Physiology & Fluid Dynamics

Chapter 02

Heart

- The flow generator that is the foundation of the circulatory system
- Consists of 2 pumps in series:
  - Pumps blood through the lungs for O_2 / CO_2 exchange
  - Propels the re-oxygenated blood to all body parts
- Cardiac status plays a significant role in the entire vascular system
- Cardiac output governs the amount of blood that enters the arterial system

Heart

- Each beat pumps approximately 70 mL of blood into the aorta and causes a pressure pulse
- Cardiac contraction begins:
  - Pressure in the left ventricle rises rapidly
  - Left ventricle pressure exceeds that in the aorta
  - Aortic valve opens, blood is ejected, BP rises

- ***Stroke Volume***: The amount of blood ejected

Heart Pump

- Generates the pressure (potential energy) to move the blood
- Pumping action of the heart results in a high volume of blood in the arteries to maintain a high-pressure gradient between the arteries and veins
  - This pressure gradient is necessary to maintain flow
- Results in a pressure (energy) wave that travels rapidly throughout the system

Pressure

- The driving force behind blood flow
- Pressure is greater at the heart
- Gradually decreases as the blood moves further away

*** **This pressure difference is necessary to maintain blood flow** ***

❖ <u>Equal pressure at both ends of a vessel will results in ***NO FLOW***</u>

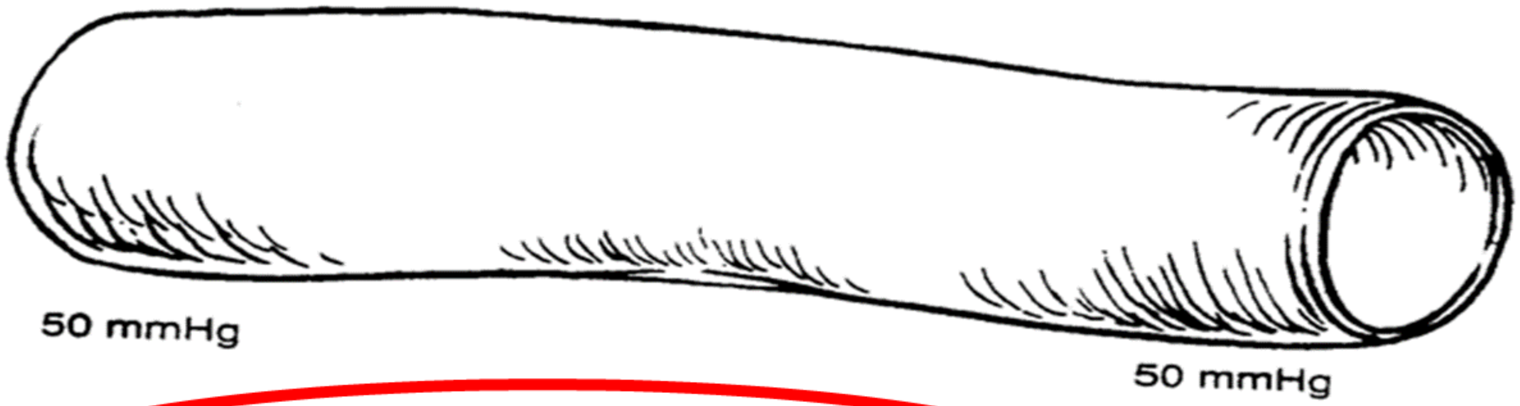
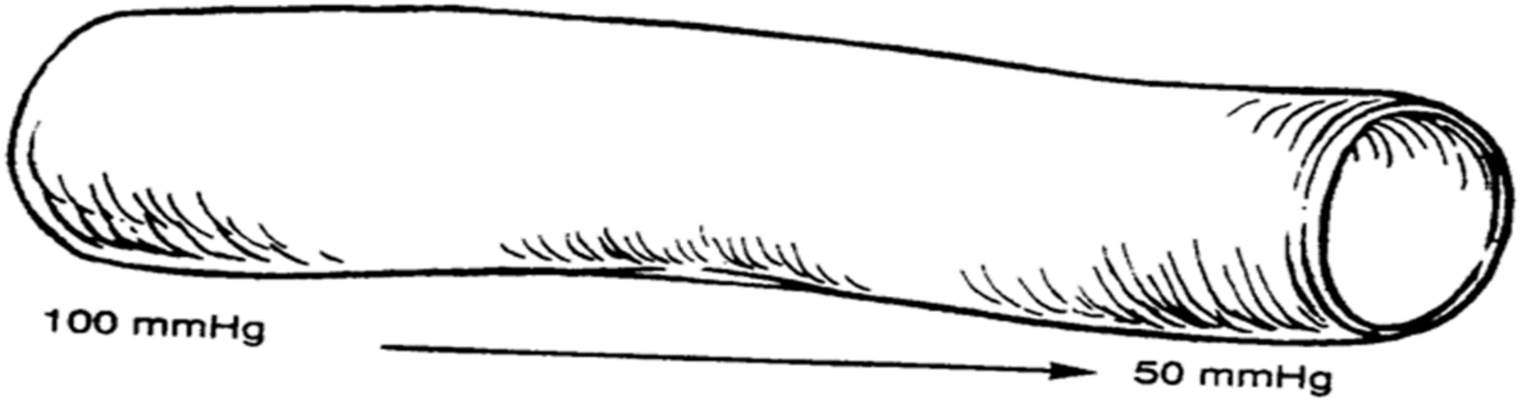


Figure 33.
There is no flow (usually) if there is no pressure gradient.



Pressure

- Circulatory systems consists of a
  - High pressure-High energy arterial reservoir
  - Lower pressure-Lower energy venous pool
- These 2 systems are connected by vessels of various sizes and are directly related by the resistance vessels that make up the microcirculation (arterioles, capillaries, and venules)
  - Arterioles are the principle points of resistance to blood flow

Energy

- The movement of fluid medium between any two points requires two things:
  - 1. Route along which the fluid can flow (blood vessel)
  - 2. Difference in energy (pressure) levels between two points
- The amount of flow depends on the resistance:
  - **Lower Resistance = Higher Flow Rate**
  - **Higher Resistance = Lower Flow Rate**

Energy

- Energy – power to produce motion, to overcome resistance, and to effect physical changes
- Three Types:

Potential Energy (Pressure)
+ Kinetic Energy
+ Gravitational Energy (Hydrostatic Pressure)
= Total Fluid Energy

Resistance

- Viscosity and vessel length affect resistance; however, a change in vessel radius will dramatically impact the resistance:

$$\text{Resistance (R)} = \frac{8\eta L}{\pi r^4}$$

- r = radius of vessel
- L = length of vessel
- η = viscosity of the fluid

Potential Energy

- Pressure Energy
  - Main form of energy present in flowing blood
  - *Stored or Resting Energy*
- Measured in mmHg
- Created by the continuous pumping action of the heart, followed by contraction of the Aorta
  - Pressure distends the vessel walls

Kinetic Energy

- *The energy of motion and work*
- The ability of flowing blood to do work as a result of its velocity
- Expressed in terms of fluid density and velocity measurements
- Increases occur whenever flow is high
  - During exercise
  - After stenotic lesions (high velocity)

Gravitational Energy

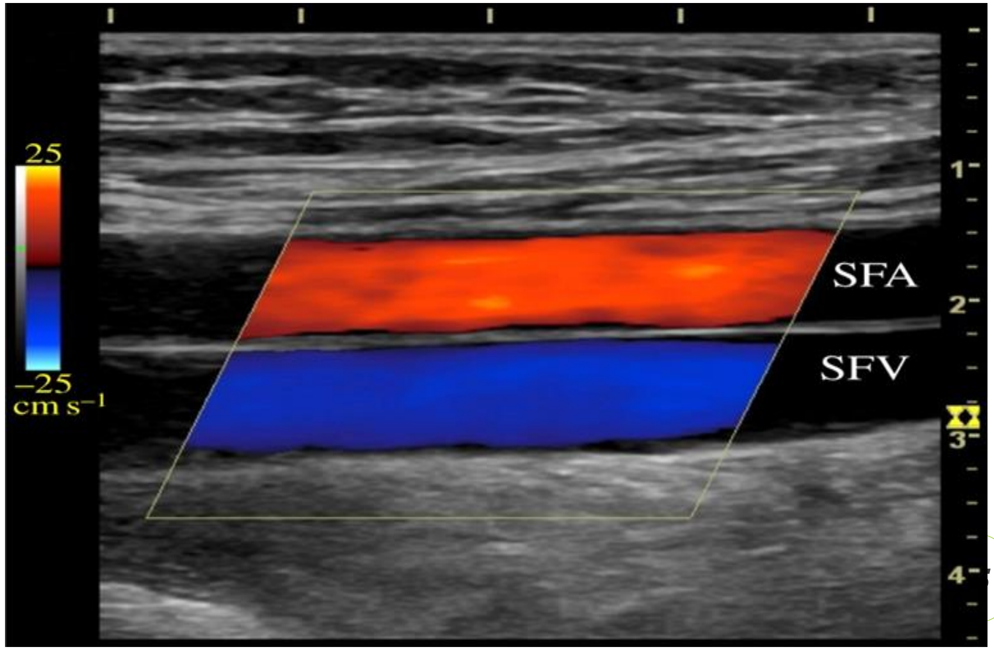
- **Hydrostatic pressure**
- Measured in mmHg
- Due to the weight of a column of blood when a person is erect
- Increases the pressure on the vessel walls – increasing the degree of distention of the vessel
- **Right atrium is considered the "0" pressure reference point**

Energy Gradient

- Needed to move blood from one point to another
- Greater the gradient; greater the flow
- Inertia helps to maintain the flow
- Blood moving to periphery; energy is lost largely in the form of heat (due to frictions from different layers of blood flow and vessel walls)
- Energy is constantly restored by the pumping action of the heart

Laminar Flow

- Consists of layers of fluid particles moving against one another
  - Moves in concentric layers or laminae
- Stable Flow
  - Fastest flow is in the center of the vessel
  - Slowest flow is at the wall of the vessel



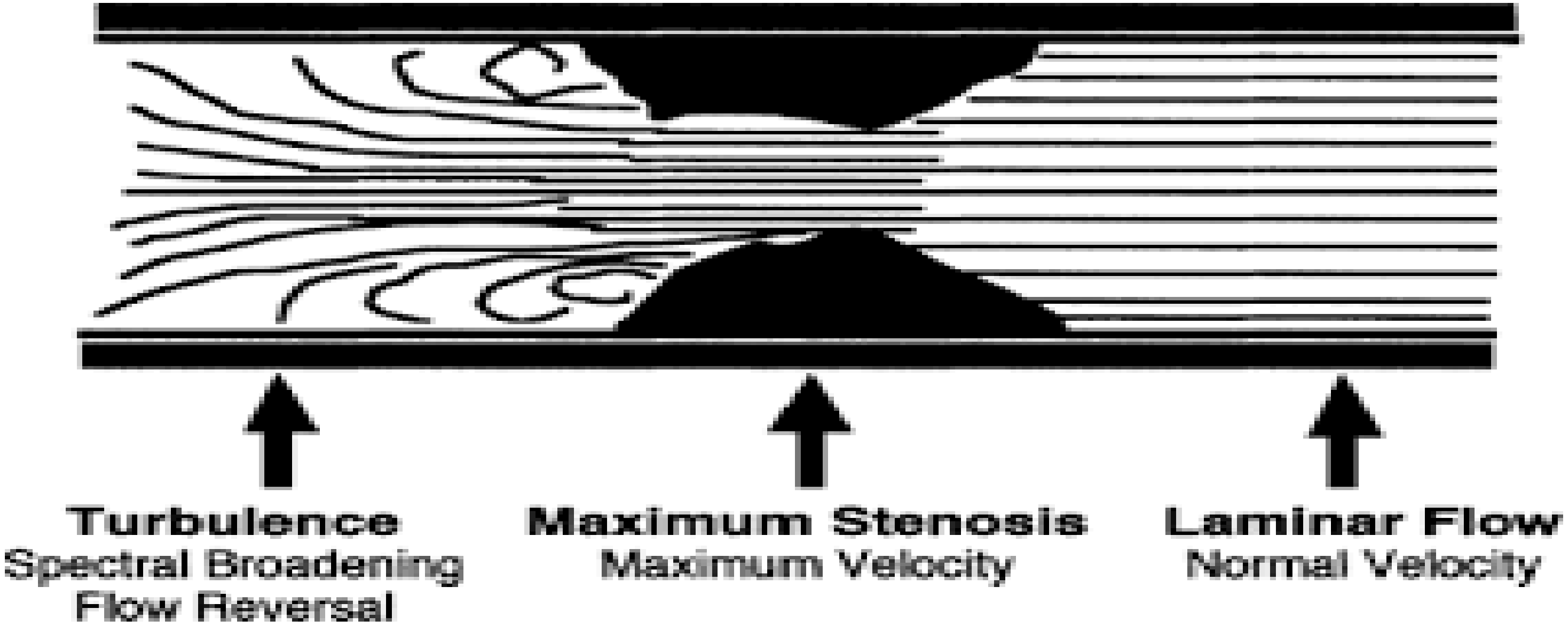
Energy Losses

- Viscous Energy Loss – determined by the thickness of a fluid
  - Thinner fluid moves more freely, allowing for higher velocities
    - Anemic patients
  - Thicker fluid moves less freely, slowing down the velocity
    - Patients with elevated hematocrits

- Heat is one method of viscous energy loss
  - Friction of RBC’s rubbing against the vessel wall creates heat
  - Smaller the vessels, the greater the friction

Energy Gradient

- Inertial Energy Loss – occurs as a result of changes from laminar flow due to changes in velocity and direction
  - Parabolic flow is flattened; flow moves in disorganized fashion
  - Occurs at the exit of a stenosis



Poiseuille's Law

- Describes the viscous or frictional loss of energy that occurs with changing vessel diameter
- Defines the relationship between:
  - Pressure
  - Volume Flow
  - Resistance

??? How much fluid is moving through a vessel ???

Poiseuille's Law

$$Q = \frac{(P_1 - P_2)\,\pi r^4}{8\,\eta L}$$

- Q = Volume Flow
- P_1 = Pressure at proximal end of vessel
- P_2 = Pressure at distal end of vessel
- r = radius of vessel
- L = length of the vessel
- η = viscosity of the fluid

$$R = \frac{\pi r^4}{8\eta L}$$

Poiseuille's Law

- Diameter change has the most dramatic effect on resistance
- Radius of a vessel is proportional to volume flow
- Small changes in radius may result in large changes of volume flow

$$Q = \frac{(P_1 - P_2)\,\pi r^4}{8\,\eta L}$$

$$R = \frac{\pi r^4}{8\eta L}$$

Reynold's Number

- A dimensionless number that expresses the elements that affect the development of turbulent flow

- The following are factors that affect the Reynolds number:
  - Velocity
  - Density of blood
  - Radius of vessel
  - Viscosity of blood

Reynold's Number

$$Re = \frac{V\rho 2r}{\eta}$$

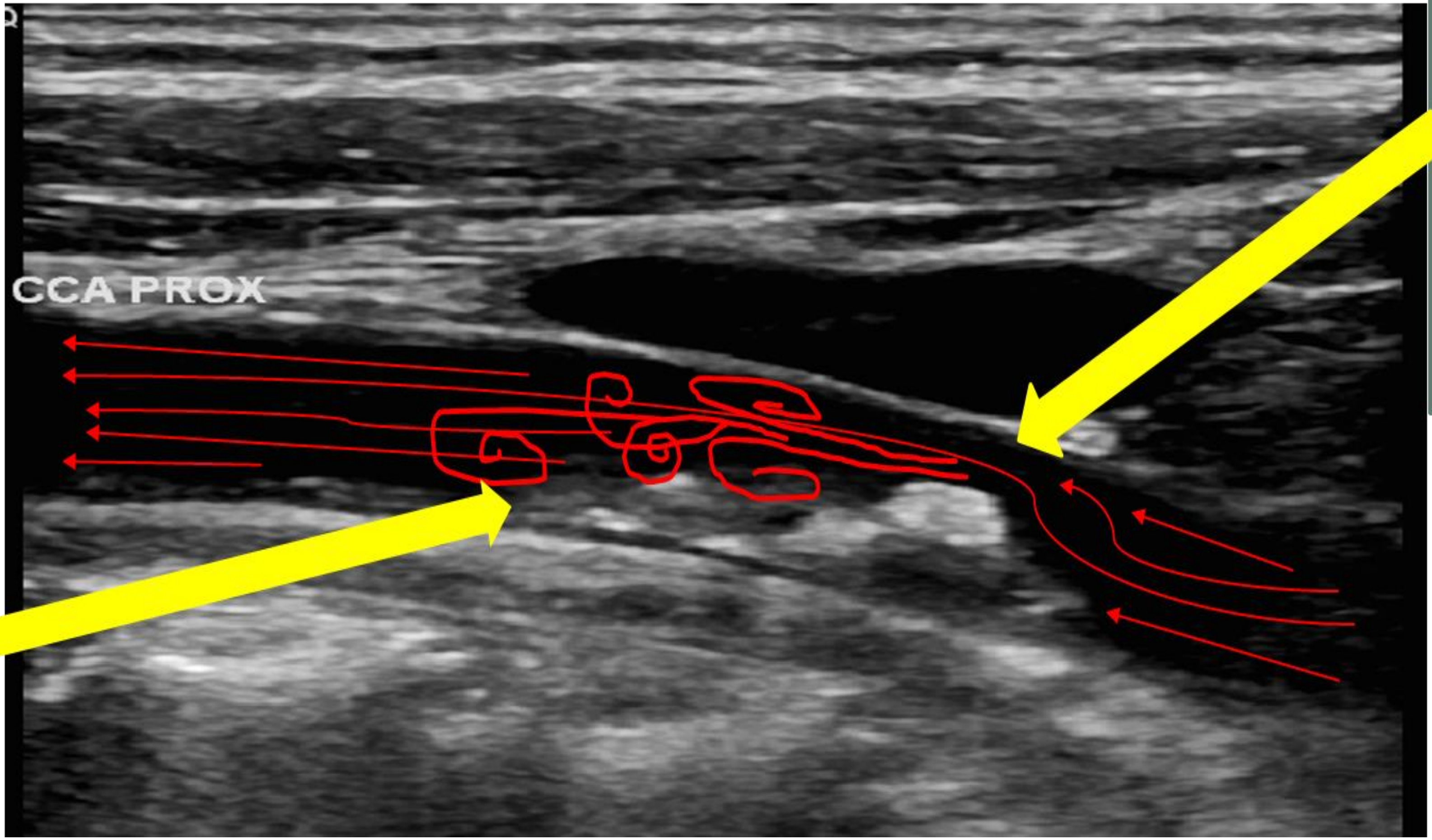
*** Reynolds Number > 2,000 = Turbulent Flow ***

- Turbulent flow may cause vessel walls to vibrate
  - The harmonics of the vibrations produces vascular bruits
- Eddy currents or vortices may be visible
  - Swirling patterns of rotational flow demonstrates turbulence

Bernoulli Principle

- Pressure and Velocity are inversely related
  - *Law of Conservation of Energy*:
    - High Velocity – Low Pressure
    - Low Velocity – High Pressure
- At a stenosis: blood velocity increases in the portion of the narrowing and pressure decreases
- At the stenosis outlet: velocity decreases and the pressure increases

Bernoulli Principle



Velocity Decreases; Pressure Increases

Velocity Increases; Pressure Decreases

Bernoulli Principle

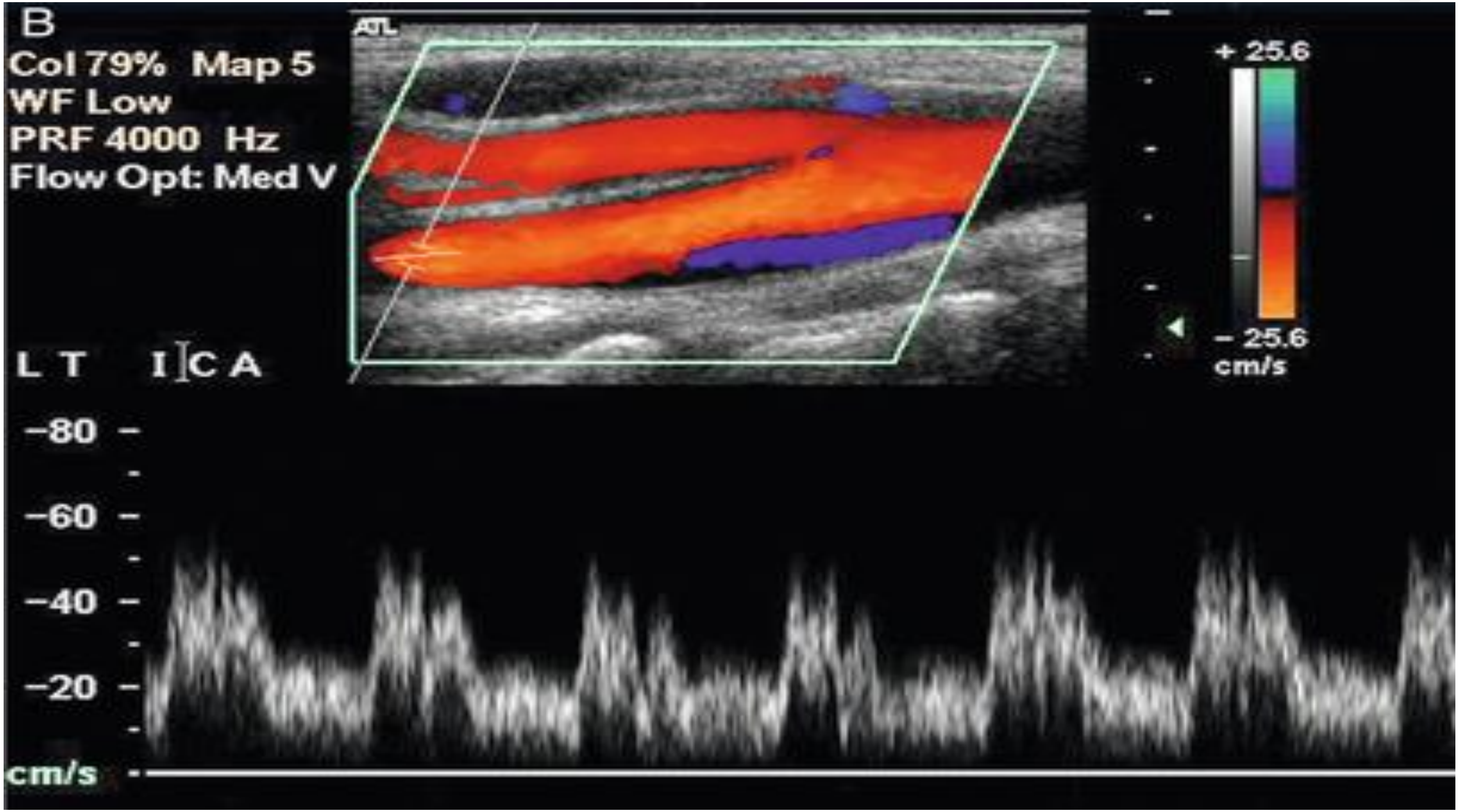
- Law of Conservation of Energy:

1. Pre-stenosis – pressure energy is high, kinetic energy is low
2. In the area of stenosis – pressure energy decreases, kinetic energy increases
    a) Energy is lost as heat due to friction at the stenosis
3. Post-stenosis – kinetic energy decreases, pressure energy increases

Flow Separations

- Created by differences in pressure between two points in a vessel
- Can be caused by the geometry of the vessel (i.e. tortuous, directional changes, widening of the bulb in the CCA, etc)
- During systole, a visible color change is noted
- During diastole, there is absence of color because blood is not moving

Flow Separations



Steady Flow

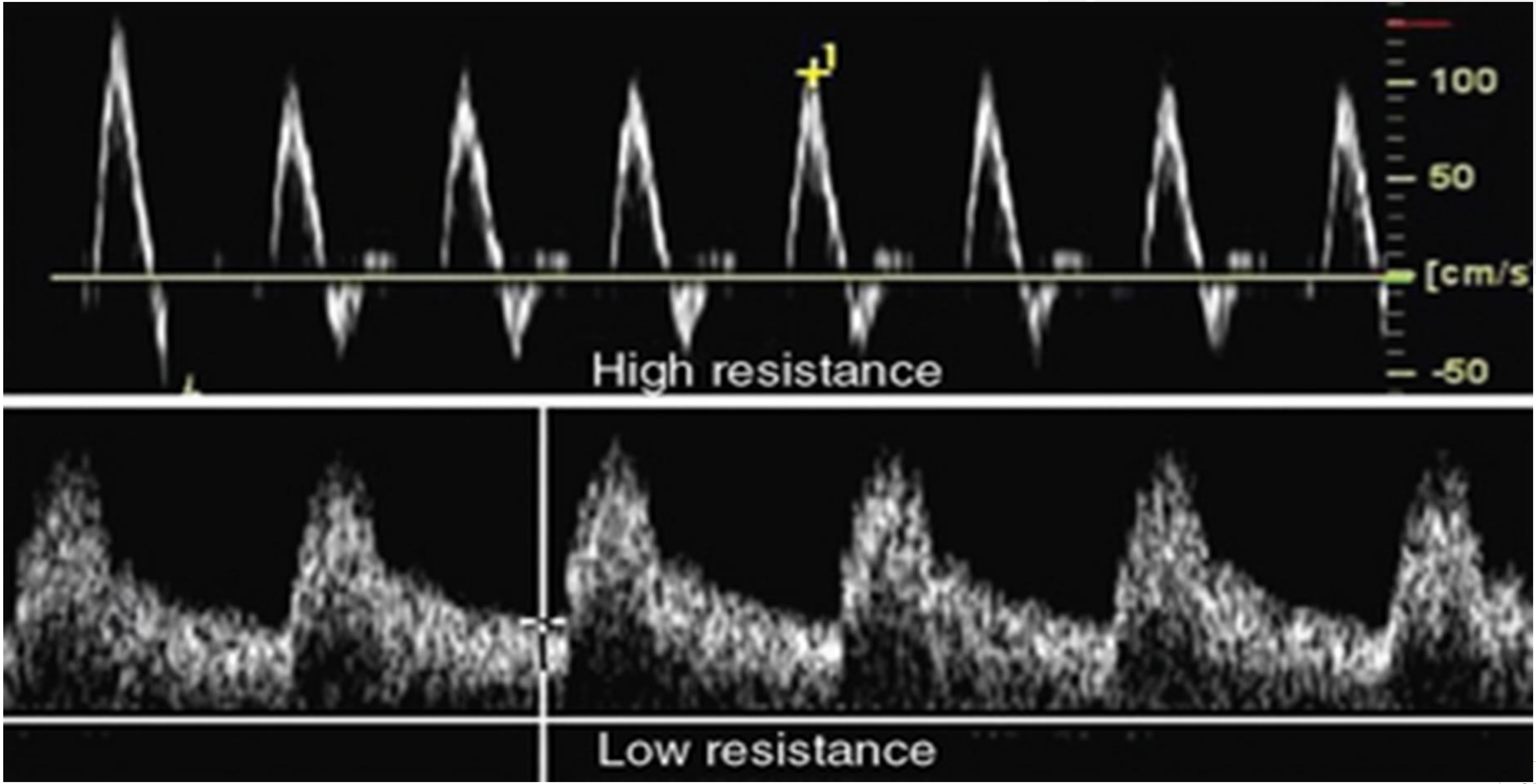
- Originates from a steading driving pressure that initiates movement
  - No decrease in pressure downstream, then No flow away from driving pressure
- Easy to analyze and describe because fluid dynamics are more predictable
- In a rigid tube, energy losses are mainly viscous

Pulsatile Flow

- Reflects changes in both the driving pressure conditions as well as the response of the vascular system
  - During systole: forward flow throughout the periphery (fluid acceleration)
  - During late systole/early diastole: temporary flow reversal due to a phase shifted negative pressure gradient and peripheral resistance causing a reflection of the wave proximally (deceleration and rest)
  - During diastole: flow moves forward again as the reflective wave hits the proximal resistance of the next oncoming wave and reverses direction again

Peripheral Resistance

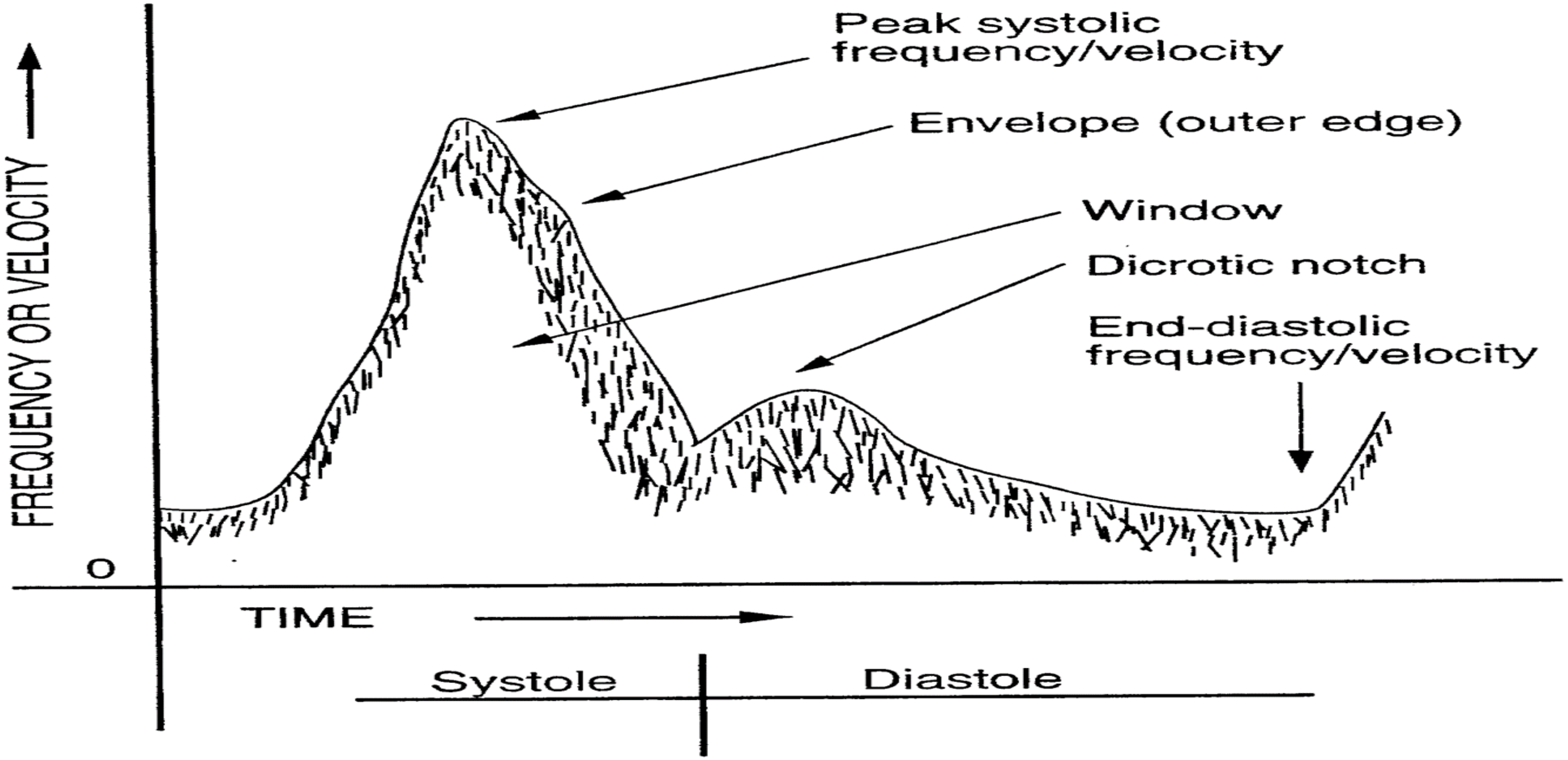
- Low Resistance Flow – flow of a continuous nature feeding a dilated vascular bed
  - i.e. ICA, vertebral, renal, celiac, splenic, hepatic
- High Resistance Flow – flow of a pulsatile nature (flow reversals evident between pulses)
  - i.e. ECA, subclavian, aorta, iliac, extremity arteries, fasting SMA
- Reversal quality of a high resistant signal may disappear distal to a stenosis because of a decrease in peripheral resistance, secondary to ischemia


100
50
[cm/s]
-50
High resistance
Low resistance

Waveforms

- Each cycle of the cardiac activity produces a distinct “wave”
  - It begins with systole
  - Ends in diastole

- “Waveform” – refers to the systolic and diastolic changes
  - This shape defines a very important flow property called “pulsatility”

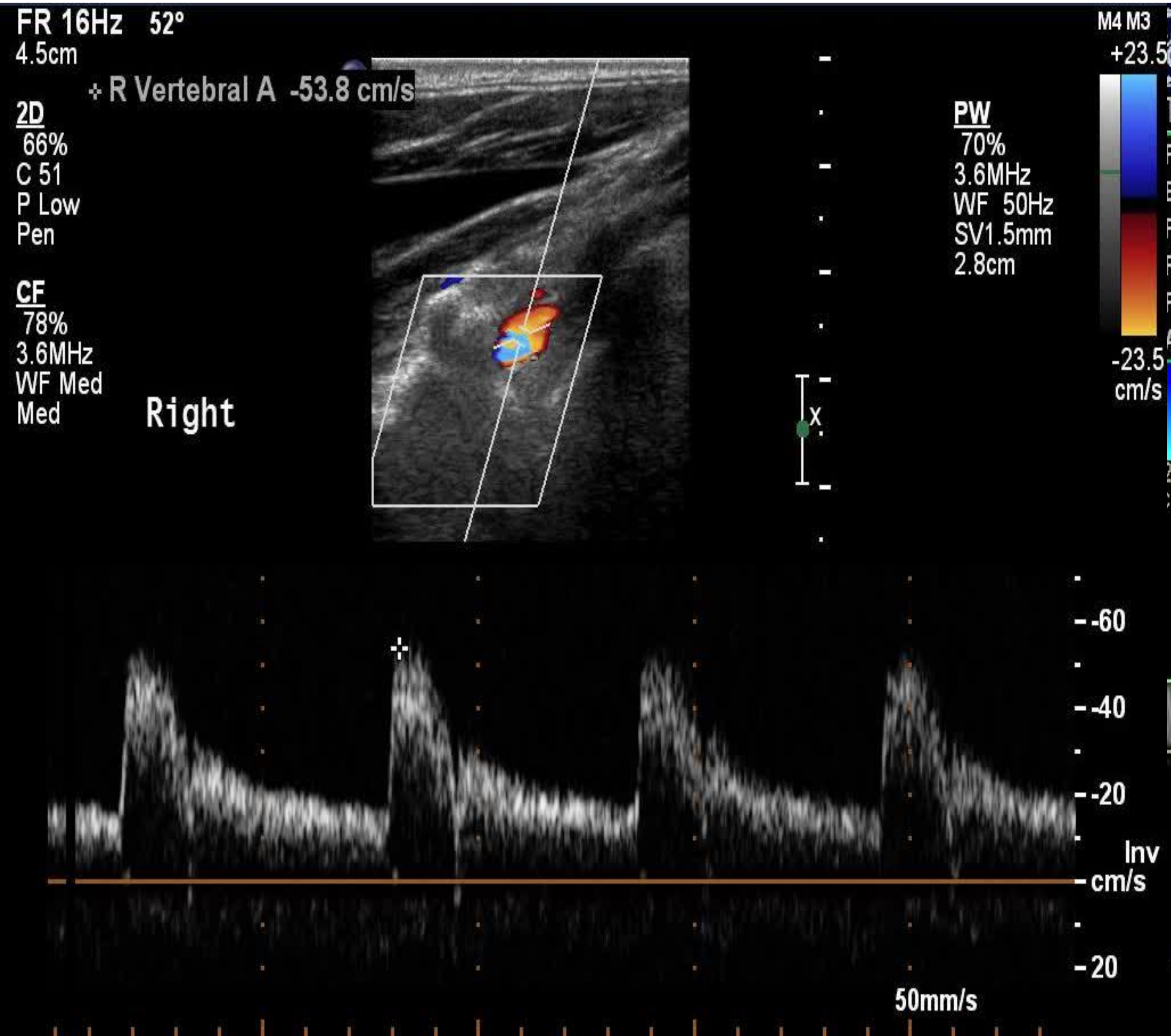

Peak systolic frequency/velocity
Envelope (outer edge)
Window
Dicrotic notch
End-diastolic frequency/velocity
FREQUENCY OR VELOCITY
0
TIME
Systole
Diastole

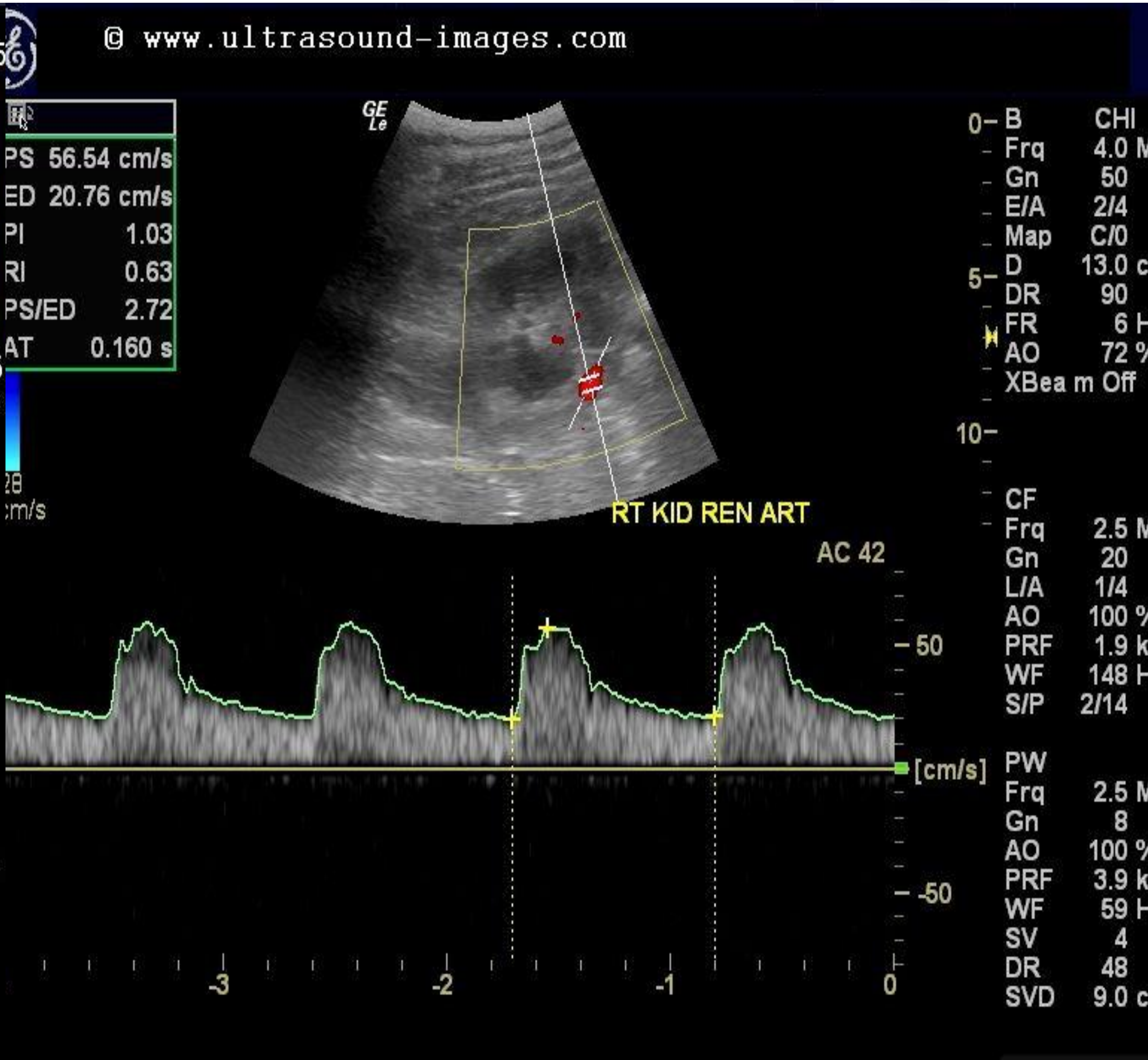
Low Pulsatility

- Monophasic:
  - Forward flow
  - Entire waveform is either above or below the baseline
    - i.e. carotid, vertebral, renal, and celiac arteries

*** Feed low resistance vessels (low peripheral resistance)***

Low Pulsatility

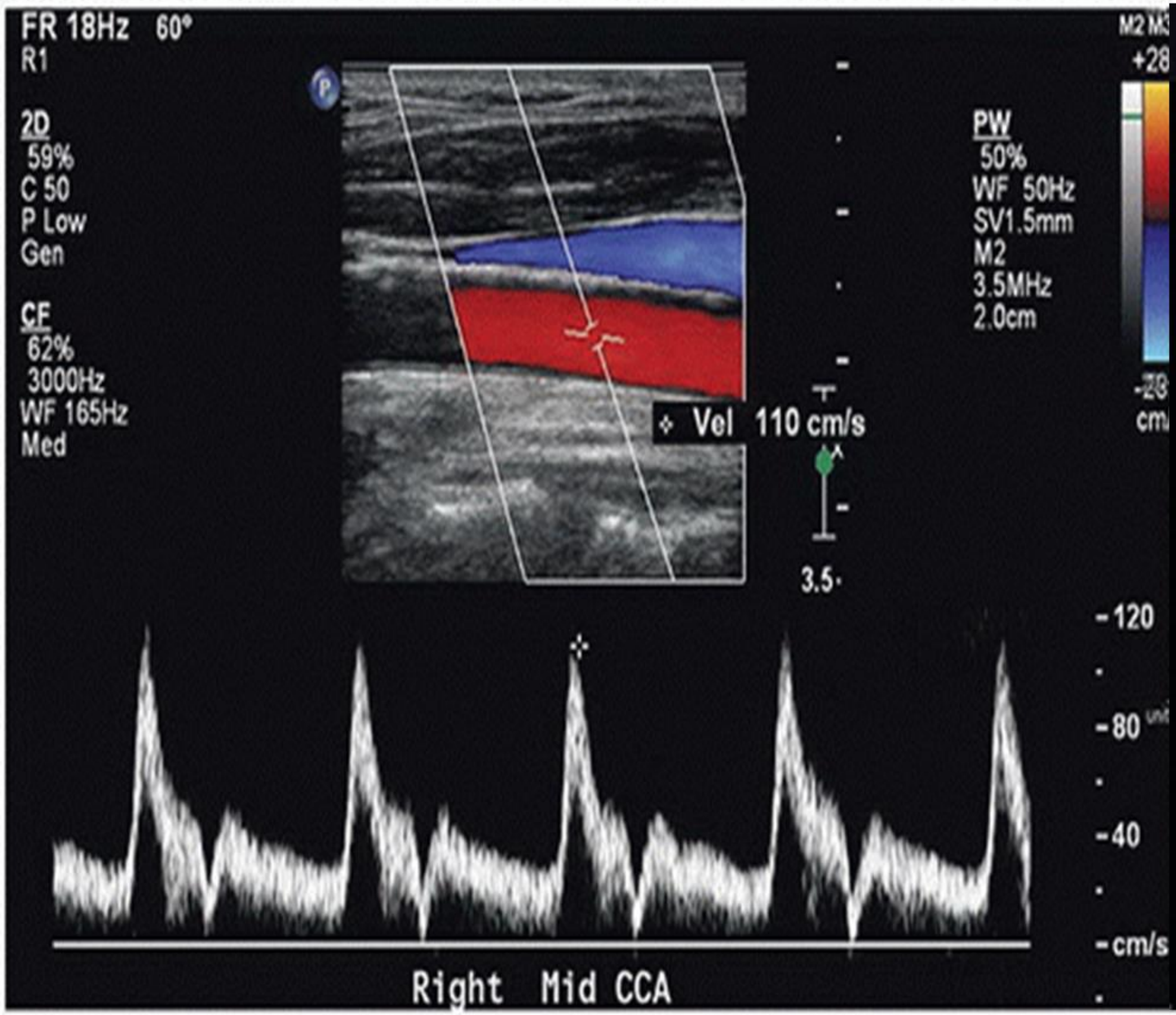


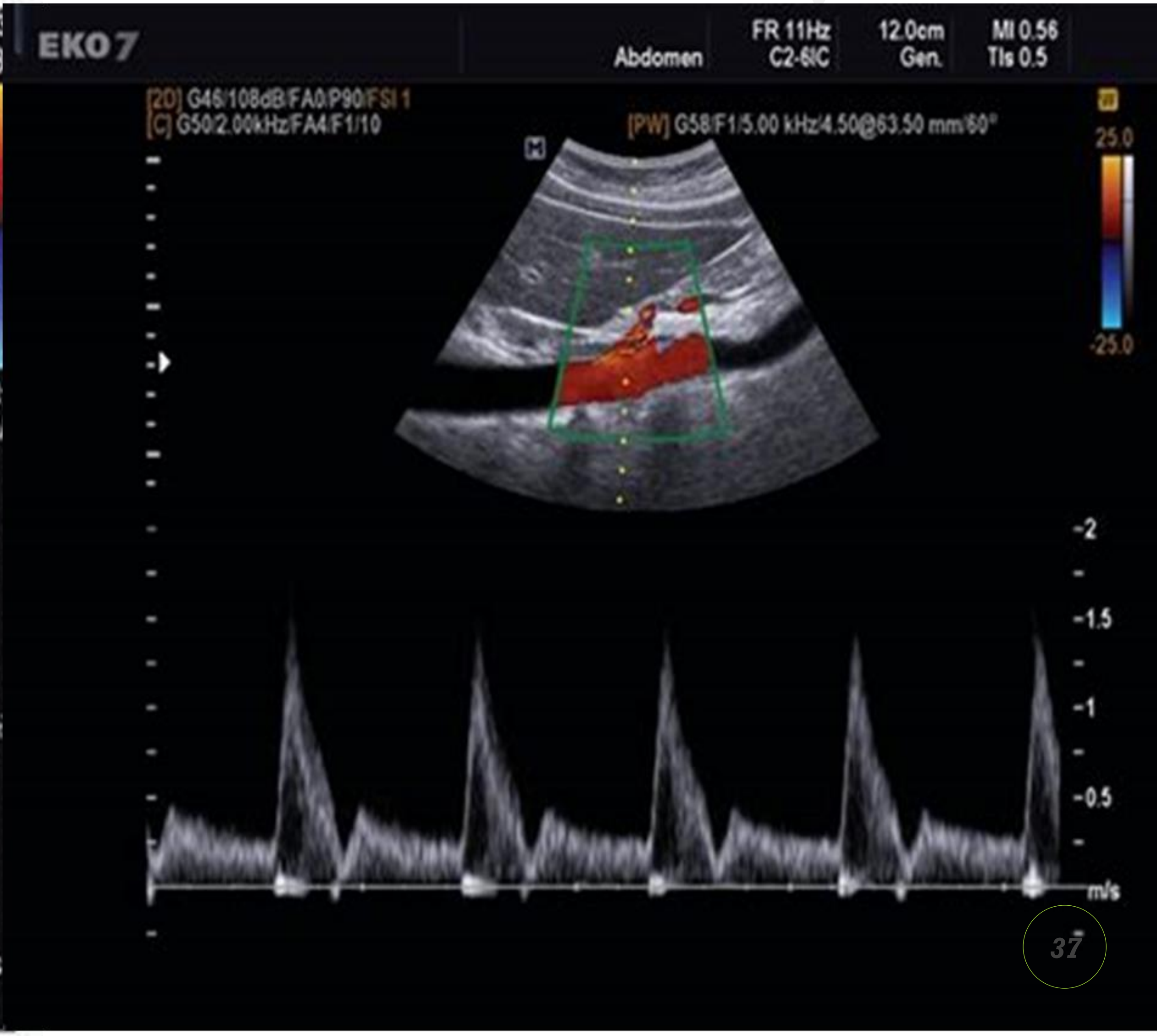


Moderate Pulsatility

- Waveforms have:
  - Tall and sharp systolic peaks
  - Forward flow throughout diastole with possible early diastolic flow reversal
    - i.e. ECA, fasting SMA

Moderate Pulsatility



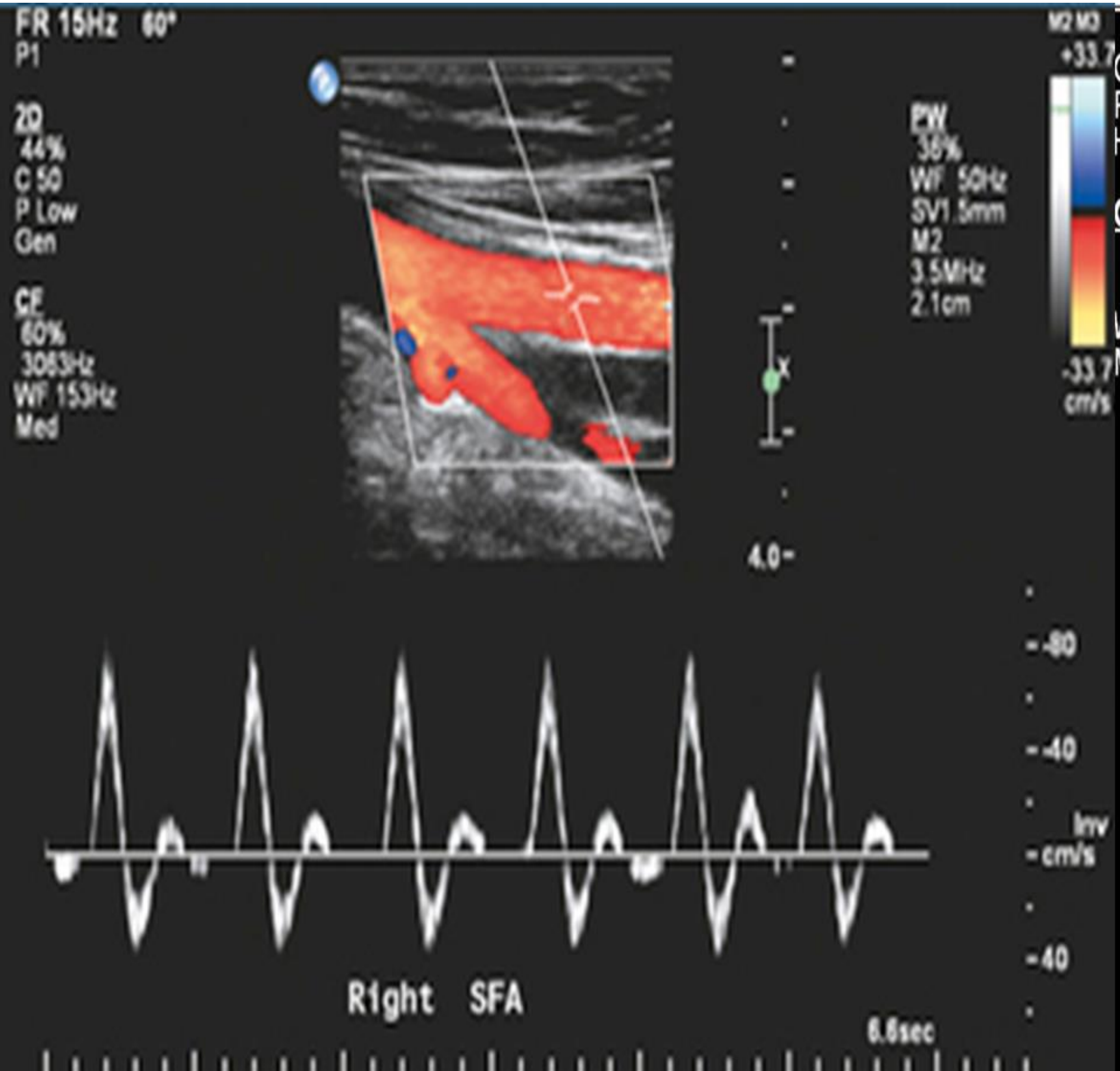


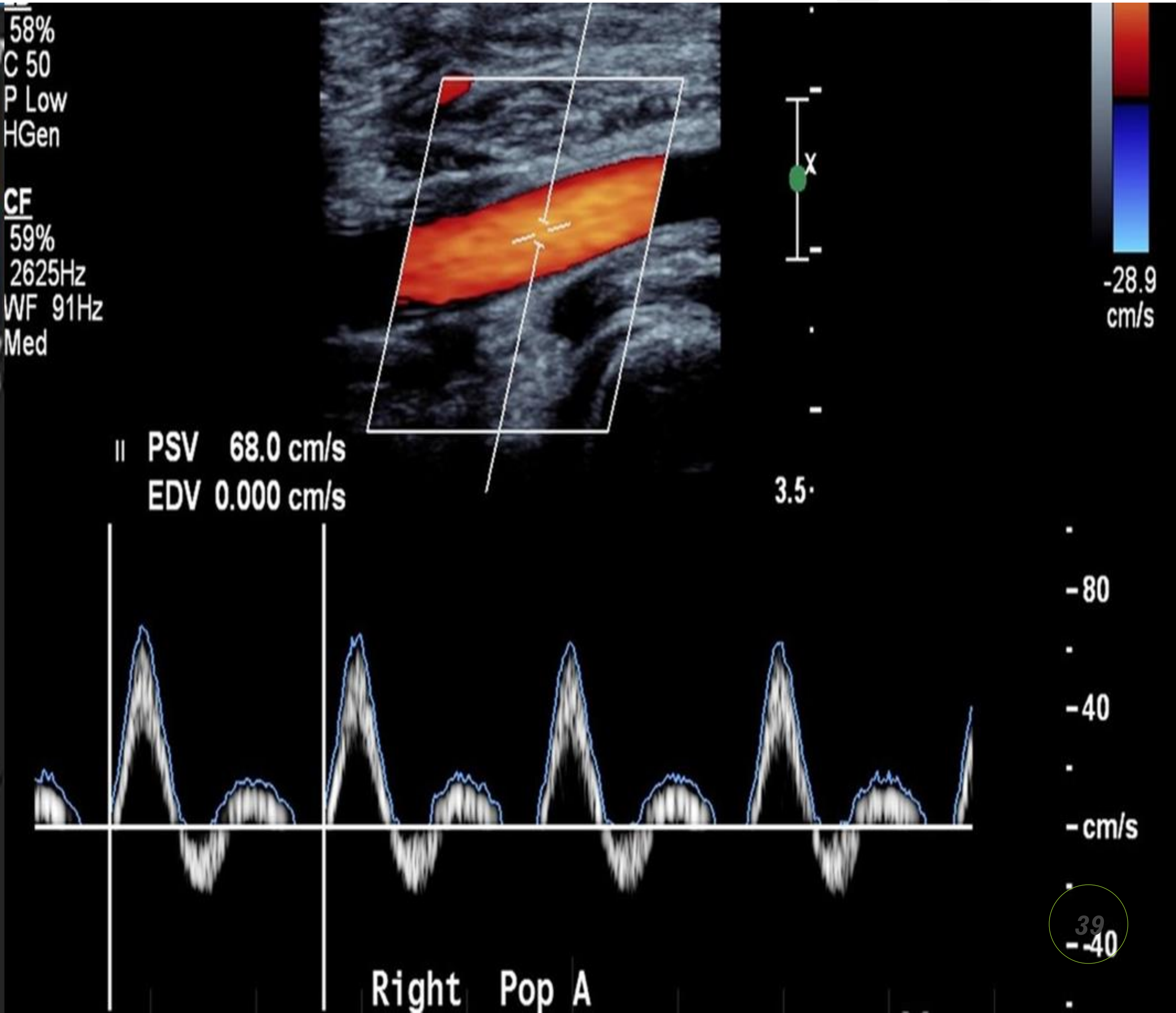
High Pulsatility

- **Triphasic:**
  - Sharp systolic peak (1st phase)
  - Brief flow reversal (2nd phase)
  - Brief flow forward (3rd phase)
    - i.e. SFA, Pop A., lower extremity arteries

*** Feeds high resistance vessels (high peripheral resistance) ***

High Pulsatility





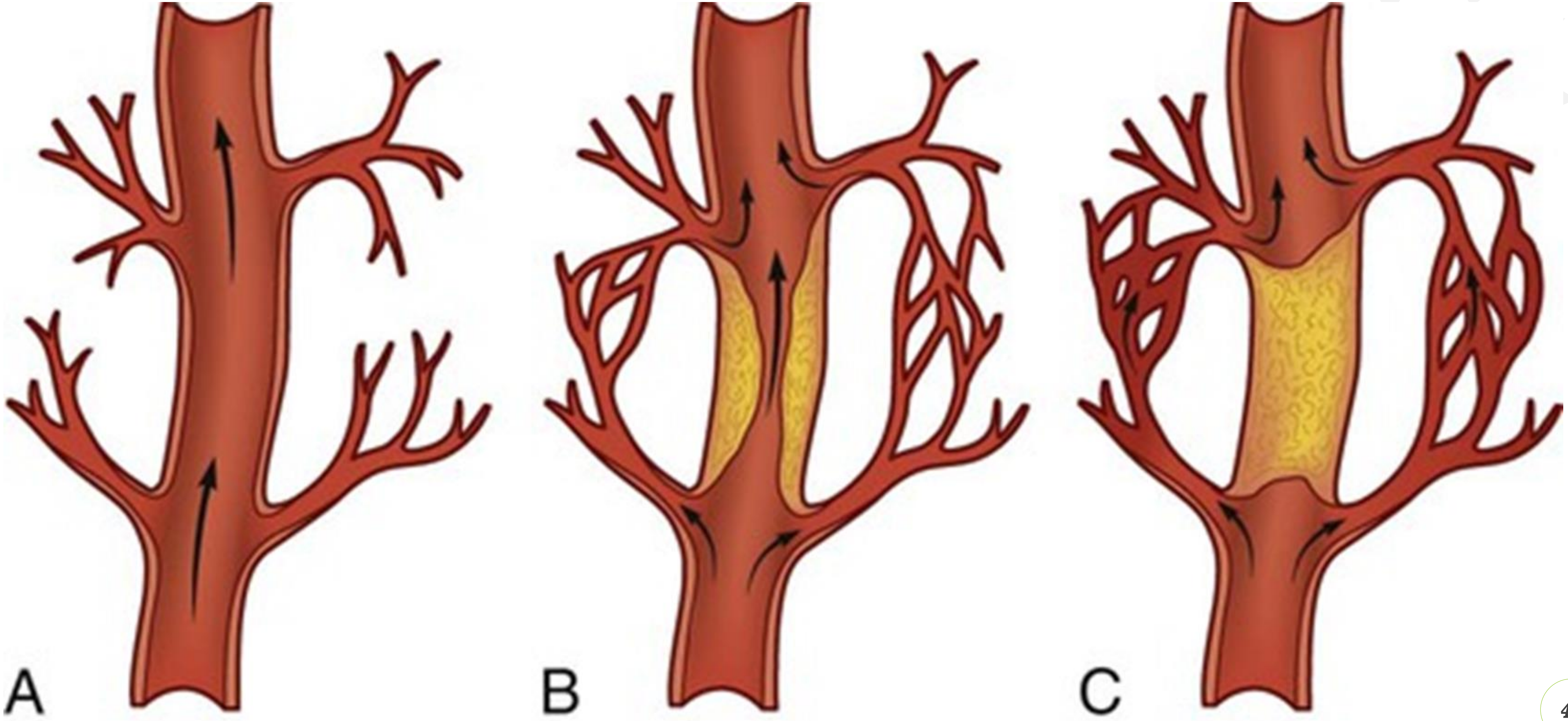
Cardiac Effects

- Cardiac activity plays an important role in the interpretation of Doppler patterns
- Common alterations in cardiac function that affect Doppler waveforms:
  - Cardiac Arrhythmias
  - Stenosis of Aortic Valve
  - Aortic Valve Regurgitation
  - High Cardiac Output
  - Low Cardiac output
  - Intra-aortic Balloon pump
  - Ventricular Assist Device (VAD)

Collateral Effects

- When a patient is resting, total blood flow may appear normal in the presence of a total occlusion/stenosis due to collaterals
- Location of the collaterals will give an indication to the level of obstruction
- Collaterals can be assessed by Duplex imaging or by using Doppler segmental pressures

Collateralization Process

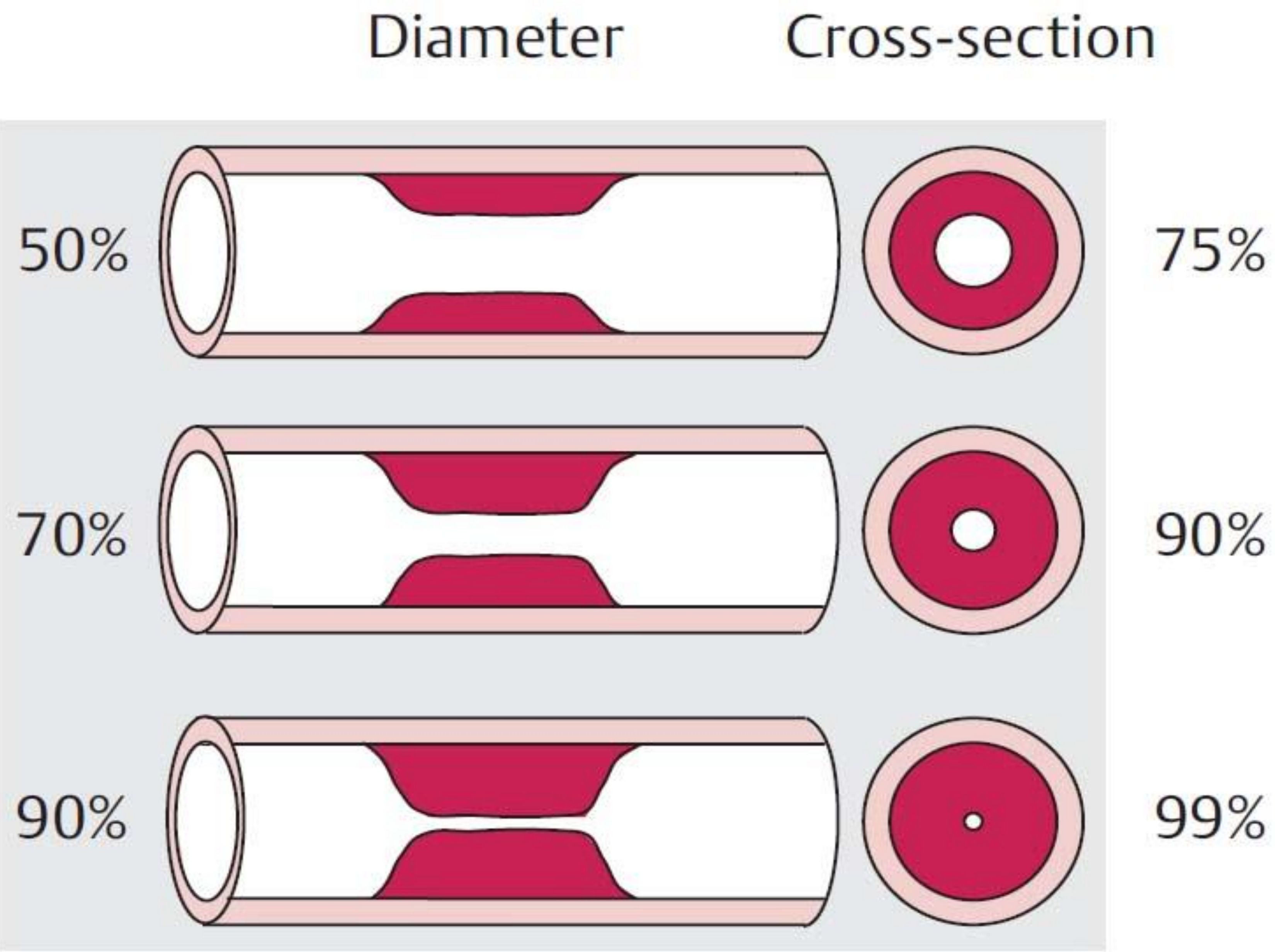


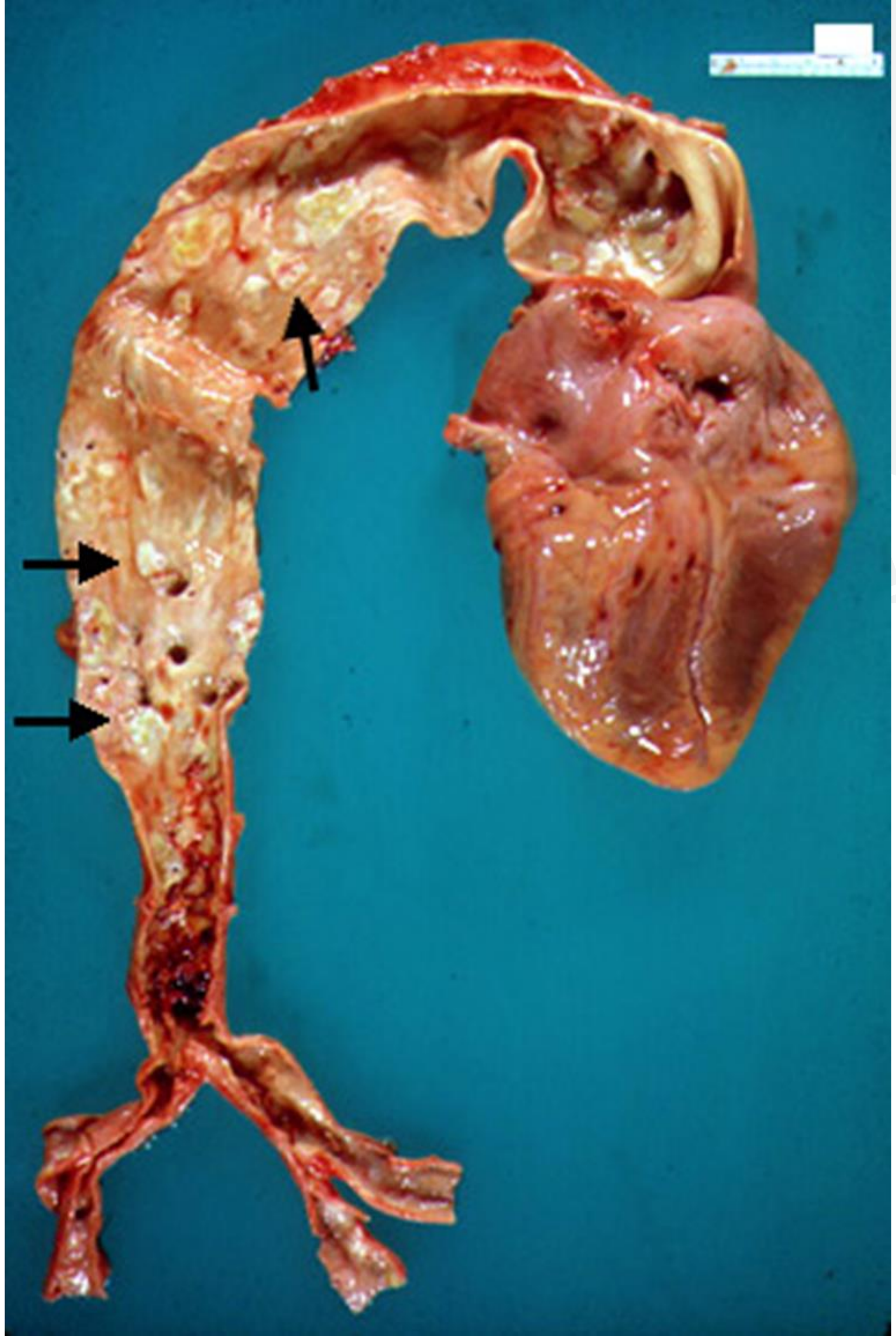
Effects of Exercise

- Exercise should induce peripheral vasodilatation
  - Increases blood flow
  - Decreases distal peripheral resistance
- Exercise is probably the best vasodilator of high-resistance vessels
- Questions needs to be asked: Was the extremity cooled or warmed? Has it been exercised prior to the exam?
  - Flow to a cool, vasoconstricted extremity will be pulsatile
  - Flow to a warm, vasodilated extremity will have continuous, steady flow

Effects of Stenosis on Flow

- Hemodynamically significant stenosis causes a reduction in volume flow and pressure
- Hemodynamically significant stenosis is when:
  - Cross sectional area reduction is 75%
    - This corresponds to a diameter reduction of 50%
    - In hemodynamically significant stenoses, both pressure and flow volume decrease


Diameter
Cross-section
50%
75%
70%
90%
90%
99%



Effect of Stenosis on Flow

- Two or more stenotic lesions that occur in a series have a greater effect on volume flow and distal pressure than a single lesion of equal total length
  - Significant energy is lost at the entrance and exit of lesions; two lesions create a greater energy loss
- Degree of stenosis significance is dependent on many factors:
  - Length of narrowing
  - Diameter of narrowing
  - Roughness of endothelial surface
  - Shape and degree of narrowing
  - Arteriovenous Pressure Gradient
  - Distal peripheral resistance
  - Collateral formation

Effects of Stenosis on Flow

- Proximal to a stenosis; flow velocities are dampened
- At the stenosis; flow velocities increase
  - May demonstrate spectral broadening
- Post-stenotic turbulence is seen at the stenosis outlet
  - Most energy loss is due to heat as the eddy currents and vortices work against the viscosity of the blood