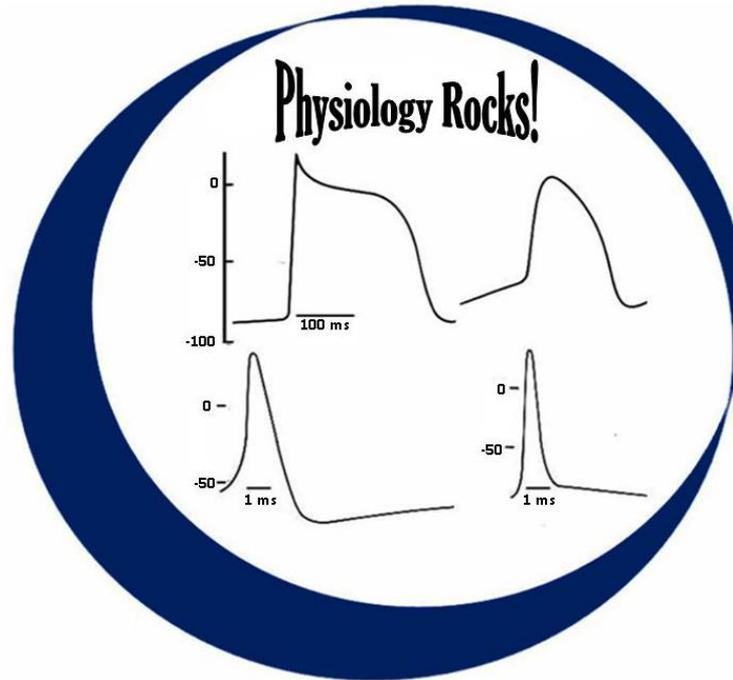


# Lectures 10 -11

## Pump Failure and Hemodynamics

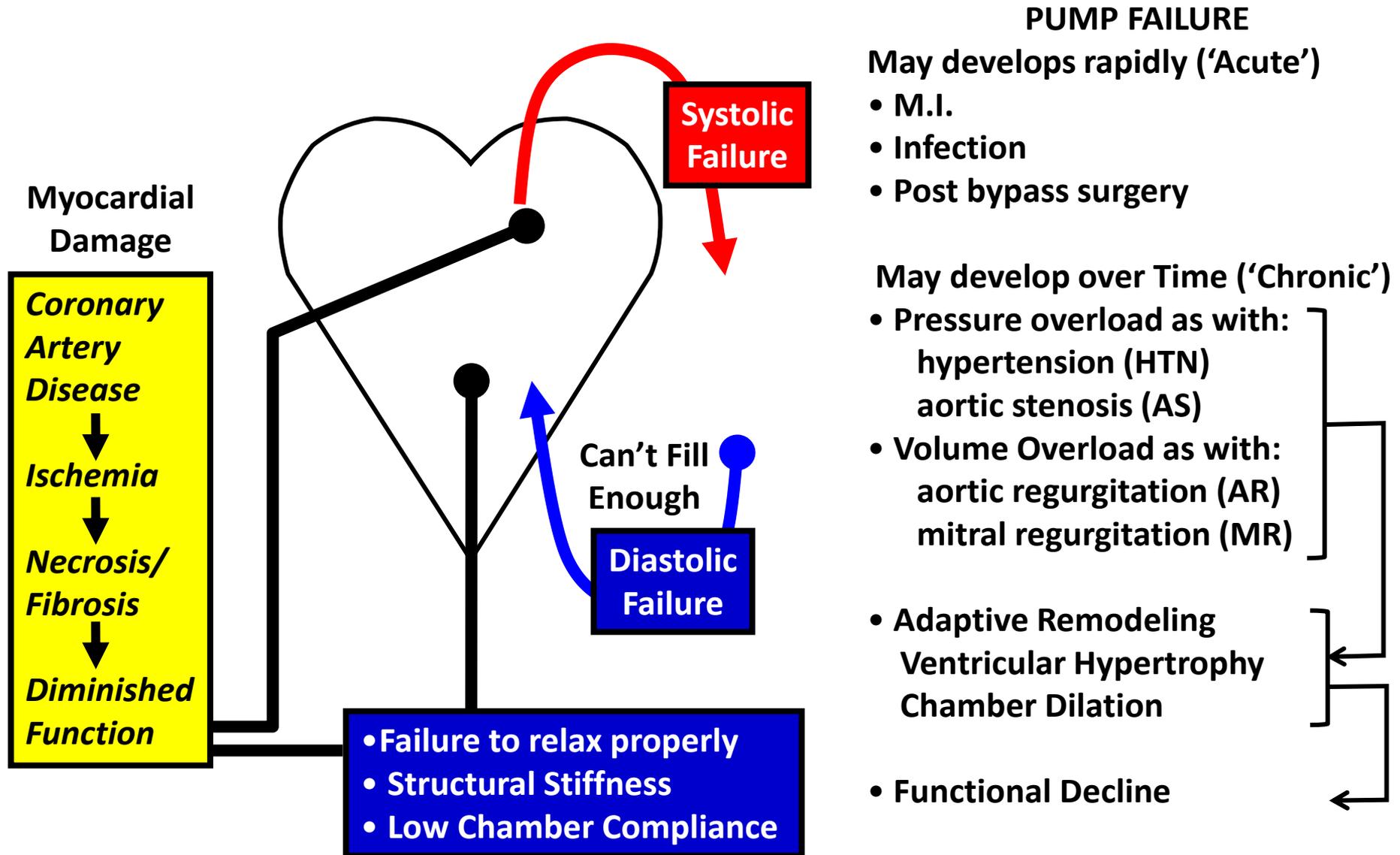


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# Topics

- Heart failure overview
- PV loops for systolic and diastolic dysfunction
- Cardiac valve conditions affecting cardiac function
- Aortic stenosis
- Mitral stenosis
- Aortic regurgitation
- Mitral regurgitation
- PV loops for cardiac valve conditions
- Cardiac adaptations to volume and pressure overloads
- PV loops associated with cardiac remodeling
- Murmurs of cardiac valve conditions
- Valsalva hemodynamic responses
- Interactive questions at various insertions

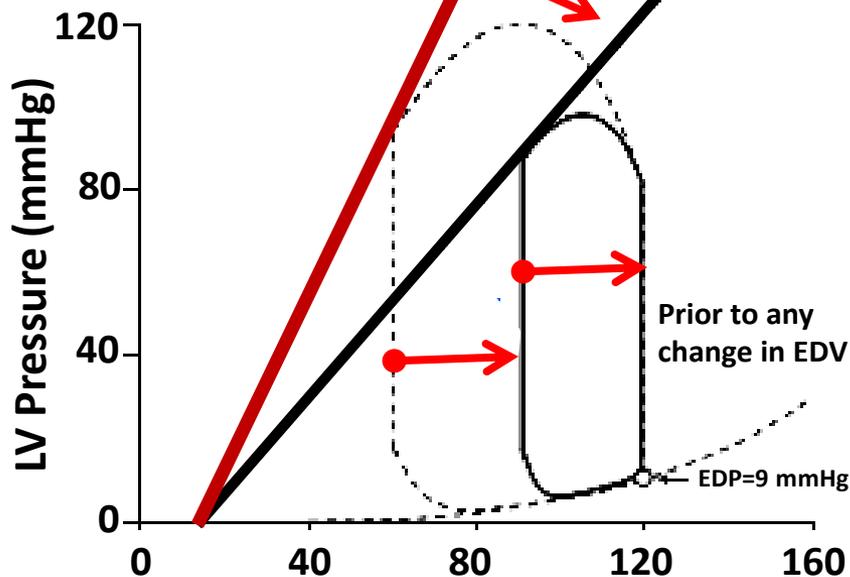
# Pump Failure → Heart Failure: **Overview**



# Pump Failure → Systolic vs. Diastolic Dysfunction

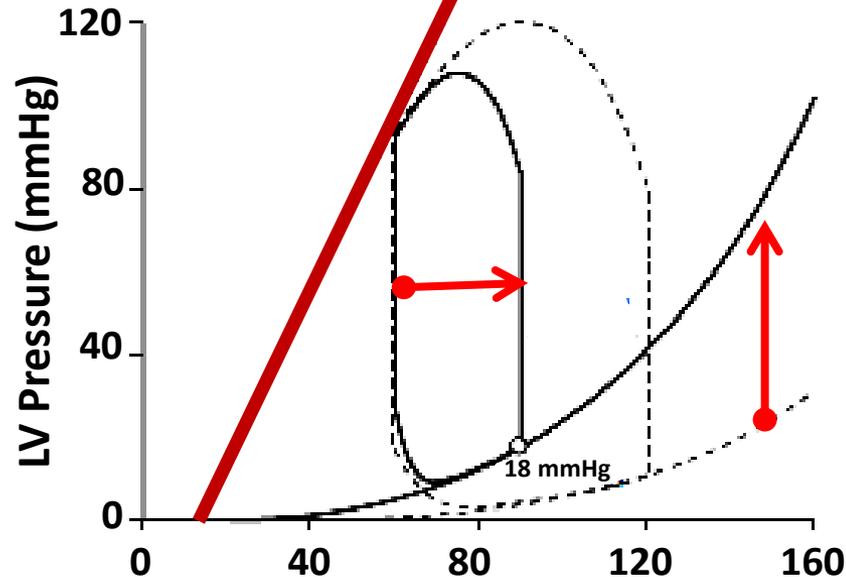
## Acute Initial Changes

### Systolic Dysfunction



- Contractility is reduced
- ESV is increased
- Stroke volume is reduced

### Diastolic Dysfunction

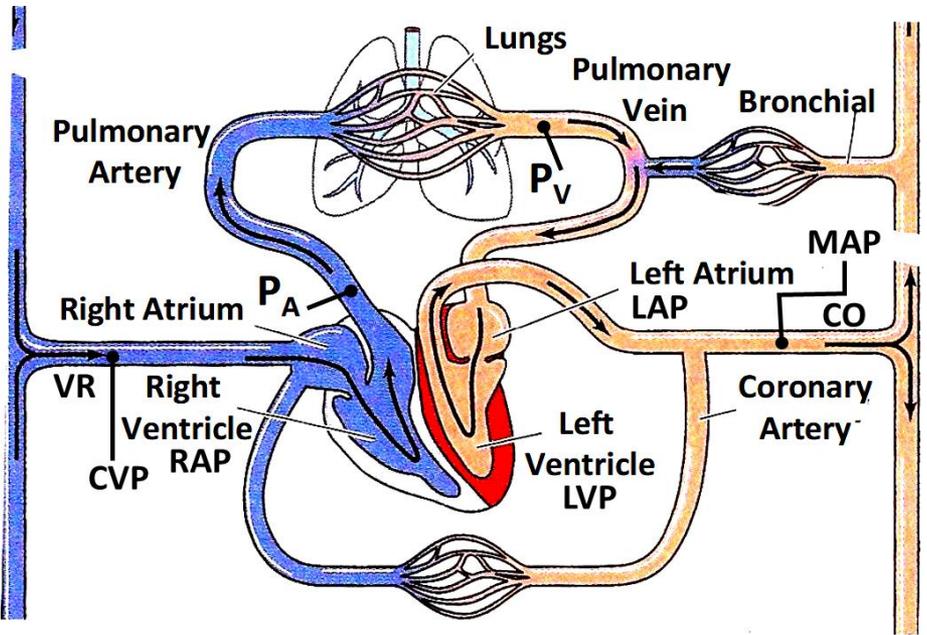


- Contractility is unchanged
- EDP is increased
- Stroke volume is reduced

# Cardiac Valve Conditions Affecting Pump Function

<ul style="list-style-type: none"> <li>• Aortic Stenosis</li> <li>• Mitral Stenosis</li> </ul>	<p>→</p>	<p>Pressure “overload”</p> <ul style="list-style-type: none"> <li>• LVP</li> <li>• LAP</li> </ul>
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<ul style="list-style-type: none"> <li>• Aortic Insufficiency (Regurgitation)</li> <li>• Mitral Insufficiency (Regurgitation)</li> </ul>	<p>→</p>	<p>Volume “overload”</p> <ul style="list-style-type: none"> <li>• LV</li> <li>• LA</li> </ul>
--	----------	---



- $P_A$  = Pulmonary artery pressure
- $P_V$  = Pulmonary vein pressure
- MAP = Mean aortic pressure
- CVP = Central venous pressure
- RAP = Right atrial pressure
- LAP = Left atrial pressure
- LVP = Left ventricular pressure
- RVP = Right ventricular pressure

# Aortic Stenosis

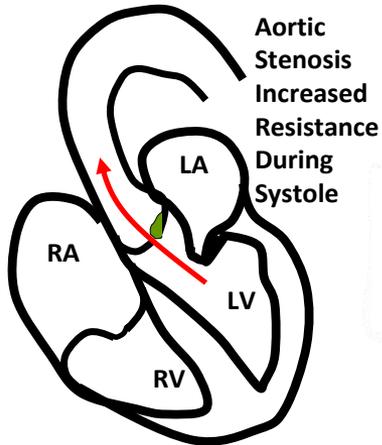
**Outflow obstruction**

Systolic Velocity Increase

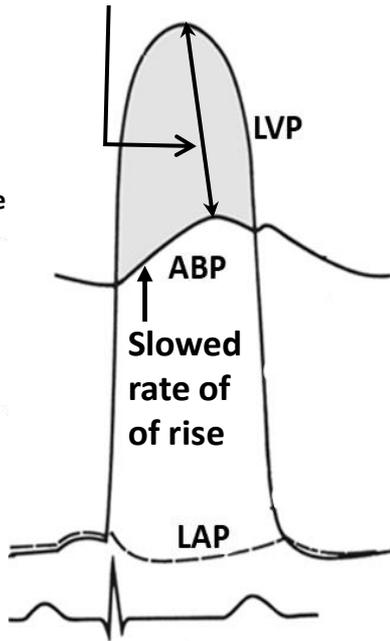
**Systolic Murmur**

+ Ventricle Pressure  
+ Pressure Loss

**Decreased Stroke Volume**



Gradient=LVP-ABP



**Outflow obstruction summary**

- (+) Valve Resistance and (+) LVP
- (-) SV and (-) SBP and (-)  $d(ABP)/dt$
- + LVP predisposes to LVH
- Peripheral pulse weak and non-crisp on palpation
- Reduced valve area with high flow (CO) causes high Reynold's number  
→ systolic murmur

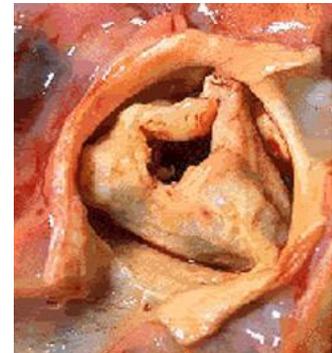
Older Age

• Calcification

Rheumatic

• Fibrosis

• Calcification



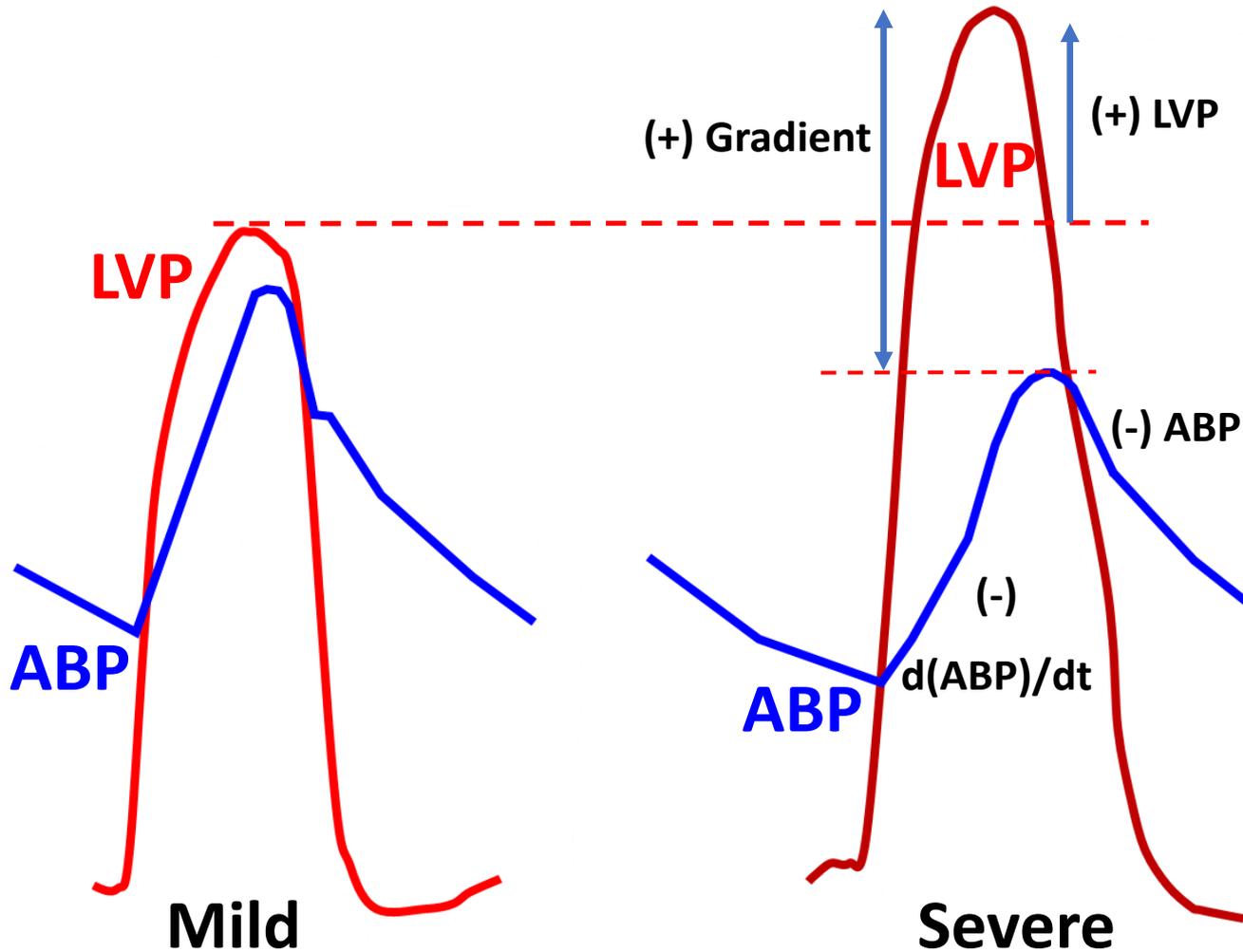
Stenotic

Q

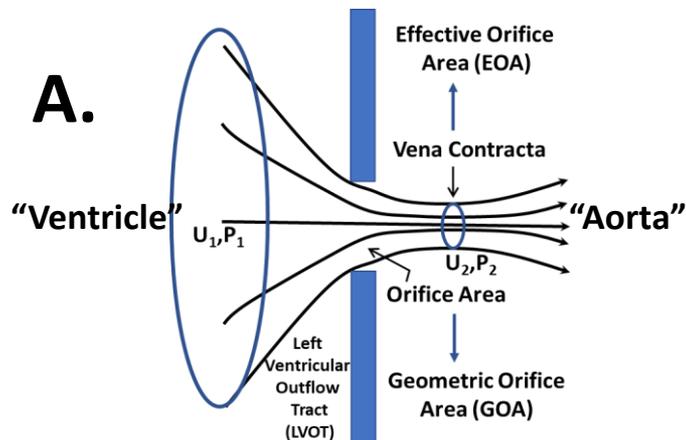
$\Delta P$  LARGE

High flow combined with small orifice causes high velocity and turbulence

# Aortic Stenosis: Mild vs. Severe



# Aortic Stenosis: Pressure "Gradient" Determination



Bernoulli's Lossless Equation

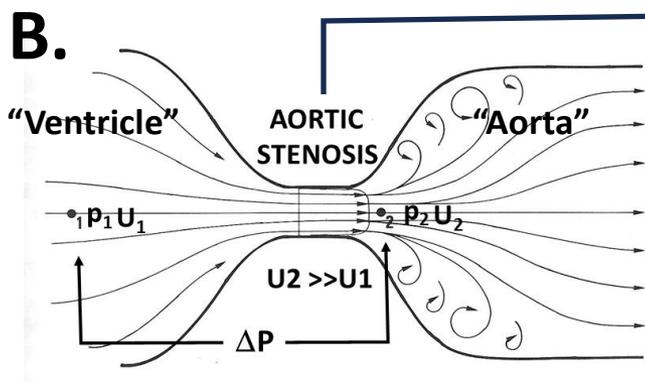
$$P_1 + 0.5\rho U_1^2 = P_2 + 0.5\rho U_2^2$$

Hemodynamic  
Dominance  
Inertial  $\gg$  Viscous

$\downarrow$   
1060 Kg/m<sup>3</sup>

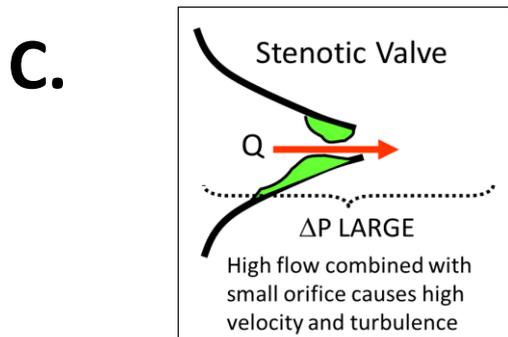
$$\Delta P = P_1 - P_2 = 4(U_2^2 - U_1^2), U_1^2 \ll U_2^2$$

$$\Delta P \text{ (mmHg)} \approx 4U_2^2 \text{ mmHg with } U \text{ in m/s}$$



Measured by ultrasound  
Yields stenosis gradient

@ 3 m/s  $\rightarrow$  36 mmHg



Normal  
< 20  
mmHg

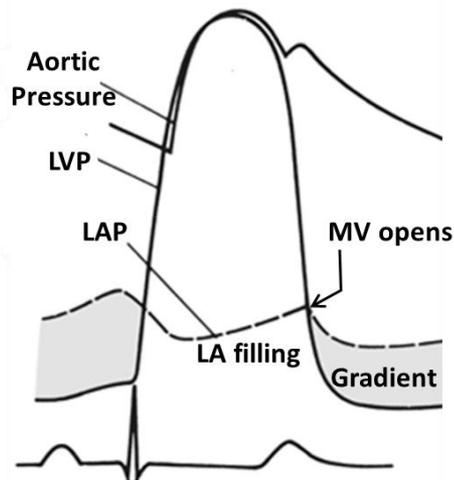
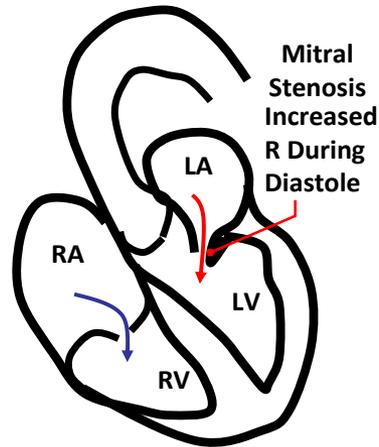
	Mild	Moderate	Severe
	20-25 mmHg	20-39 mmHg	$\geq$ 40 mmHg

Aortic Stenosis Stages by Peak Gradient

# Mitral Stenosis

Inflow obstruction

Diastolic velocity increase



+ LAP to overcome +R

## Inflow obstruction summary

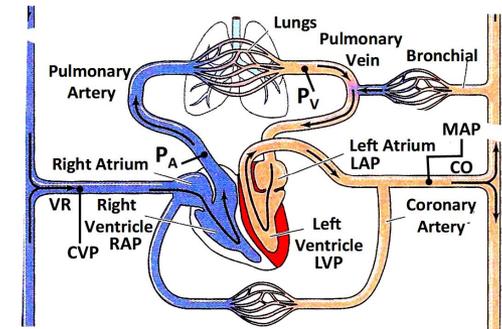
- + Valve resistance and + LAP
- + LAP predisposes to
  - LA enlargement and volume increase
  - Atrial Arrhythmias
  - Pulmonary edema
- Severity measurable via the LAP – LVP gradient
- Since ventricular filling is during diastole, the stenosis causes a diastolic murmur

Normal	Mild	Moderate	Severe
< 2 mmHg	2-5 mmHg	6-10 mmHg	>10 mmHg
Mitral Stenosis Stages by Peak Gradient			

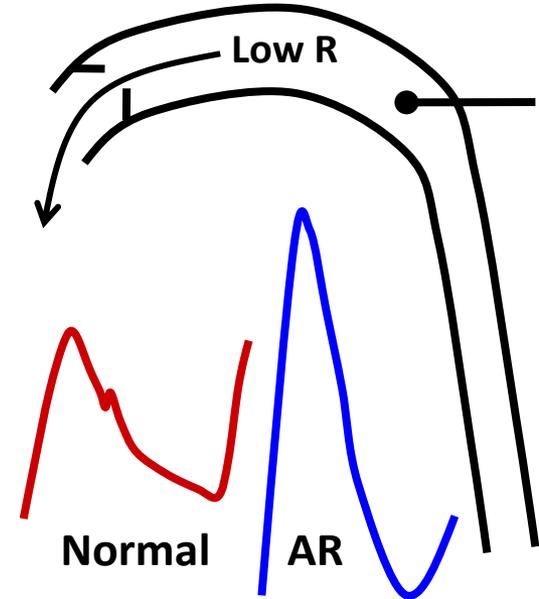
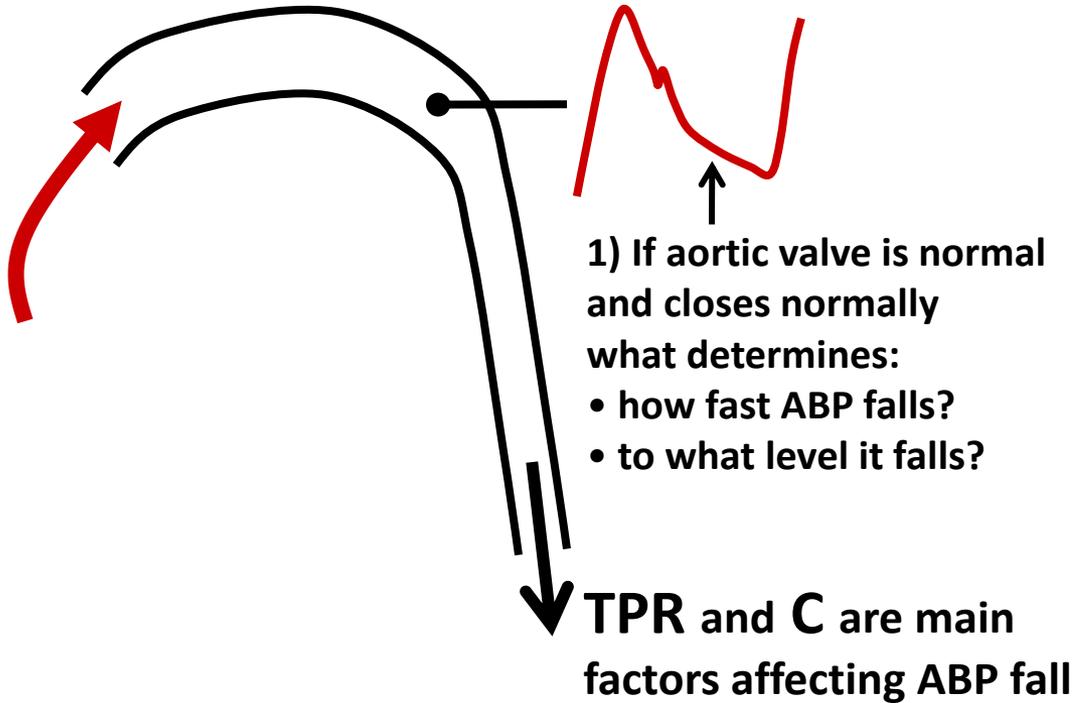
Diastolic Murmur

Rheumatic Carditis

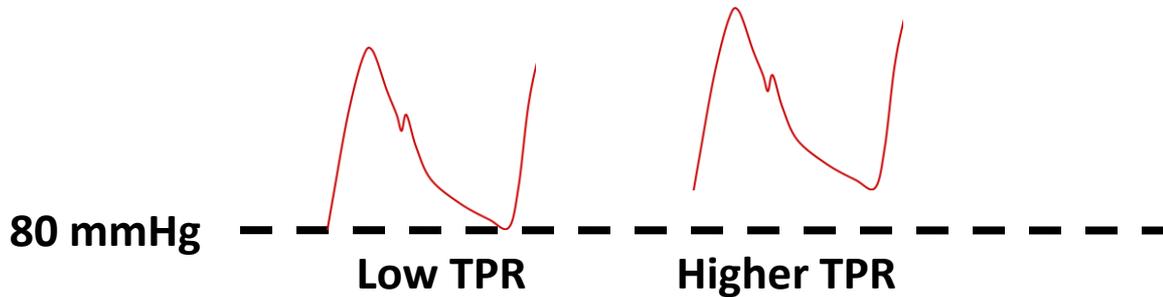
- Fibrosis
- Calcification



# Aortic Insufficiency – Regurgitation (AR)



2) If TPR increases, what would you expect to happen to diastolic pressure in the absence of AR?



3) What happens if the valve fails to close normally?

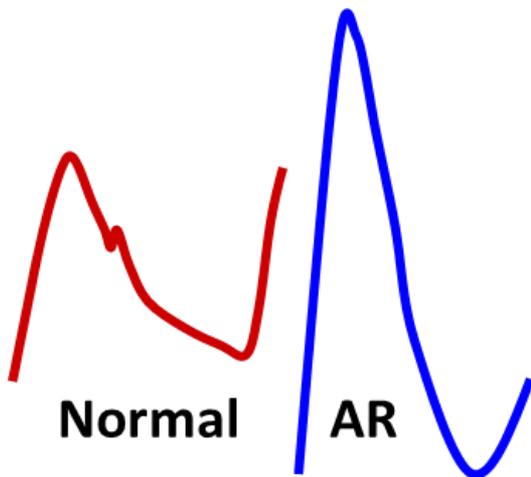
4) What accounts for the increased Systolic Pressure?

+Preload → +SV

# Aortic Insufficiency – Regurgitation: **Summary**

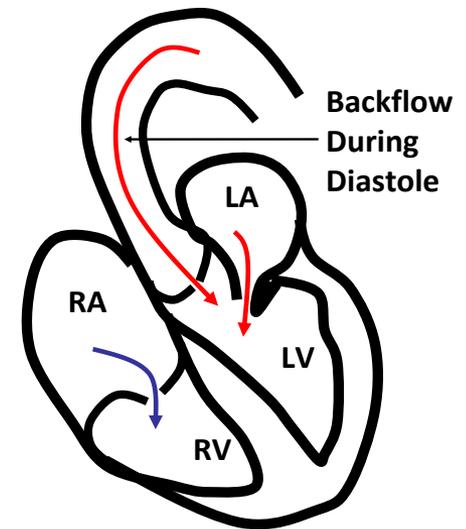
Diastolic backflow → Diastolic velocity increase → Diastolic Murmur

- + EDV → + SV → + Systolic Pressure
- Low R pathway → - Diastolic Pressure
- Combination → + Pulse Pressure



## Aortic Insufficiency summary

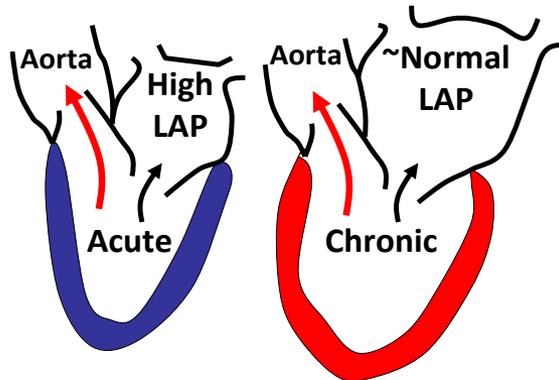
- Aortic valve does not close fully during diastole
- Backflow from aorta to LV as long as  $ABP > LVP$
- This low resistance pathway causes a rapid decline in ABP
- Effective SV is compromised
- Ventricle will hypertrophy (LVH) as it tries to compensate for “lost” effective SV
- Reduced valve area causes increased  $N_R$  during backflow
- Diastolic murmur!



# Mitral Insufficiency - Regurgitation

Systolic backflow

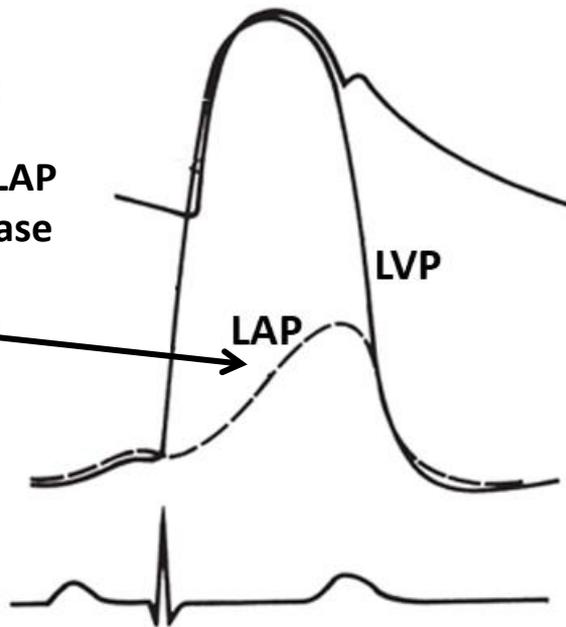
Systolic Murmur



## Mitral Insufficiency Summary

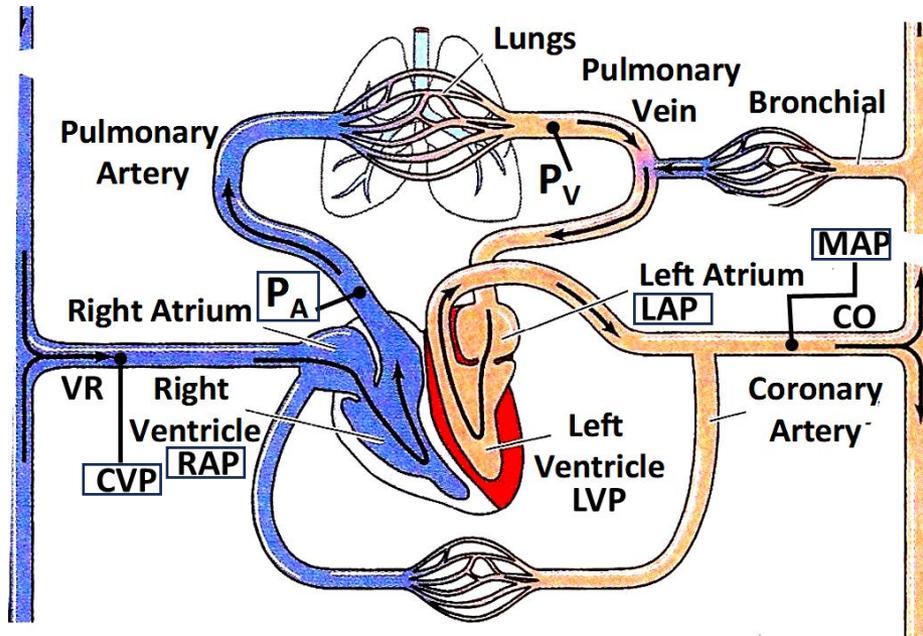
- Effect depends on if acute or slowly developing
- Acute (e.g. rupture of the chordae tendineae) causes volume to enter atrium during systole
- Result is increase in LAP since no adaption of atrial size to accommodate increased volume
- Chronic, that develops over time permits atrium to adjust to accommodate added volume with a lessor increase in LAP

Causes LAP to increase



# Interactive Questions

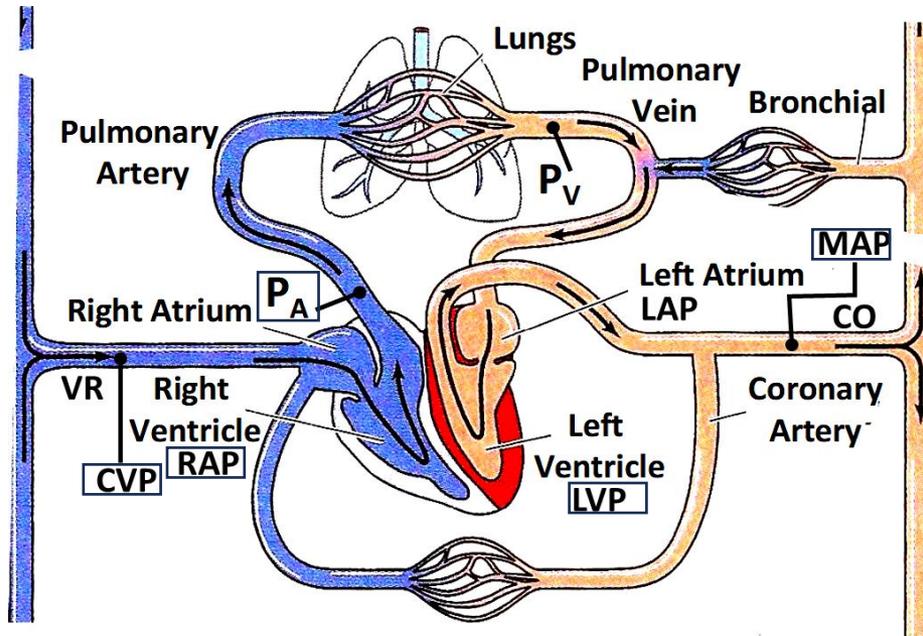
# Interactive Question



In the early stages of a hemodynamically significant aortic stenosis, which one of the *following* pressures increases first?

- A) RAP
- B) CVP
- C) MAP
- D) LAP
- E)  $P_A$

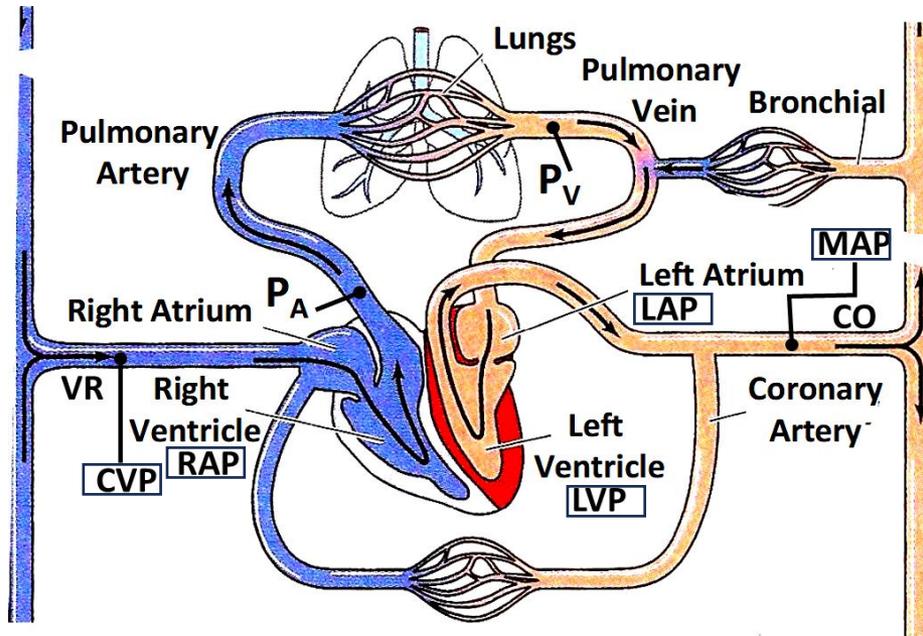
# Interactive Question



Bill is a 72-year-old gentleman with a history of aortic stenosis and significant arterial hypertension. He is complaining of breathing difficulties. An elevation in which one of the following pressures most directly contributes to his symptom?

- A) RAP
- B) CVP
- C) MAP
- D) LVP
- E)  $P_V$

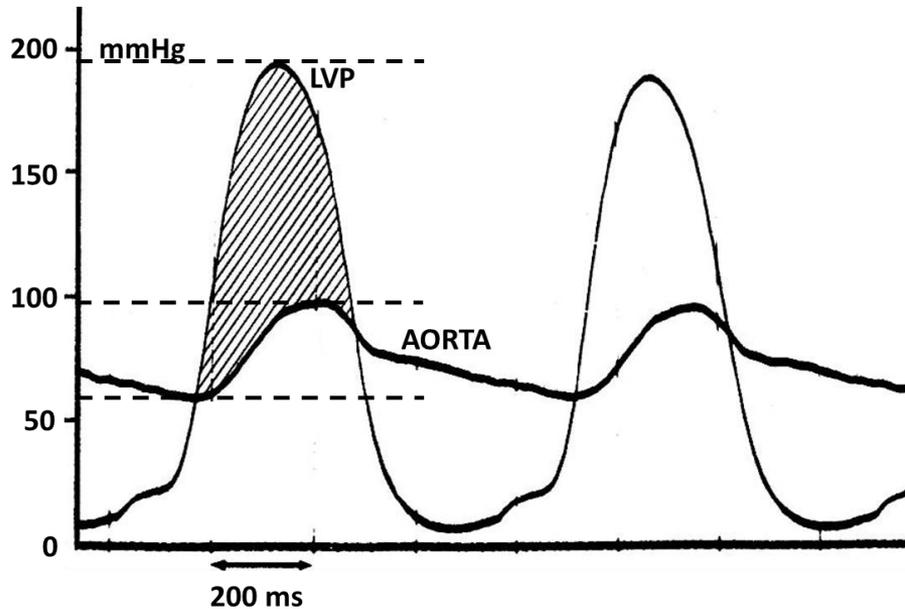
# Interactive Question



Jill is a 68-year-old retired nurse who presents with significant bilateral ankle edema (swelling) and breathing difficulties on exertion. An elevation in which one of the following pressures most directly contributes to her ankle edema?

- A) LAP
- B) CVP
- C) MAP
- D) LVP
- E) P<sub>V</sub>

# Interactive Question



The figure shows hemodynamic measurements in a 62-year-old patient with a childhood history of rheumatic fever.

1) Which of the following cardiac valve conditions is most likely present?

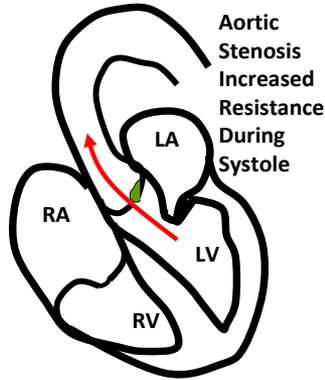
- A) Mitral stenosis
- B) Aortic stenosis
- C) Aortic regurgitation
- D) Aortic insufficiency
- E) Mitral regurgitation

2) His gradient is closest to which of the following values in mmHg?

- A) 50
- B) 75
- C) 100
- D) 150
- E) 200

# Impact of Valve Dysfunction on P-V Loops

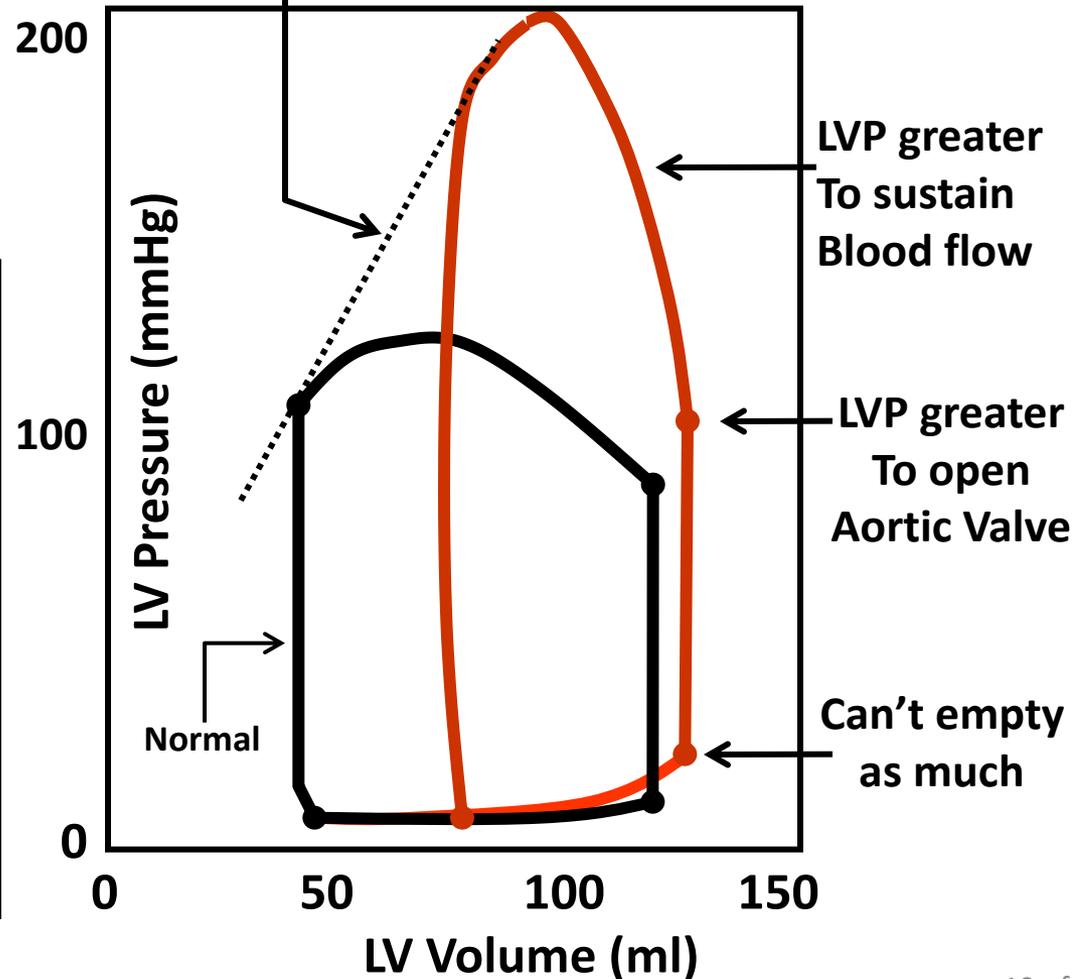
# Aortic Stenosis: P-V LOOPS



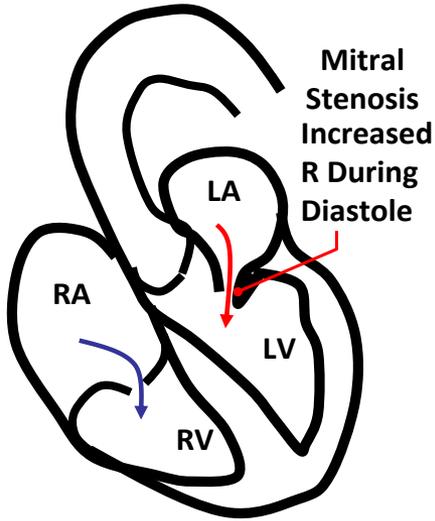
## AORTIC STENOSIS

- Increased outflow R causes increase in effective afterload
- SV & EF are reduced
- LV pressures are elevated and don't represent aortic pressure as they normally would

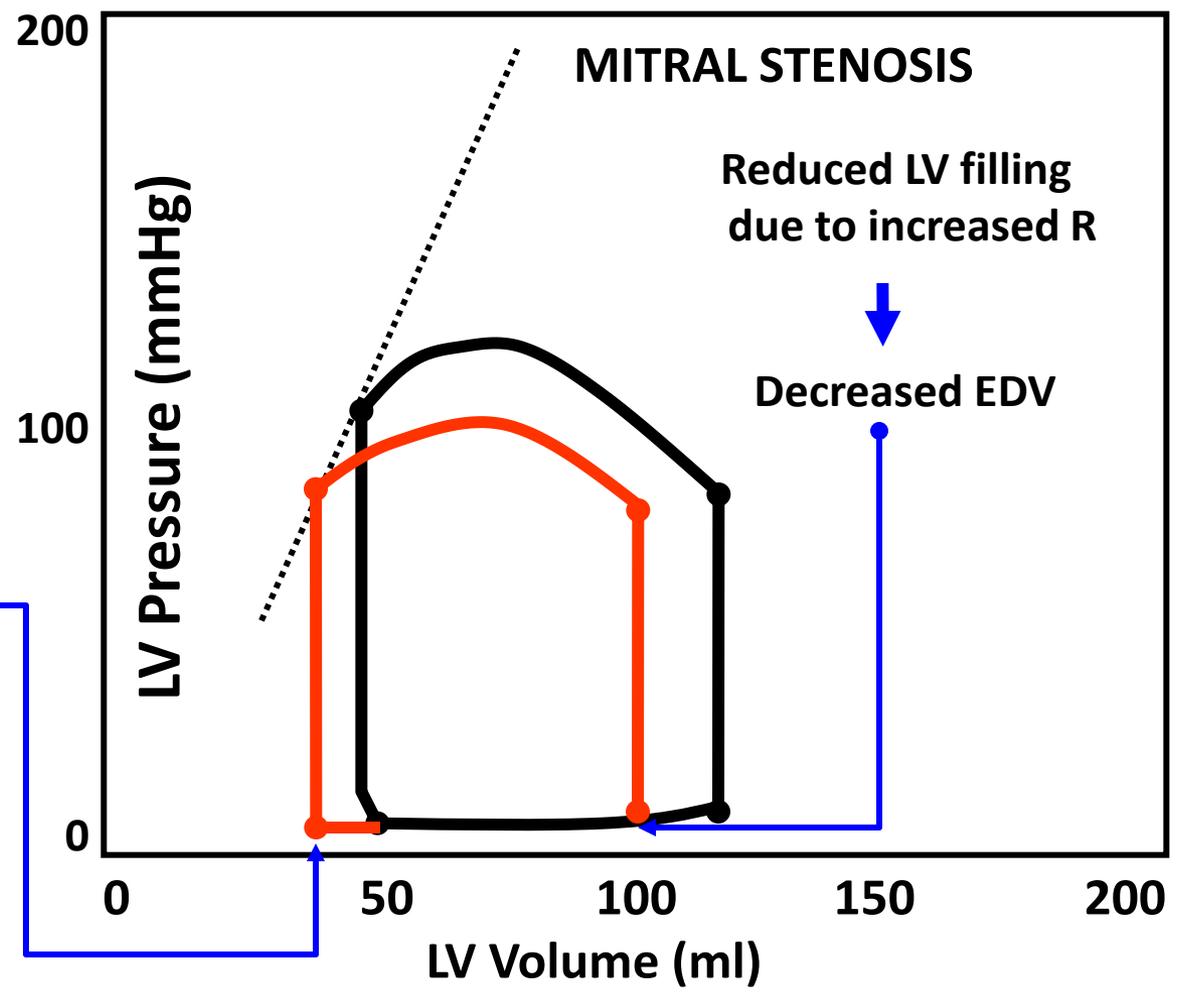
No change in contractility in this example



# P-V LOOPS: Mitral Stenosis (MS)

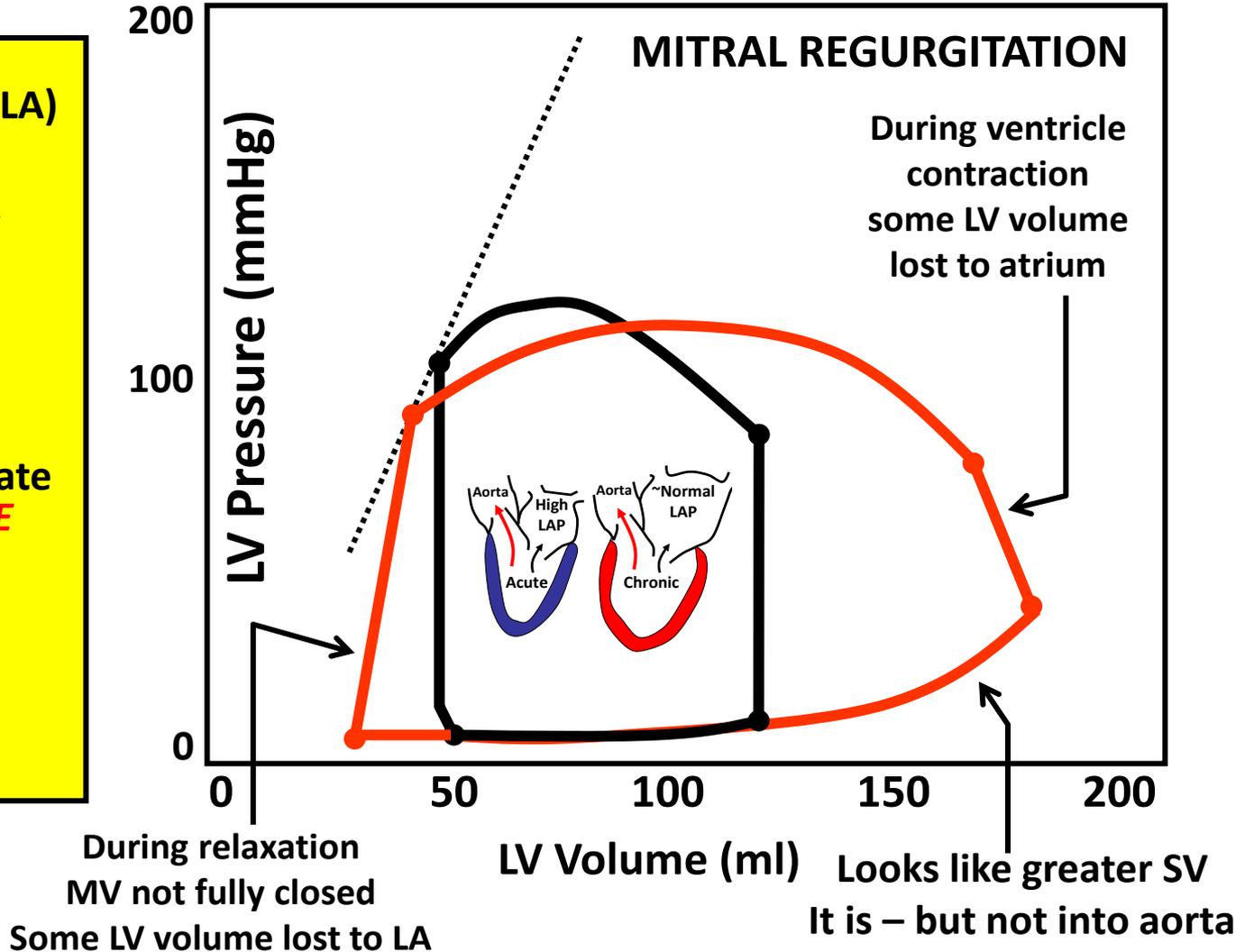


Decreased EDV  
↓  
Decreased ESV  
But reduced SV  
and reduced EF



# P-V LOOPS: Mitral Regurgitation (MR)

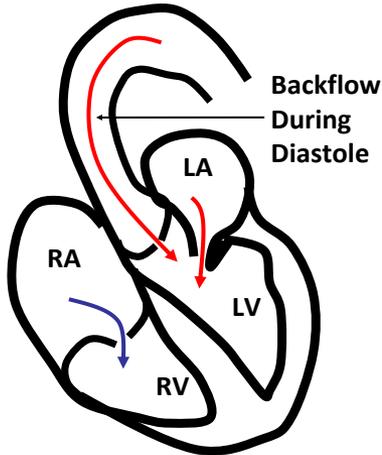
- Systolic backflow into Left Atrium (LA)
- Elevated LAP transmitted to LV during filling
- EDV is increased
- Adaptation over time to compensate for lost **EFFECTIVE** SV further increases EDV
- No isovolumic contraction or relaxation



# P-V LOOPS: Aortic Regurgitation (AR or AI)

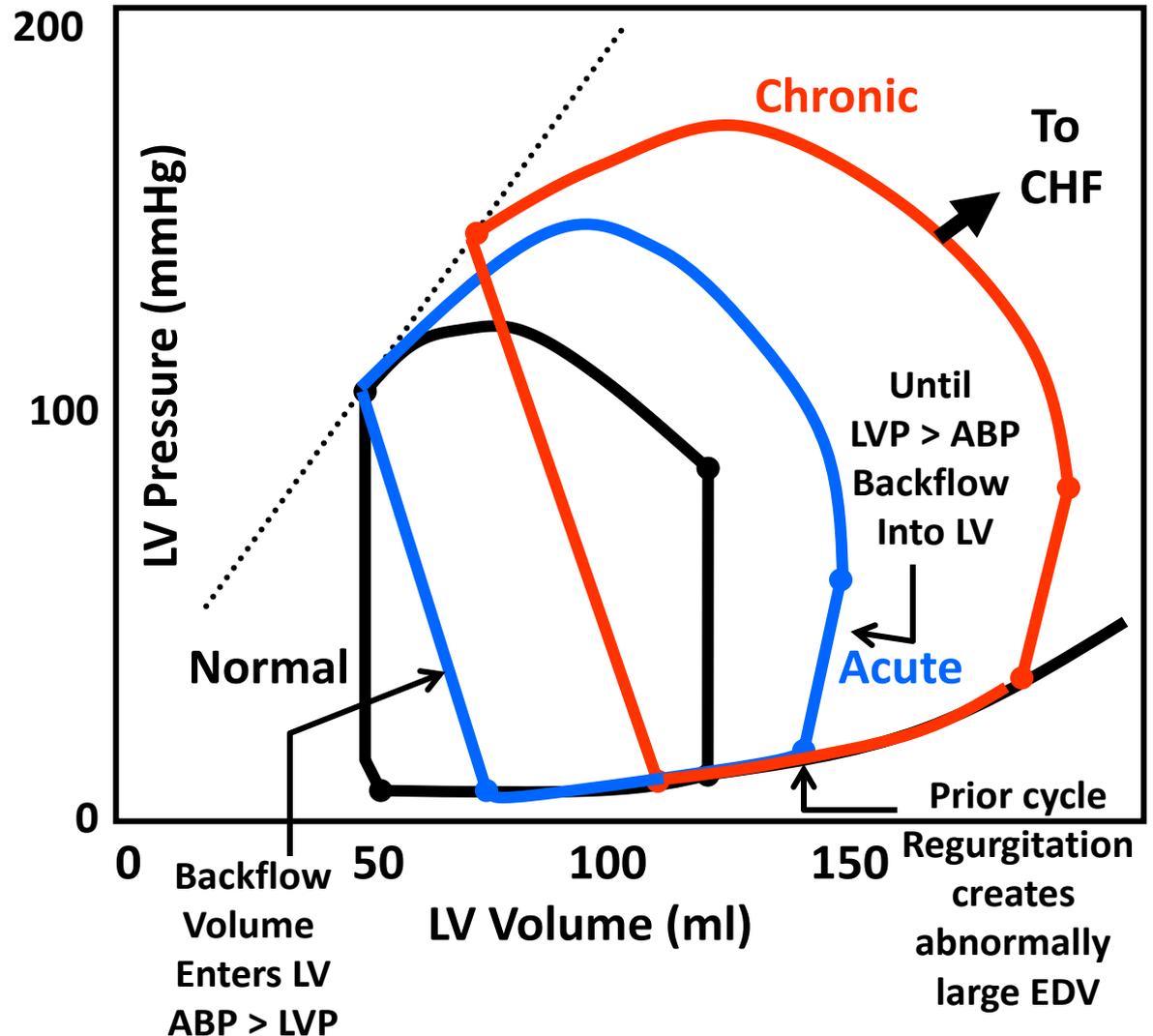
## AORTIC REGURGITATION

- Regurge during *diastole* increases EDV and ESV



Relaxation & Contraction  
NOT isovolumic

Remodeling over time  
adds to EDV increase  
(eccentric hypertrophy)



# Adaptations and Remodeling

## Heart Failure = Pump Failure

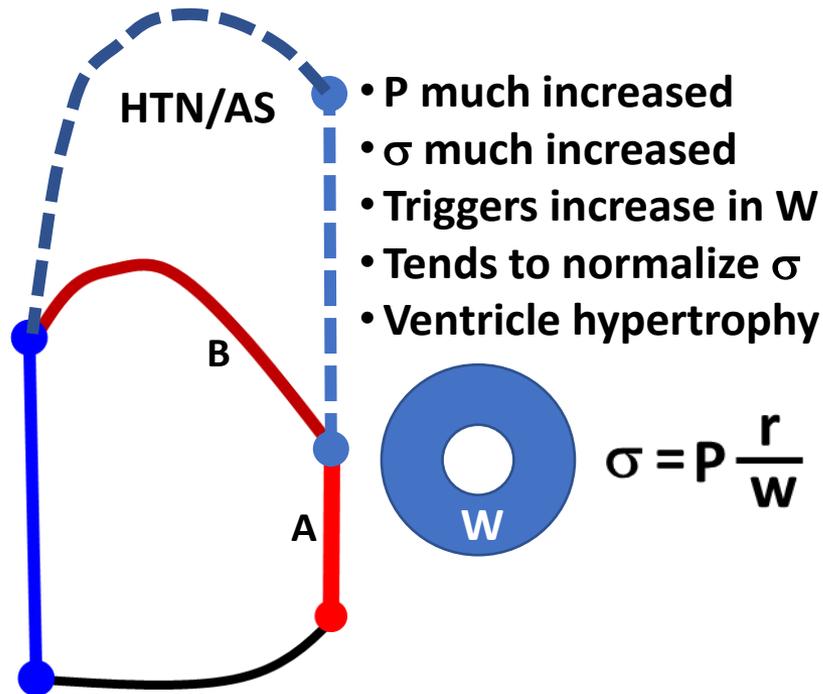
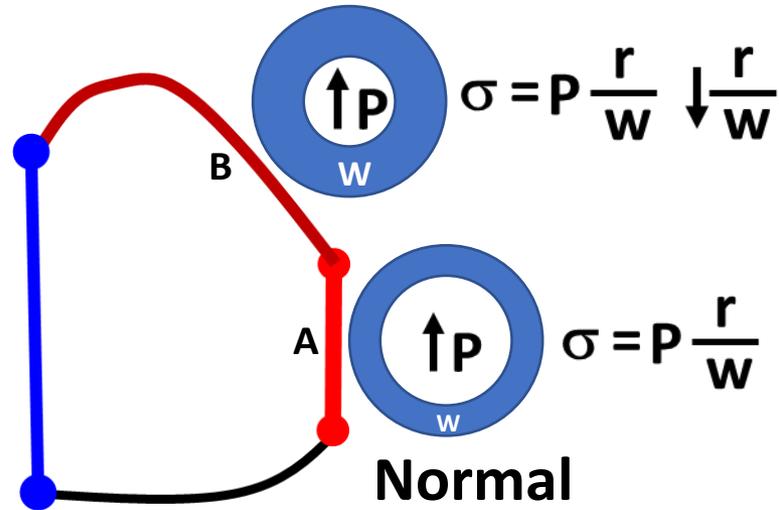
### Develops Rapidly ('Acute')

- M.I.
- Infection
- Post bypass surgery

### Over Time ('Chronic')

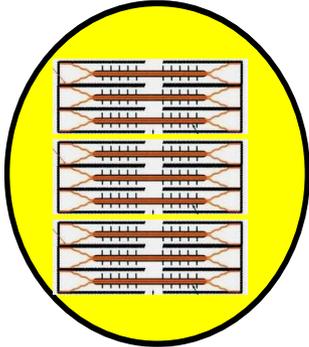
- Pressure / Volume Overload  
HTN/AS / AR/MR
- Adaptive Remodeling
- Functional Decline

# Adaptation Impacts on Myocardial Wall Stress



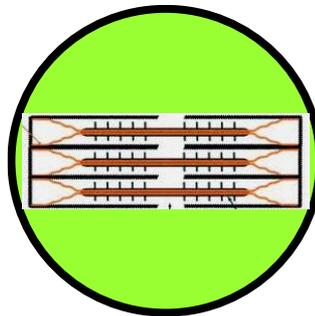
# Adaptations and Remodeling

**+ Afterload**  
more force  
needed to  
overcome  
greater load



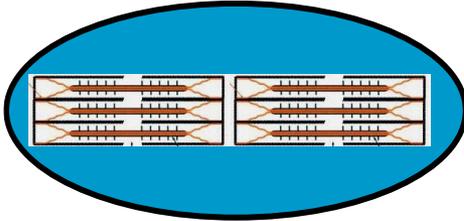
**Concentric  
+ Muscle Mass  
AS or HTN**

## HYPERTROPHY



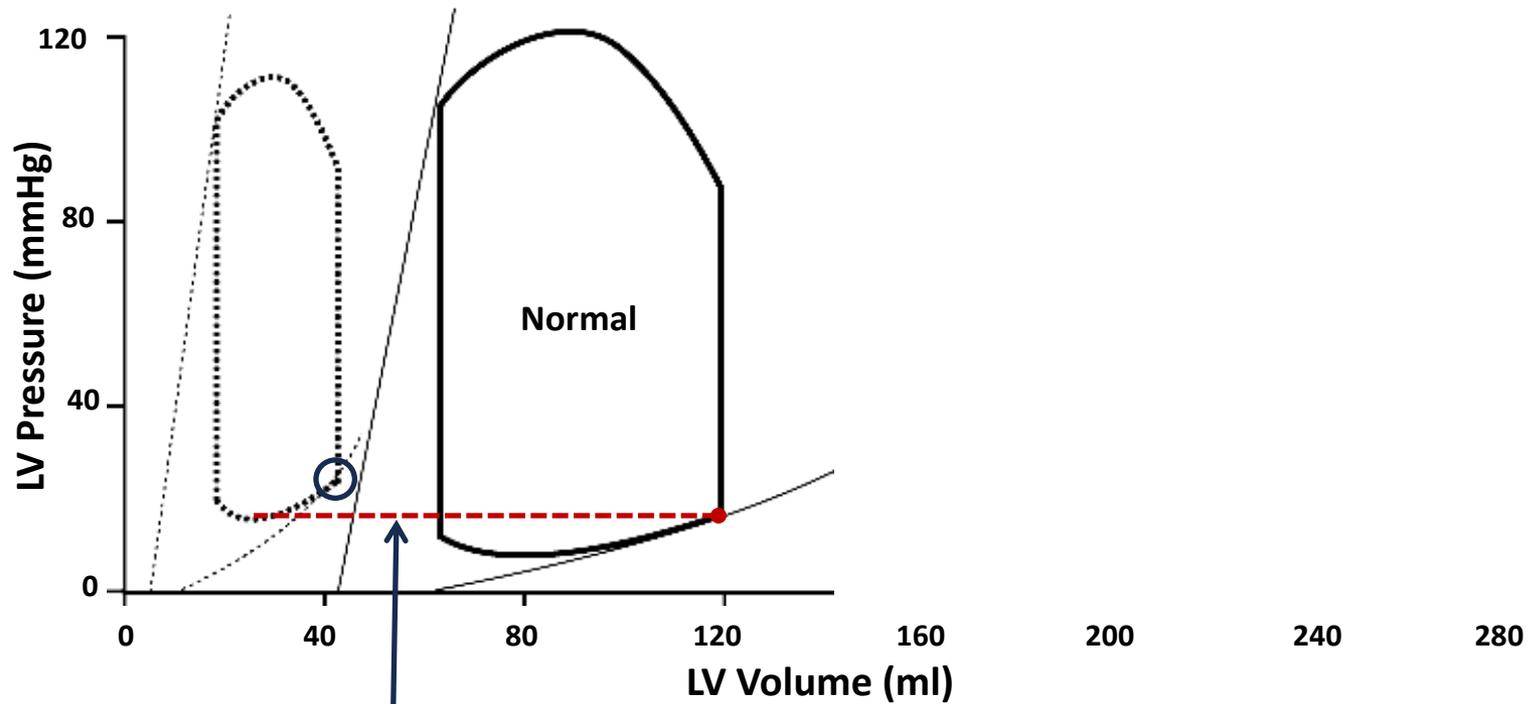
**Normal  
Mass &  
Volume**

**+ Preload**  
chamber expands  
to accommodate  
larger volume



**Eccentric  
+ Chamber Size  
MR or AR**

# Remodeling Impacts on P-V Loops: Overview



Caused by  
Ventricular  
Pressure  
Overload

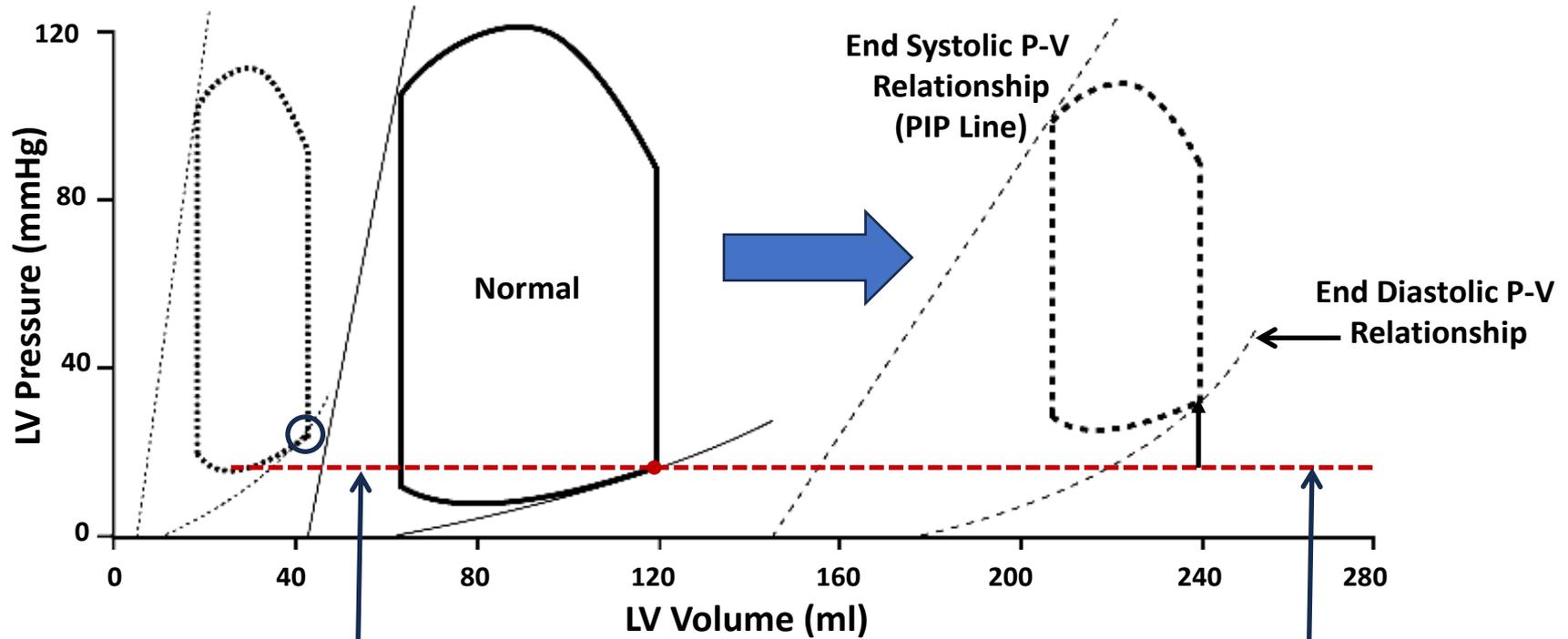


**Concentric Hypertrophy**

- Diastolic Failure
- EDV Decreased
- EDP Increased
- SV Decreased

**Normal**

# Remodeling Impacts on P-V Loops: Overview



Caused by Ventricular Pressure Overload



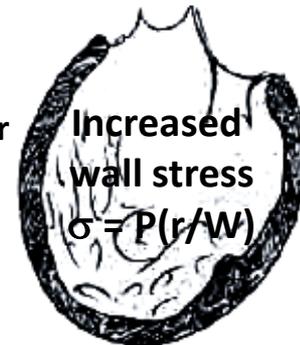
Concentric Hypertrophy

- Diastolic Failure
- EDV Decreased
- EDP Increased
- SV Decreased



Normal

Caused by Ventricular Volume Overload



Eccentric Hypertrophy

- Systolic Failure
- EDV Increased
- EDP Increased
- SV Decreased

Increased wall stress  
 $\sigma = P(r/W)$

# Summary of Systolic Dysfunction

## Systolic Dysfunction

-Myocardial Contractility



Impaired Contraction



-SV



+EDV



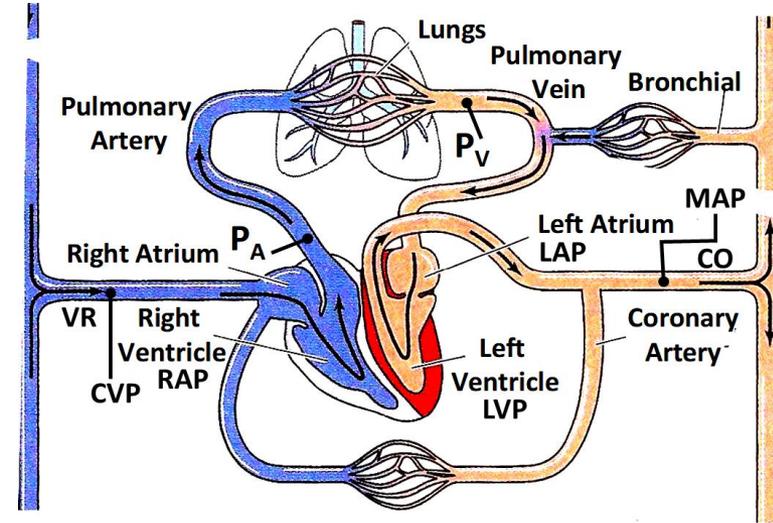
+EDP



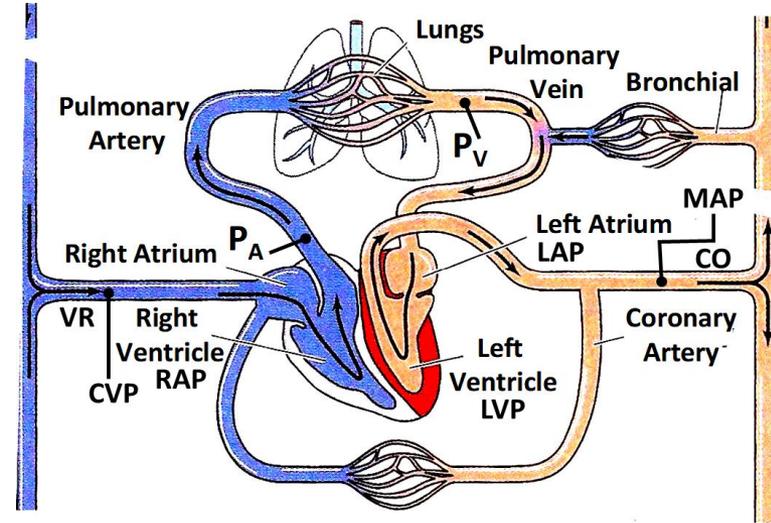
Intrinsic dysfunction of contractile apparatus  
e.g. - inotropy

Loss of Viable Contracting Muscle  
e.g. M.I.

IF LV involved: → initially pulmonary congestion & edema  
IF RV involved: → initially peripheral edema and ascites



# Summary of Diastolic Dysfunction



## Diastolic Dysfunction

-Ventricle Compliance

↓  
- EDV

↓  
- SV

↓  
+ EDP

↓  
Pulmonary  
Congestion

• Reduced lusitropy

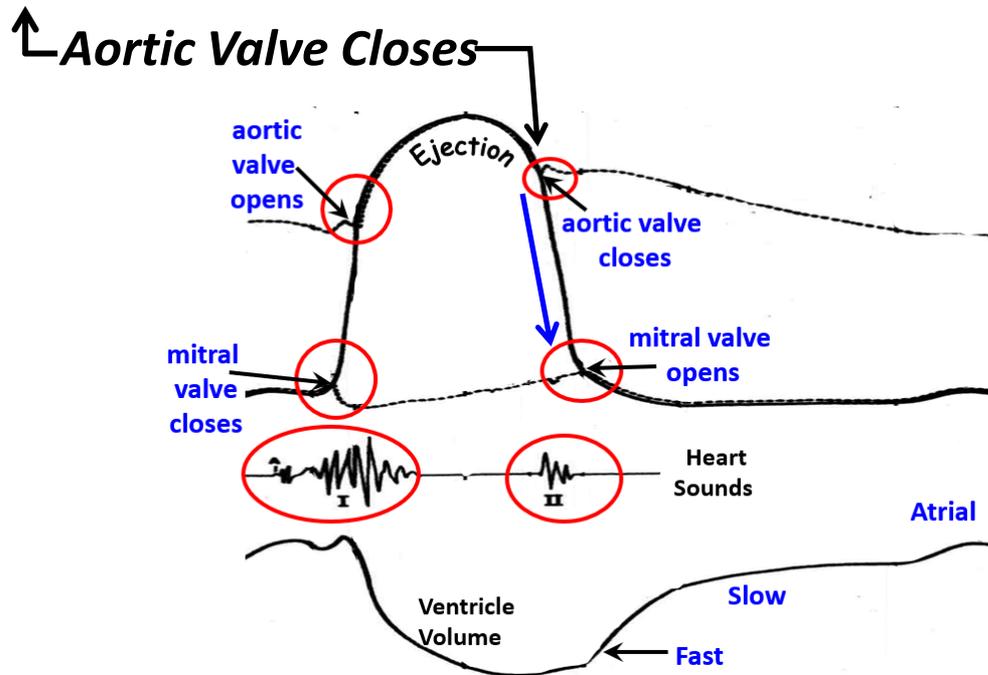
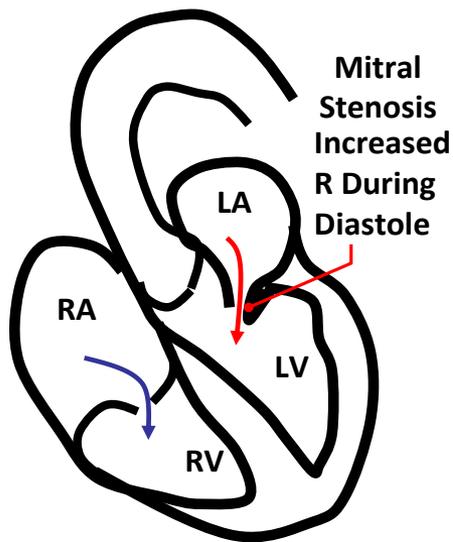
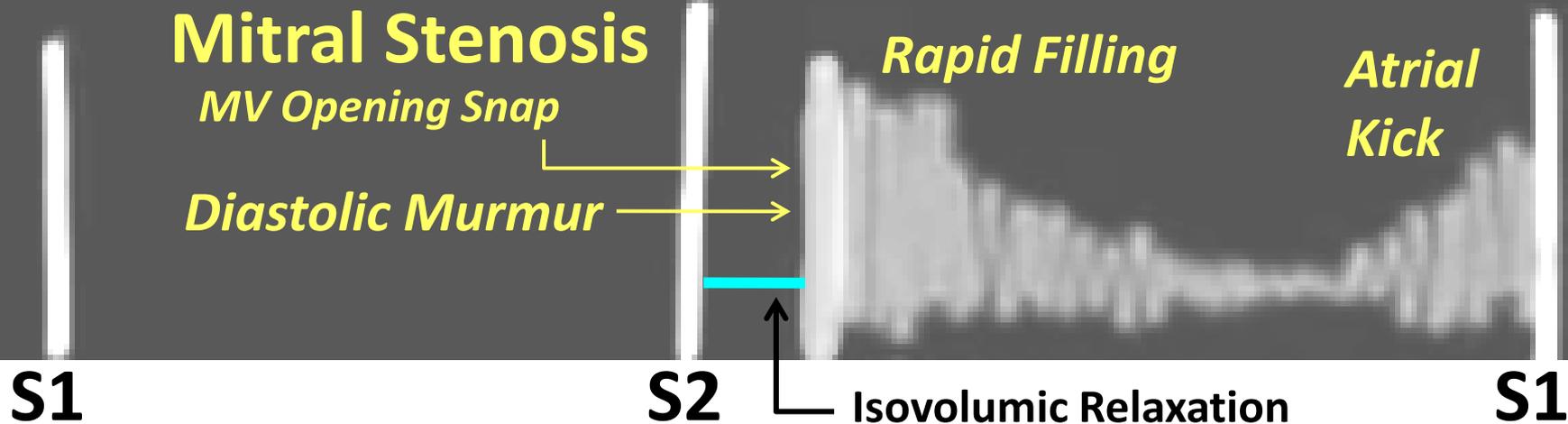
• Structural Changes

Reduced  
removal rate  
or amount of  
Ca<sup>++</sup> from SR  
during diastole

Hypertrophy  
+ Muscle mass  
+ Wall Thickness  
+ Tissue fibrosis

# Cardiac Valve-Related Murmurs

# Mitral Stenosis – Diastolic Murmur



# Aortic Stenosis – Systolic Murmur

*Ejection Click*

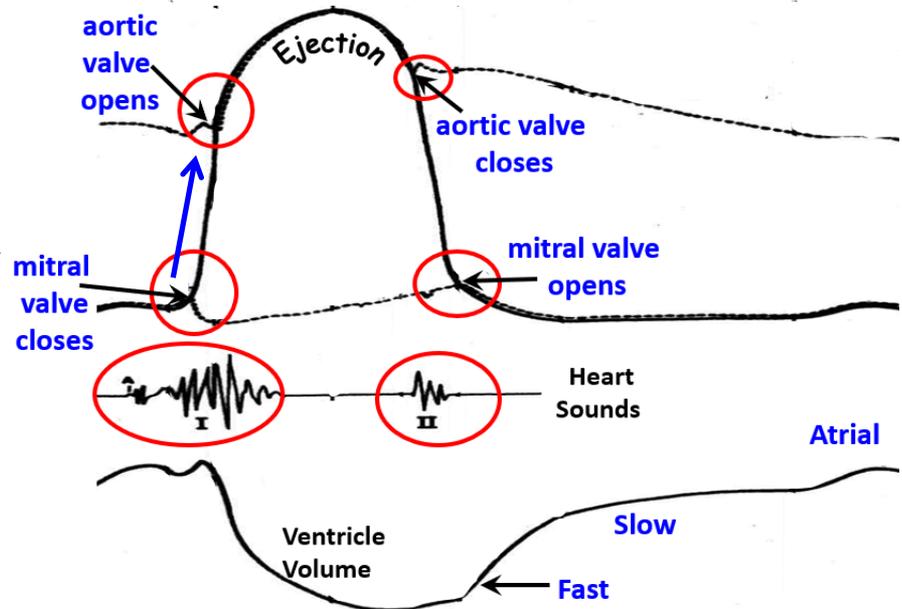
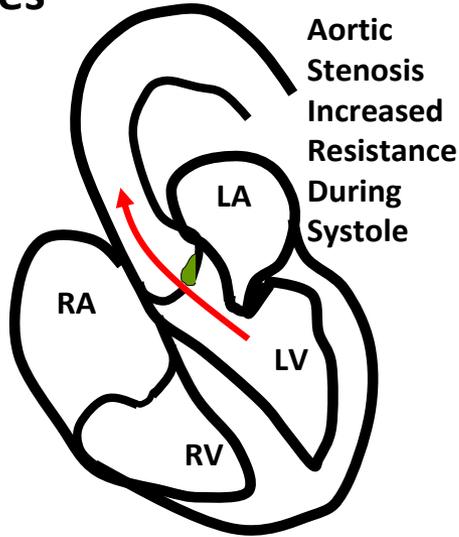
## Aortic Stenosis

- Systolic murmur
- Aortic blood flow increases-Decreases
- crescendo-decrescendo

**S1** ↑ Isovolumic Contraction  
 ↑ MV Closes

**S2**

**S1**



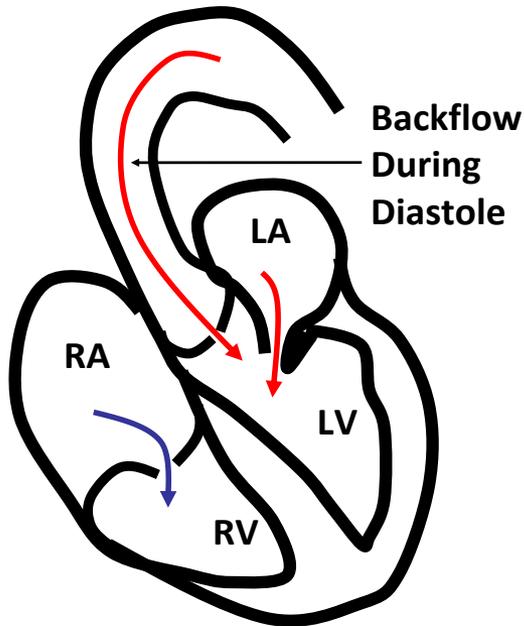
# Aortic Regurgitation – Diastolic Murmur

- Back flow initially large
- Diminishes as ABP falls
- Becomes non-turbulent
- Murmur ends

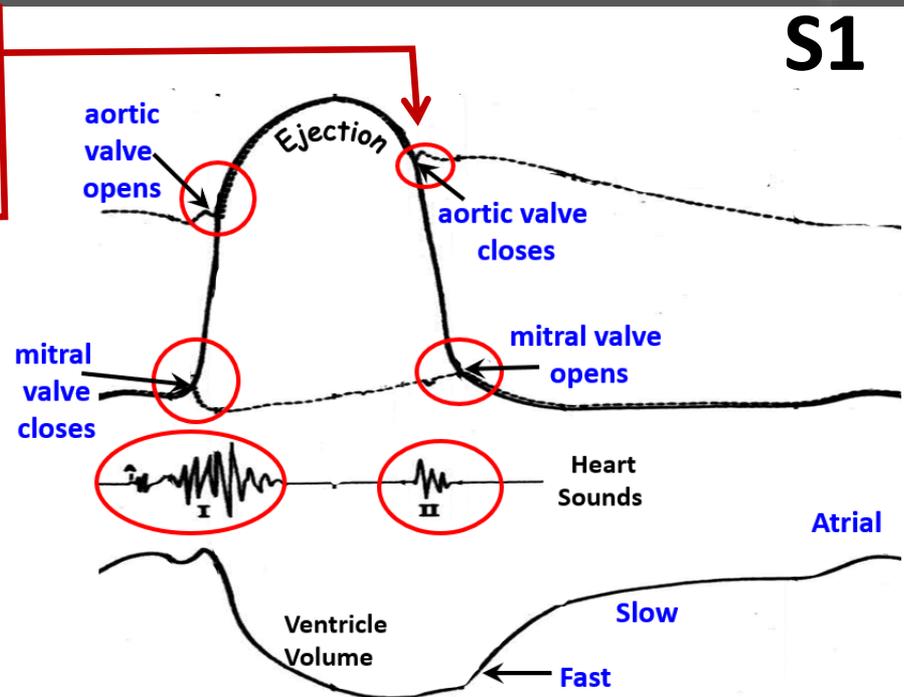
## Aortic Regurgitation

Early diastolic murmur

S1

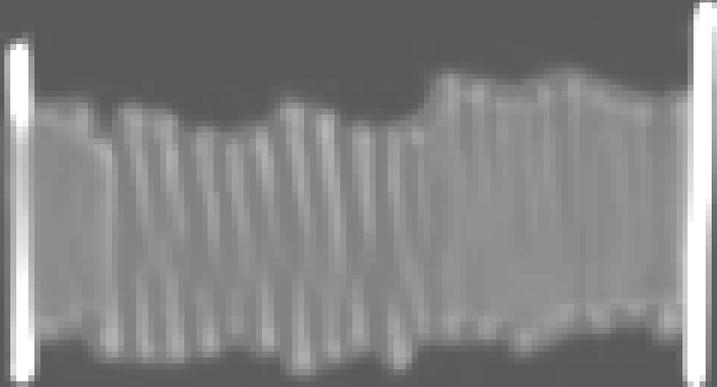


S2



S1

# Mitral Regurgitation – Systolic Murmur

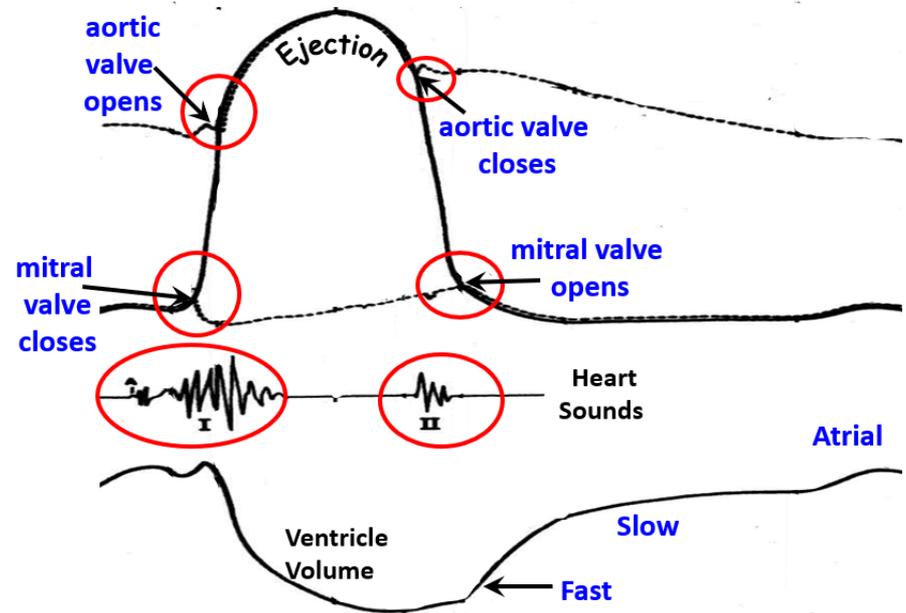
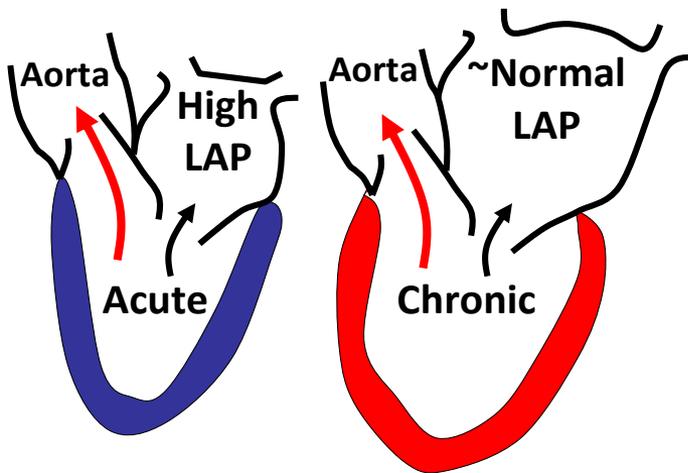


## Mitral Regurgitation

*Pan Systolic Murmur  
(Holo Systolic)*

**S1** Ventricular Systole **S2**

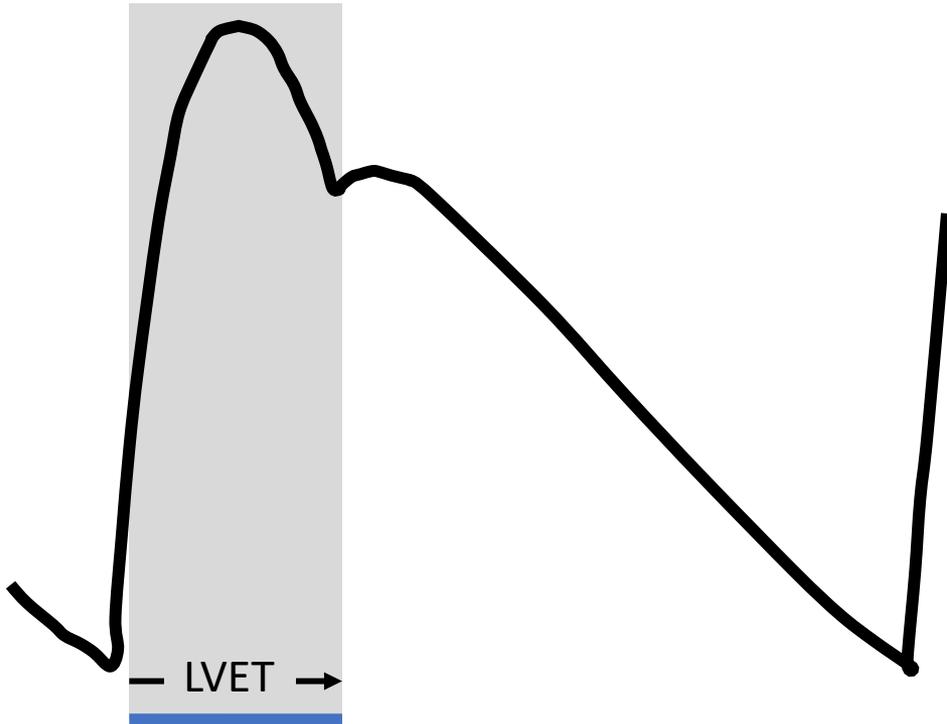
**S1**



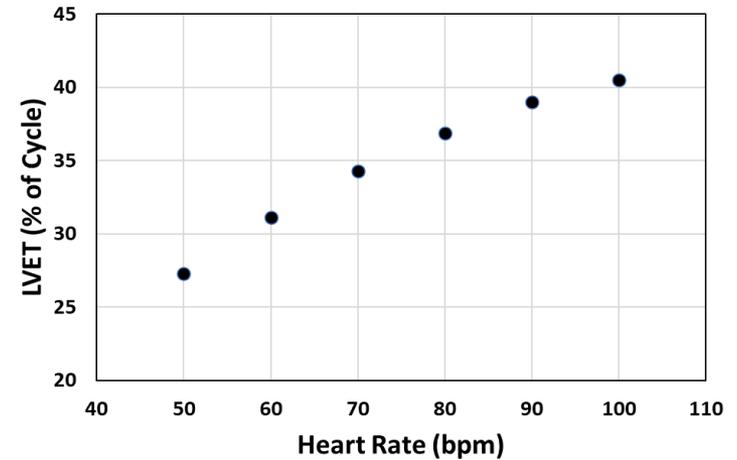
# Normal Responses

- **Exercise**
- **Valsalva**

# Normal Left Ventricular Ejection Time (LVET)



- LVET decreases with increasing HR
- $\text{LVET (sec)} = 0.413 - 0.0017 \times \text{HR (bpm)}$
- LVET increases as a pct of cycle time



- Systolic blood flow/minute increases with increasing HR

# Demonstrating LVET changes with HR

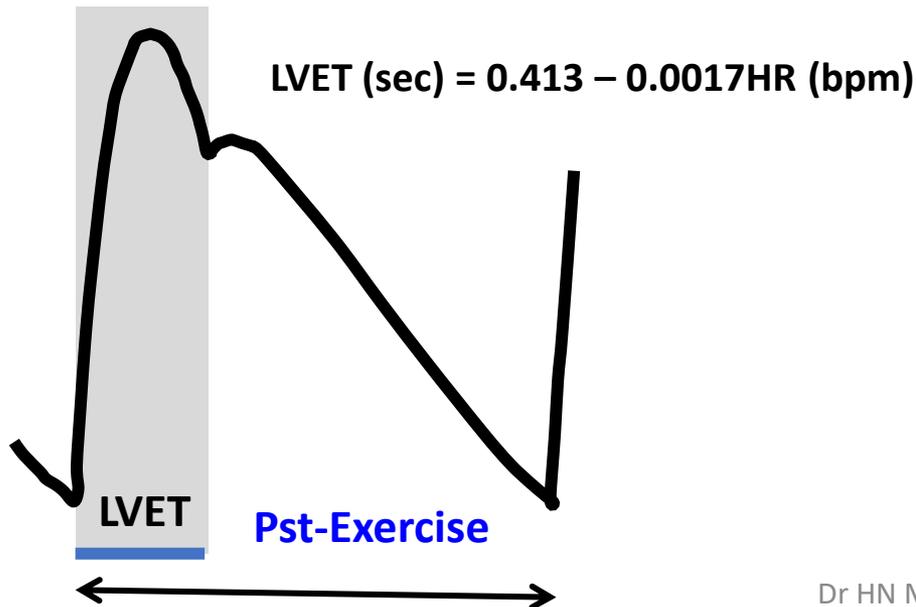
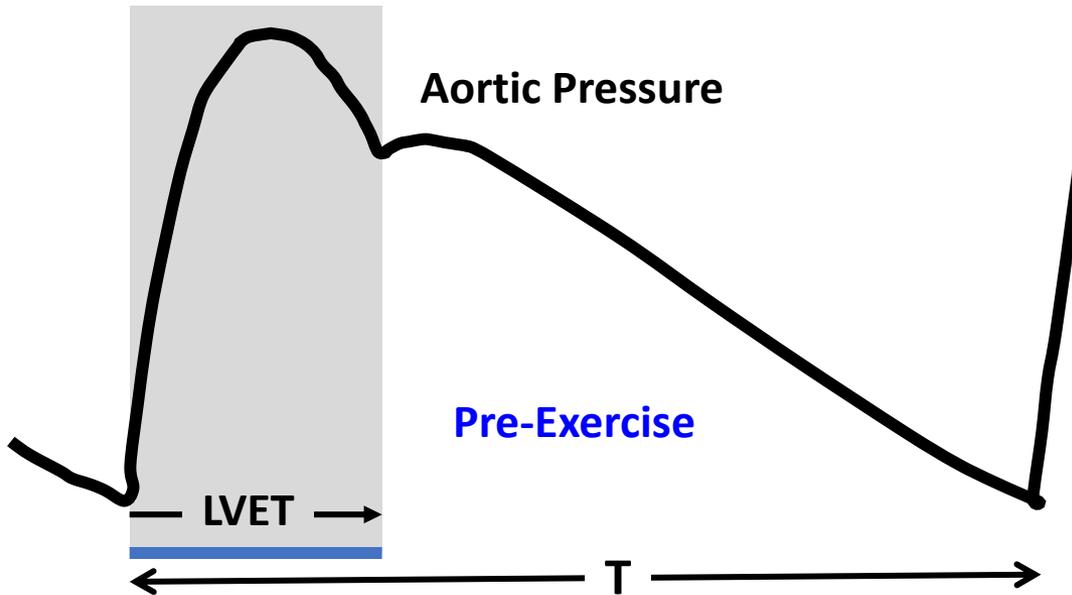


Bill is a healthy 25-year-old medical student. During his daily jogging routine his HR increases from his resting pre-exercise level of 60 to 120 bpm.

1. What is the value of time T?

2. What is his LVET before and after exercise?

3. What happens to the ratio of LVET to cycle time (T)?



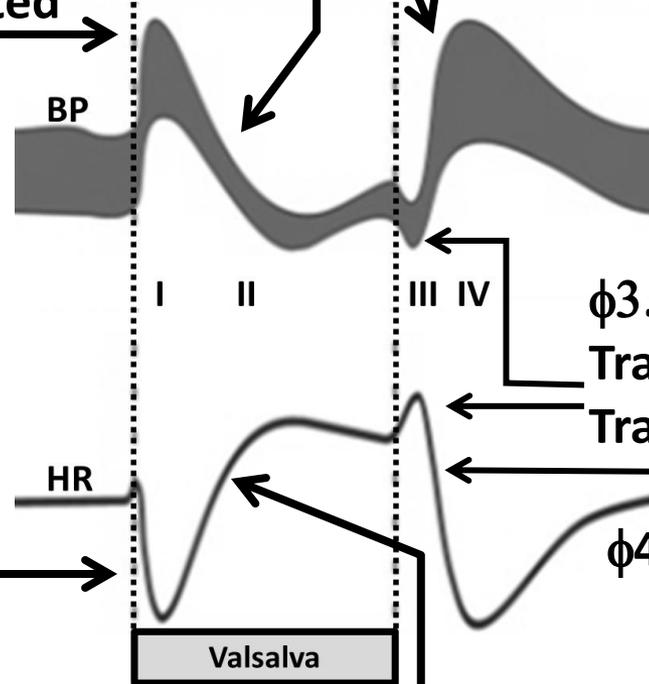
# Valsalva Maneuver: Normal CV Effects

φ2. Maintained  $+P_{TH}$  inhibits venous return to RA and compresses pulmonary vein causing reduced LA & LV filling. Reduced preload  $\rightarrow -SV$  &  $-BP$

φ1. Initial  $P_{TH}$  increase partly transmitted to aorta causes transient  $+BP$

φ4. Recovery  
 $+LV$  filling as “trapped” lung blood freed  
 $\rightarrow +SV \rightarrow +BP$

Forced expiration against a closed glottis



φ1. Baroreceptor initiated  $-HR$

φ3. Release  
 Transient  $-BP$   
 Transient  $+HR$

φ4. Recovery  
 $\rightarrow -HR$  (reflex)

φ2. Increase in HR initiated via baroreceptors sensing fall in BP

Valsalva may snuff out some Supraventricular Arrhythmias!

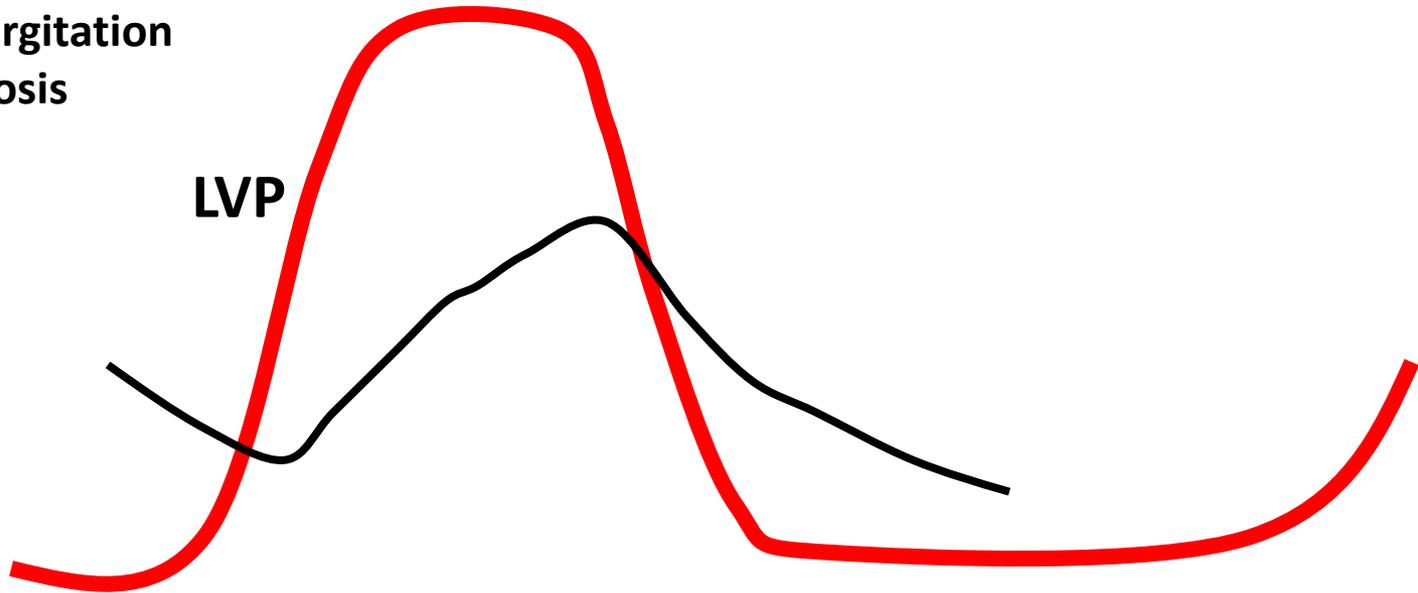
# Interactive Questions



# Interactive Question

- A. Normal
- B. Mitral Stenosis
- C. Mitral Regurgitation
- D. Aortic Regurgitation
- E. Aortic Stenosis

**What is Cardiac Valve Condition?**

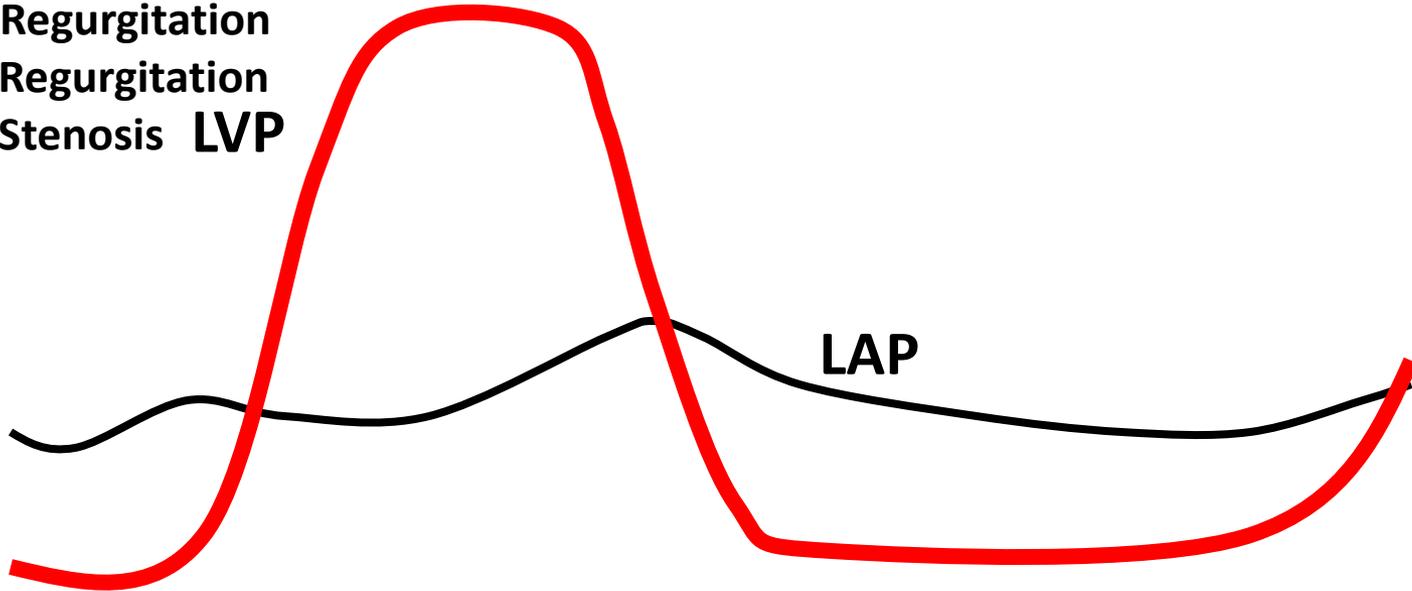




# Interactive Question

What is Cardiac Valve Condition?

- A. Normal
- B. Mitral Stenosis
- C. Mitral Regurgitation
- D. Aortic Regurgitation
- E. Aortic Stenosis **LVP**

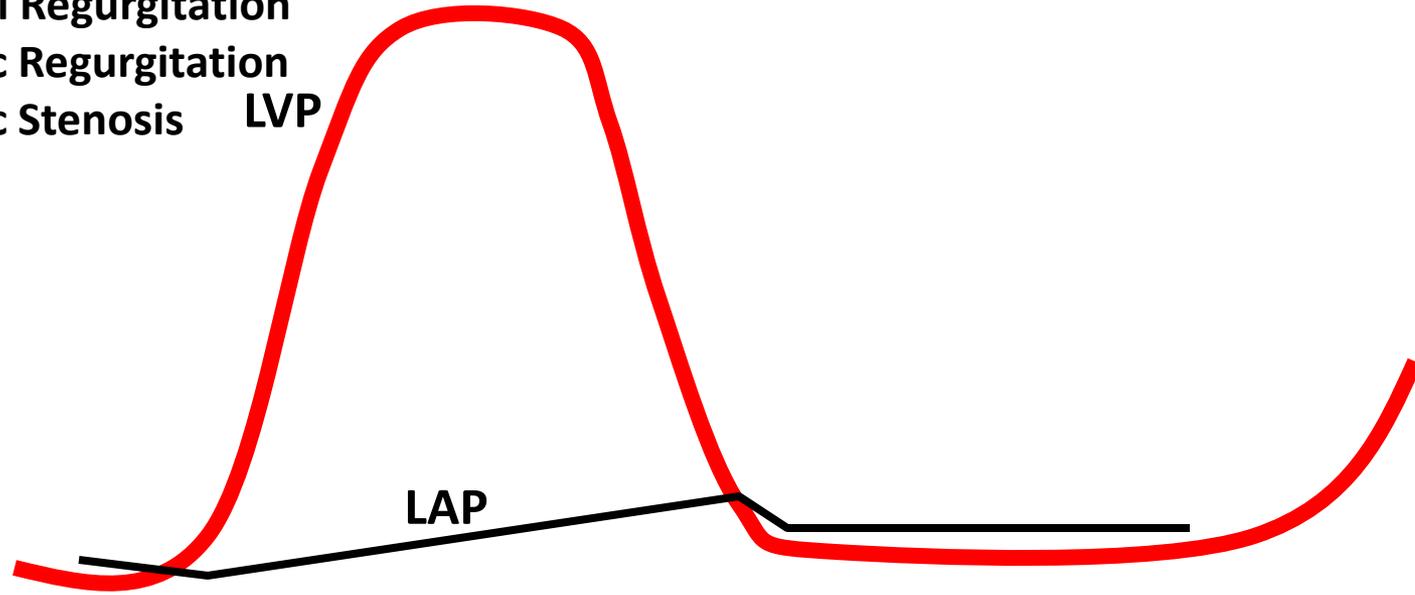




# Interactive Question

## What is Cardiac Valve Condition?

- A. Normal
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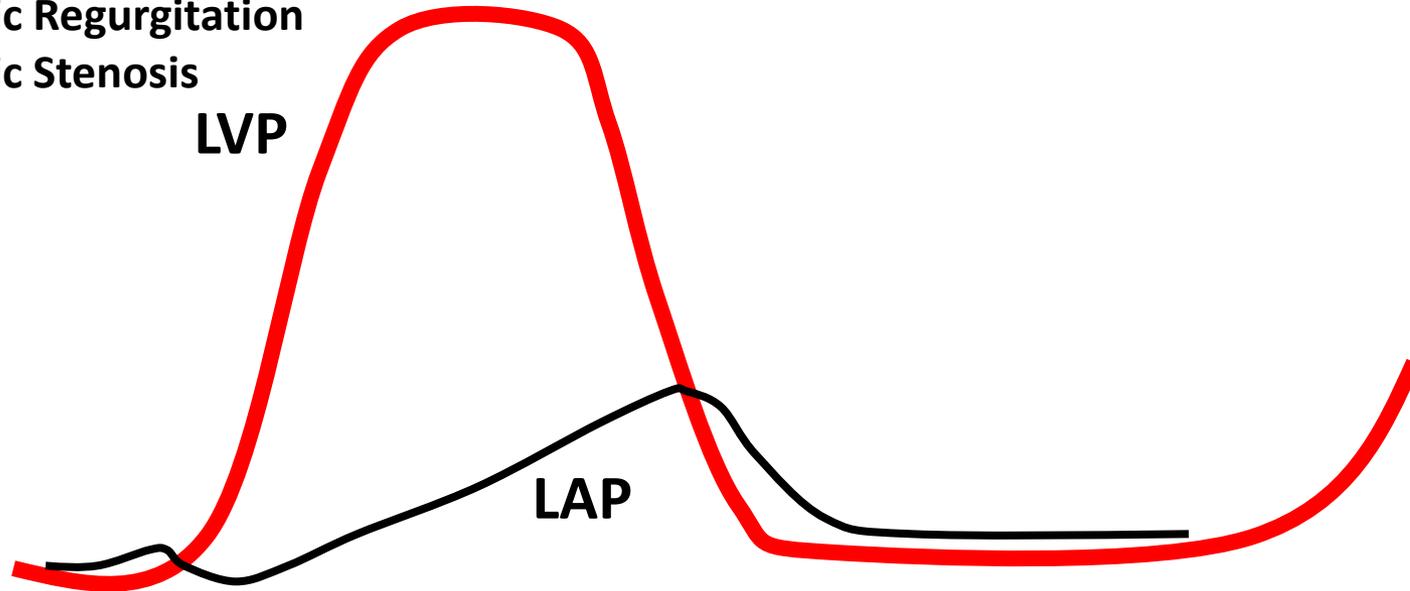




# Interactive Question

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What is Cardiac Valve Condition?

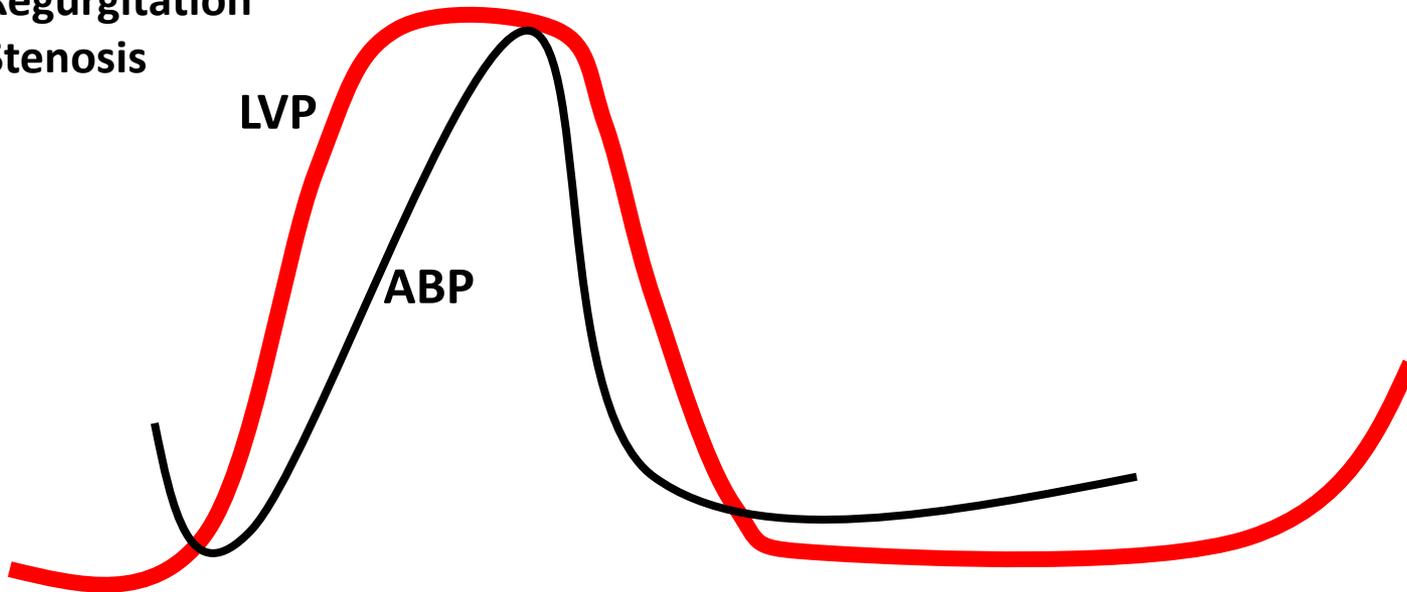


# Interactive Question



- A. Normal
- B. Mitral Stenosis
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- D. Aortic Regurgitation
- E. Aortic Stenosis

**What is Cardiac Valve Condition?**



# End CV Physiology Lecture 11