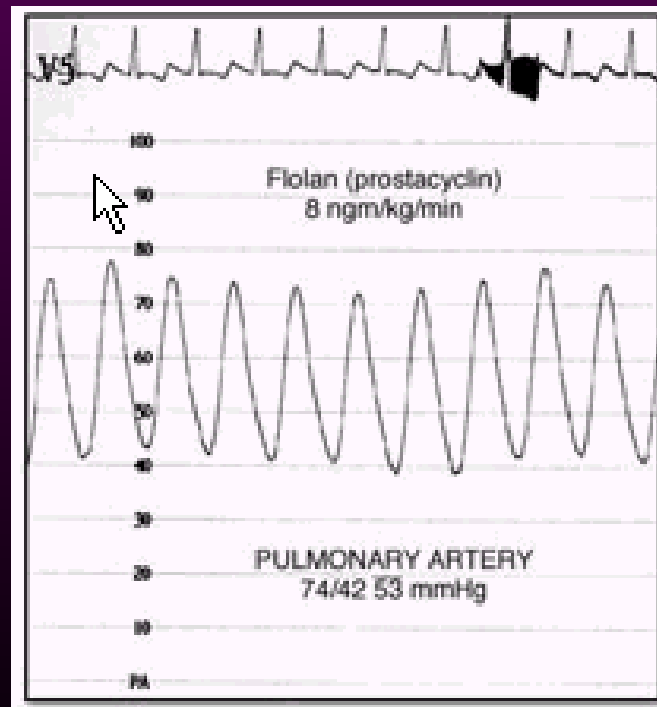
Hemodynamic Principles

A Flolan (IV prostacyclin) infusion was begun. At a dose of 8 ngm/kg/minute, she had moderate cutaneous flushing and her systemic arterial pressure was reduced from the baseline of 107/81 (mean 90 mmHg) with a heart rate of 136bpm to 86/61 (mean 67 mmHg) with a heart rate of 137 bpm. Thermodilution cardiac output was 2.50 L/min at baseline and 4.20 L/min during the maximum prostacyclin infusion. The pressure tracing below was recorded before prostacyclin was initiated.



Hemodynamic Principles

The pressure tracing below was recorded after prostacyclin was initiated.



Hemodynamic Principles

Which of the following correctly describes these data or the management of this patient?

- A. Further reductions in pulmonary artery pressure can likely be achieved at higher dose of this prostaglandin.
- B. The hydrogen curve result suggests there is an intracardiac left-to-right shunt.
- C. At baseline, the pulmonary resistance is elevated at 20 Wood units.
- D. At baseline, the pulmonary resistance is elevated at 20 dyne/sec/cm-5.
- E. Primary pulmonary hypertension has no genetic determinants.



Hemodynamic Principles

Which of the following correctly describes these data or the management of this patient?

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- C. At baseline, the pulmonary resistance is elevated at 20 Wood units.**
- D. At baseline, the pulmonary resistance is elevated at 20 dyne/sec/cm-5.
- E. Primary pulmonary hypertension has no genetic determinants.

Hemodynamic Principles

3. The patient is a 42-year-old woman who presents with mild dyspnea. She has gained considerable weight and feels that it is the primary reason for the new symptoms. Her initial exam suggests no CHF, but a pulmonic flow murmur is heard. The second heart sound is clearly widely split. She has a right bundle branch block on her ECG. An echocardiogram is obtained that reveals an enlarged RA and RV. By Doppler/echocardiogram, a left-to-right shunt is noted across the atrial septum. Using saline contrast a few microcavitations appear on the left side of the heart. A cardiac catheterization is performed to assess size of shunt and pulmonary pressures.

Hemodynamic Principles

3. The cardiac catheterization revealed:

Pressures (mmHg): RA: mean 7, RV: 45/6, PA: 45/25, mean 33, PCW: mean 10, LV: 120/5, Aortic: 120/80, mean 95.

Saturations (%): SVC: 60, IVC: 65, (Mixed Venous 62), RA: 80, RV: 75, PA: 75, PV: 95, Aortic: 95.

Hemoglobin: 13 mg/dl, Oxygen consumption: 250 ml/min.

LA angiogram: Consistent with secundum atrial septal defect.

Using these data, the pulmonary blood flow was determined to be 7.1 liters/min and the systemic blood flow was found to be 4.3 liters/min.

Select the correct answer based on the findings at cardiac catheterization.

- A. The Q_p/Q_s suggests that no therapy is required at this time.
- B. The PVR/SVR ratio suggests the elevated PA pressure is due to Eisenmenger's syndrome, and it is too late to consider ASD closure.
- C. The PVR/SVR ratio is low enough that she would be a candidate for ASD closure at this time.
- D. There are inadequate data to decide the patient's operability.
- E. Endocarditis prophylaxis is highly recommended to prevent endocarditis given these hemodynamics.



Hemodynamic Principles

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Pressures (mmHg): RA: mean 7, RV: 45/6, PA: 45/25, mean 33, PCW: mean 10, LV: 120/5, Aortic: 120/80, mean 95.

Saturations (%): SVC: 60, IVC: 65, (Mixed Venous 62), RA: 80, RV: 75, PA: 75, PV: 95, Aortic: 95.

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- E. Endocarditis prophylaxis is highly recommended to prevent endocarditis given these hemodynamics.

Hemodynamic Principles

4. A 48-year-old patient with pulmonary hypertension is admitted with profound cyanosis and clubbing. Her workup reveals primary pulmonary hypertension with a patent foramen ovale and right-to-left shunt. Given the following information, calculate her pulmonary vascular resistance.

Hemodynamic Principles

4. At catheterization, the SVC oxygen saturation is 43%, the IVC oxygen saturation is 50%, the RA saturation is 45%, the PA oxygen saturation is 45%, the PV saturation is 90%, the aortic oxygen saturation is 80%. Oxygen consumption is 275 ml/min. The hemoglobin is 15gm%. The RA pressure mean is 15, the RV pressure is 90/15, the PA pressure is 90/60 with a mean of 75, the pulmonary wedge pressure is 10, the LV pressure is 110/10, the aortic pressure is 110/80 with a mean of 95 mmHg.
- A. There is inadequate information to calculate the PVR.
 - B. The PVR is 21.7 Wood units.
 - C. The PVR is 16.2 Wood units.
 - D. The PVR is 10.3 Wood units.
 - E. The PVR is 8.8 Wood units.



Hemodynamic Principles

4. At catheterization, the SVC oxygen saturation is 43%, the IVC oxygen saturation is 50%, the RA saturation is 45%, the PA oxygen saturation is 45%, the PV saturation is 90%, the aortic oxygen saturation is 80%. Oxygen consumption is 275 ml/min. The hemoglobin is 15gm%. The RA pressure mean is 15, the RV pressure is 90/15, the PA pressure is 90/60 with a mean of 75, the pulmonary wedge pressure is 10, the LV pressure is 110/10, the aortic pressure is 110/80 with a mean of 95 mmHg.
- A. There is inadequate information to calculate the PVR.
 - B. The PVR is 21.7 Wood units.**
 - C. The PVR is 16.2 Wood units.
 - D. The PVR is 10.3 Wood units.
 - E. The PVR is 8.8 Wood units.

Hemodynamic Principles

An Overview

- Pressure measurement
- Right and left heart catheterization
- Cardiac output measurement
 - Fick-oxygen method
 - Arterial-venous oxygen difference
 - Indicator-dilution methods
 - Indocyanine green
 - Thermodilution
- Vascular resistance
- Shunt detection and measurement
- Gradients and valve stenoses

Shunt Detection & Measurement Indications

- **Arterial desaturation (<95%)**
 - Alveolar hypoventilation (Physiologic Shunt) corrects with deep inspiration and/or O₂
 - Sedation from medication
 - COPD / Pulmonary parenchymal disease
 - Pulmonary congestion
 - Anatomic shunt (Rt→Lf) does not correct with O₂
- **Unexpectedly high PA saturation (>80%) due to Lf→Rt shunt**

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Shunt Detection & Measurement Methods

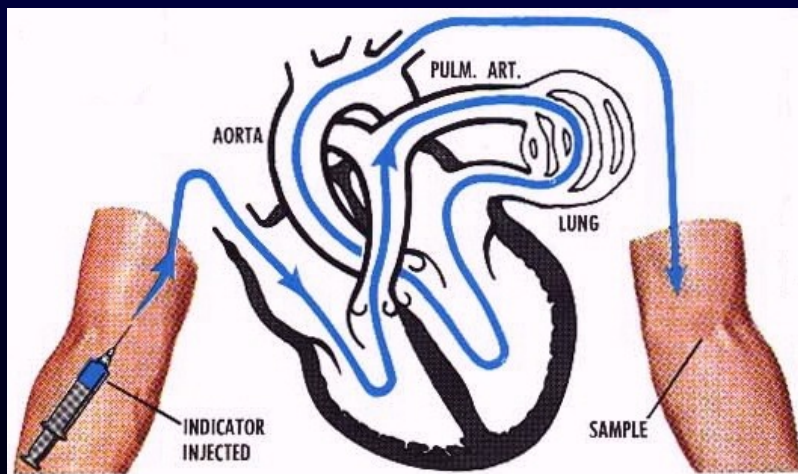
- **Shunt Detection**
 - **Indocyanine green method**
 - Oximetric method
- **Shunt Measurement**
 - Left-to-Right Shunt
 - Right-to-Left Shunt
 - Bidirectional Shunt

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Shunt Detection & Measurement

Indocyanine Green Method

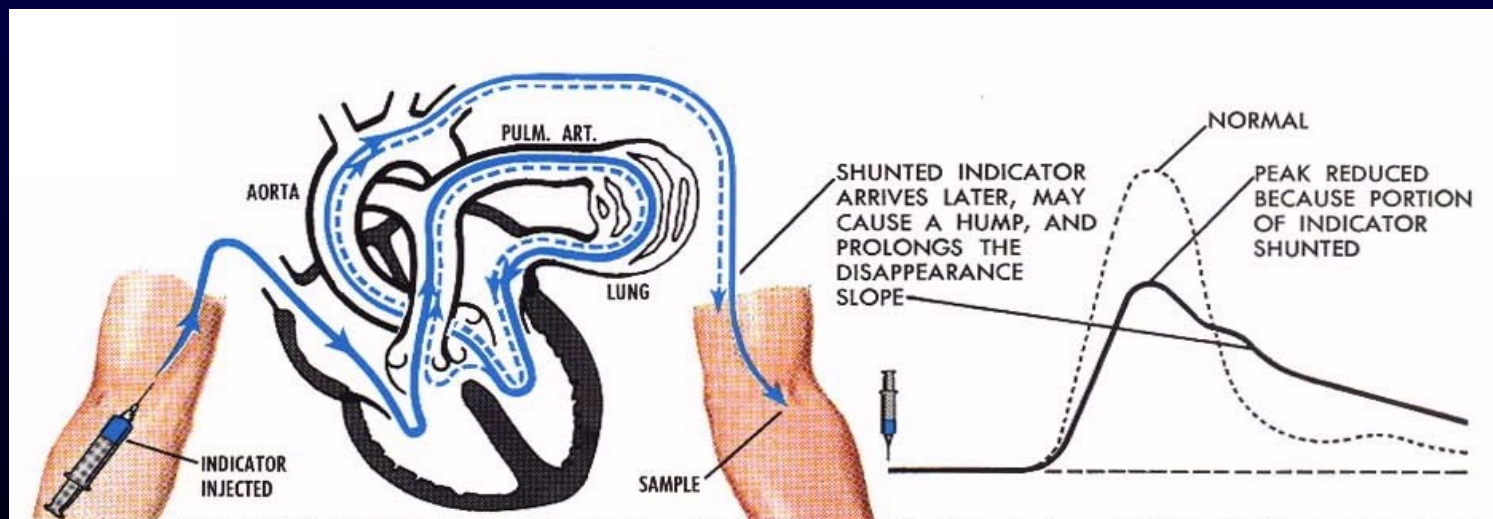
- Indocyanine green (1 cc) injected as a bolus into right side of circulation (pulmonary artery)
- Concentration measured from peripheral artery
- Appearance and washout of dye produces initial 1st pass curve followed by recirculation in normal adults



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Shunt Detection & Measurement

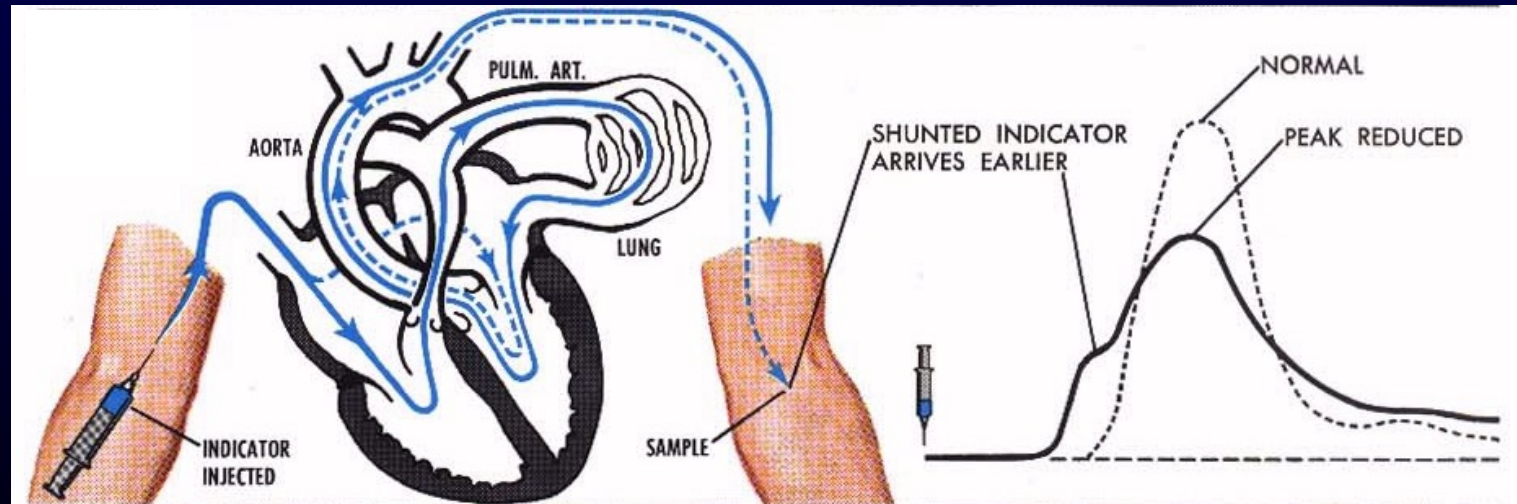
Left-to-Right Shunt



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Shunt Detection & Measurement

Right-to-Left Shunt

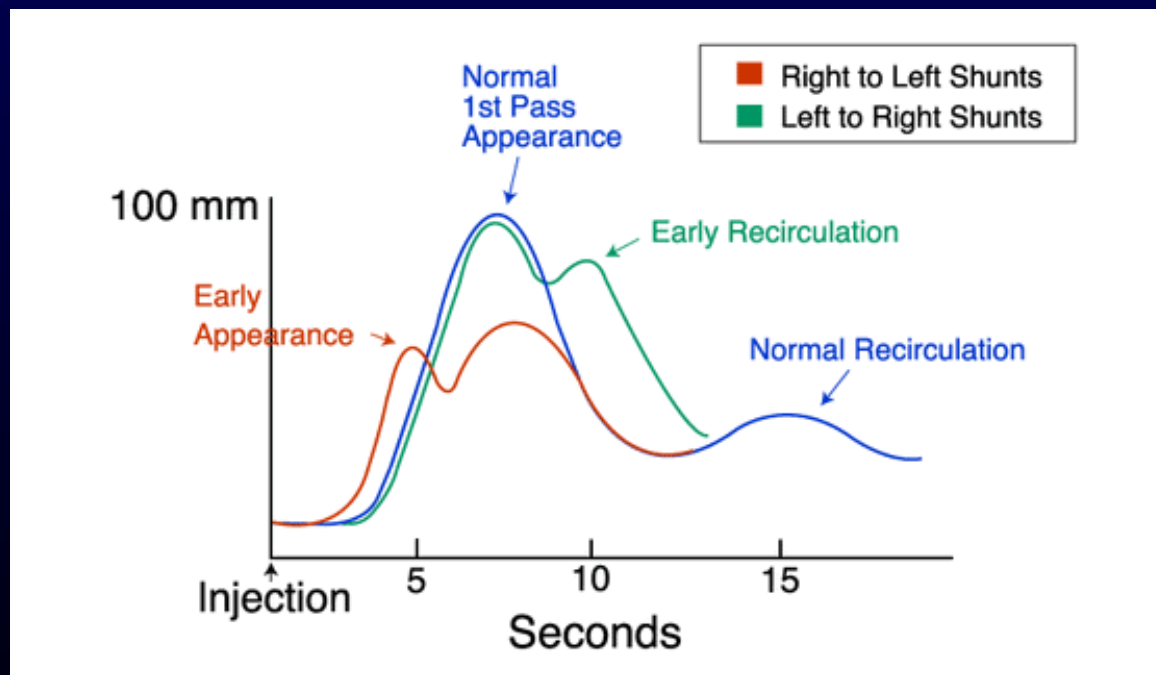


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IPR2017-02151

Shunt Detection & Measurement Indocyanine Green Method



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Shunt Detection & Measurement Methods

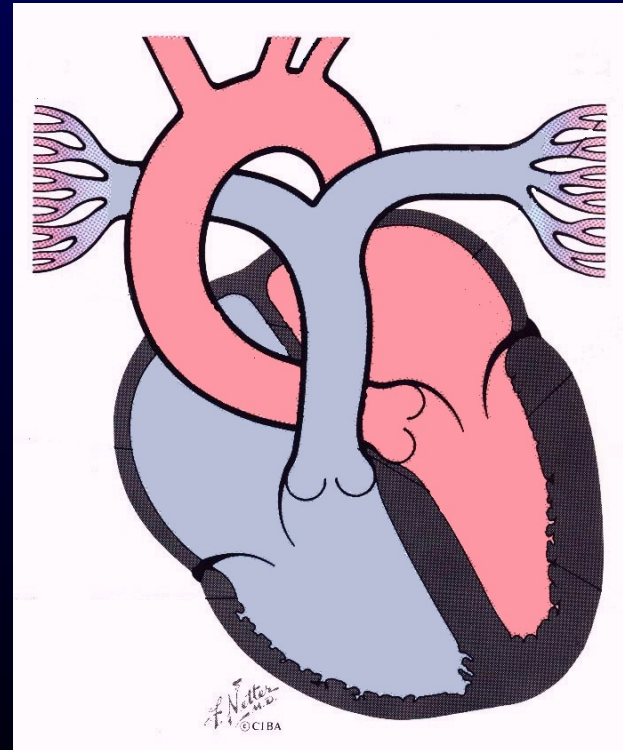
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Shunt Detection & Measurement

Oximetric Methods

- Obtain O₂ saturations in sequential chambers, identifying both step-up and drop-off in O₂ sat
- Insensitive for small shunts (< 1.3:1)

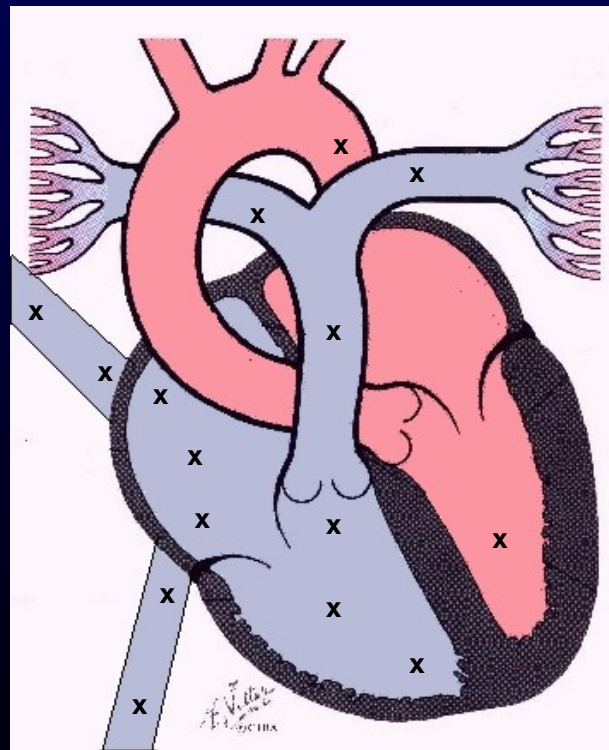


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Shunt Detection & Measurement

Oximetry Run

- IVC, L4-5 level
- IVC, above diaphragm
- SVC, innominate
- SVC, at RA
- RA, high
- RA, mid
- RA, low
- RV, mid
- RV, apex
- RV, outflow tract
- PA, main
- PA, right or left
- Left ventricle
- Aorta, distal to ductus



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Shunt Detection & Measurement

Oximetric Methods

- RA receives blood from several sources
 - SVC: Saturation most closely approximates true systemic venous saturation
 - IVC: Highly saturated because kidneys receive 25% of CO and extract minimal oxygen
 - Coronary sinus: Markedly desaturated because heart maximizes O₂ extraction
- Phlamm Equation: Mixed venous saturation used to normalize for differences in blood saturations that enter RA

$$\text{Mixed venous saturation} = \frac{3 (\text{SVC}) + \text{IVC}}{4}$$

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Shunt Detection & Measurement Methods

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Shunt Detection & Measurement

Detection of Left-to-Right Shunt

Level of shunt	Mean ΔO_2 % Sat	Mean ΔO_2 Vol %	Minimal Q_p/Q_s detected	Differential diagnosis
Atrial (SVC/IVC → RA)	≥ 7	≥ 1.3	1.5 – 1.9	ASD, PAPVR, VSD with TR, Ruptured sinus of Valsalva, Coronary fistula to RA
Ventricular (RA → RV)	≥ 5	≥ 1.0	1.3 – 1.5	VSD, PDA with PR, Coronary fistula to RV
Great vessel (RV → PA)	≥ 5	≥ 1.0	1.3	Aorto-pulmonary window, Aberrant coronary origin, PDA
ANY LEVEL (SVC → PA)	≥ 7	≥ 1.3	1.3	All of the above

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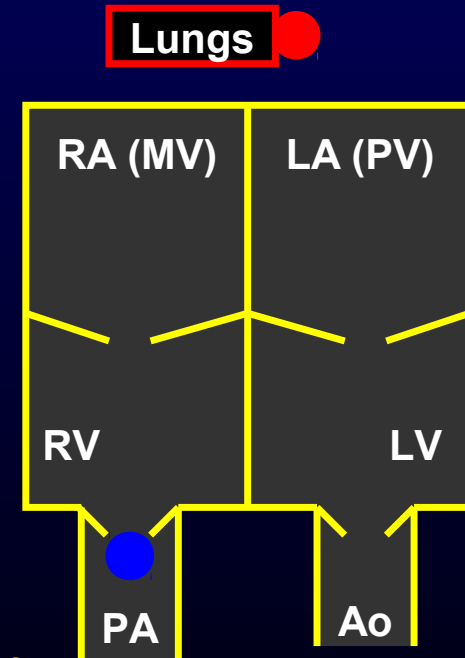
Shunt Detection & Measurement

Oximetric Methods

- **Fick Principle:** The total uptake or release of any substance by an organ is the product of blood flow to the organ and the arteriovenous concentration difference of the substance.
 - Pulmonary circulation (Qp) utilizes PA and PV saturations

$O_2 \text{ content} = 1.36 \times \text{Hgb} \times O_2 \text{ saturation}$

$$\text{PBF} = \frac{O_2 \text{ consumption}}{(\text{PvO}_2 - \text{PaO}_2) \times 10}$$



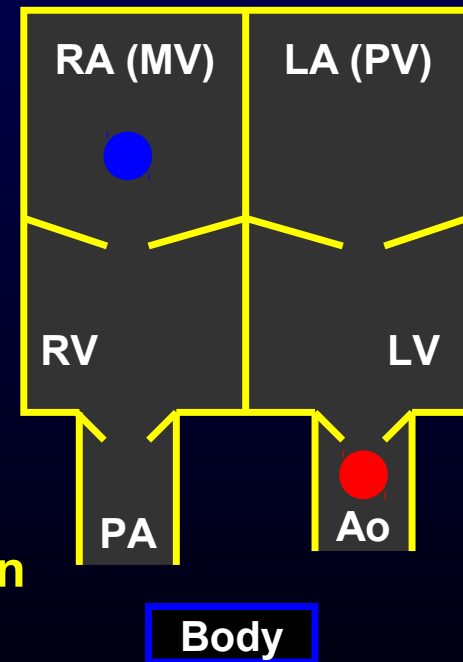
Shunt Detection & Measurement

Oximetric Methods

- **Fick Principle:** The total uptake or release of any substance by an organ is the product of blood flow to the organ and the arteriovenous concentration difference of the substance.
 - Systemic circulation (Q_s) utilizes MV and Ao saturations

$$O_2 \text{ content} = 1.36 \times \text{Hgb} \times O_2 \text{ saturation}$$

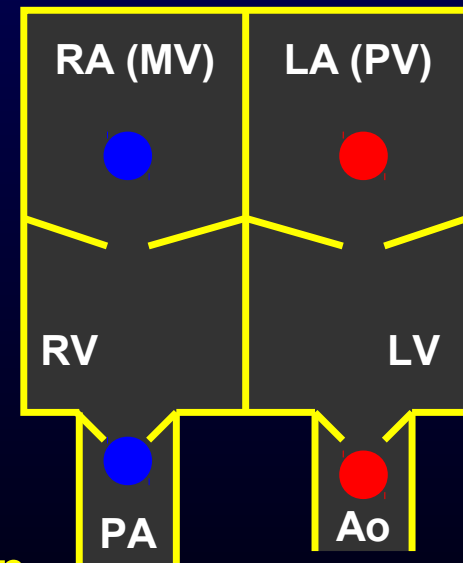
$$SBF = \frac{O_2 \text{ consumption}}{(AoO_2 - MVO_2) \times 10}$$



Shunt Detection & Measurement

Oximetric Methods

- **Fick Principle:** The total uptake or release of any substance by an organ is the product of blood flow to the organ and the arteriovenous concentration difference of the substance.
 - Pulmonary circulation (Q_p) utilizes PA and PV saturations
 - Systemic circulation (Q_s) utilizes MV and Ao saturations



$O_2 \text{ content} = 1.36 \times \text{Hgb} \times O_2 \text{ saturation}$

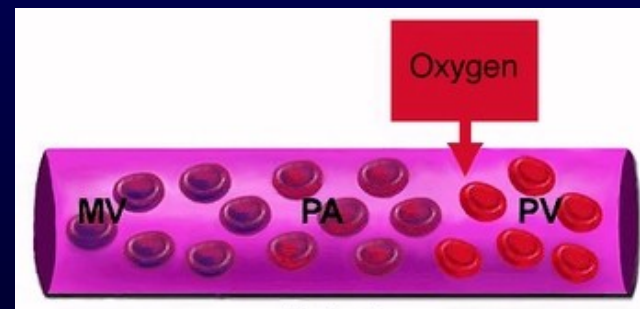
$$PBF = \frac{O_2 \text{ consumption}}{(PvO_2 - PaO_2) \times 10}$$

$$SBF = \frac{O_2 \text{ consumption}}{(AoO_2 - MVO_2) \times 10}$$

Shunt Detection & Measurement

Effective Pulmonary Blood Flow

- **Effective Pulmonary Blood Flow:** flow that would be present if no shunt were present
- **Requires**
 - MV = PA saturation
 - PV – PA = PV - MV



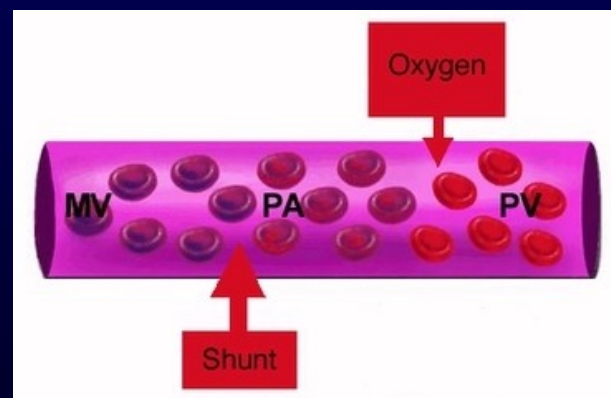
$$\text{Effective Pulmonary Blood Flow} = \frac{\text{O}_2 \text{ consumption}}{(\text{Pv} - \text{MV O}_2) \times 10} = \overbrace{\frac{\text{O}_2 \text{ consumption}}{(\text{Pv} - \text{Pa O}_2) \times 10}}^{\text{PBF}}$$

Bashore, TM. Congenital Heart Disease in Adults. The Measurement of Intracardiac Shunts. In: CATHSAP II. Bethesda: American College of Cardiology, 2001.

Shunt Detection & Measurement

Left-to-Right Shunt

- Left to right shunt results in step-up in O_2 between MV and PA
- Shunt is the difference between pulmonary flow measured and what it would be in the absence of shunt (EPBF)
- Systemic Blood Flow = EPBF



Left-Right Shunt = Pulmonary Blood Flow – Effective Blood Flow

$$= \frac{O_2 \text{ consumption}}{(PvO_2 - PaO_2) \times 10} - \frac{O_2 \text{ consumption}}{(PvO_2 - MVO_2) \times 10}$$

$$Q_p / Q_s \text{ Ratio} = PBF / SBF = \frac{(AoO_2 - MVO_2)}{(PvO_2 - PaO_2)}$$

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Shunt Detection & Measurement

Left-to-Right Shunt

- **ASD**
- **VSD**
- **Coronary Cameral Fistula**
- **Ruptured Sinus of Valsalva**
- **Partial Anomalous Pulmonary Venous Return**
- **Aorto Pulmonary Window**
- **PDA**
- **Aberrant Coronary Origin**

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Shunt Detection & Measurement Methods

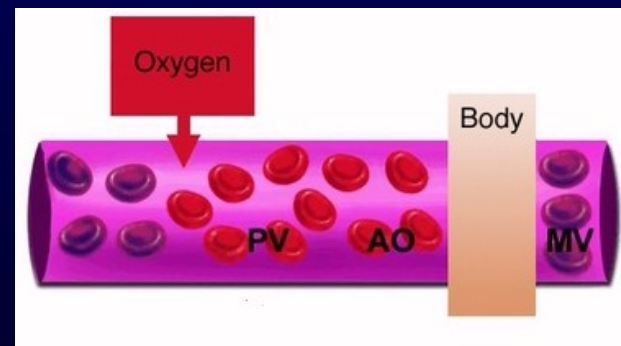
- **Shunt Detection**
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Shunt Detection & Measurement

Effective Pulmonary Blood Flow

- **Effective Pulmonary Blood Flow:** flow that would be present if no shunt were present
- **Requires**
 - PV = Ao saturation
 - PV – MV = Ao - MV



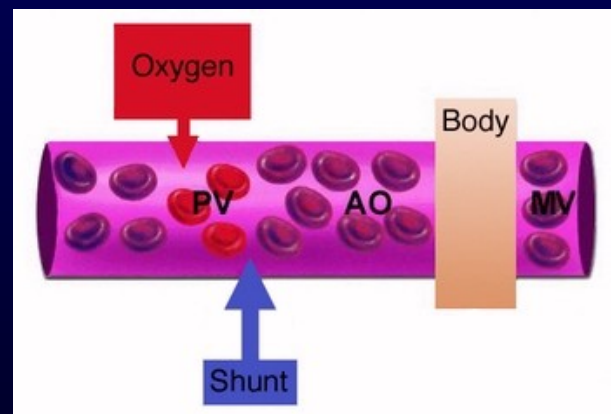
$$\text{Effective Pulmonary Flow} = \frac{\text{O}_2 \text{ consumption}}{(\text{Pv} - \text{MV O}_2) \times 10} = \overbrace{\frac{\text{O}_2 \text{ consumption}}{(\text{Ao} - \text{MV O}_2) \times 10}}^{\text{SBF}}$$

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Shunt Detection & Measurement

Right-to-Left Shunt

- Left to right shunt results in step-down in O_2 between PV and Ao
- Shunt is the difference between systemic flow measured and what it would be in the absence of shunt (EPBF)
- Pulmonary Blood Flow = EPBF



Right-Left Shunt = Systemic Blood Flow – Effective Blood Flow

$$= \frac{O_2 \text{ consumption}}{(AoO_2 - MVO_2) \times 10} - \frac{O_2 \text{ consumption}}{(PvO_2 - MVO_2) \times 10}$$

$$Q_p / Q_s \text{ Ratio} = PBF / SBF = \frac{(AoO_2 - MVO_2)}{(PvO_2 - PaO_2)}$$

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Shunt Detection & Measurement

Right-to-Left Shunt

- **Tetralogy of Fallot**
- **Eisenmenger Syndrome**
- **Pulmonary arteriovenous malformation**
- **Total anomalous pulmonary venous return (mixed)**

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Shunt Detection & Measurement Methods

- **Shunt Detection**
 - Indocyanine green method
 - Oximetric method
- **Shunt Measurement**
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 - **Bidirectional Shunt**

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Shunt Detection & Measurement

Bidirectional Shunts

- Left-to-Right Shunt

$$= \frac{Q_p (\text{MV O}_2 \text{ content} - \text{PA O}_2 \text{ content})}{(\text{MV O}_2 \text{ content} - \text{PV O}_2 \text{ content})}$$

- Right-to-Left Shunt

$$= \frac{Q_p (\text{PV O}_2 \text{ content} - \text{SA O}_2 \text{ content}) (\text{PA O}_2 \text{ content} - \text{PV O}_2 \text{ content})}{(\text{SA O}_2 \text{ content} - \text{PV O}_2 \text{ content}) (\text{MV O}_2 \text{ content} - \text{PV O}_2 \text{ content})}$$

* If pulmonary vein not entered, use 98% x O₂ capacity.

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Shunt Detection & Measurement

Bidirectional Shunt

- **Transposition of Great Arteries**
- **Tricuspid atresia**
- **Total anomalous pulmonary venous return**
- **Truncus arteriosus**
- **Common atrium (AV canal)**
- **Single ventricle**

Shunt Detection & Measurement

Limitations of Oximetric Method

- Requires steady state with rapid collection of O_2 samples
- Insensitive to small shunts
- Flow dependent
 - Normal variability of blood oxygen saturation in the right heart chambers is influenced by magnitude of SBF
 - High flow state may simulate a left-to-right shunt
- When O_2 content is utilized (as opposed to O_2 sat), the step-up is dependent on hemoglobin.

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Hemodynamic Principles

1. A patient undergoes right and left heart catheterization. The patient is breathing room air, hemoglobin is 13.6 gm/dl, and measured oxygen consumption is 250 ml/minute. The systemic arterial oxygen content is 195 ml/liter and the mixed venous oxygen content is 145 ml/liter. Which of the following is the correct cardiac output?
- A. 5.0 liters/minute.
 - B. 5.3 liters/minute.
 - C. 5.8 liters/minute.
 - D. 6.2 liters/minute.
 - E. 6.5 liters/minute.



Hemodynamic Principles

1. A patient undergoes right and left heart catheterization. The patient is breathing room air, hemoglobin is 13.6 gm/dl, and measured oxygen consumption is 250 ml/minute. The systemic arterial oxygen content is 195 ml/liter and the mixed venous oxygen content is 145 ml/liter. Which of the following is the correct cardiac output?

- A. 5.0 liters/minute.**
- B. 5.3 liters/minute.
- C. 5.8 liters/minute.
- D. 6.2 liters/minute.
- E. 6.5 liters/minute.

Hemodynamic Principles

2. The following oxygen saturations were obtained during cardiac catheterization from a patient with a suspected shunt. The saturations shown are the means of multiple values.

Superior vena cava	55%	High right atrium	70%
Mid-right atrium	79%	Low right atrium	83%
Inferior vena cava	75%	Right ventricle	78%
Pulmonary artery	80%	Left atrium	98%
Pulmonary vein	99%	Aorta	98%

Which of the following is the correct location and Q_p/Q_s ratio?

- A. 3-to-1 shunt at the atrial level.
- B. 2-to-1 shunt at the ventricular level.
- C. Bidirectional shunting at the atrial level with a 1.8-to-1 left to right shunt and 1.2-to-1 right-to-left shunt.
- D. 2-to-1 at the atrial level.
- E. 3-to-1 at the ventricular level.



Hemodynamic Principles

2. The following oxygen saturations were obtained during cardiac catheterization from a patient with a suspected shunt. The saturations shown are the means of multiple values.

Superior vena cava	55%	High right atrium	70%
Mid-right atrium	79%	Low right atrium	83%
Inferior vena cava	75%	Right ventricle	78%
Pulmonary artery	80%	Left atrium	98%
Pulmonary vein	99%	Aorta	98%

Which of the following is the correct location and Q_p/Q_s ratio?

- A. 3-to-1 shunt at the atrial level.
- B. 2-to-1 shunt at the ventricular level.
- C. Bidirectional shunting at the atrial level with a 1.8-to-1 left to right shunt and 1.2-to-1 right-to-left shunt.
- D. 2-to-1 at the atrial level.**
- E. 3-to-1 at the ventricular level.

Hemodynamic Principles

3. A 40-year-old obese woman is admitted to the hospital with shortness of breath and you are asked to consult. She has ruddy cheeks and perhaps mild cyanosis, but there is no clubbing. Her jugular venous pulse is not elevated and lungs are clear. A right ventricular heave is palpated, as is the second heart sound along the left sternal border. Her left ventricular apex is not displaced. Auscultation shows a soft systolic murmur along the left sternal border that radiates slightly toward the left with an S3 present, but you cannot distinguish whether it is a left or right-sided S3. The pulmonary component of her second heart sound is loud. There is no hepatomegaly or edema. Her echocardiogram is of marginal quality, but there is marked enlargement of the right atrium and right ventricle. Agitated saline injection results in filling of the left heart structures immediately through what appears to be a secundum atrial septal defect (ASD).

Hemodynamic Principles

3. Cardiac catheterization shows the following hemodynamics and oxygen saturations:

Pressures (mmHg):

RA: a=15, v=13, mean=14

RV: 50/15

PA: 50/25 mean= 32

PCW: mean=10

LV: 130/10

Aorta: 115/60 mean=78

Saturations:

SVC: 60%

IVC: 70%

RA: 80%

RV: 79%

PA: 79%

Ao: 97%

LA: 97%

PV: 98%

Oxygen consumption: 275 ml/min

Hemoglobin: 15.0 gm%

Which of the following is the most appropriate assessment and management of this patient?

Hemodynamic Principles

- A. The patient has excessively high pulmonary vascular resistance and irreversible pulmonary hypertension, thus it is too late to consider surgical closure of her ASD.
- B. Her pulmonary hypertension is primarily due to the increased pulmonary blood flow with a mild increase in pulmonary vascular resistance. Her PVR/SVR ratio falls within the acceptable range, and surgical closure of the ASD is appropriate.
- C. Although her pulmonary hypertension is mostly due to increased pulmonary blood flow, the elevated right atrial pressure indicates right heart failure and thus she would not benefit from surgical closure.
- D. The patient has a balanced shunt ($Q_p/Q_s = 1.1$) and should undergo surgery to prevent further deterioration in her condition and progressive cyanosis in the future.
- E. None of the above is correct.



Hemodynamic Principles

- A. The patient has excessively high pulmonary vascular resistance and irreversible pulmonary hypertension, thus it is too late to consider surgical closure of her ASD.
- B. Her pulmonary hypertension is primarily due to the increased pulmonary blood flow with a mild increase in pulmonary vascular resistance. Her PVR/SVR ratio falls within the acceptable range, and surgical closure of the ASD is appropriate.**
- C. Although her pulmonary hypertension is mostly due to increased pulmonary blood flow, the high PVR indicates irreversible pulmonary hypertension, and surgical closure of the ASD is not indicated.
- D. The patient's pulmonary hypertension is due to increased pulmonary blood flow, and surgical closure of the ASD would undergo and prevent progressive cyanosis in the future.
- E. None of the above is correct.

Calculate PVR / SVR

> 0.5 Risk of surgery increased

> 0.7 No benefit from surgery

Hemodynamic Principles

4. A 52-year-old man undergoes catheterization for unexplained right ventricular dilatation seen on echocardiography. His spiral CT scan and a radionuclide ventilation perfusion scan are normal. Oximetry is performed during right and left heart catheterization. The following saturations are noted:

Left ventricle	96%
Aorta	96%
Main pulmonary artery	80%
Right ventricular outflow tract	80%
Right ventricular apex	79%
High-right atrium	74%
Mid-right atrium	84%
Low-right atrium	79%
SVC	64%
IVC	70%

Hemodynamic Principles

4. Which of the following is the most likely diagnosis?
- A. Partial anomalous pulmonary venous return with a Q_p/Q_s less than 1.5.
 - B. Atrial septal defect with a Q_p/Q_s between 1.5 and 2.0.
 - C. Patent ductus arteriosus.
 - D. Bi-directional shunt.
 - E. Atrial septal defect with a Q_p/Q_s greater than 2.0.



Hemodynamic Principles

4. Which of the following is the most likely diagnosis?

- A. Partial anomalous pulmonary venous return with a Q_p/Q_s less than 1.5.
- B. Atrial septal defect with a Q_p/Q_s between 1.5 and 2.0.**
- C. Patent ductus arteriosus.
- D. Bi-directional shunt.
- E. Atrial septal defect with a Q_p/Q_s greater than 2.0.

Hemodynamic Principles

5. Given the following information, calculate the approximate left-to-right shunt in a patient with a secundum ASD: SVC oxygen saturation= 55%, IVC oxygen saturation= 65%, RA oxygen saturation= 78%, PA oxygen saturation= 75%, aortic oxygen saturation= 95%, oxygen consumption= 280 ml/min, hemoglobin= 13.0. Assume a PV oxygen saturation of 95%.
- A. The left-to-right shunt is 3.7 liters/min.
 - B. The left-to-right shunt is 2.8 liters/min.
 - C. The left-to-right shunt is 2.4 liters/min.
 - D. The left-to-right shunt is 3.0 liters/min.



Hemodynamic Principles

5. Given the following information, calculate the approximate left-to-right shunt in a patient with a secundum ASD: SVC oxygen saturation= 55%, IVC oxygen saturation= 65%, RA oxygen saturation= 78%, PA oxygen saturation= 75%, aortic oxygen saturation= 95%, oxygen consumption= 280 ml/min, hemoglobin= 13.0. Assume a PV oxygen saturation of 95%.
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 - B. The left-to-right shunt is 2.8 liters/min.
 - C. The left-to-right shunt is 2.4 liters/min.
 - D. The left-to-right shunt is 3.0 liters/min.

Hemodynamic Principles

6. Calculation of the Q_p/Q_s (pulmonary blood flow/systemic blood flow) ratio provides information regarding relative shunt size. In a patient with an atrial septal defect and a left-to-right shunt, but no right-to-left shunt, select the minimal amount of information required to determine the Q_p/Q_s ratio.
- A. The SVC (superior vena cava) oxygen saturation, the PV (pulmonary venous) oxygen saturation, and the oxygen consumption.
 - B. The PA (pulmonary artery) oxygen saturation, the AO (aortic) oxygen saturation, and the MV (mixed venous) oxygen saturation.
 - C. The PA oxygen saturation, the AO oxygen saturation, and the oxygen consumption.
 - D. The MV oxygen saturation, the PV oxygen saturation, and the oxygen consumption.
 - E. The MV oxygen saturation, the PA oxygen saturation, and the oxygen consumption.



Hemodynamic Principles

6. Calculation of the Q_p/Q_s (pulmonary blood flow/systemic blood flow) ratio provides information regarding relative shunt size. In a patient with an atrial septal defect and a left-to-right shunt, but no right-to-left shunt, select the minimal amount of information required to determine the Q_p/Q_s ratio.
- A. The SVC (superior vena cava) oxygen saturation, the PV (pulmonary venous) oxygen saturation, and the oxygen consumption.
 - B. The PA (pulmonary artery) oxygen saturation, the AO (aortic) oxygen saturation, and the MV (mixed venous) oxygen saturation.**
 - C. The PA oxygen saturation, the AO oxygen saturation, and the oxygen consumption.
 - D. The MV oxygen saturation, the PV oxygen saturation, and the oxygen consumption.
 - E. The MV oxygen saturation, the PA oxygen saturation, and the oxygen consumption.

Hemodynamic Principles

7. A 45-year-old woman presents with a murmur heard by her gynecologist. She is asymptomatic. On exam she has wide splitting of the second heart sound and a pulmonic flow murmur. On echocardiography, she has evidence for an enlarged right atrium and right ventricle. Injecting agitated saline contrast, a small number of "bubbles" are seen in the left atrium. The septum is well seen, and there is no secundum atrial septal defect. Pulmonary pressure is estimated to be normal. A sinus venosus ASD is suspected and flow through an anomalous pulmonary vein to the SVC is suggested.

Hemodynamic Principles

7. Select the correct answer given the following information. The high SVC oxygen saturation is 60%; the IVC oxygen saturation is 70%. The PA saturation is 80%; the AO saturation is 95%. Assume a PV saturation of 95%. The oxygen consumption is 250 ml/min.
- A. The Q_p/Q_s ratio is about 2.2.
 - B. The Q_p/Q_s ratio is about 1.8.
 - C. The Q_p/Q_s ratio is about 1.6.
 - D. The Q_p/Q_s ratio is about 2.0.
 - E. There is inadequate information to determine the shunt ratio.



Hemodynamic Principles

7. Select the correct answer given the following information. The high SVC oxygen saturation is 60%; the IVC oxygen saturation is 70%. The PA saturation is 80%; the AO saturation is 95%. Assume a PV saturation of 95%. The oxygen consumption is 250 ml/min.

- A. The Q_p/Q_s ratio is about 2.2.**
- B. The Q_p/Q_s ratio is about 1.8.
- C. The Q_p/Q_s ratio is about 1.6.
- D. The Q_p/Q_s ratio is about 2.0.
- E. There is inadequate information to determine the shunt ratio.

Hemodynamic Principles

8. Because of advances in therapy, many children with congenital heart disease are living longer and well into adulthood. Therefore, the recognition and treatment of congenital heart disease in adults is becoming important for adult cardiologists. Which of the following conditions is associated with a left-to-right shunt?
- A. Scimitar syndrome
 - B. Persistent left superior vena cava syndrome
 - C. IVC interruption with azygous continuation
 - D. Shone syndrome
 - E. Williams Syndrome



Hemodynamic Principles

8. Because of advances in therapy, many children with congenital heart disease are living longer and well into adulthood. Therefore, the recognition and treatment of congenital heart disease in adults is becoming important for adult cardiologists. Which of the following conditions is associated with a left-to-right shunt?

A. Scimitar syndrome

B. Persistent left superior vena cava syndrome

C. IVC interruption with azygous continuation

D. Shone syndrome

E. Williams Syndrome

Hemodynamic Principles

An Overview

- Pressure measurement
- Right and left heart catheterization
- Cardiac output measurement
 - Fick-oxygen method
 - Arterial-venous oxygen difference
 - Indicator-dilution methods
 - Indocyanine green
 - Thermodilution
- Vascular resistance
- Shunt detection and measurement
- Gradients and valve stenoses

Valve Stenoses

Gorlin Formula Derivation

Hydraulic Principle # 1 (Torricelli's Law)

$$F = A \cdot V \cdot C$$

F = flow rate

A = area of orifice

V = velocity of flow

C_c = coefficient of orifice contraction

Hydraulic Principle # 2

$$V^2 = C_v^2 \cdot 2 g h$$

V = velocity of flow

C_v = coefficient of velocity

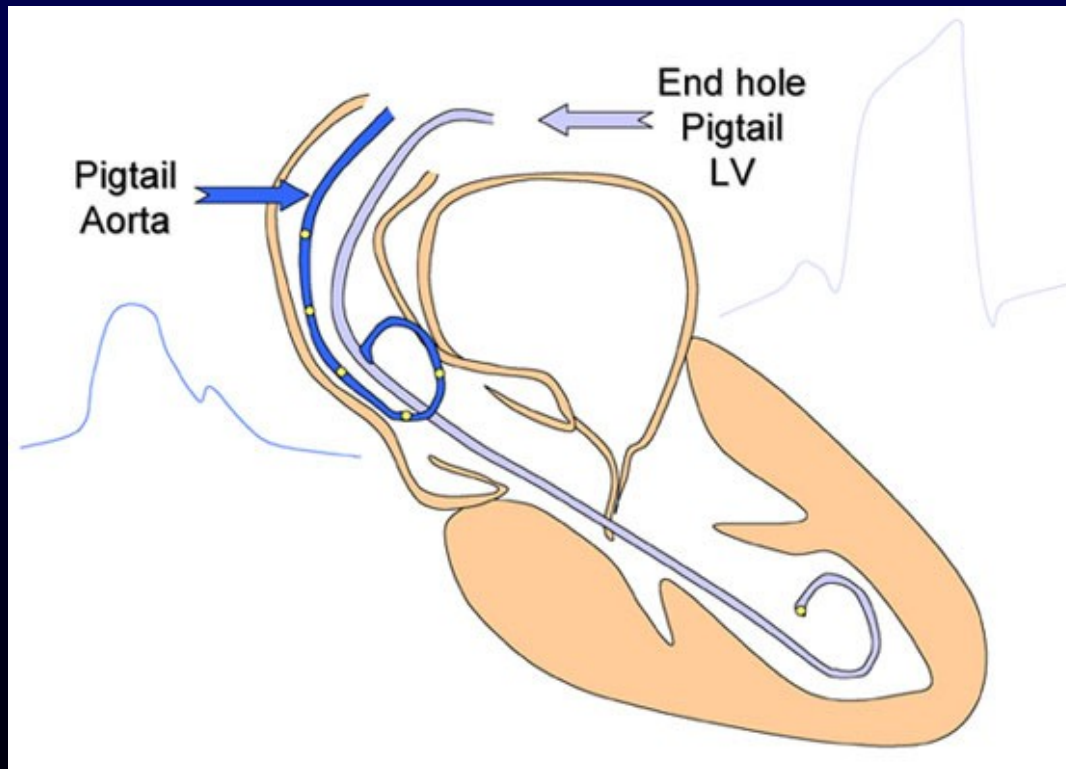
g = acceleration gravity constant

h = pressure gradient in cm H₂O

$$A = \frac{\text{Flow}}{C_c C_v \cdot \sqrt{2 g h}} = \frac{\text{Flow}}{C \cdot 44.3 \sqrt{h}}$$

Valve Stenoses

Two Catheter Technique



Valve Stenoses

Gorlin Formula Derivation

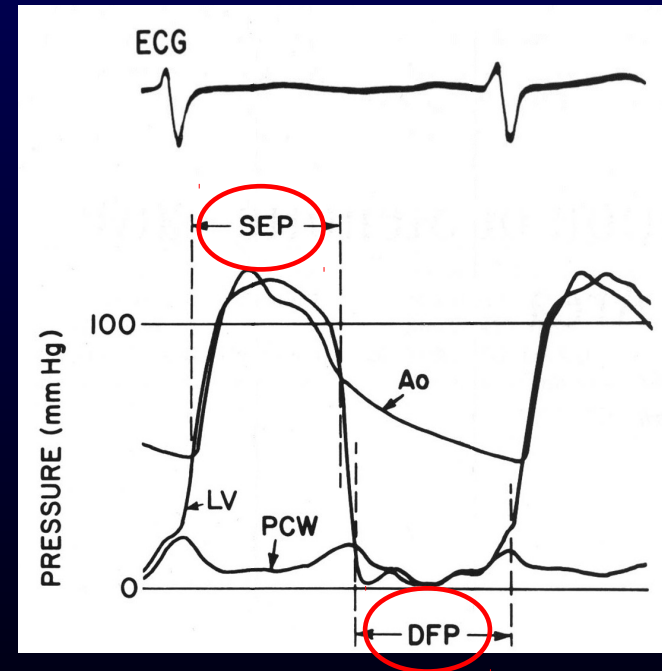
$$A = \frac{\text{Flow}}{C \cdot 44.3 \sqrt{h}}$$

Flow has to be corrected for the time during which there is cardiac output across the valve.

Aortic	}	Systolic Flow (SEP)
Pulmonic		
Tricuspid	}	Diastolic Flow (DFP)
Mitral		

Gorlin Formula:

$$A = \frac{CO / (\text{DFP or SEP}) \cdot HR}{C \cdot 44.3 \sqrt{\Delta P}}$$



Constant:

Aortic, Tricuspid, Pulmonic: $C = 1.0$

Mitral: $C = 0.85$

VSD, PDA: $C = 1.0$

Valve Stenoses

The “Quick Valve Area” Formula

Gorlin Formula:

$$A = \frac{CO / (DFP \text{ or } SEP) \cdot HR}{C \cdot 44.3 \sqrt{\Delta P}}$$

Quick Valve Area Formula (Hakki Formula):

Determine peak gradient across valve.

$$A = \frac{CO}{\sqrt{\text{Peak gradient}}}$$

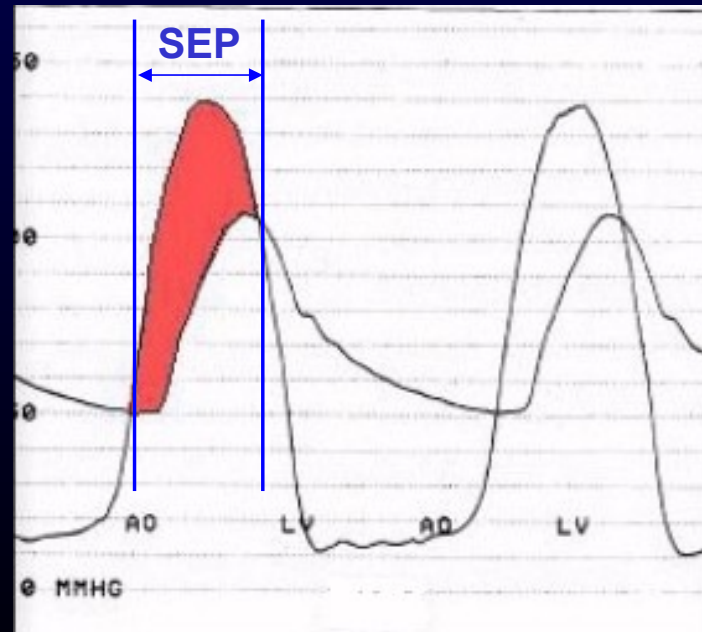
Aortic Valve Stenosis

Calculating Valve Area

Step 1: Planimeter area and calculate SEP

	Area of gradient (mm ²)	Length of SEP (mm)	Gradient Deflection (mm)
#1	_____	_____	_____
#2	_____	_____	_____
#3	_____	_____	_____
#4	_____	_____	_____
#5	_____	_____	_____

Average deflection = _____ mm



Aortic Valve Stenosis

Calculating Valve Area

Step 2: Calculate mean gradient

$$\text{Mean gradient (mm Hg)} = \text{Average deflection (mm deflection)} \times \text{Scale Factor (mm Hg / mm deflection)}$$

Step 3: Calculate average systolic period

$$\text{Average SEP (sec / beat)} = \frac{\text{Average SEP (mm)}}{\text{Paper speed (mm / sec)}}$$

Step 4: Calculate valve area

$$\text{Valve area (cm}^2\text{)} = \frac{\dot{Q} \text{ (cm}^3\text{ / min)} / [\text{Average SEP (sec / beat)} \times \text{HR (beat / min)}]}{44.3 \times \sqrt{\text{mean gradient}}}$$

Aortic Stenosis

Reference Values

Aortic valve area

Normal	3.0 cm²
Mild stenosis	> 1.0 cm²
Moderate stenosis	0.7 – 1.0 cm²
Moderate-severe stenosis	0.5 – 0.7 cm²
Severe stenosis	≤ 0.5 cm²

Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

Aortic Stenosis

Pitfalls in Gorlin Formula

- **Hydraulic principles**
 - Gorlin formula substitutes pressure for velocity
- Low cardiac output
- Mixed valvular disease
- Pullback hemodynamics
- Improper alignment

Aortic Stenosis

Pitfalls in Gorlin Formula

- Hydraulic principles
- **Low cardiac output**
 - Distinguish true anatomic stenosis from aortic psuedostenosis, a physiologic state in which there is insufficient flow through the valve secondary to decreased LV pressure (valve partially opens)
 - Nitroprusside or dobutamine to distinguish conditions
- Mixed valvular disease
- Pullback hemodynamics
- Improper alignment

Aortic Stenosis

Pitfalls in Gorlin Formula

- **75 consecutive patients with isolated AS**
- **Compare Gorlin AVA and continuity equation (Doppler) AVA**
- **Doppler AVA systematically larger than Gorlin AVA ($0.10 \pm 0.17 \text{ cm}^2$, $p < 0.0001$)**
- **AVA difference was accentuated at low flow states (cardiac index $< 2.5 \text{ L/min/m}^2$)**

Burwash JG, et al. Aortic valve discrepancy by Gorlin equation and Doppler echocardiography continuity equation: relationship to flow in patients with valvular AS. Can J of Cardiol 2000; 16: 985-92.

Aortic Stenosis

Gorlin Conundrum

Symptomatic low-gradient, low-output AS

- $AVA < 0.5 \text{ cm}^2$
- Mean gradient $\leq 30 \text{ mm Hg}$
- $LVEF \leq 0.45$

Fixed AS

Dobutamine induced increases in peak velocity, mean gradient, and valve resistance with no change in AVA

Relative AS

Dobutamine induced increases in AVA ($\geq 0.3 \text{ cm}^2$) without significant change in peak velocity, mean gradient, or valve resistance

No Contractile Reserve

Dobutamine induced no change in any hemodynamic variable

Aortic Stenosis

Gorlin Conundrum

- 32 patients with low-output, low-gradient AS and an EF < 40% received dobutamine infusion in cath lab
- Dobutamine continued until:
 - Peak dose 40 ug/kg/min
 - Mean gradient > 40 mm Hg
 - HR > 140
 - 50% increase in CO
- 21 patients had AVR at discretion of MD
- All patients with final AVR $\leq 1.2 \text{ cm}^2$ at peak dobutamine infusion and a mean gradient > 30 mm Hg were found to have severe AS at time of surgery
- 15 patients showed contractile reserve (SV > 20%), 1 died perioperatively and 12 were alive in Class I or II at median 32 month follow-up

Nishimura R et al. Circulation 2009; 119: 1166-77

Aortic Stenosis

Low-Flow, Low-Gradient AS

- **Low-Gradient**
 - Mean gradient < 30 mm Hg
 - AVA < 1.0 cm²
- **Low-Flow**
 - Diminished forward stroke volume
 - Not necessarily diminished LVEF

Aortic Stenosis

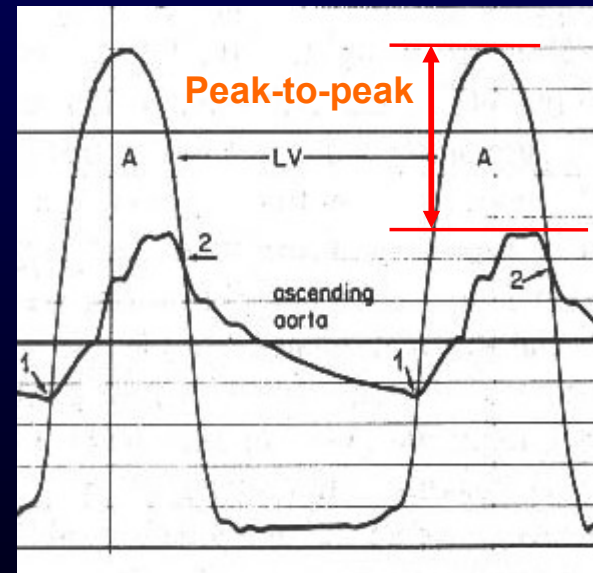
Pitfalls in Gorlin Formula

- Hydraulic principles
- Low cardiac output
- **Mixed valvular disease**
 - AS & AI: CO underestimates transvalvular flow
→ Gorlin underestimates AVA
 - AS & MR: CO overestimates forward stroke volume
→ Gorlin overestimates AVA
- Pullback hemodynamics
- Improper alignment

Aortic Stenosis

Pitfalls in Gorlin Formula

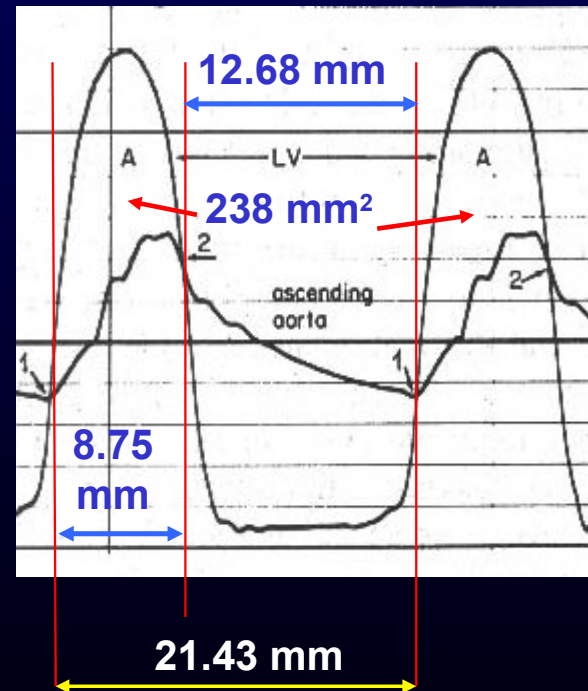
- Hydraulic principles
- Low cardiac output
- **Pullback hemodynamics**
 - Peak-to-peak gradient larger than mean gradient
 - Large (≥ 7 Fr) catheter may obstruct lumen and overestimate severity
 - Pullback of catheter may reduce severity
 - Augmentation in peripheral systolic pressure by > 5 mm Hg during pullback \rightarrow $AVA \leq 0.5 \text{ cm}^2$
- Improper alignment



Aortic Stenosis

Test Question

- Right heart catheterization
 - RA (a, v, mean): 7, 6, 5
 - RV: 25 / 5
 - PA: 25 / 11, mean 15; Sat = 76%
 - PCW (a, v, mean): 12, 11, 10
- Left heart catheterization
 - LV: 176 / 16; Sat = 96%
 - Ao: 100 / 66, mean 84; Sat = 96%
- O₂ consumption: 225 mL/min
- BSA = 1.87 m²
- Hgb = 14.7 g/dL
- Pulse = 70 bpm
- LVEF = 69%

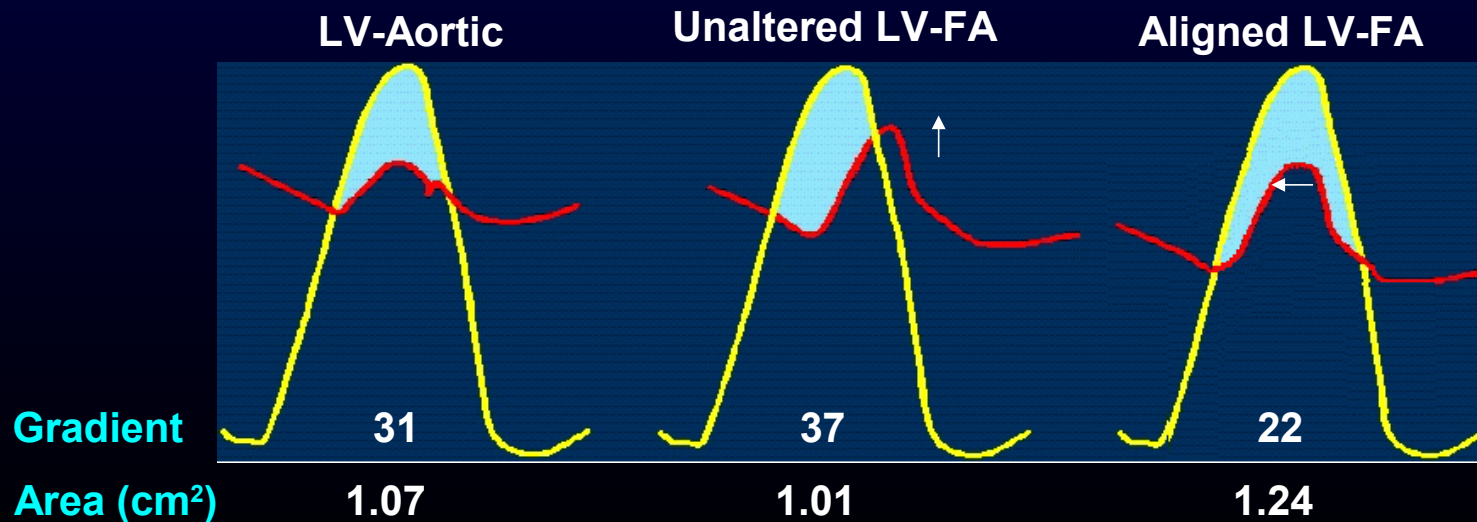


- Paper speed = 25 mm/sec
- Paper scale = 20 mm Hg / 10 mm Hg

Aortic Stenosis

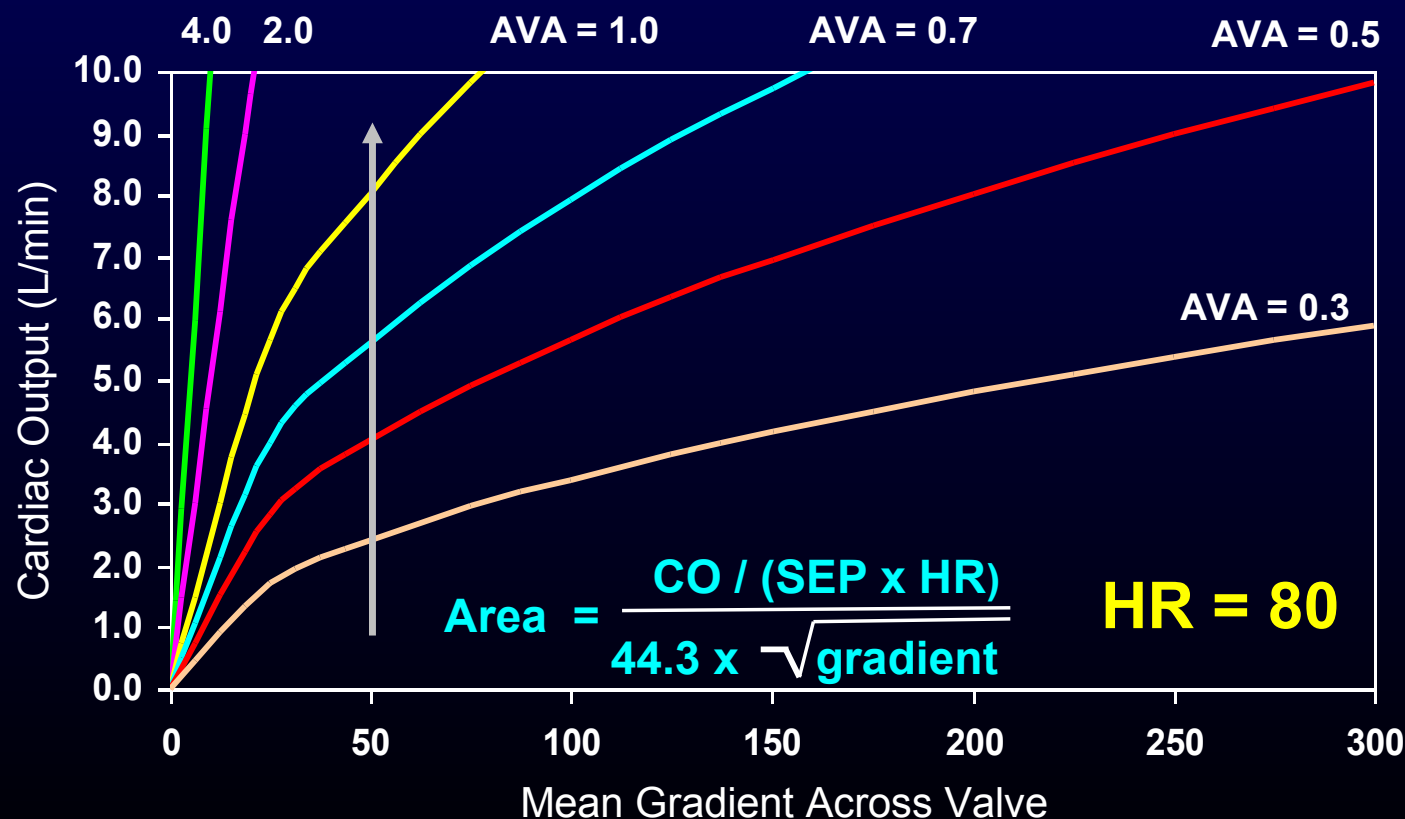
Pitfalls in Gorlin Formula

- Hydraulic principles
- Low cardiac output
- Pullback hemodynamics
- **Improper alignment**

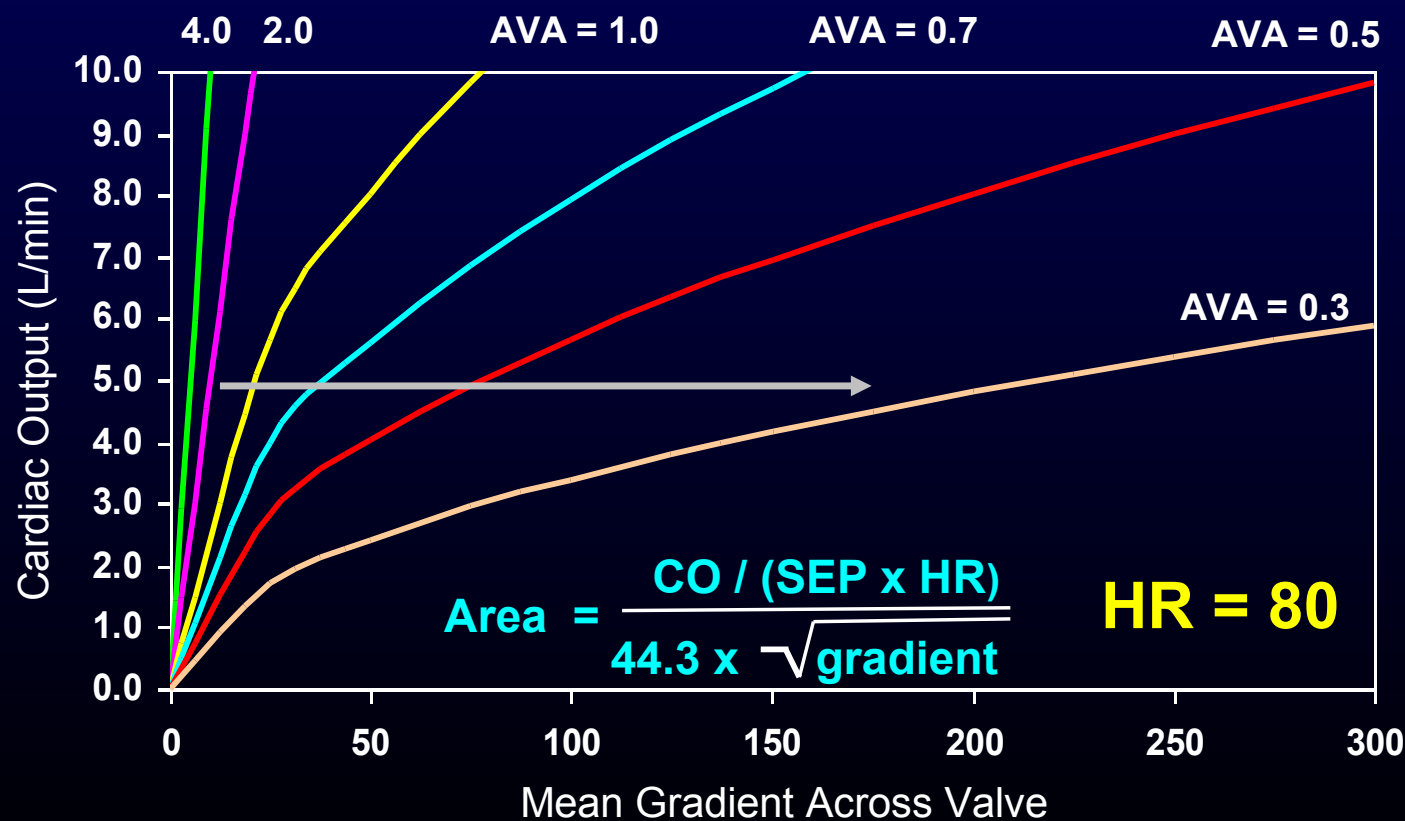


Aortic Stenosis

Increasing Cardiac Output

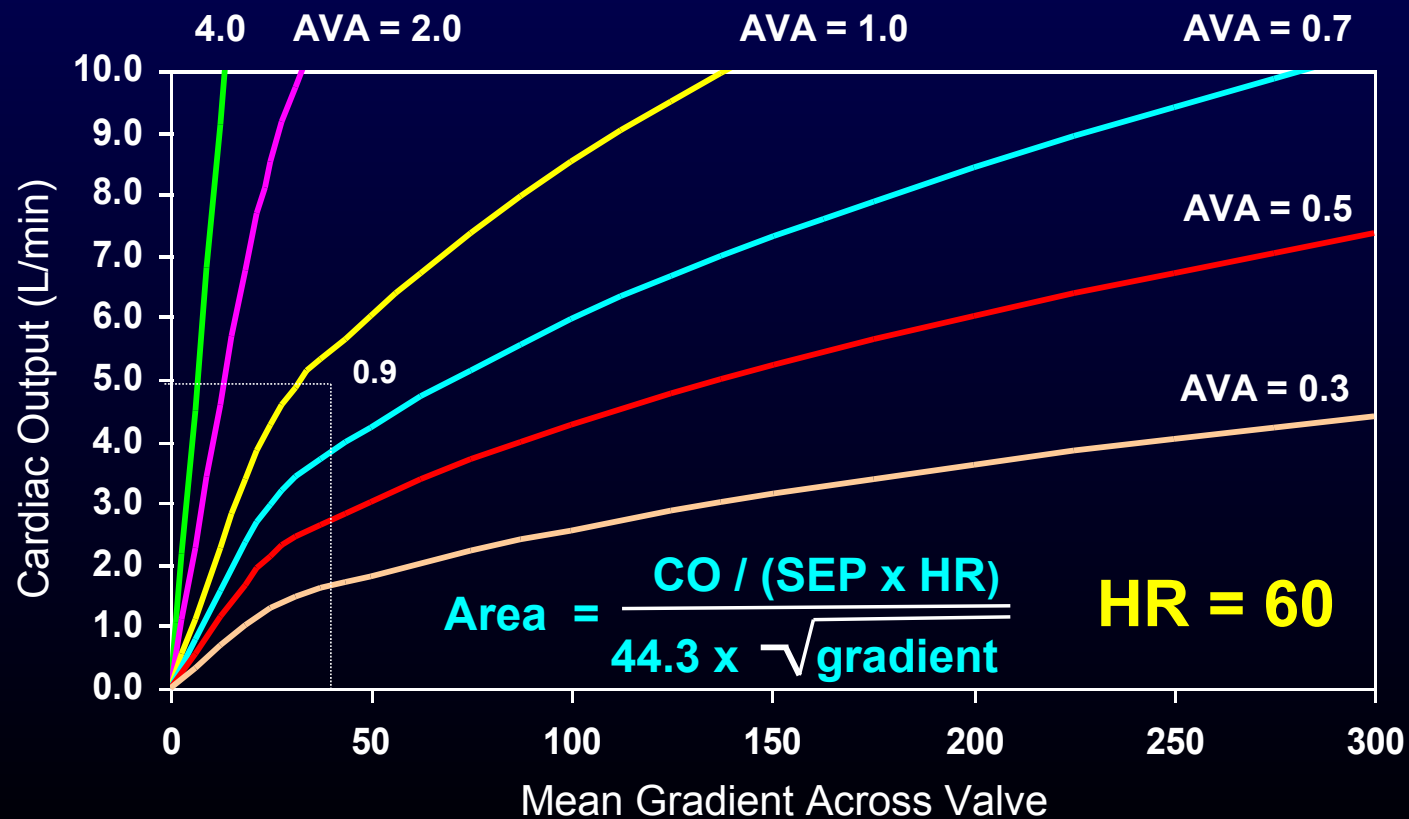


Aortic Stenosis Increasing Gradient



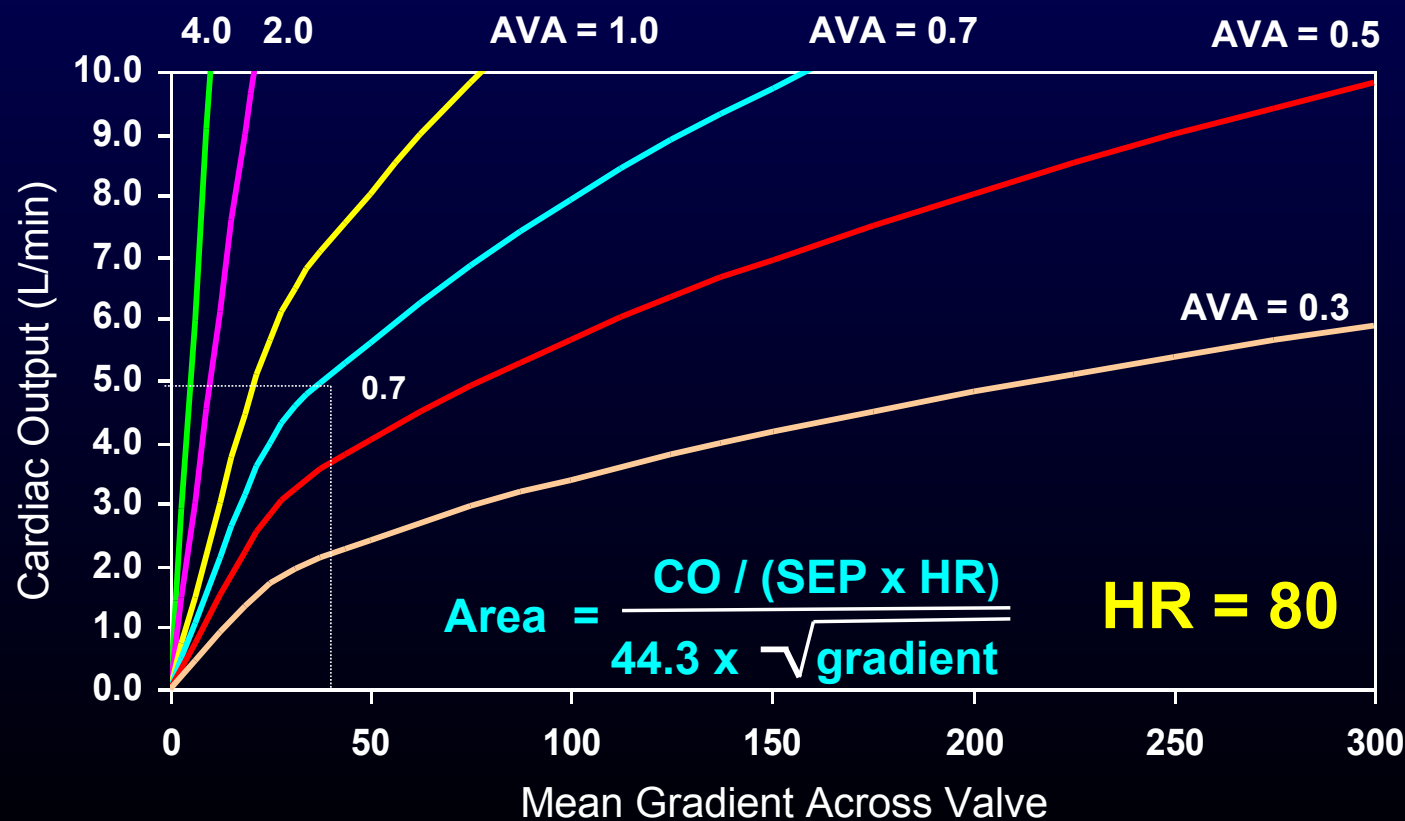
Aortic Stenosis

Increasing Pulse



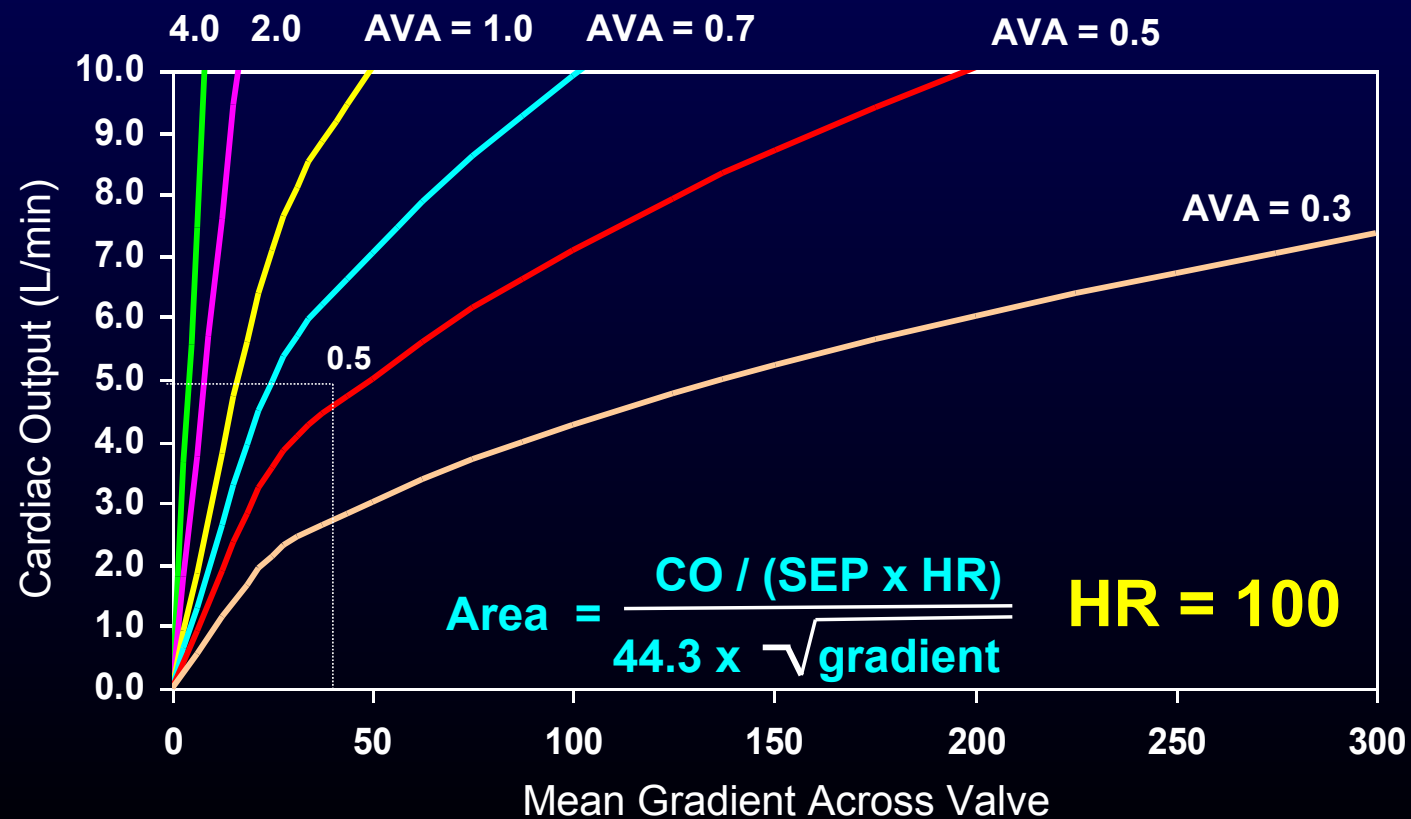
Aortic Stenosis

Increasing Pulse



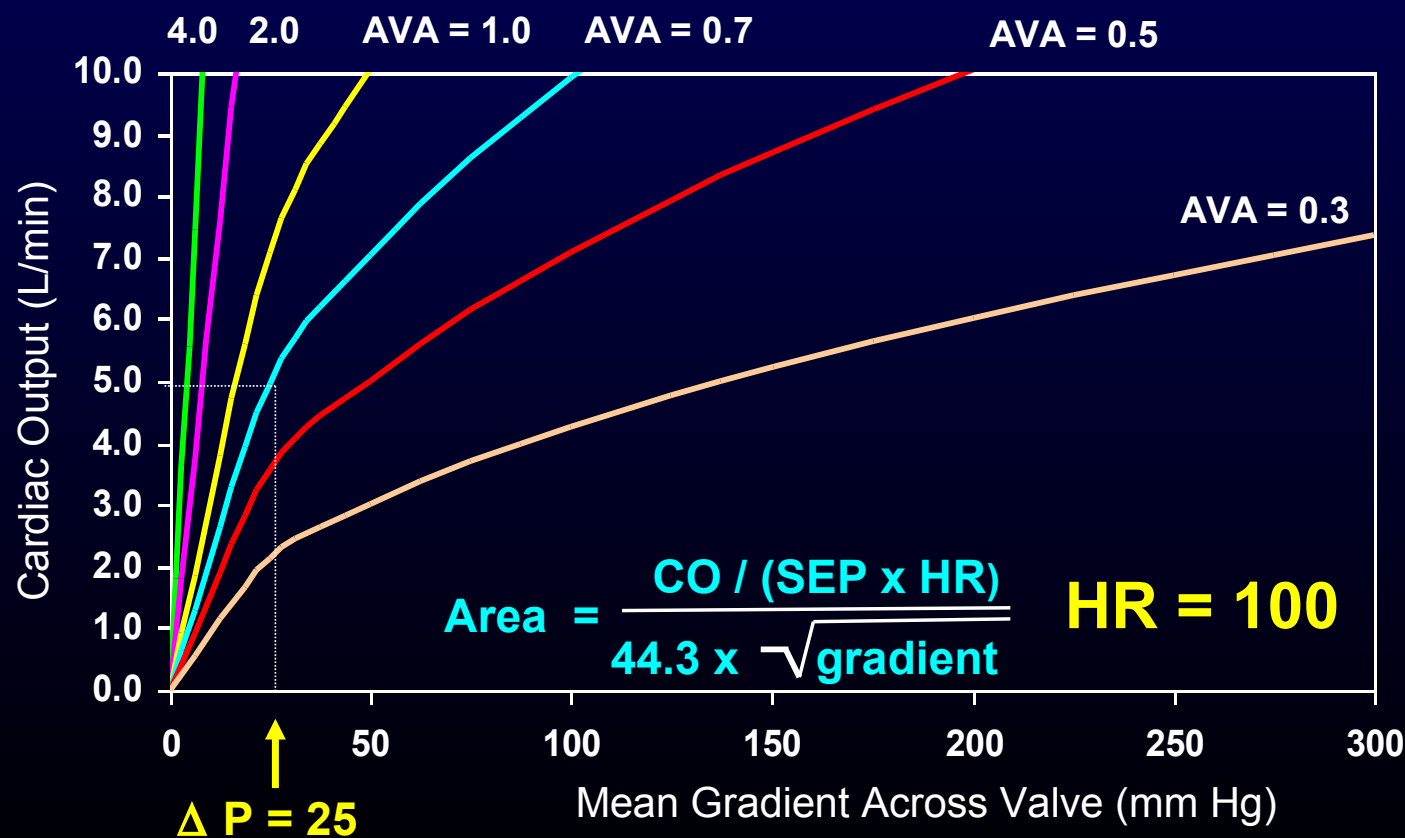
Aortic Stenosis

Increasing Pulse



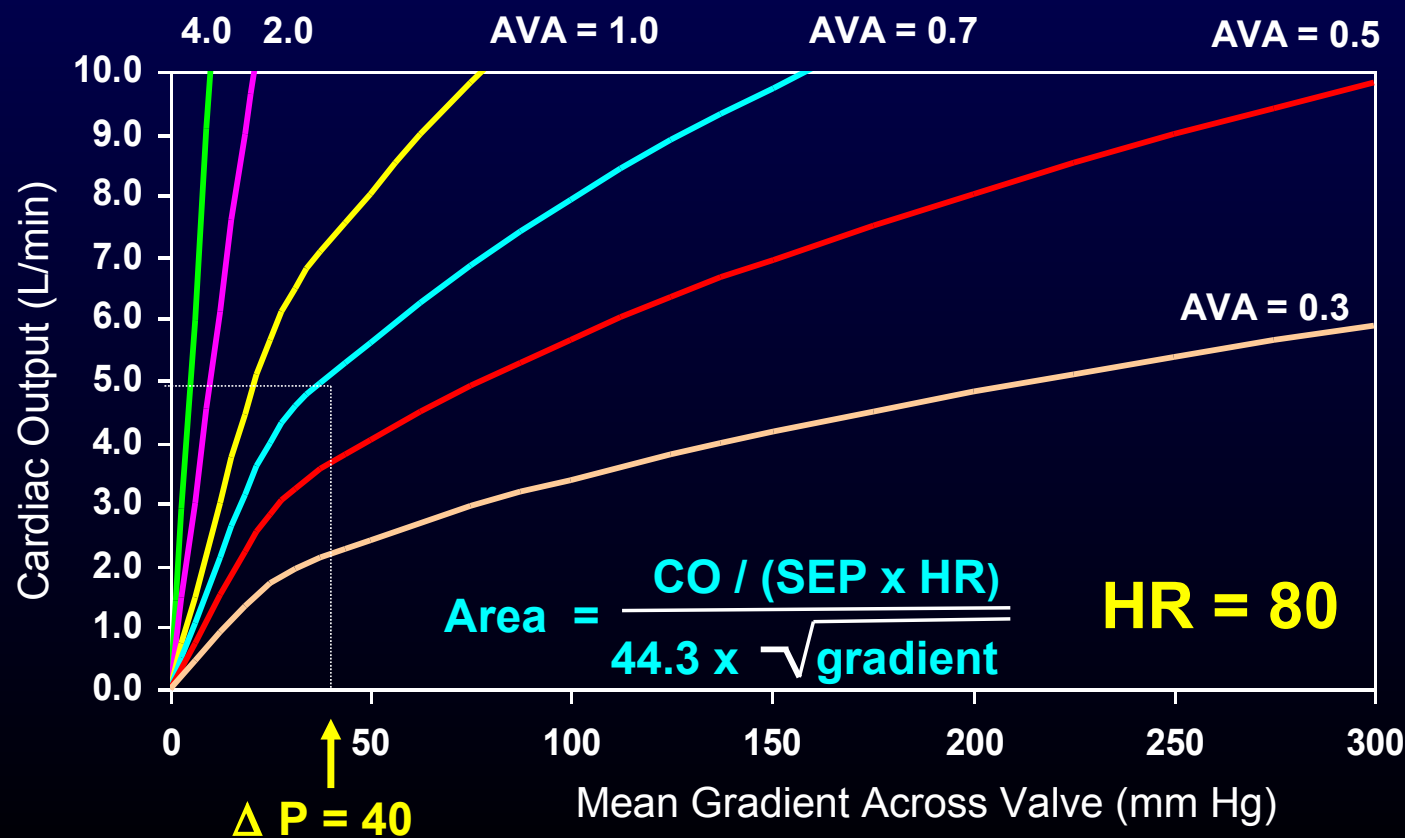
Aortic Stenosis

Impact of Bradycardia on Fixed Stenosis



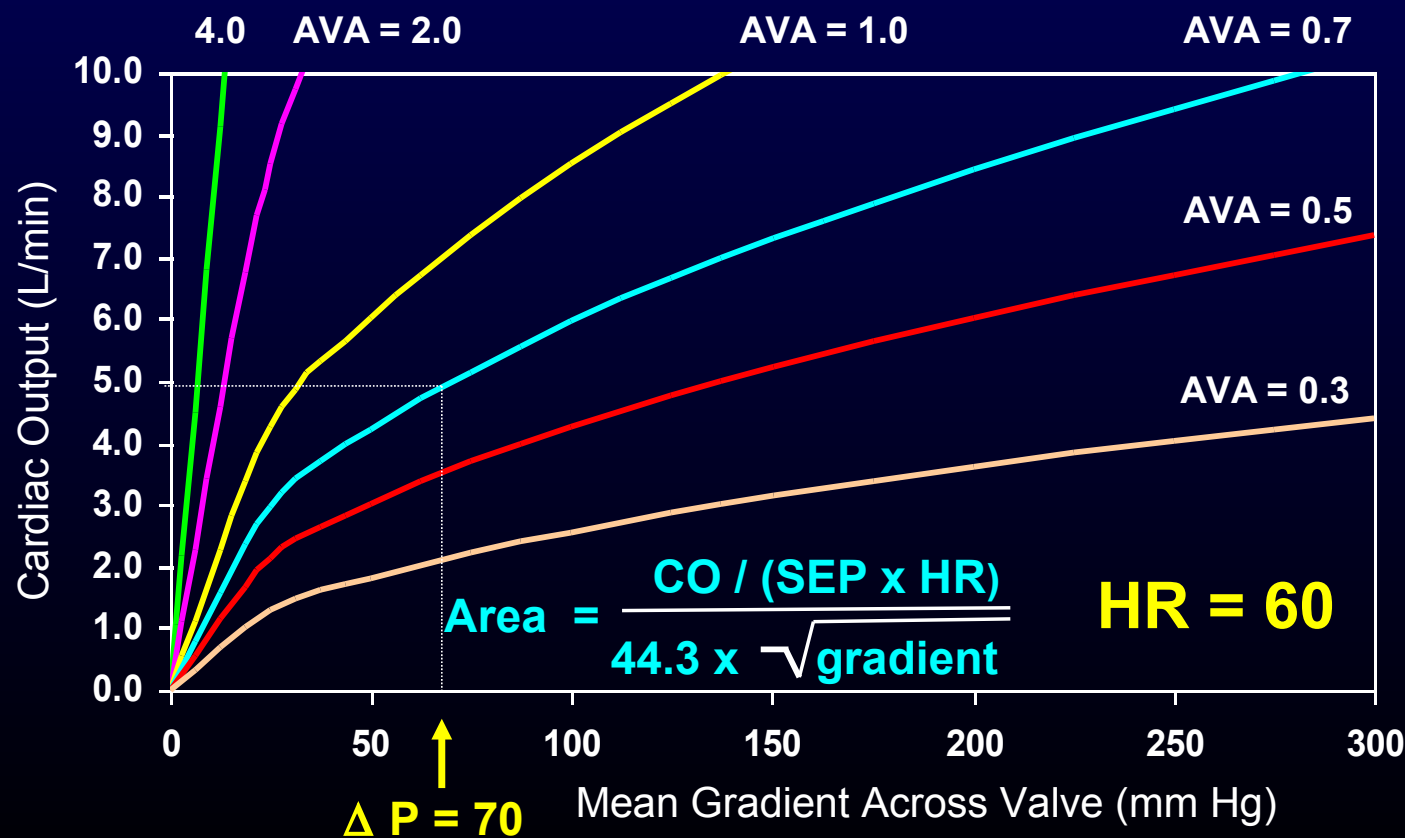
Aortic Stenosis

Impact of Bradycardia on Fixed Stenosis



Aortic Stenosis

Impact of Bradycardia on Fixed Stenosis

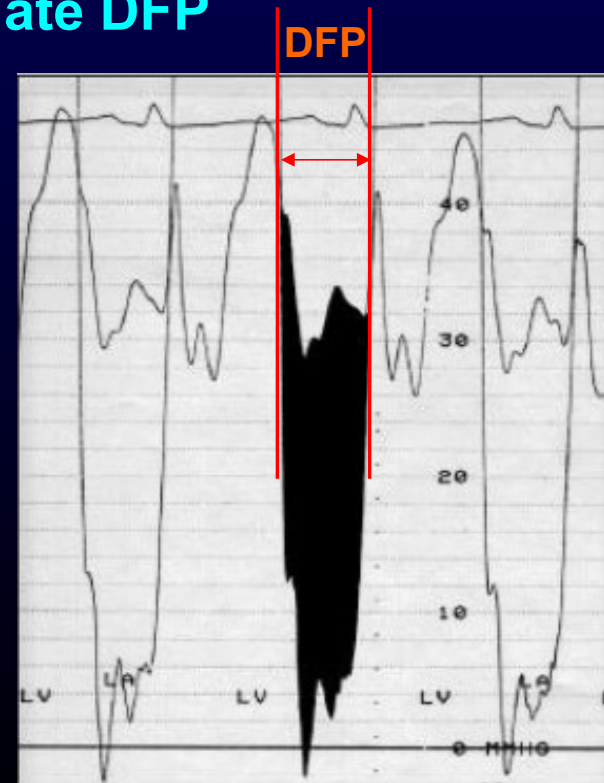


Mitral Stenosis

Calculating Valve Area

Step 1: Planimeter area and calculate DFP

	Area of gradient (mm ²)	DFP (mm)	Gradient Deflection (mm)
#1	_____	_____	_____
#2	_____	_____	_____
#3	_____	_____	_____
#4	_____	_____	_____
#5	_____	_____	_____
Average gradient = _____ mm			



Mitral Stenosis

Calculating Valve Area

Step 2: Calculate mean gradient

$$\text{Mean gradient (mm Hg)} = \text{Average deflection (mm deflection)} \times \text{Scale Factor (mm Hg / mm deflection)}$$

Step 3: Calculate average systolic period

$$\text{Average SEP (sec / beat)} = \frac{\text{Average DFP (mm)}}{\text{Paper speed (mm / sec)}}$$

Step 4: Calculate valve area

$$\text{Valve area (cm}^2\text{)} = \frac{\dot{Q} \text{ (cm}^3\text{ / min)} / [\text{Average DFP (sec / beat)} \times \text{HR (beat / min)}]}{37.7 \times \sqrt{\text{mean gradient}}}$$

Mitral Stenosis

Reference Values

Mitral valve area

Normal	4.0 – 6.0 cm ²
Mild stenosis	> 2.0 cm ²
Moderate stenosis	1.0 – 2.0 cm ²
Severe stenosis	< 1.0 cm ²

Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.

Mitral Stenosis

Pitfalls in Gorlin Formula

- **Pulmonary capillary wedge tracing**
 - Mean PCWP < mean PAP
 - PCW O₂ sat > 95% or > Art O₂ sat
- Alignment mismatch
- Calibration errors
- Cardiac output determination
- Early diastasis

Mitral Stenosis

Pitfalls in Gorlin Formula

- Pulmonary capillary wedge tracing
- **Alignment mismatch**
 - LV & PCW traces do not match LV & LA traces because transmission of LA pressure back thru PV and capillary bed delayed 50-70 msec
 - Realign tracings
 - Shift PCW tracing leftward by 50-70 msec
 - V wave should peak immediately before LV downslope
- Calibration errors
- Cardiac output determination
- Early diastasis

Mitral Stenosis

Pitfalls in Gorlin Formula

- Pulmonary capillary wedge tracing
- Alignment mismatch
- **Calibration errors**
 - Errors in calibration and zero
 - Quick check: switch transducers between catheters and see if gradient identical
- Cardiac output determination
- Early diastasis

Mitral Stenosis

Pitfalls in Gorlin Formula

- Pulmonary capillary wedge tracing
- Alignment mismatch
- Calibration errors
- **Cardiac output determination**
 - Measure CO at same time gradient measured
 - Fick and thermodilution measure “forward” flow but Gorlin formula relies on total flow (antegrade and retrograde) across valve
 - In setting of MR, Gorlin formula will underestimate actual anatomic stenosis
- Early diastasis

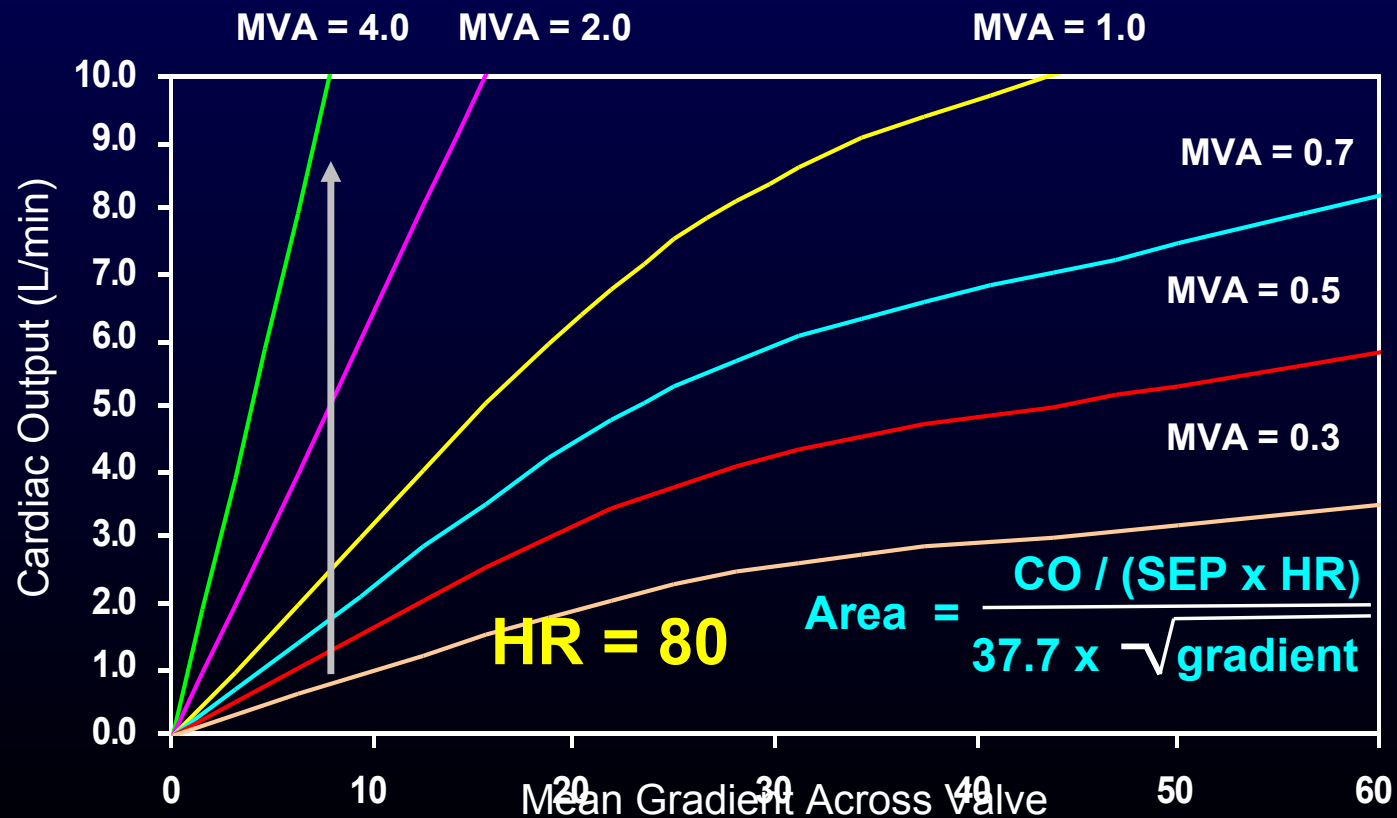
Mitral Stenosis

Pitfalls in Gorlin Formula

- Pulmonary capillary wedge tracing
- Alignment mismatch
- Calibration errors
- Cardiac output determination
- **Early diastasis**
 - If PCWP and LV diastolic pressures equalize early, the “gradient” will appear to disappear early in diastole. The diastolic filling period (DFP) used in the calculation should include all of the nonisovolumic diastole.

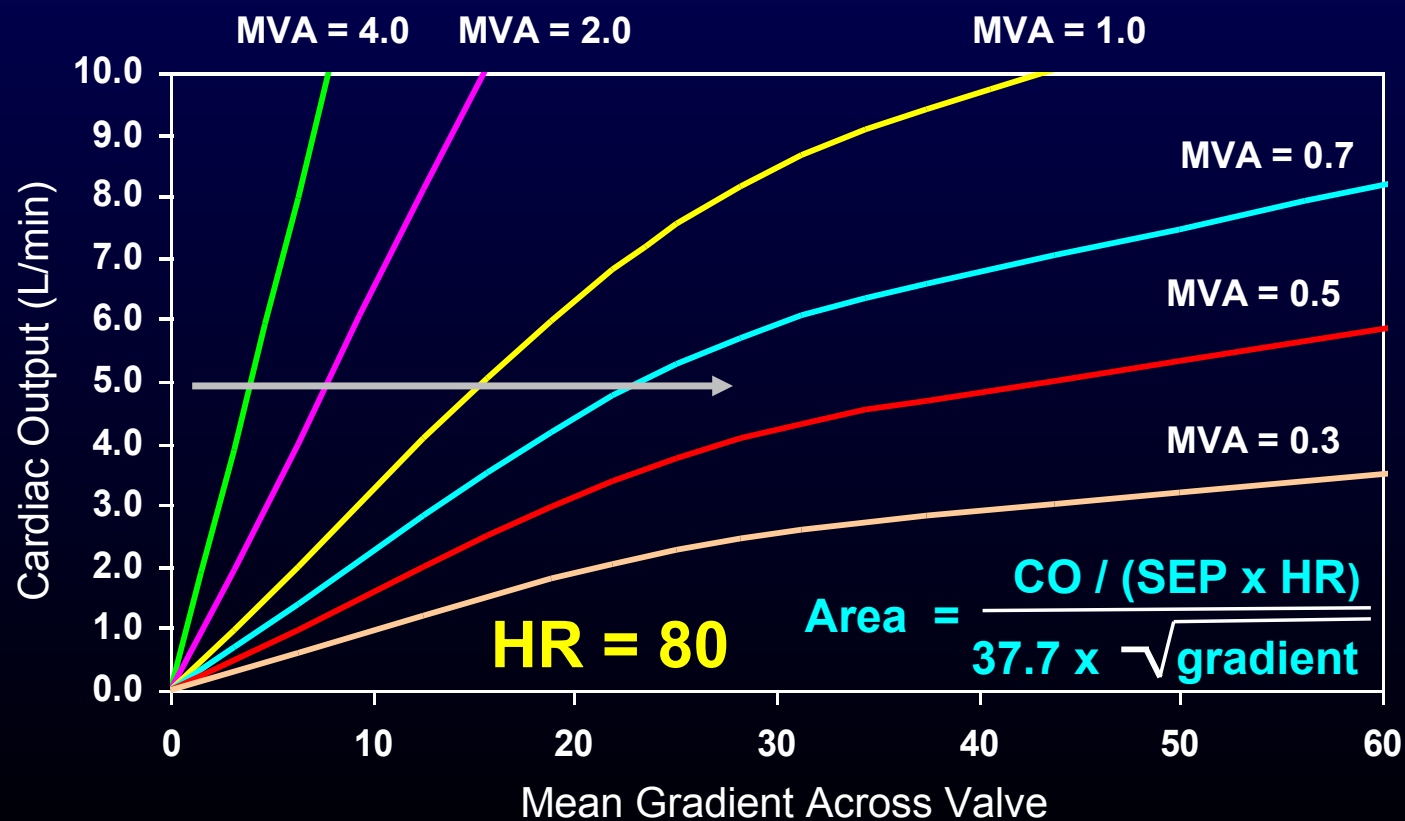
Mitral Stenosis

Increasing Cardiac Output



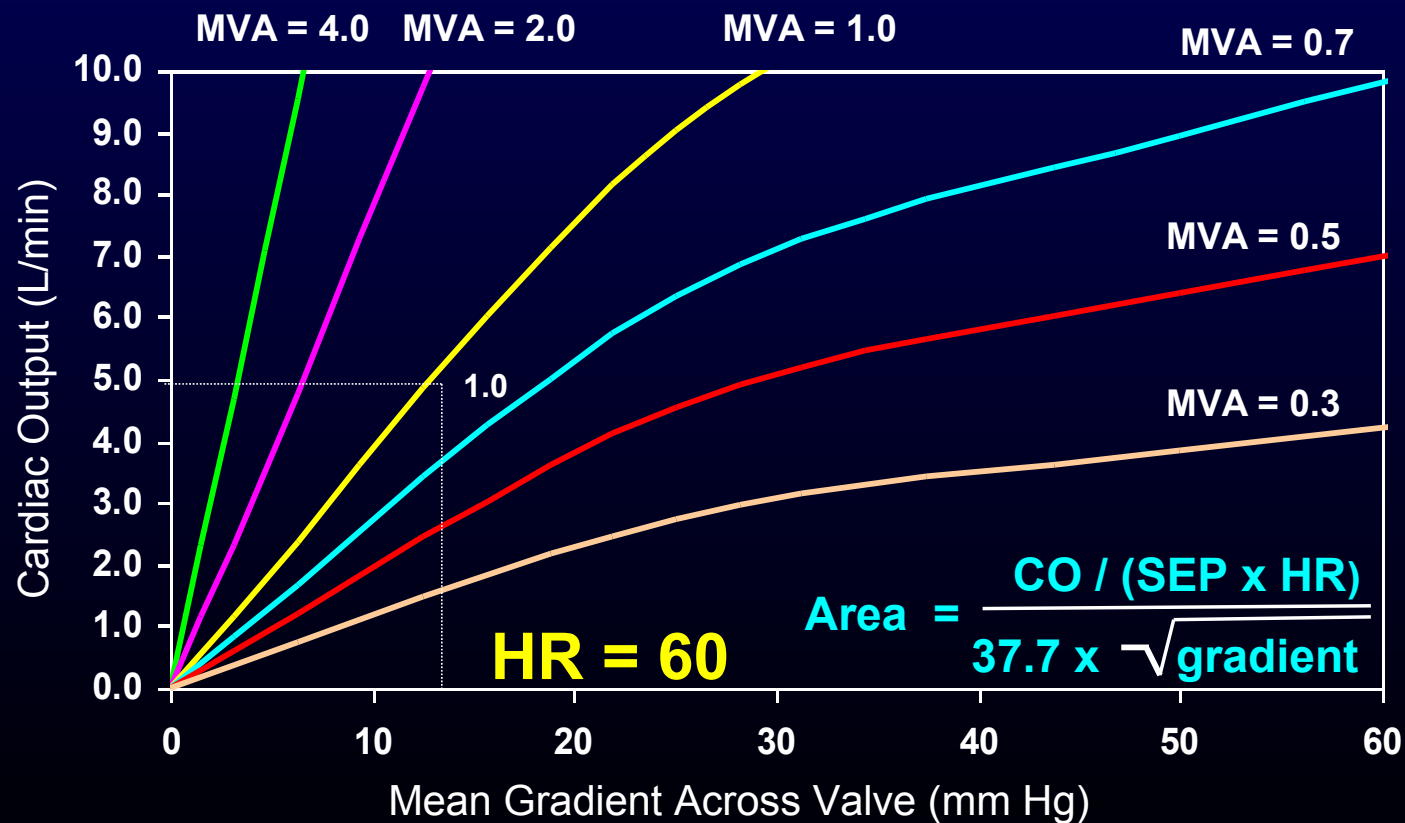
Mitral Stenosis

Increasing Mean Gradient



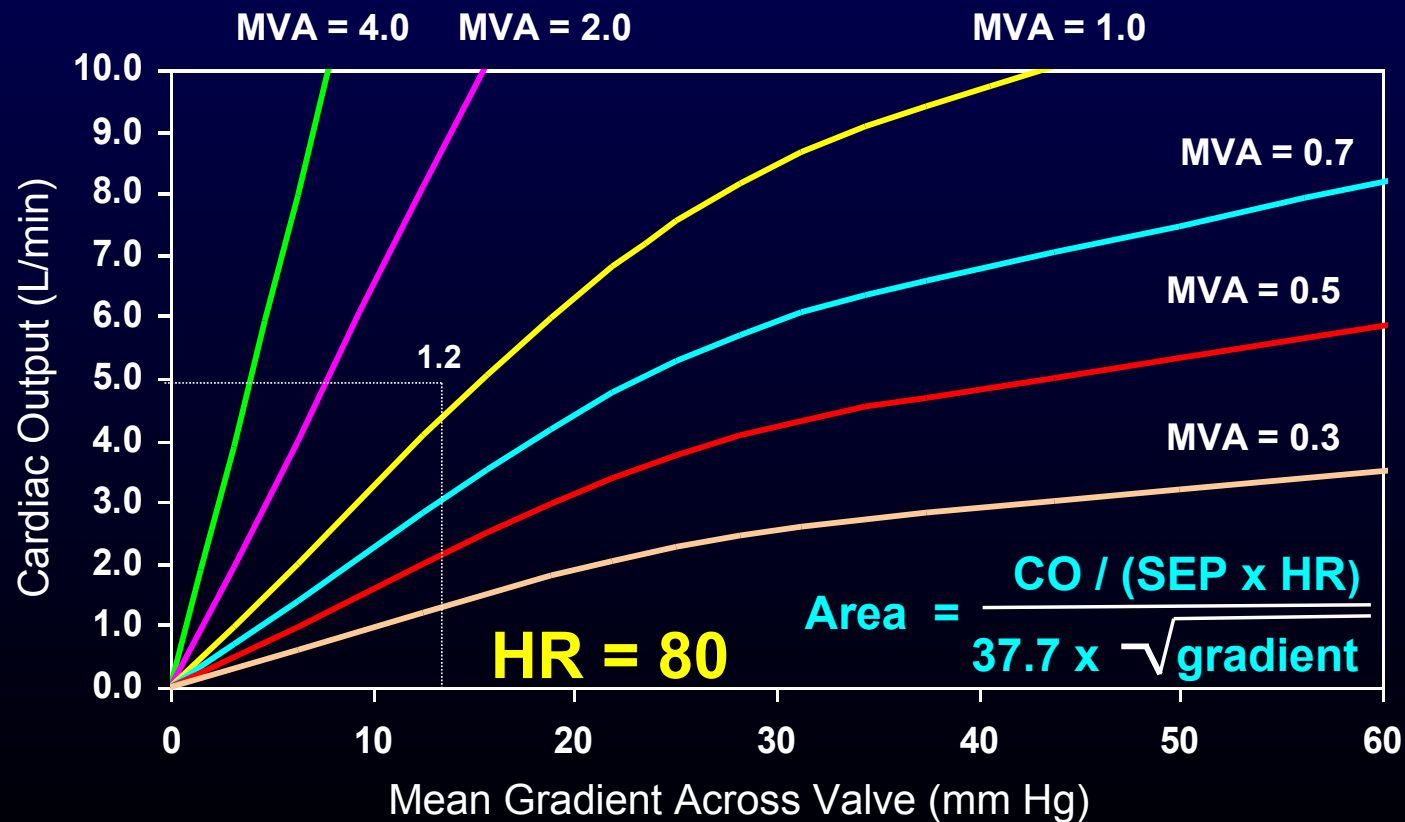
Mitral Stenosis

Increasing Pulse



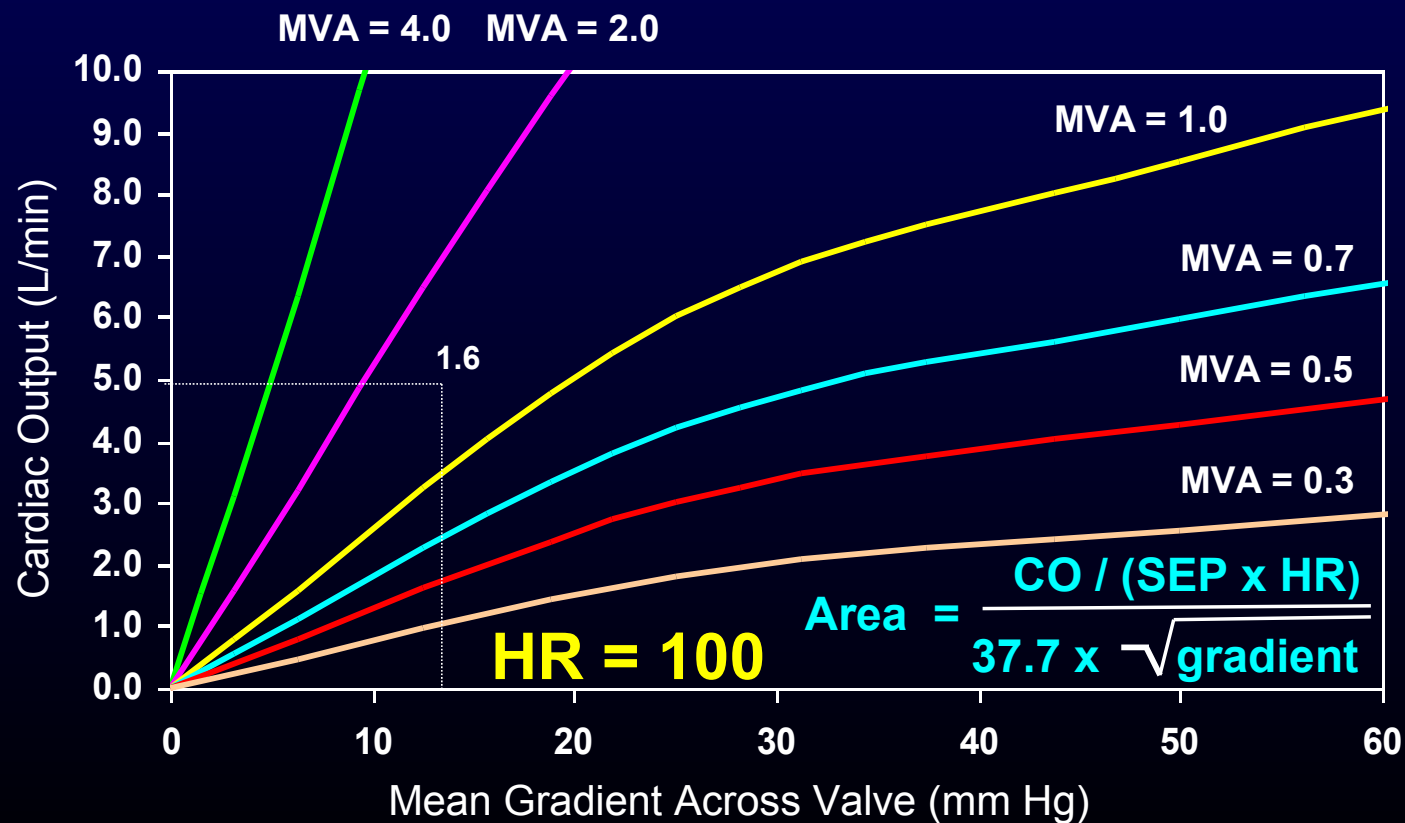
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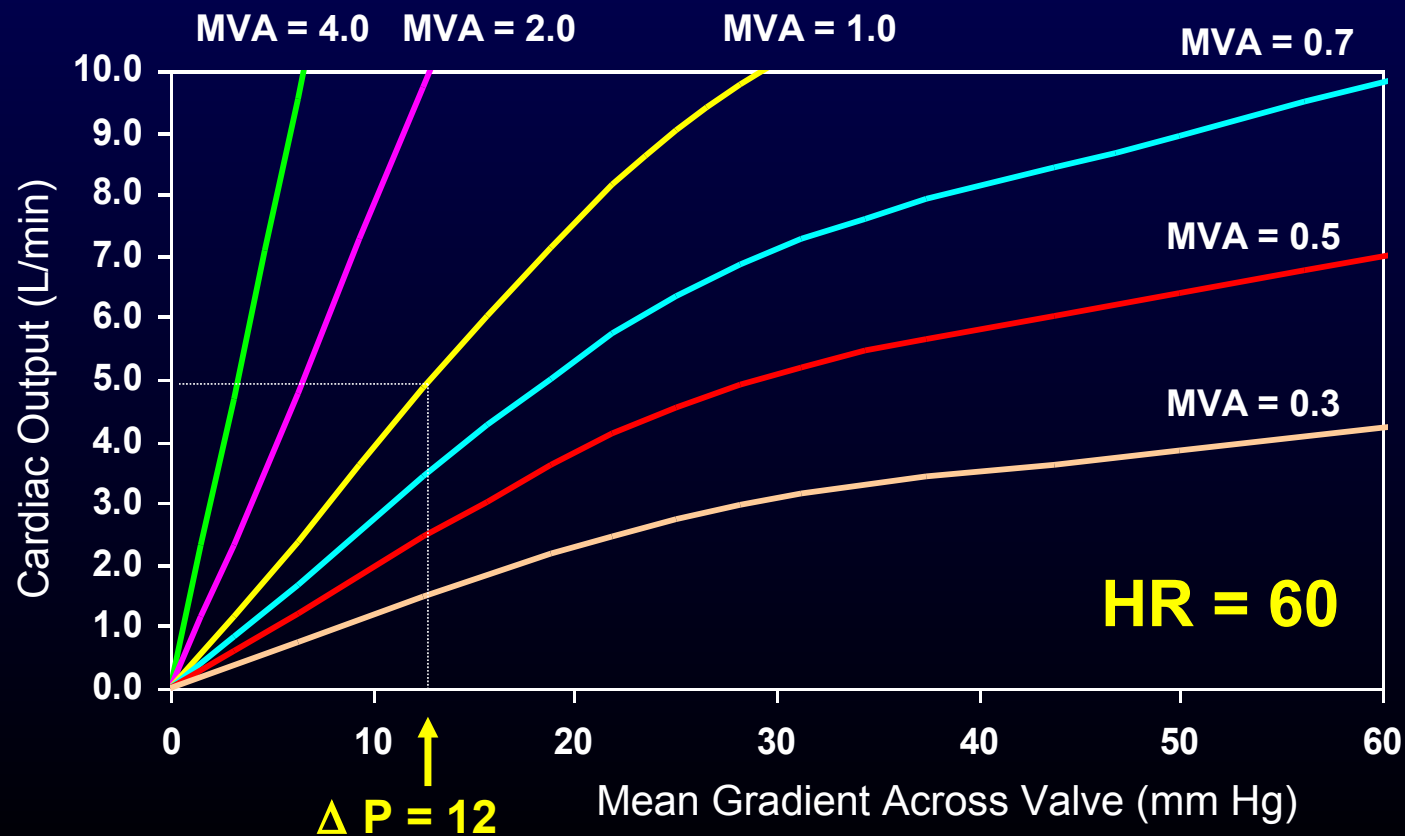
Mitral Stenosis

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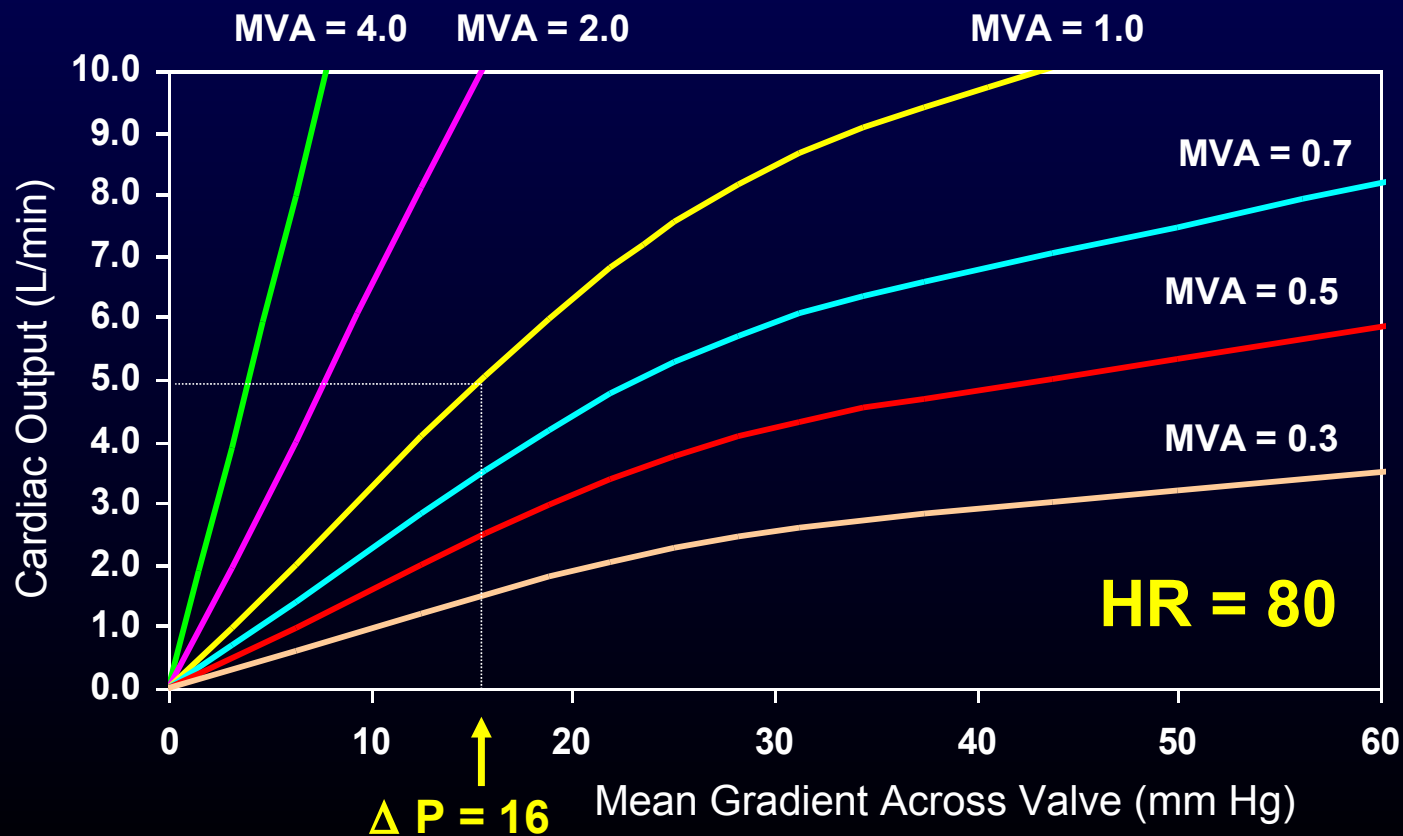
Mitral Stenosis

Impact of Tachycardia on Fixed Stenosis



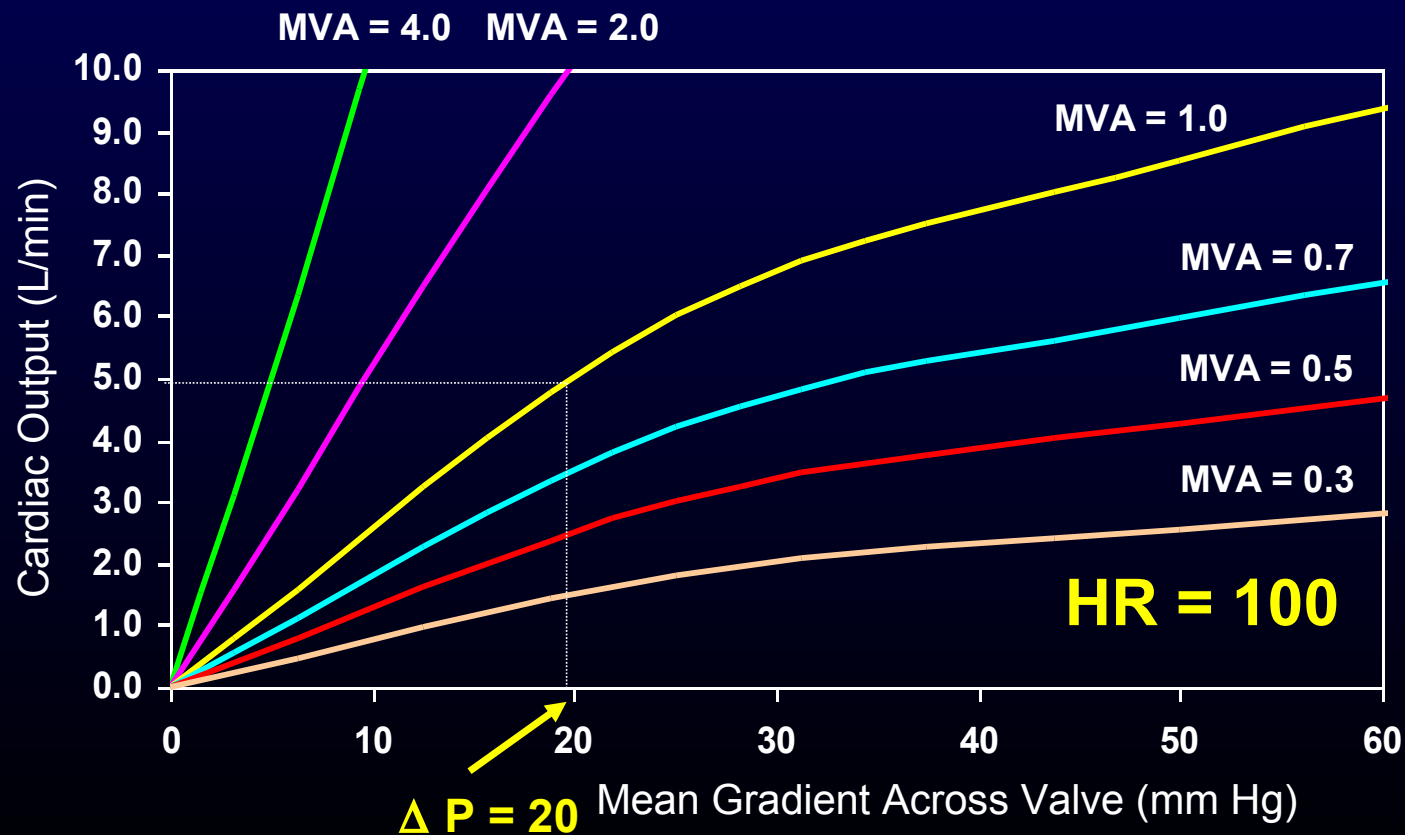
Mitral Stenosis

Impact of Tachycardia on Fixed Stenosis



Mitral Stenosis

Impact of Tachycardia on Fixed Stenosis



Hemodynamic Principles

1. A 71 yo woman is referred for cardiac catheterization to evaluate her aortic valve. She complains of progressive DOE but denies chest pain. She has a history of 2 prior MIs and has inferior Q-waves on her ECG. A murmur of aortic stenosis was first noted about 14 years ago, and 3 years ago a soft diastolic murmur consistent with aortic insufficiency was detected. Her echo shows moderate LV enlargement with inferior akinesis and decreased LV function. By echo the aortic valve gradient is 20 mmHg, and the valve area is calculated to be 1.3 cm². She has mild to moderate aortic regurgitation and no mitral regurgitation by echo. Because her referring physician is concerned about the severity of her aortic valve disease as a potential cause for her symptoms and left ventricular dysfunction, she is referred for cardiac catheterization. During the catheterization, her cardiac output measured by the Fick method is 5.0 L/min and her mean aortic valve gradient is 16 mmHg. Biplane left ventriculography and coronary angiography are performed.

Hemodynamic Principles

1. Which of the following is the most appropriate step in the analysis of these hemodynamic data?
 - A. The Gorlin formula should not be used to calculate valve area because it is less accurate when a low gradient is present.
 - B. Using the Fick cardiac output in the Gorlin formula will overestimate her actual valve area.
 - C. She should receive a dobutamine infusion and then recalculate the valve area with the new hemodynamics.
 - D. The Gorlin formula can be used to calculate her aortic valve area, but the angiographic output determined from the left ventriculogram should be used.
 - E. The correct valve area is calculated using the Gorlin formula and the difference between the angiographic output and forward output.



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Hemodynamic Principles

2. A patient with hypertrophic obstructive cardiomyopathy has a premature ventricular contraction during cardiac catheterization. Which one of the following responses would be seen on the beat after the premature ventricular contraction which would not be seen in a patient with valvular aortic stenosis?
- A. An increase in the peak-to-peak gradient between the aorta and left ventricle.
 - B. An increase in the maximum instantaneous gradient between the aorta and left ventricle.
 - C. A decrease in the pulse pressure of the aortic pressure.
 - D. An increase in the left ventricular systolic pressure.
 - E. An increase in the aortic systolic pressure.



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Hemodynamic Principles

3. In patients in whom low cardiac output and low ejection fraction are associated with aortic stenosis, which calculation provides the strongest confirmation of fixed valvular obstruction?
- A. Aortic valve area, Gorlin formula.
 - B. Planimetry of orifice area.
 - C. Aortic valve resistance.
 - D. Peak-to-peak left-ventricular-to-aortic gradient.
 - E. Aortic valve area, Hakki formula.



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 - C. Aortic valve resistance ($\text{Mean gradient} / \text{CO}$) > 250**
 - D. Peak-to-peak left-ventricular-to-aortic gradient.
 - E. Aortic valve area, Hakki formula.

Hemodynamic Principles

4. To secure the diagnosis of aortic stenosis, what is the best technique to obtain the most accurate hemodynamic data?
- A. Left ventricular and femoral artery pressures.
 - B. Left ventricular and ascending aortic pressures.
 - C. Aortic and left atrial pressures.
 - D. Left ventricular pressure at the apex and left ventricular pressure at the outflow tract.
 - E. Left ventricular and right ventricular pressures.



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Hemodynamic Principles

5. A 78-year-old woman has increasing shortness of breath, DOE, and mild pedal edema. Physical examination demonstrates irregular pulse with moderate neck vein distension, a diastolic murmur over the left sternal border radiating to the apex, a brief systolic murmur at the apex, a quiet left precordium, and +1 pitting edema. Echocardiography suggests restricted transmitral flow and marked mitral annular calcification with a nondilated ventricle. Which of the following data sets most accurately characterizes the hemodynamics of this patient's mitral valve disease?
- A. RA pressure = 10 mmHg; RV pressure = 60/12 mmHg; PA pressure = 30/16 mmHg; LVEDP = 16 mmHg.
 - B. RA pressure = 5 mmHg; RV pressure = 30/6 mmHg; PA pressure = 30/12 mmHg; LVEDP = 6 mmHg.
 - C. RA pressure = 15 mmHg; RV pressure = 80/16 mmHg; PA pressure = 80/40 mmHg; LVEDP = 18 mmHg.
 - D. RA pressure = 20 mmHg; RV pressure = 36/20 mmHg; PA pressure = 36/20 mmHg; LVEDP = 20 mmHg.
 - E. RA pressure = 5 mmHg; RV pressure = 60/6 mmHg; PA pressure = 20/10 mmHg; LVEDP = 10 mmHg.



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 - E. RA pressure = 5 mmHg; RV pressure = 60/6 mmHg; PA pressure = 20/10 mmHg; LVEDP = 10 mmHg.

Hemodynamic Principles

6. Excluding coronary artery disease, which of the following additional conditions may be present and obscure the presumptive diagnosis of aortic stenosis?
- A. Mitral regurgitation.
 - B. Mitral stenosis.
 - C. Bilateral iliac stenoses.
 - D. Right ventricular pressure overload.
 - E. Hypertrophic obstructive cardiomyopathy.



Hemodynamic Principles

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Hemodynamic Principles

7. A symptomatic 35-year-old woman with congenital aortic stenosis undergoes echocardiography and cardiac catheterization. Her echocardiogram shows an aortic valve gradient of 54 mmHg. However, at catheterization the mean gradient recorded by simultaneous pressures is only 25 mmHg. Which of the following is not an explanation for the discrepancy between the gradient values?
- A. A femoral artery pressure was used instead of a central aortic pressure during the catheterization.
 - B. The physiological recorder's internal calibration was used to standardize the pressure transducers.
 - C. The left ventricular catheter was positioned in the left ventricular outflow tract.
 - D. There was a difference in physiologic conditions during the two determinations.
 - E. Echocardiography is inaccurate in estimating aortic valve gradients at high flow.



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Hemodynamic Principles

8. Carabello's sign refers to:

- A. The reduced peripheral arterial pressure compared to the LV systolic pressure
- B. An increment of 5 mm Hg or more in the peripheral pressure associated with the pullback of catheter from LV into aorta
- C. A narrowing of the pulse pressure observed with simultaneous LV and Ao tracings following a PVC
- D. The change in pulse pressure observed in patients with aortic stenosis during inspiration



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Hemodynamic Principles

9. A patient with aortic stenosis is referred to you for a second opinion to see if aortic valve replacement is warranted. Specifically, you must compare the risk of the operation with the potential benefit.
- A. A 68 year old patient with CHF, LVEF=20%, an AVA of 0.6 cm², an mean transvalvular gradient of 60 mm Hg.
 - B. A 67 year old patient with CHF, LVEF=20%, an AVA of 0.6 cm², an mean transvalvular gradient of 25 mm Hg in whom dobutamine doubles his CO and increases the valve gradient such that the calculated AVA remains 0.6 cm².
 - C. A 66 year old patient with CHF, LVEF=20%, an AVA of 0.6 cm², an mean transvalvular gradient of 25 mm Hg in whom dobutamine doubles his CO with little change in the gradient.
 - D. A 74 year old man who is symptomatic with normal LV function, a valve area of 0.9 cm², and a mean transvalvular gradient of 70 mm Hg.
 - E. An 80 year old otherwise healthy man, asymptomatic, with a valve area of 0.7 cm² and a mean transvalvular gradient of 70 mm Hg.

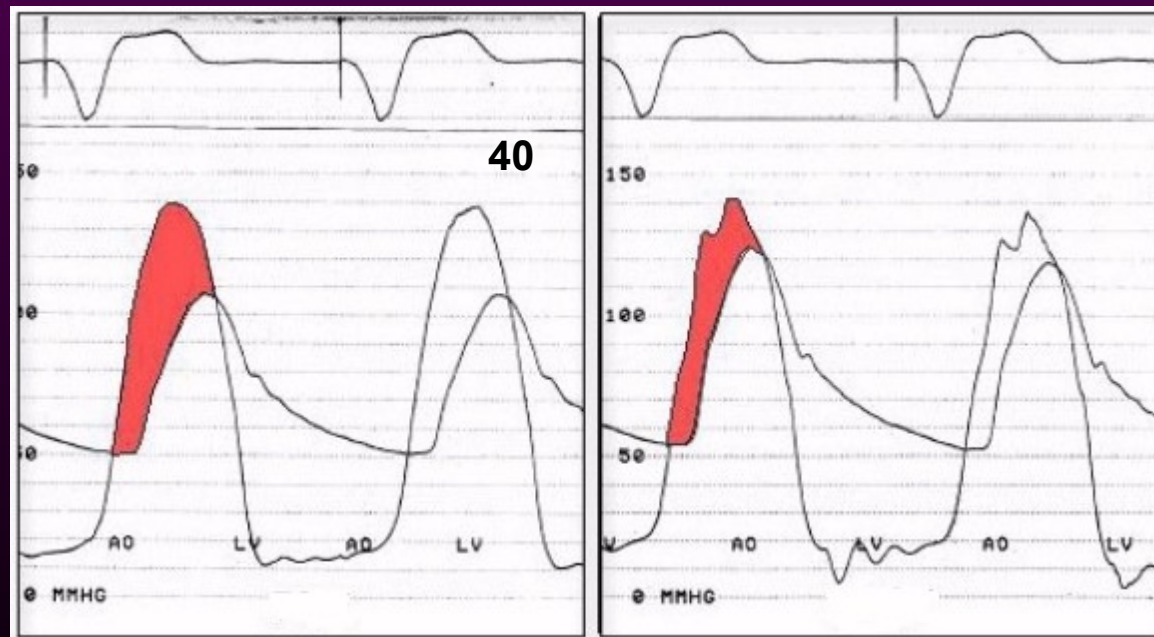


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Hemodynamic Principles

10. What accounts for the change in the patient's hemodynamics between the left and right frame?



Baim DS and Grossman W. Cardiac Catheterization, Angiography, and Intervention. 5th Edition. Baltimore: Williams and Wilkins, 1996.



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