

# Doppler Imaging Concepts

Chapter 4



# *Hemodynamics*

# Types of Energy

- Hemodynamics is the study of blood flow through the vessels in the body
- Blood moves through vessels because of a difference in fluid energy, called an **energy gradient**
  - Without the energy gradient, no flow would exist
  - Energy is higher at the beginning of the vessel ( $E_1$ ) and lower at the end of the vessel ( $E_2$ )

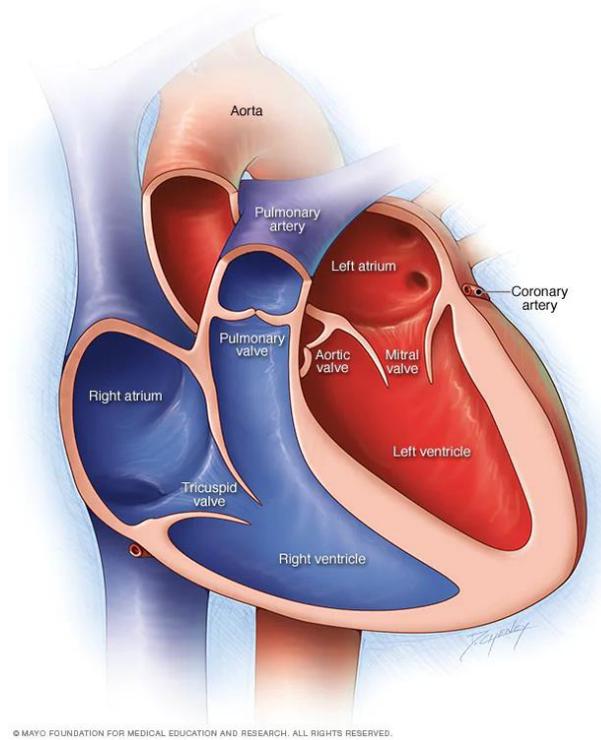
$$\text{Energy gradient} = E_1 - E_2$$

# Types of Energy

- Many different types of energy gradients exist within the circulatory system:
  - Potential Energy (Pressure)
  - Kinetic Energy (Velocity)
  - Gravitational Energy (Hydrostatic Pressure)
- Total Fluid Energy is the summation of all three types of energy

# Types of Energy

- **Pressure Energy** is the driving force of the blood through the blood vessels
  - **Created by left ventricular contraction**
  - Provides the necessary **Potential Energy** (i.e. **pressure**) at the beginning of the system
  - Think of potential energy as having the ability to perform work, like a can of spray paint
    - Aerosolized paint is contained within the can, but its not able to paint anything until you press down on the nozzle and release the paint



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# Types of Energy

- As blood flow moves through the vessel, the potential energy is converted into **Kinetic Energy** (i.e. **velocity**)
  - Kinetic energy is energy created by flowing blood
  - **Potential energy is converted into kinetic energy minus the energy lost as a result of friction**
- Kinetic energy is determined by an object's mass and the speed at which it moves
  - Heavier objects will move faster (golf ball)
  - Light objects will move slower (ping-pong ball)

# Types of Energy

- **Hydrostatic pressure**, also called gravitational potential energy, examines how gravity, the density of blood, and distance can affect blood flow
  - Associated with any elevated object
  - Downhill skier vs. cross-country skier

# Types of Energy

- Blood flow loses energy as it travels through a vessel
- Two major forms of energy loss:
  - 1. Viscous (frictional)**
  - 2. Inertial**

# Types of Energy

- Viscous energy loss occurs when kinetic energy is converted to heat as a result of friction
  - Viscosity is related to the thickness of fluid - higher viscosity means more energy loss
  - Based off hematocrit levels (% of RBC)
  - The thicker the fluid, the more friction that will occur
  - Viscosity is measured in units of **POISE**

# Types of Energy

- Blood also undergoes inertial losses, which occur when blood vessels divide, forcing the blood flow to change direction
- Inertia is described by Newton's First Law
  - **An object at rest stays at rest and an object in motion stays in motion, unless acted on by an outside force**
- Each time blood changes direction, there is an energy loss related to inertia

# Types of Energy

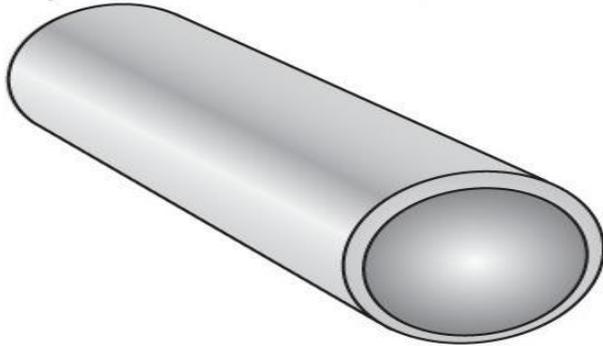
- Total energy in the system never changes (Law of Conservation of Energy)
  - There is the same total energy at the beginning of the vessel as there is at the end, however the types of energy might be different
- Potential energy is greatest at the beginning of a vessel, but it quickly converts into kinetic energy and heat (from friction)
  - Kinetic + heat energy = potential energy that was originally seen at the beginning of the vessel

# Pressure Gradient

- **Flow (Q)** is the **volume** of blood moving through a vessel per unit of time
  - Units: Liters/min, ml/s - (volume/time)
  - Answers the question "How much?"
- For flow to occur, there must be higher pressure at one end of a blood vessel and lower pressure at the other end (known as pressure gradient)
  - Larger the pressure gradient, the more flow that will occur
    - $\Delta P$  (pressure gradient) =  $P_1 - P_2$

# Pressure Gradient

$P_1 = 100 \text{ mm Hg}$

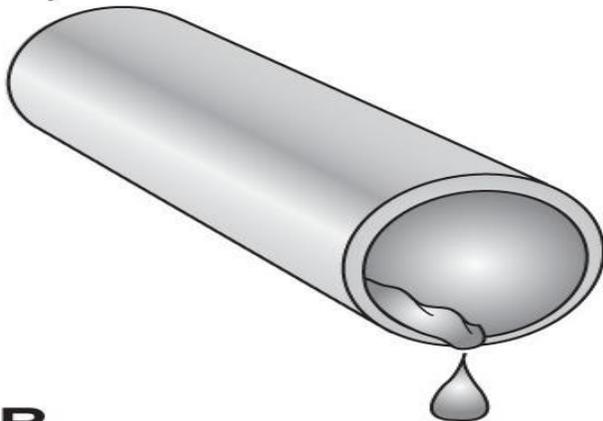


Identical pressures ( $P_1 - P_2 = 0 \text{ mm Hg}$ ) = no flow

$P_2 = 100 \text{ mm Hg}$

**A**

$P_1 = 100 \text{ mm Hg}$



Pressure gradient ( $P_1 - P_2 = 1 \text{ mm Hg}$ ) = flow  
Amount of flow is proportional to pressure gradient

$P_2 = 99 \text{ mm Hg}$

**B**

# Pressure Gradient

- The systemic circulation begins with the left ventricle of the heart to the aorta, and from the aorta to the arteries of the body
- The arteries become arterioles, the vessels responsible for **vasoconstriction** and **vasodilatation** in the body
- Arterioles then become the capillaries, where nutrient and waste exchange occurs

# Pressure Gradient

- From the capillaries, the blood flows into the venules and then into the veins
- The venous part of the systemic circulation is known for its **capacitance**, as approximately 2/3 of the blood is stored in the veins
- The veins drain into the inferior vena cava or superior vena cava, both of which empty into the right atrium

# Blood Vessels and Blood Flow

- The walls of the arteries and veins are similar in that they consist of the same layers
- Both arteries and veins have a tunica intima, tunica media, and tunica adventitia
  - The vasa vasorum supplies blood flow to the tunica adventitia
- As blood travels through the cardiovascular system, the arteries and veins experience differences in pressure
  - It is because of this pressure that arteries typically have a much thicker tunica media compared with veins

# Types of Blood Flow

- Three types of flow are found in blood vessels:

## 1. Plug flow

- Plug flow can be found in large blood vessels and at the entrance of vessels; eventually becomes parabolic

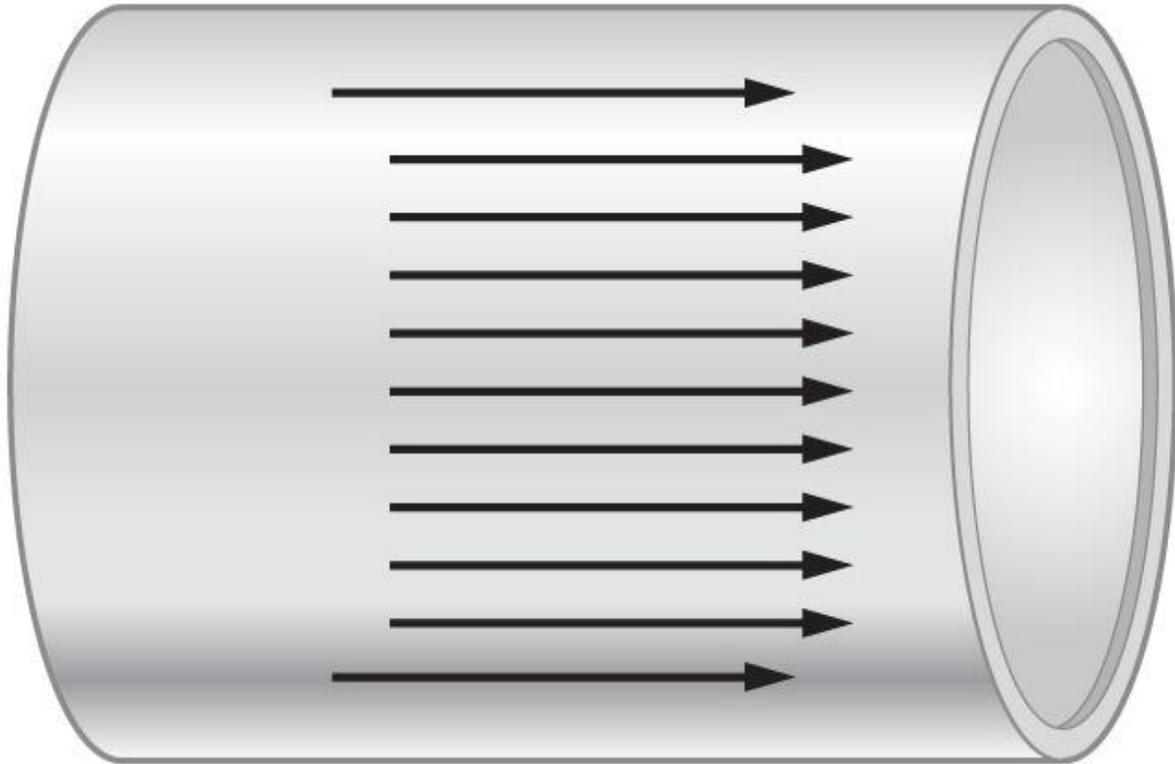
## 2. Laminar flow

- Most common type of blood flow in arteries; contains a boundary layer near the vessel wall with fastest blood flow in the center of the lumen

## 3. Turbulent flow

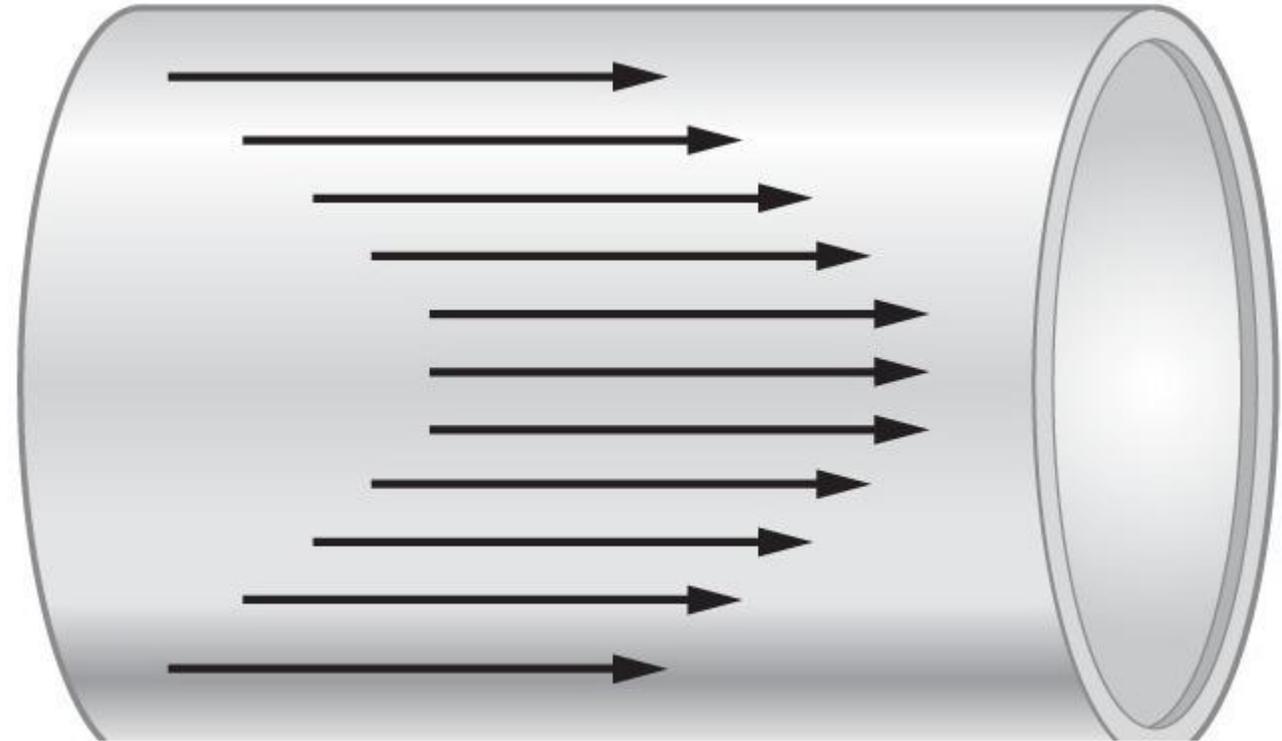
- Chaotic and disorganized resulting from many different velocities
- Does not always indicate pathology; can be seen in normal vessels

# Types of Blood Flow



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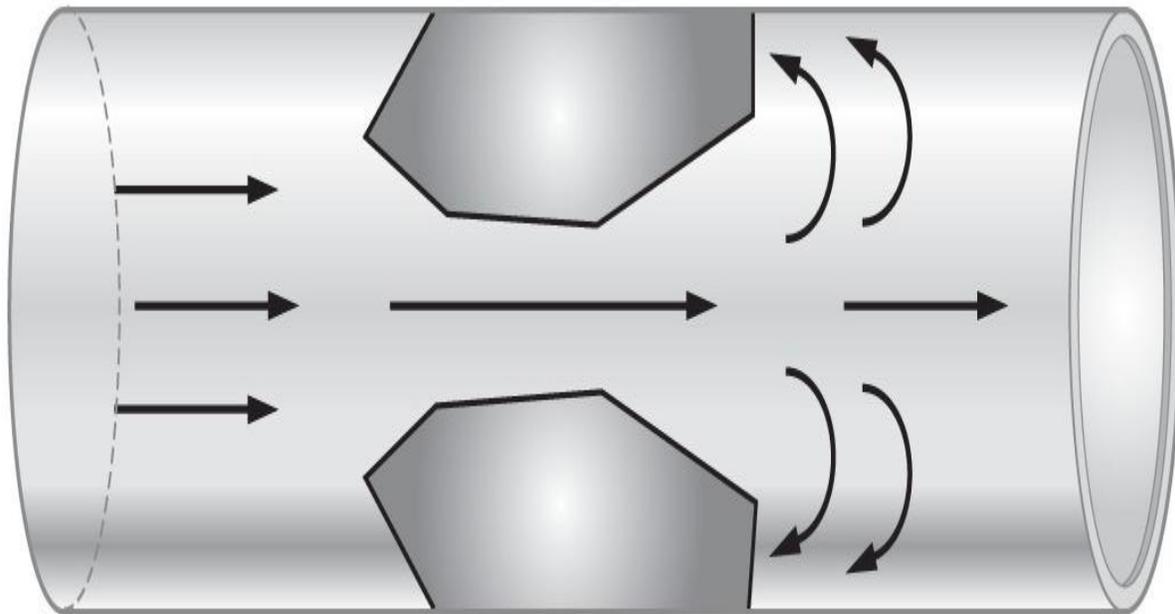
**Plug Flow**



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**Parabolic (Laminar) Flow**

# Types of Blood Flow



**Turbulent Flow**

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- Turbulence may also occur from high-velocity flow and from tortuous vessels
- The equation used to quantify the degree of turbulence in a blood vessel is the **Reynolds number**
  - **A Reynolds number greater than 2000 is considered to represent true turbulence**

# Continuity Equation & Bernoulli's Principle

- As blood flows through the body, it may encounter vessels that have a decreased radius (narrowing/stenosis)
  - Same amount of blood flow must still travel through this area
- Continuity equation ties together the relationship between the vessel area, velocity of blood, and volume of blood flow

# Continuity Equation & Bernoulli's Principle

- **Bernoulli's Principle**

- Relationship between velocity and pressure in moving fluid
- Inverse relationship between pressure and velocity is linked to the Law of Conservation of Energy

# Continuity Equation & Bernoulli's Principle

- If there is a narrowed segment of a vessel, the velocity of blood flow is highest in that narrowing
  - Kinetic energy increases
  - Pressure energy decreases (because the potential energy is converted into kinetic)
- Basically, if there is an increase in velocity it is an increase in energy and therefore something (the pressure) must decrease to preserve the total energy
  - Once the vessel goes back to its pre-stenotic region, there is a decrease in velocity with a corresponding increase in pressure

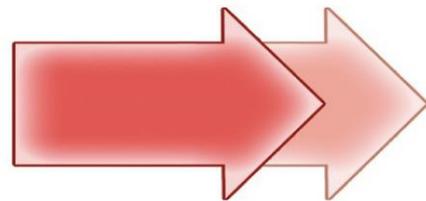
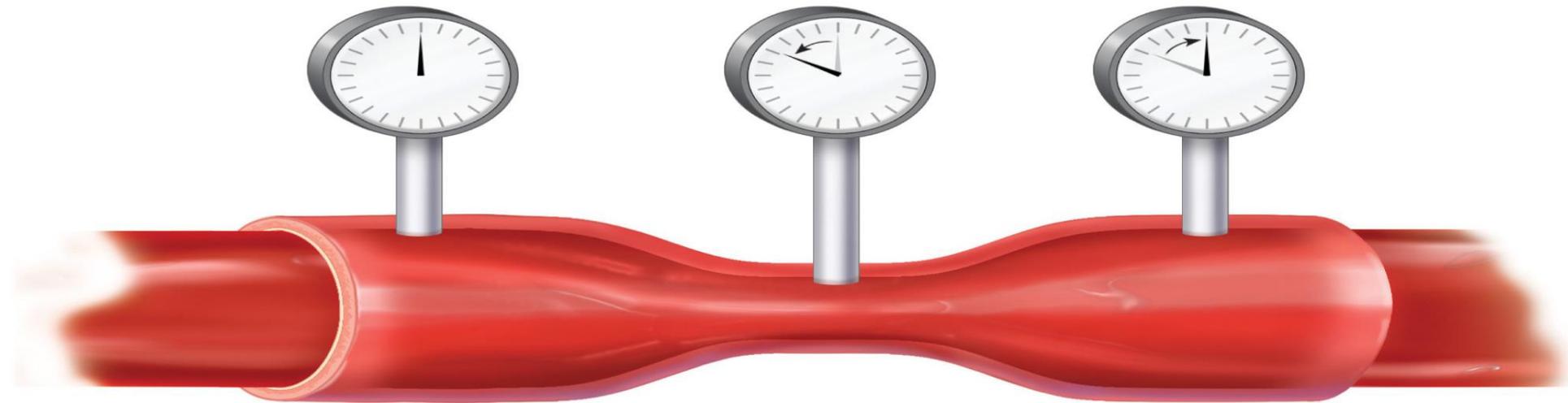
# Continuity Equation & Bernoulli's Principle

## Bernoulli's Principle

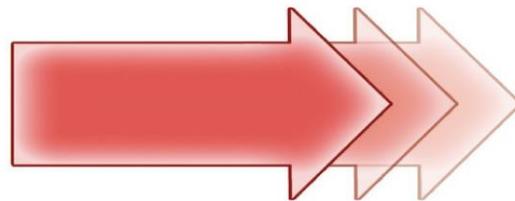
High pressure

Low pressure

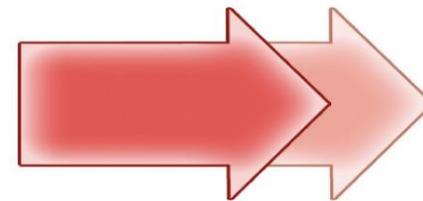
High pressure



Low velocity



High velocity



Low velocity

# Poiseuille's Law

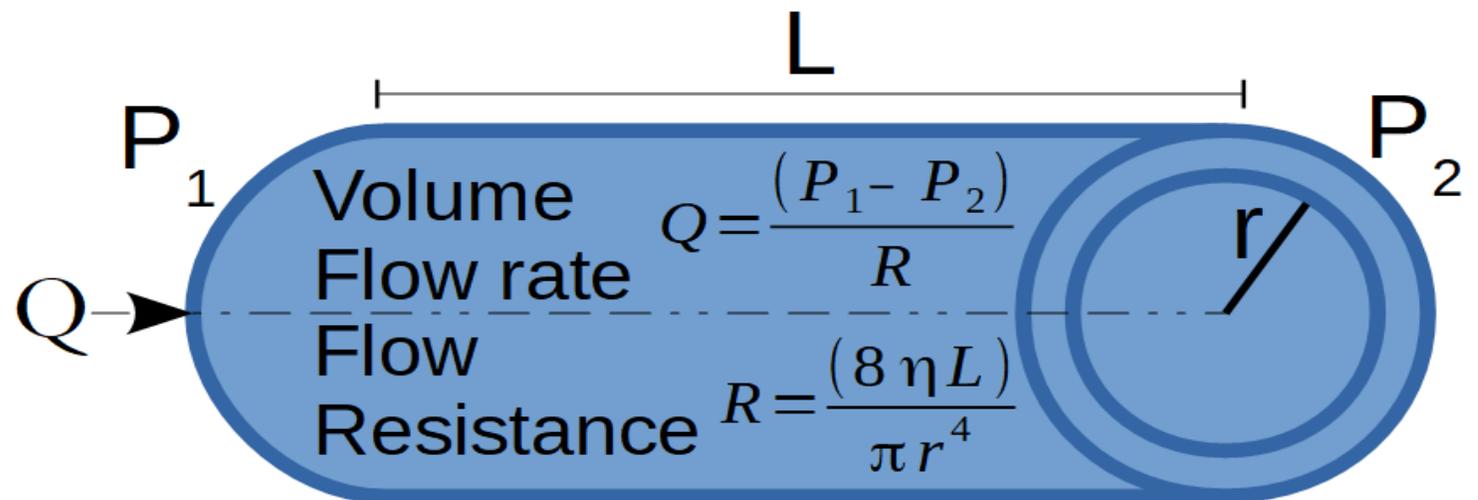
- In addition to the pressure differential, there are other factors that may increase or decrease the amount of blood flowing through a blood vessel, including:
  - 1. Length of the vessel**
  - 2. Radius of the vessel**
  - 3. Viscosity of the blood**
- Poiseuille's law describes the relationship between the volume of blood flow and the resistance to flow in a blood vessel

# Poiseuille's Law

$$\text{Flow (Q)} = \frac{\text{Change in Pressure } (\Delta P) \times \pi \text{ radius}^4}{8 \times \text{viscosity } (\eta) \times \text{length (L)}} = \frac{\Delta P \pi r^4}{8 \eta L}$$

To simplify it: Resistance (R) =  $\frac{8 \eta L}{\pi r^4}$

$$Q = \frac{\Delta P}{R}$$



$$Q = \frac{\Delta P}{R}$$

# Poiseuille's Law

$$\frac{\Delta P \pi r^4}{8 \eta L}$$

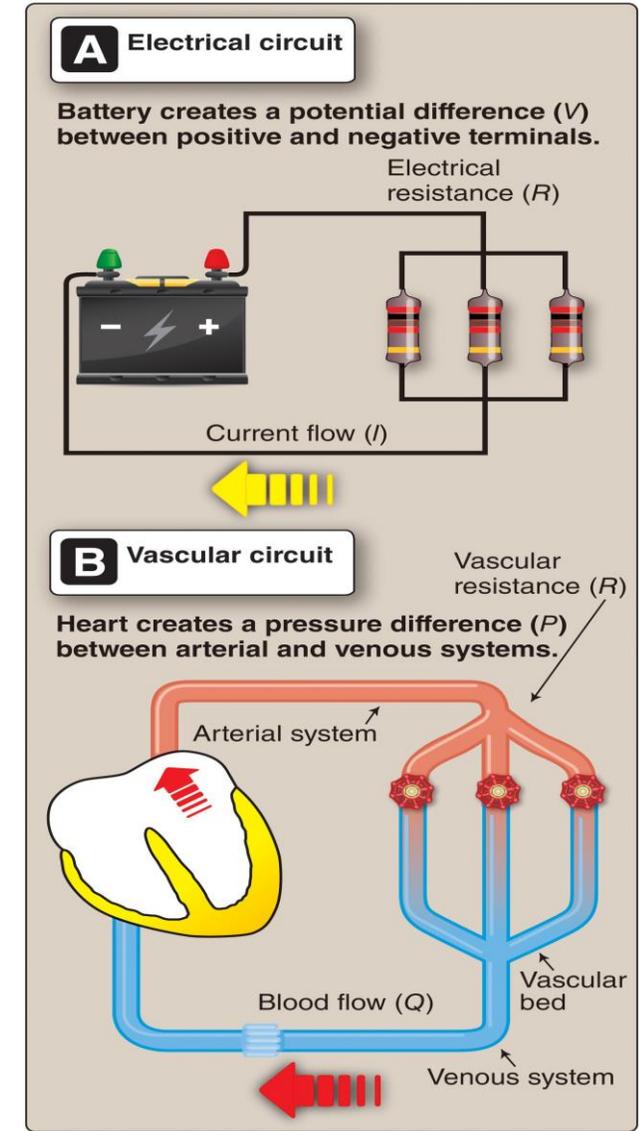
- The law states that flow is equal to the difference in pressure divided by the resistance to flow in the vessel
- If the length of the vessel or the viscosity of the blood (both of which contribute to resistance to flow) increases, there is decreased flow
- If the radius of the vessel increases, flow increases
  - **If the radius doubles, flow increases by a factor of 16**
- An increase in length or viscosity decreases flow, while an increase in radius increases flow

# Poiseuille's Law

- When arterioles branch into capillaries, frictional and inertial losses are responsible for a decrease in the velocity of the blood
  - Inertial losses occur as vessels branch and change direction
  - Frictional loss occurs in the form of heat due to resistance
- The small size of capillaries contributes to the energy loss and slow velocity of flow
  - This slow flow is essential for the exchange of nutrients and waste products within the capillaries

# Poiseuille's Law

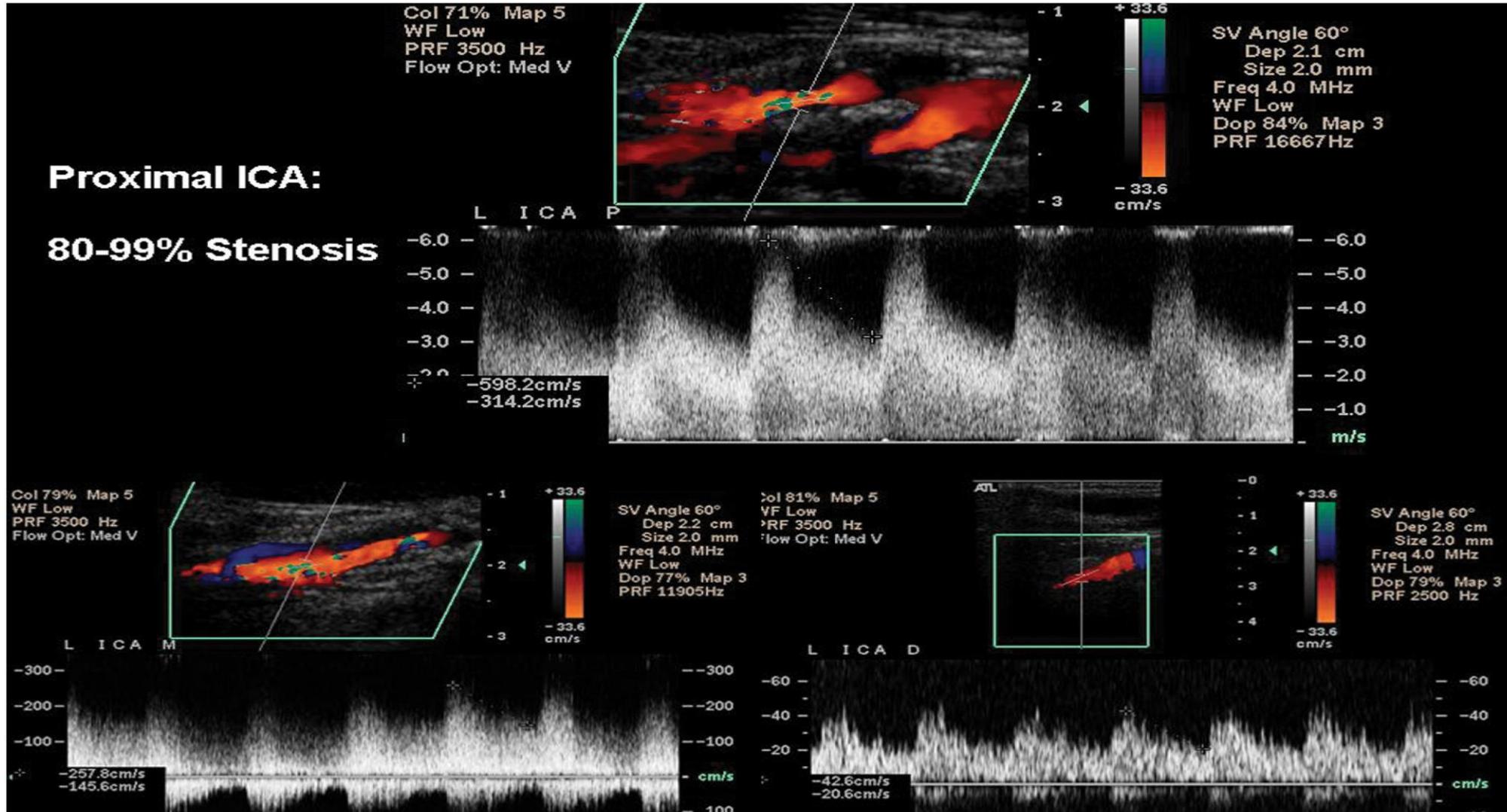
- Poiseuille's law assumes a straight (noncurved), rigid (nonelastic) pipe with a steady flow rate (non-pulsatile)
  - This does not describe the blood vessels found in the human body
- Although there is no simple way to describe the cardiovascular system, Poiseuille's law demonstrates the relationships of flow and resistance
  - Poiseuille's law is analogous to Ohm's law, a principle in electronics in which flow is equal to the pressure differential divided by resistance



# Resistance and Stenotic Flow

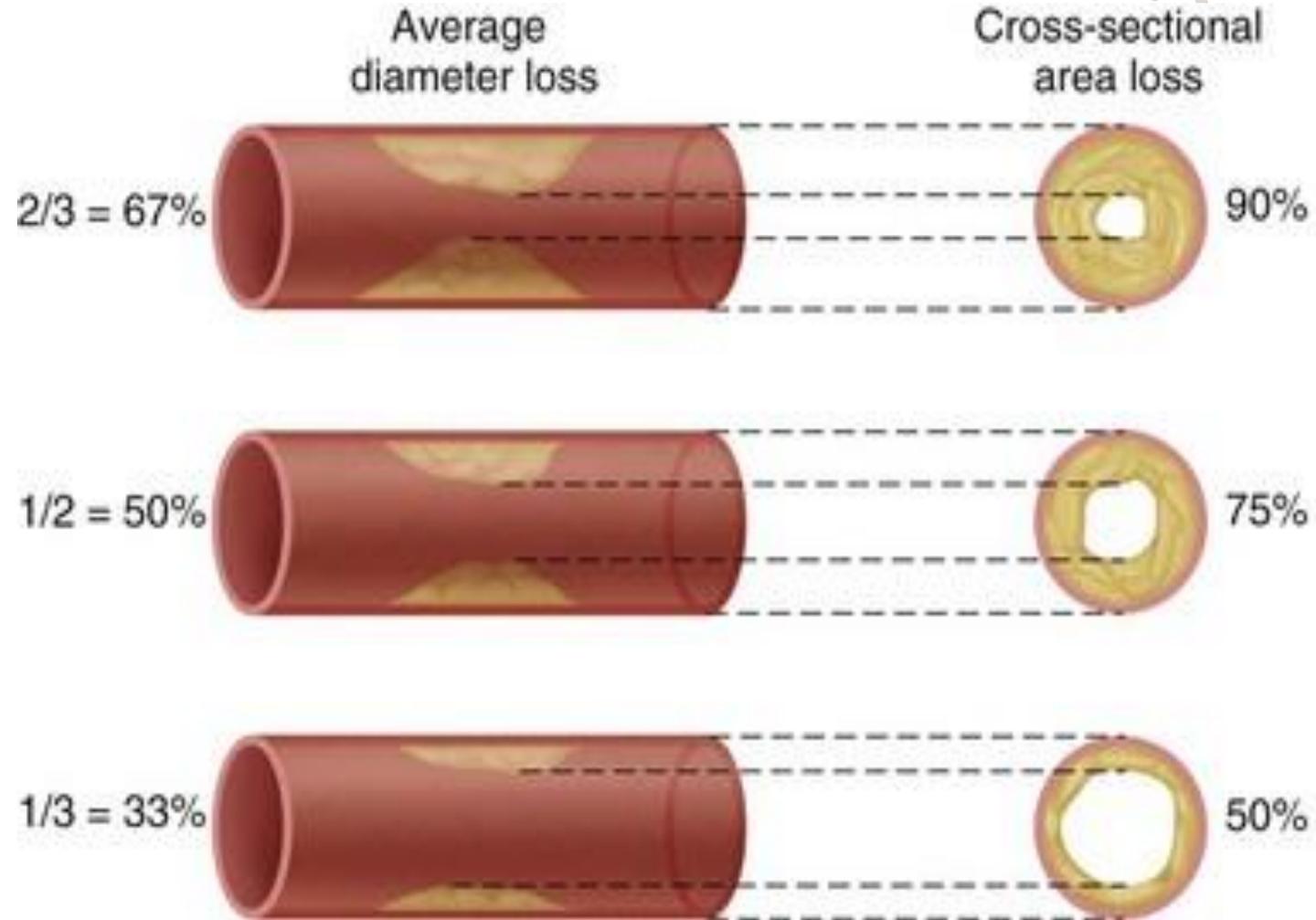
- It has been previously described that flow is a constant and does not change
  - In short, the heart continues to beat and pump the same volume of blood regardless of the presence of a stenosis downstream
- However, there can be a stenosis so severe that it compromises flow to a certain part of the body
  - A critical stenosis, also referred to as a **hemodynamically significant stenosis**, is one in which there is **decreased distal flow**
  - This situation would lead to a significant pressure gradient

# Resistance and Stenotic Flow



# Resistance and Stenotic Flow

- A cross-sectional area loss of 75% is generally considered to be hemodynamically significant, though this percentage may vary among vessels
- **A 75% decrease in area corresponds to a 50% decrease in diameter**



# Resistance and Stenotic Flow

- Blood vessels may be connected end to end (in series) or flow into multiple parallel channels (in parallel)
- The effective resistance, the resistance of the distal bed, is the sum of the individual resistances when multiple vessels are connected in series
- When vessels are connected in parallel, the effective resistance is reduced, as there are more channels or paths for flow to exploit

# Resistance and Stenotic Flow

Total resistance  $R = R_1 + R_2 + R_3 + \dots$



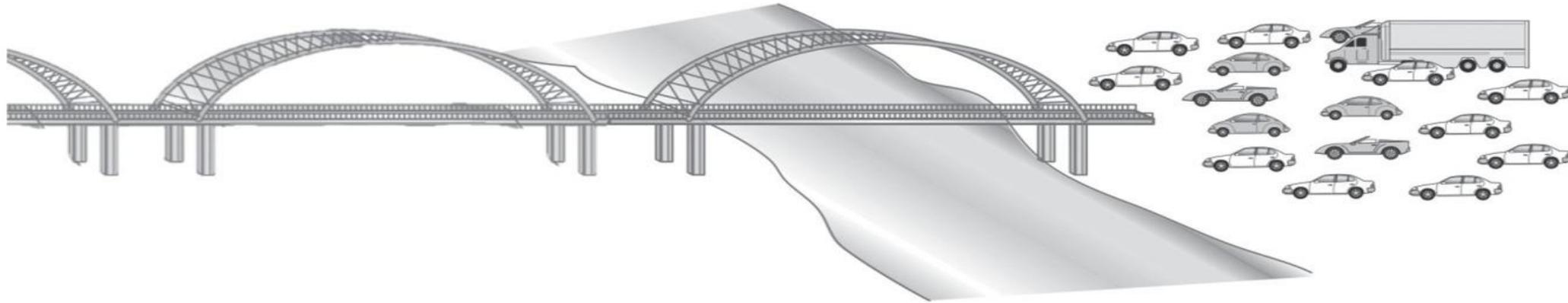
**A**

Total resistance  $R = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots$

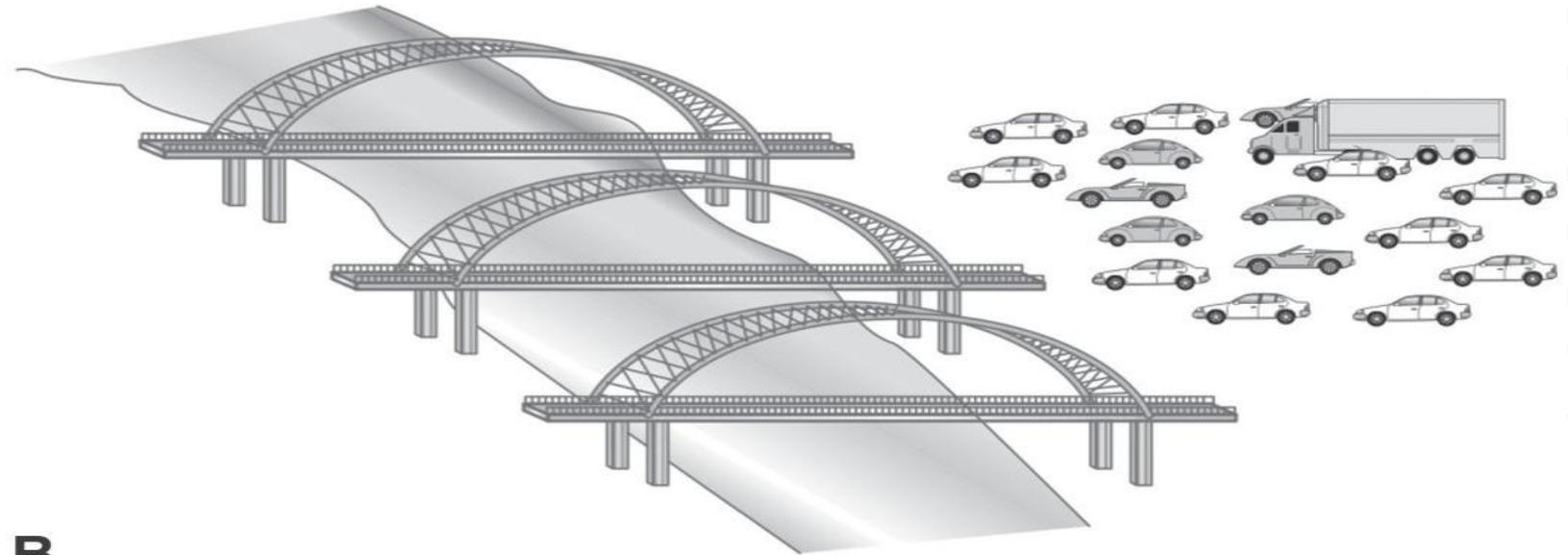


**B**

# Resistance and Stenotic Flow



**A**



**B**

# Resistance and Stenotic Flow

- Arterioles are the main contributors to the resistance in the cardiovascular system
  - **Constrict or dilate in response to signals from the brain to either increase or decrease flow distally**
- At the region of a non-hemodynamically significant stenosis, the velocity of the blood cells must increase in order to maintain the same volume flow
  - **The area of increased velocity also demonstrates decreased pressure in this region (Bernoulli's)**
  - **Turbulence will be visualized as blood exits the region of narrowing and enters a suddenly expanded vessel**
    - Turbulence will dissipate and flow will eventually return to a normal state

# Resistance and Stenotic Flow

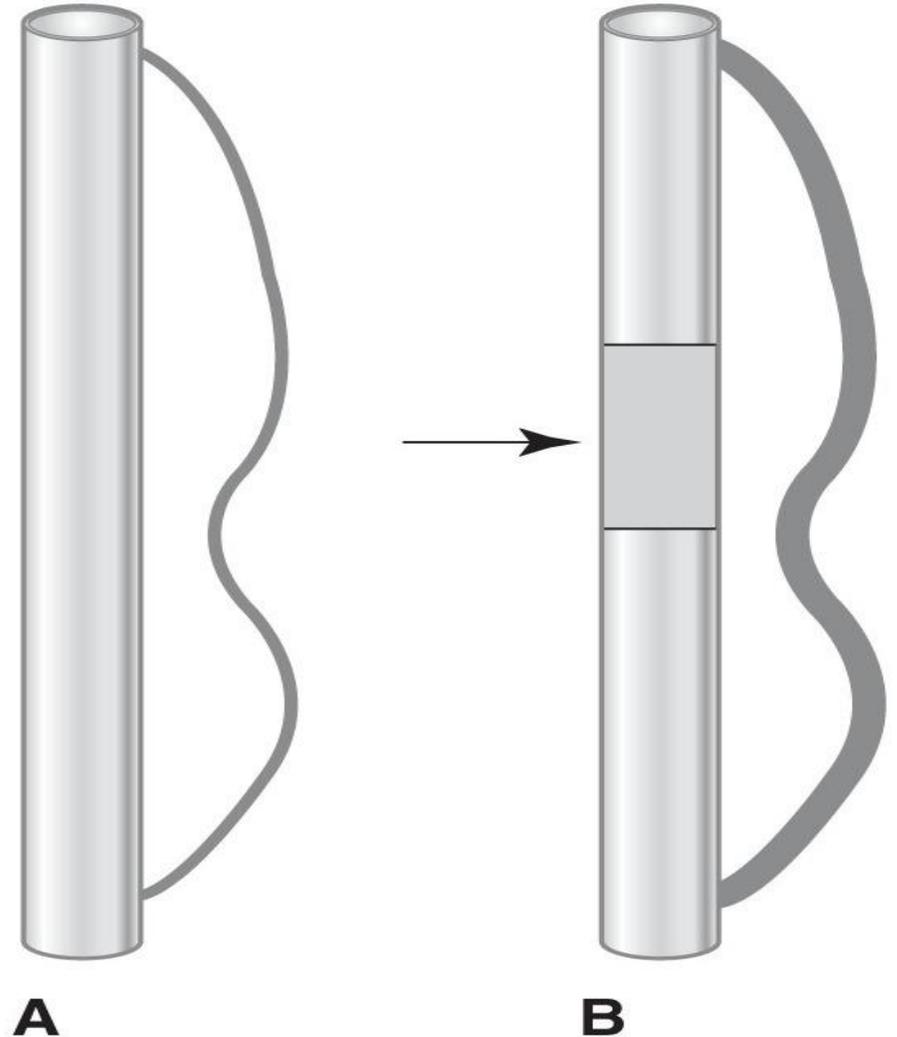
- With a stenosis, it is more detrimental to have more than one stenosis in a vessel than a single substantial lesion
- There is more energy loss with two stenoses in series
  - This relates back to effective resistance and when vessels are connected in a series, the total resistance is the sum of the segmental resistances is higher (versus when the vessels are multiple parallel channels)
  - Multiple non-hemodynamically significant lesions may act as a critical lesion

# Resistance and Stenotic Flow

- Blood flow always follows the path of least resistance
- If a major artery becomes blocked, it is now the path of highest resistance and a previously formed collateral vessel will become the path of least resistance
  - Higher pressure proximal to a stenosis causes the collateral to open and allow blood to follow the lower-resistance path

# Resistance and Stenotic Flow

- Distal to the stenosis, the collateral will rejoin the main artery
- Collaterals form over time in response to chronic change
  - Not seen in instances of acute obstruction



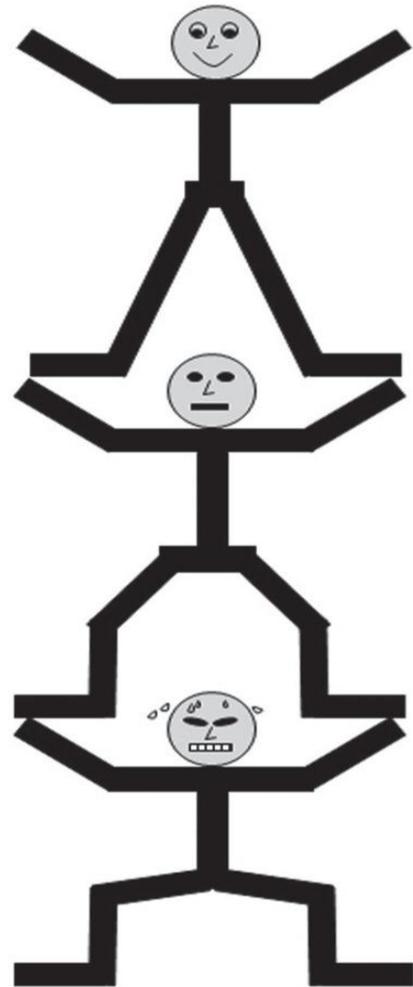
# Venous Hemodynamics and Hydrostatic Pressure

- Leaving the arterial side, blood flows from the capillaries to the slightly larger venules and then into the larger veins
  - Because the vessels on the venous system get progressively larger as they return to the heart, there is lower resistance to flow
- If the patient is **supine**, this small but significant difference in pressure creates a pressure gradient that keeps blood flowing toward the heart

# Venous Hemodynamics and Hydrostatic Pressure

- When someone is in the **standing** position, gravity acts on the blood in the form of hydrostatic pressure
  - As mentioned earlier, hydrostatic pressure is the weight of a column of fluid from a certain reference point
- **In humans, that reference point is the heart, the point at which the hydrostatic pressure is zero**
- **Below the heart, the weight of this column of blood increases with the distance from the heart**

# Venous Hemodynamics and Hydrostatic Pressure



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**A**

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**B**

# Venous Hemodynamics and Hydrostatic Pressure

Hydrostatic pressure (P) = density of blood ( $\rho$ ) x gravity (g) x height (h)

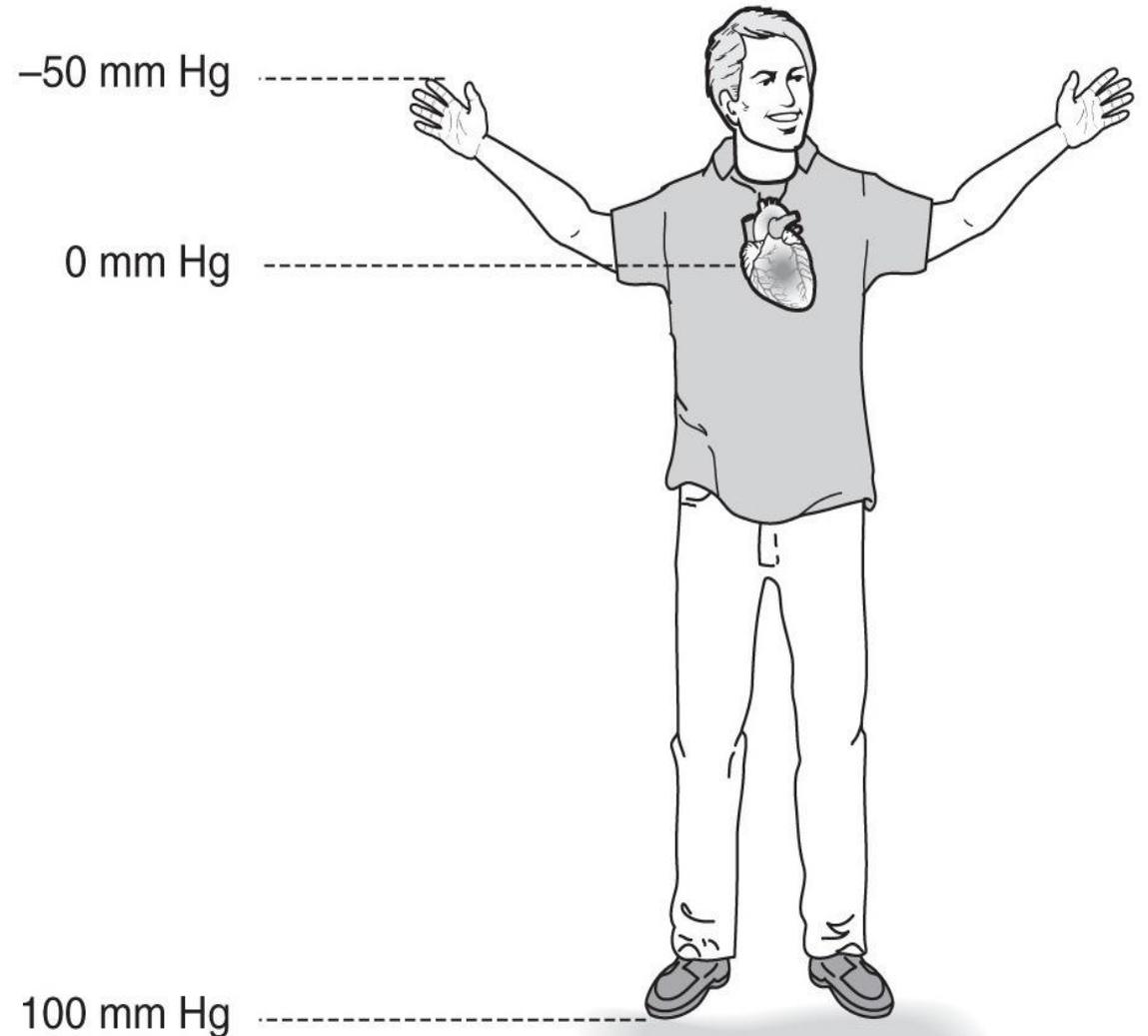
$$P = \rho gh$$

- Height is the only variable that is not a constant
- Measuring blood pressure below the heart will require you to add the effects of hydrostatic pressure into the overall blood pressure
- Measuring blood pressure above the heart will require you to subtract the effects of hydrostatic pressure into the overall blood pressure

# Hydrostatic Pressure

## When standing:

- Locations below the heart
  - Pressure is positive
  - Circulatory pressures will be too high
- Locations above heart
  - Pressure is negative
  - Circulatory pressures will be too low



# Hydrostatic Pressure in Supine Patient with a BP of 140 mmHg

Measurement Site	Blood Pressure	Level	Hydrostatic Pressure	Measured Pressure
Ankle	140 mmHg	Heart	0 mmHg	140 mmHg (140 + 0)
Knee	140 mmHg	Heart	0 mmHg	140 mmHg (140 + 0)
Mid Chest	140 mmHg	Heart	0 mmHg	140 mmHg (140 + 0)
Top of Head	140 mmHg	Heart	0 mmHg	140 mmHg (140 + 0)

# Hydrostatic Pressure in Standing Patient with a BP of 140 mmHg

Measurement Site	Blood Pressure	Level	Hydrostatic Pressure	Measured Pressure
Top of Head	140 mmHg	Above heart	-30 mmHg	110 mmHg (140 - 30)
Mid Chest	140 mmHg	Heart level	0 mmHg	140 mmHg (140 + 0)
Waist	140 mmHg	Slightly Below Heart	50 mmHg	190 mmHg (140 + 50)
Knee	140 mmHg	Somewhat below heart	75 mmHg	215 mmHg (140 + 75)
Ankle	140 mmHg	Far below heart level	100 mmHg	240 mmHg (140 + 100)

# Venous Hemodynamics and Hydrostatic Pressure

- Venous return to the heart requires several mechanisms to work properly:
  - 1. A pressure gradient must exist**
  - 2. Intrathoracic pressure changes due to respirations**
  - 3. Venous Valves**
  - 4. Calf muscle pump/Soleal sinuses**

# Venous Hemodynamics and Hydrostatic Pressure

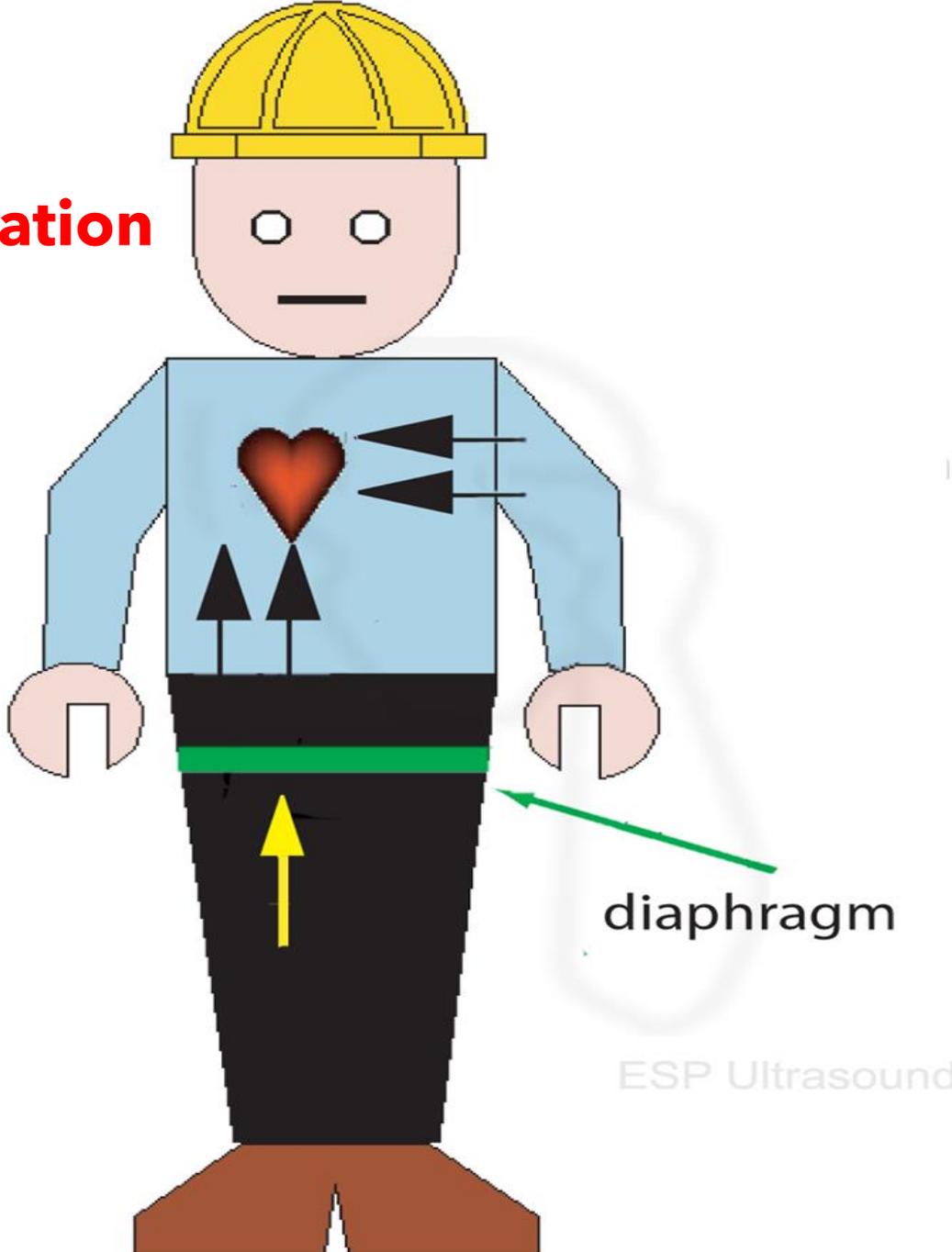
## 1. A pressure gradient must exist

- Venules/veins have higher pressure compared to right atrium of the heart

## 2. Intrathoracic pressure changes due to respirations

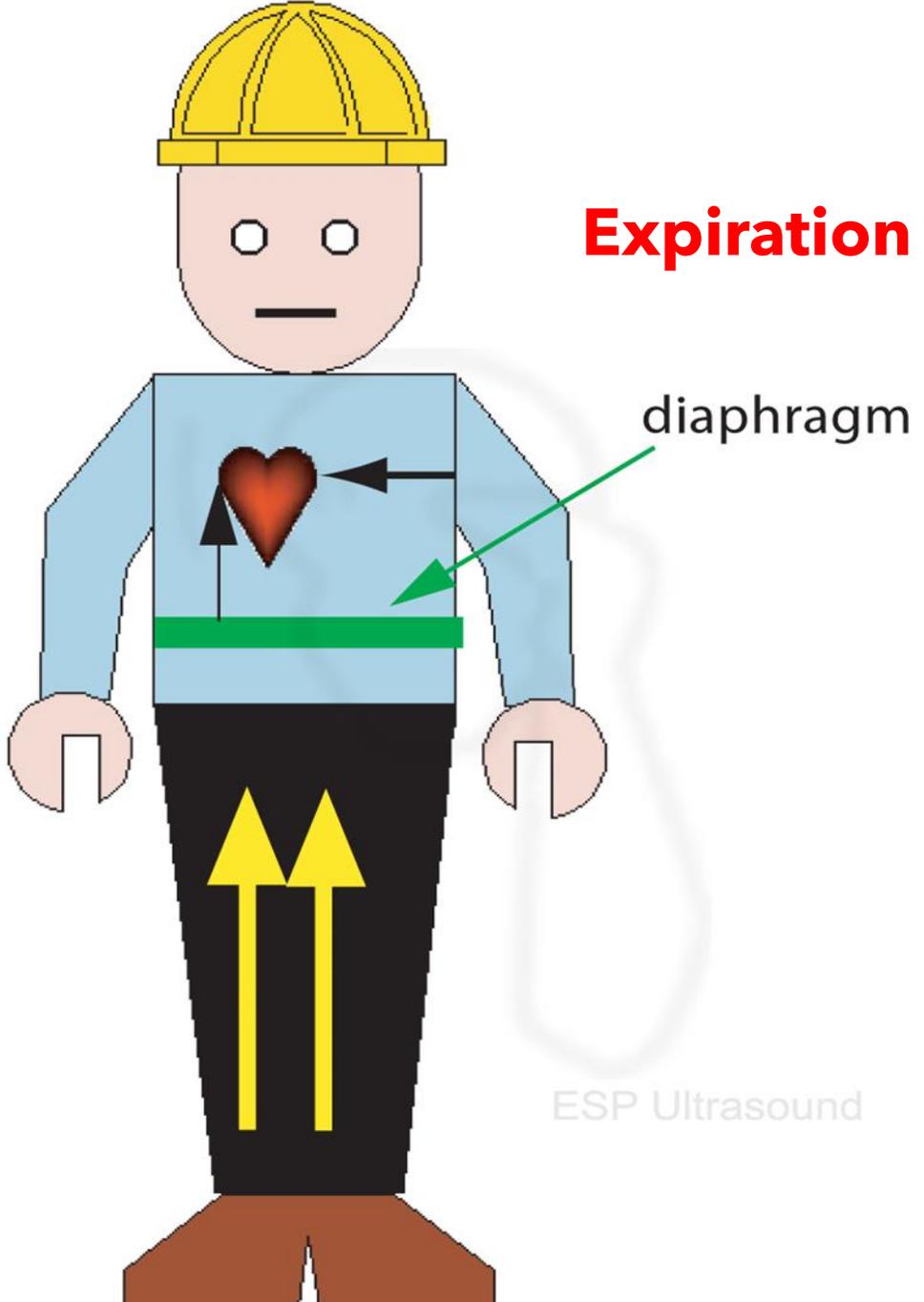
- **Venous flow in the legs correlates with movement of the diaphragm:**
- Downward movement of diaphragm (inhalation), decreases venous flow in the legs and increases venous return to the heart
- Upward movement of the diaphragm (exhalation), increases venous flow in the legs and decreases venous return to the heart

**Inspiration**



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**Expiration**



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# Venous Hemodynamics and Hydrostatic Pressure

## 3. Venous Valves

- Small folds of endothelial tissue that originate from the intimal wall of the veins
- Maintains unidirectional blood flow

## 4. Calf muscle pump/soleal sinuses

- Soleal sinuses inside the calf muscle are a reservoir for venous blood
- Calf muscles contract and force blood into the veins for return to the heart

# Venous Hemodynamics and Hydrostatic Pressure

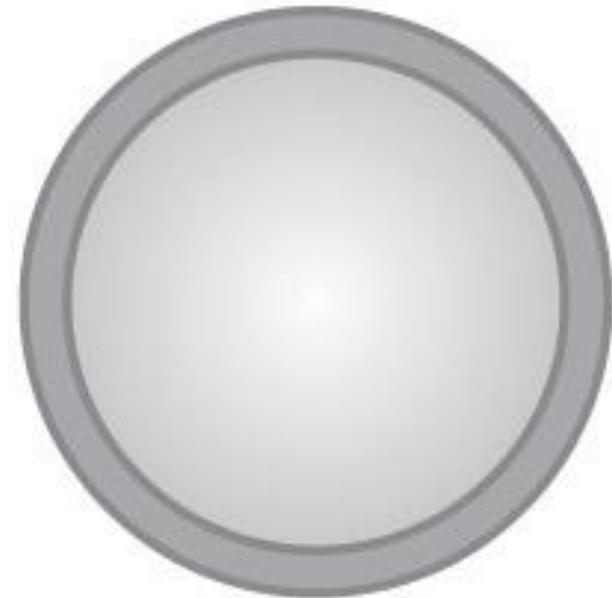
- Pressure exists not only inside the veins but also outside the veins in the form of extrinsic pressure
- **Transmural pressure** is the difference between pressure inside the veins (intravascular pressure) and the surrounding tissue (extrinsic pressure)
  - Low transmural pressure - typically when patient is laying down or at rest; the force outside of the vein exceeds the pressure inside the vein and the vein collapses/has an elliptical shape
  - High transmural pressure - patient is standing or actively moving; hydrostatic pressure increases the intravascular pressure, and the vein assumes a circular shape

# Transmural Pressure



**A**

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**B**

# Venous Hemodynamics and Hydrostatic Pressure

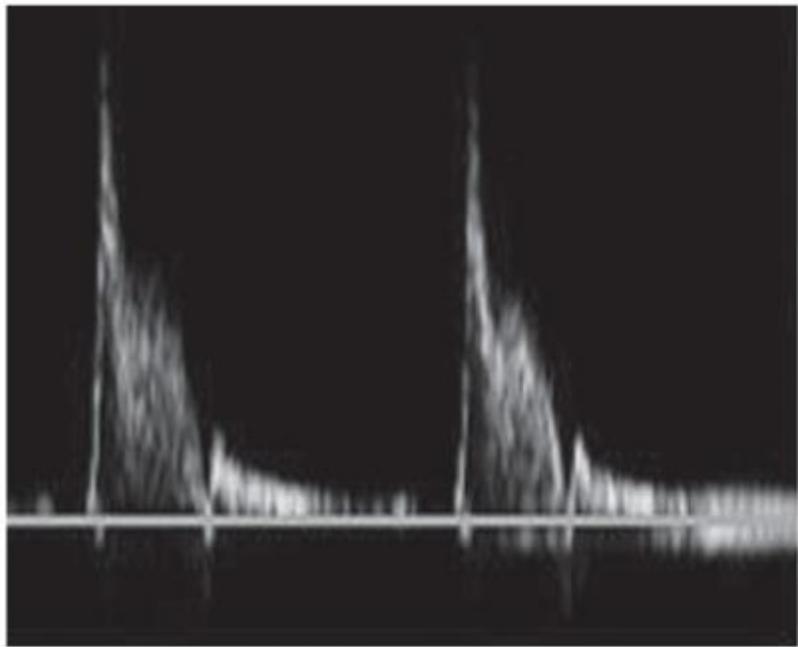
- **Veins should be phasic** or show variations that relate to respiration
  - Lack of phasicity, aka continuous flow, may be an indicator of thrombus or extrinsic compression between the vein and heart.
- **Venous flow should not be pulsatile** (exception of those larger veins near the heart)
  - Pulsatility in the peripheral veins may indicate right side heart failure

# Pulsatility and Phasicity

- Arteries are pulsatile in nature
  - Distinct systole and diastole that correspond to both the flow from the heart and to the distal vascular bed
- Flow is often described by the shape of its waveform on spectral Doppler as triphasic, biphasic (collectively known as "multiphasic"), or monophasic

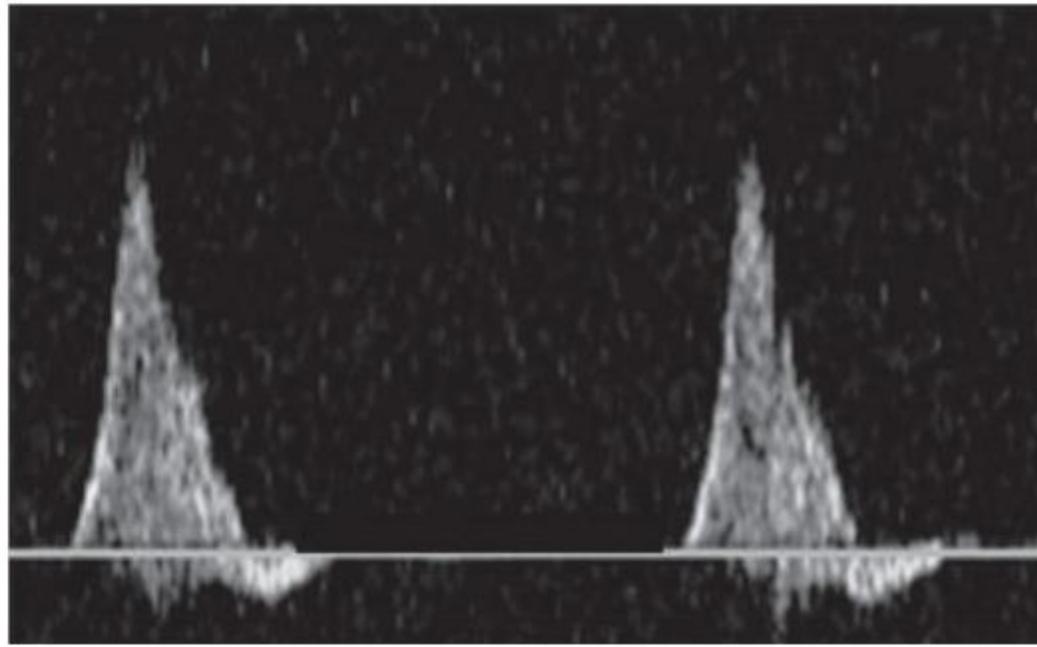
# Pulsatility and Phasicity

- Flow that is triphasic or biphasic feeds a high-resistance bed, and there is typically little diastolic flow evident, with possibly some flow reversal in diastole



**A**

**Triphasic**

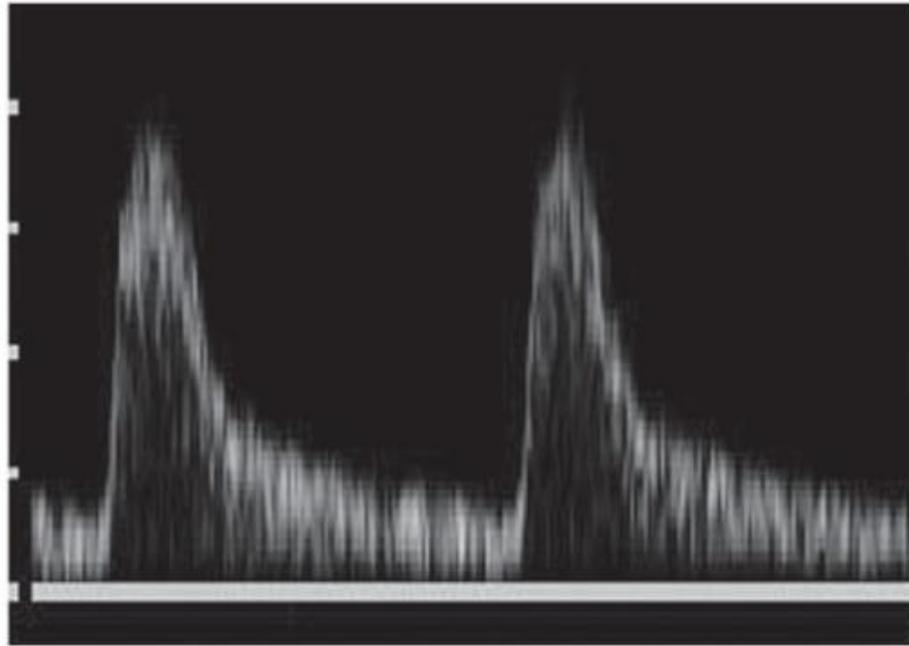


**B**

**Biphasic**

# Pulsatility and Phasicity

- Monophasic flow feeds a low-resistance bed
  - **Demands constant flow in all phases of the cardiac cycle**
  - **ICA (feeds the brain), renal arteries (supplies the kidneys)**



C

**Monophasic**

# Pulsatility and Phasicity

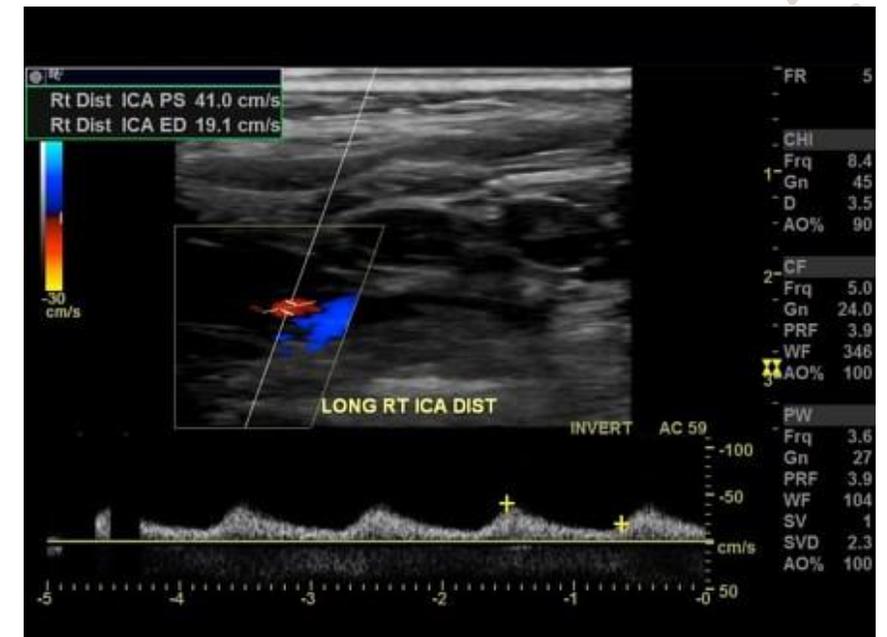
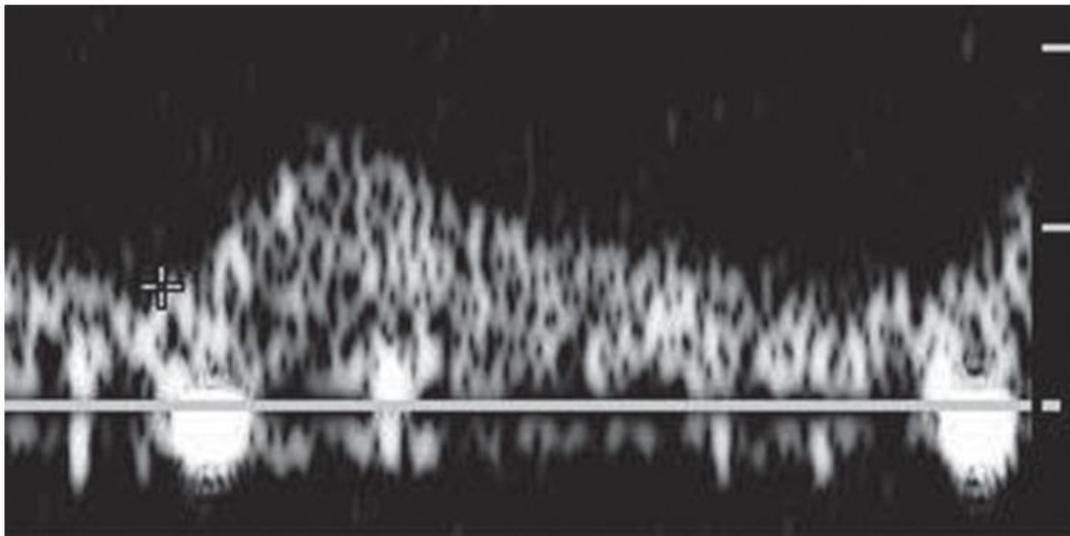
- The shape of the waveform may be an indicator of disease that is more distal or proximal to the sampling point:
  - **Normal peripheral arteries should always be triphasic because they are high-resistance vessels**
  - With a proximal stenosis, the distal arterioles dilate to get more oxygenated blood to the extremity (this increases the radius of the vessels and creates a pressure drop)
  - For example: There is a superficial femoral artery obstruction, the distal arterioles will dilate and the spectral waveform of the SFA may become monophasic
  - **Monophasic flow in the lower extremity arteries indicates an abnormal condition**

# Pulsatility and Phasicity

- Conversely, low-resistance blood vessels, like the ICA, should never exhibit a high-resistance pattern
- If a high-resistance waveform is demonstrated in the ICA it may indicate a distal occlusion or near occlusion, cerebral edema, or brain death

# Pulsatility and Phasicity

- Most arteries demonstrate a sharp upstroke for systole
- A “tardus parvus” waveform is a delay in the upstroke of the systolic component making the waveform more monophasic
  - **Tardus parvus means “slow small”**
  - **Indicates a proximal obstruction**



# Effects of Exercise on Flow

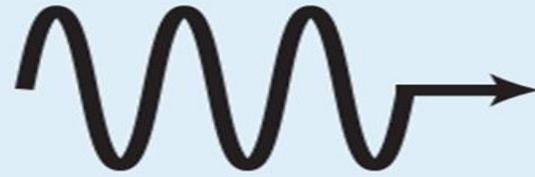
- In a resting patient, the peripheral arteries should be high resistance (triphasic) due to distal arteriolar constriction
- During exercise, there is an increased demand for oxygen which will cause the arterioles to dilate and create a lower-resistance distal vascular bed
  - Normal patients will not demonstrate much of a change to their waveforms during exercise
  - A patient with arterial obstructive disease may have normal resting waveforms but when exercising they have abnormal waveforms because they have a big pressure drop distally

# The Doppler Effect

- AKA Doppler Shift, Doppler Frequency
- Frequency changes or variations as a result of motion between:
  - **Sound Source**
  - **Receiver**
- Frequency changes when the sound source and receiver move:
  - **Closer together**
  - **Further apart**

# The Doppler Effect

- If we have a stationary reflector, sound will impinge upon it and the reflected frequency will be identical to the transmitted (incident) frequency
- If the **reflector is moving towards** the transducer, the **reflected frequency will be higher** than the transmitted frequency
- A **reflector moving away** from the transducer will produce a **reflected frequency that is lower** than the transmitted frequency

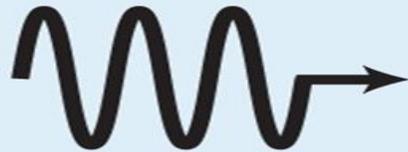
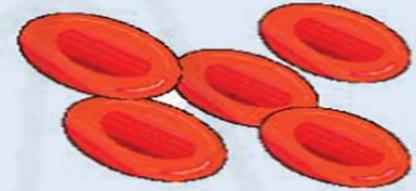


Lower



Higher

Moving Towards

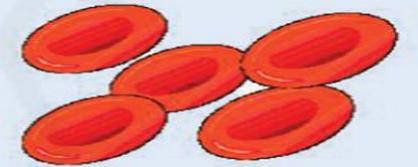


Higher



Lower

Moving Away



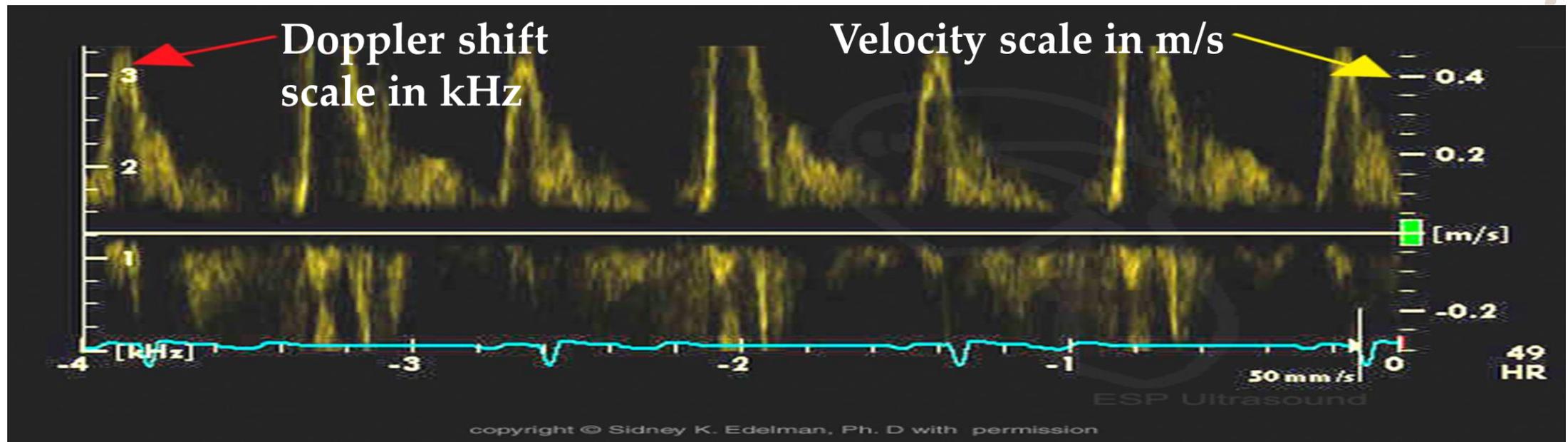
# The Doppler Effect

**Doppler shift = reflected frequency - transmitted frequency**

- Units: Hertz, cycles per second
- Typical values: audible range (20Hz - 20 kHz)
- If the reflected frequency is higher than the transmitted frequency:
  - Positive Doppler shift occurs (indicates the reflector is moving towards the transducer)
- If the reflected frequency is lower than the transmitted frequency:
  - Negative Doppler shift occurs (indicates the reflector is moving away from the transducer)

# The Doppler Effect

- While the frequency shift is measured by the machine, it is the velocity of the blood that is of interest to the imager, and not the frequency shift itself
  - The ultrasound system measures the frequency shift but calculates the velocity



# The Doppler Effect

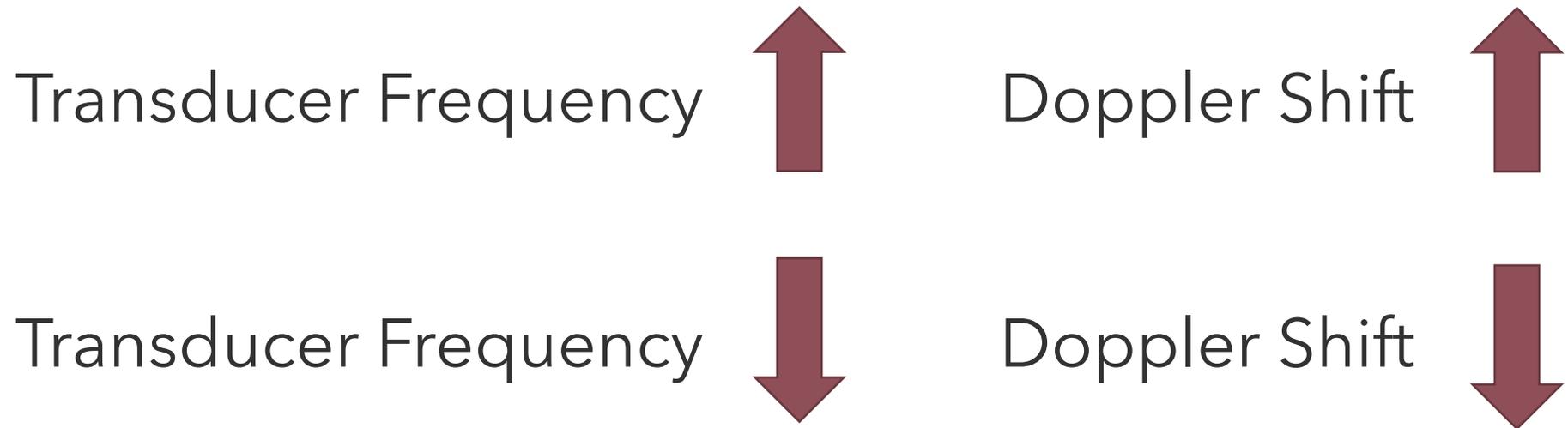
**Doppler shift =  $\frac{2 \times \text{velocity of blood} \times \text{transducer frequency} \times \cos\theta}{\text{propagation speed}}$**

$$F_D = \frac{2 v f \cos \theta}{c}$$

- Doppler shift is directly related to the velocity of blood cells
  - **Faster = greater the Doppler Frequency**
- **Why is there a "2" in the Doppler equation?**
  - Two Doppler shifts occur:
    - 1. Sound from the transducer strikes the RBC and
    - 2. Reception of reflected sound from the RBC

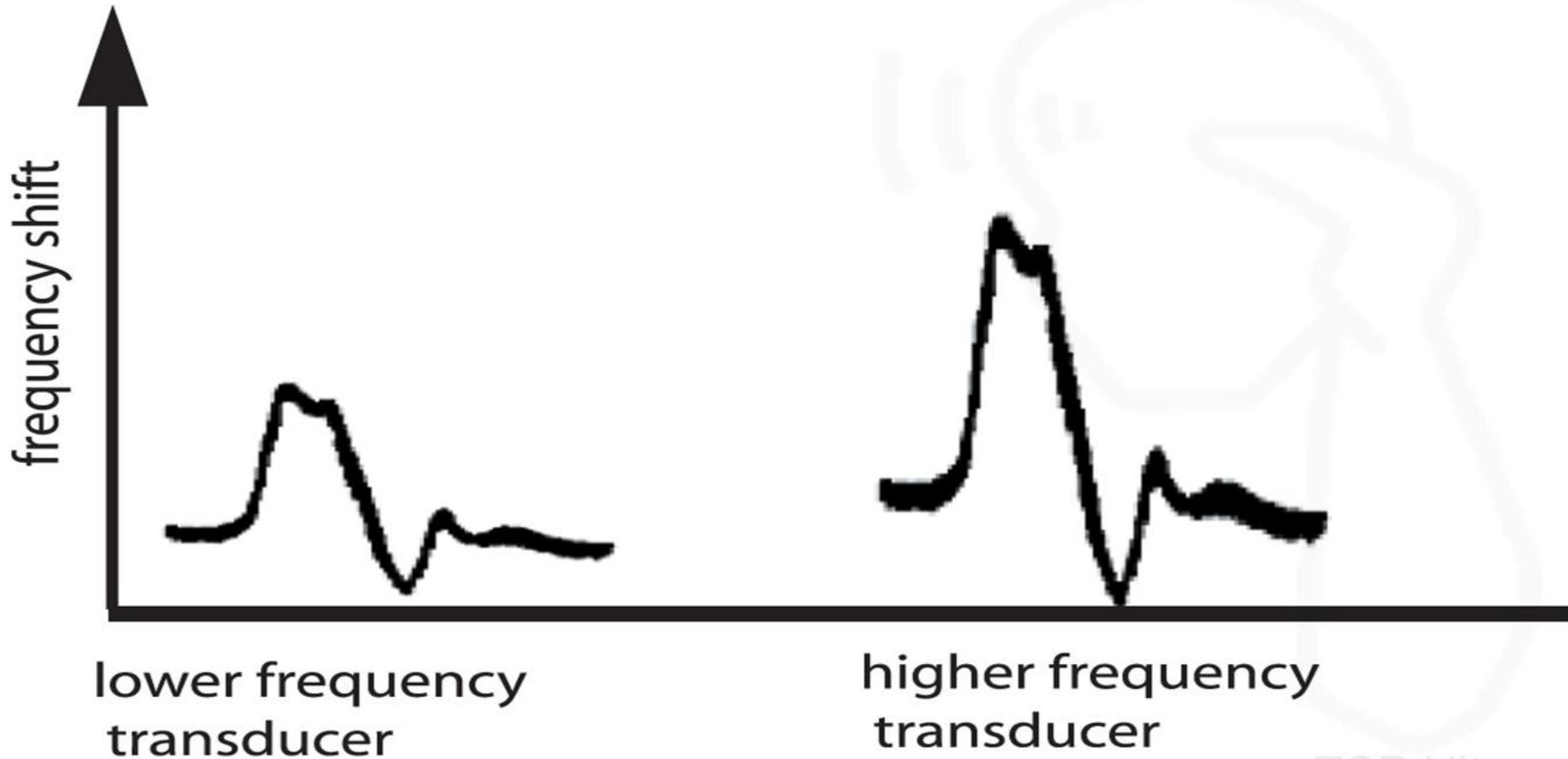
# The Doppler Effect

- Directly related to transducer frequency:



- When transmitted frequency doubles, Doppler frequency doubles

# Doppler Shift



ESP Ultrasound

# The Doppler Effect

- Doppler works because the incident sound reflects off the red blood cells in the blood
  - RBCs are small, normally about  $7.0\ \mu\text{m}$
  - Because of their size, **RBC's are natural Rayleigh scatterers**
  - Rayleigh scatterers are very small compared with the incident wavelength
  - A small increase in frequency results in a dramatic increase in scatter

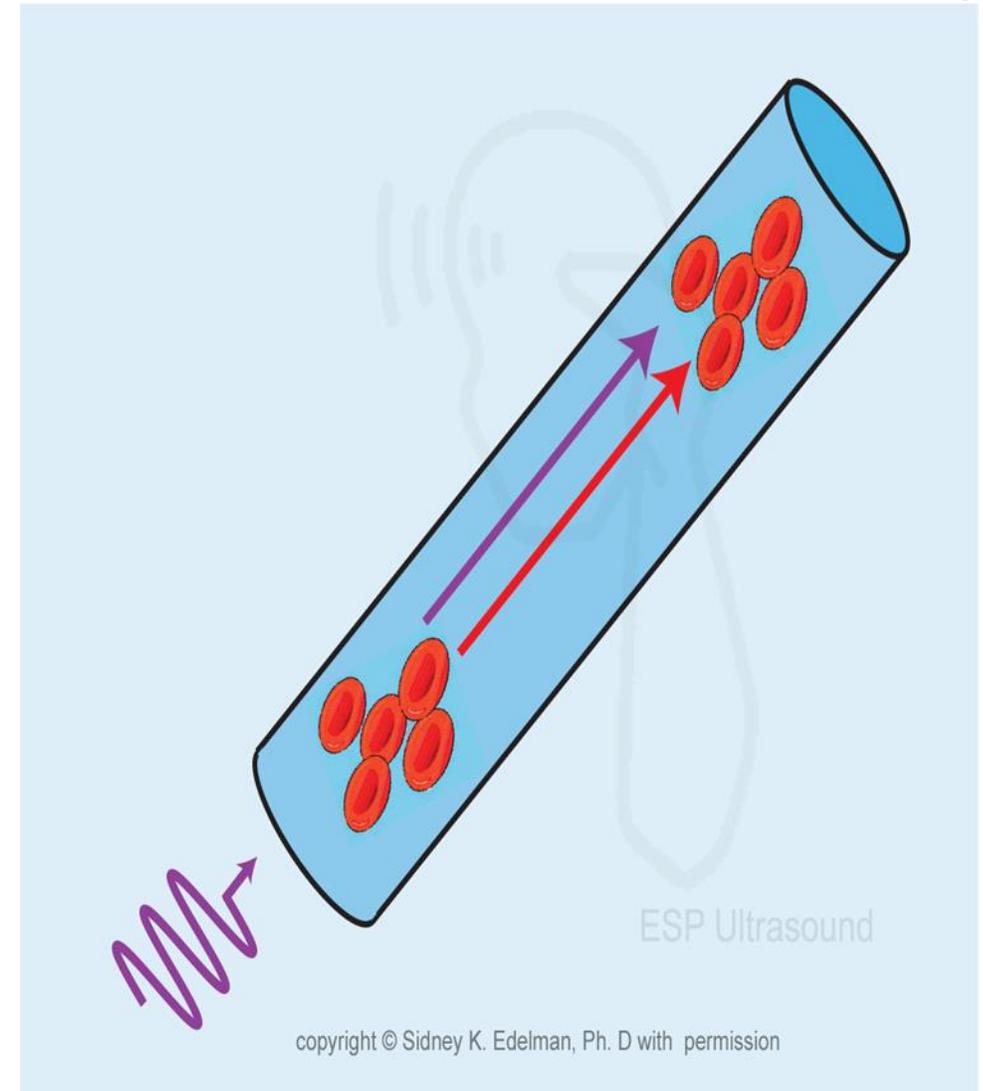
Rayleigh Scattering  $\propto$  Frequency<sup>4</sup>

# The Doppler Effect

- Higher-frequency transducers may provide stronger Doppler signals, but at the expense of the attenuation
  - **The higher the frequency, the more scatter there is, and therefore, the more attenuation**
  - **If the energy is scattered, it is not transmitted deeper into the tissue**
  - **Essentially, there must be a trade-off between improved resolution and penetration**

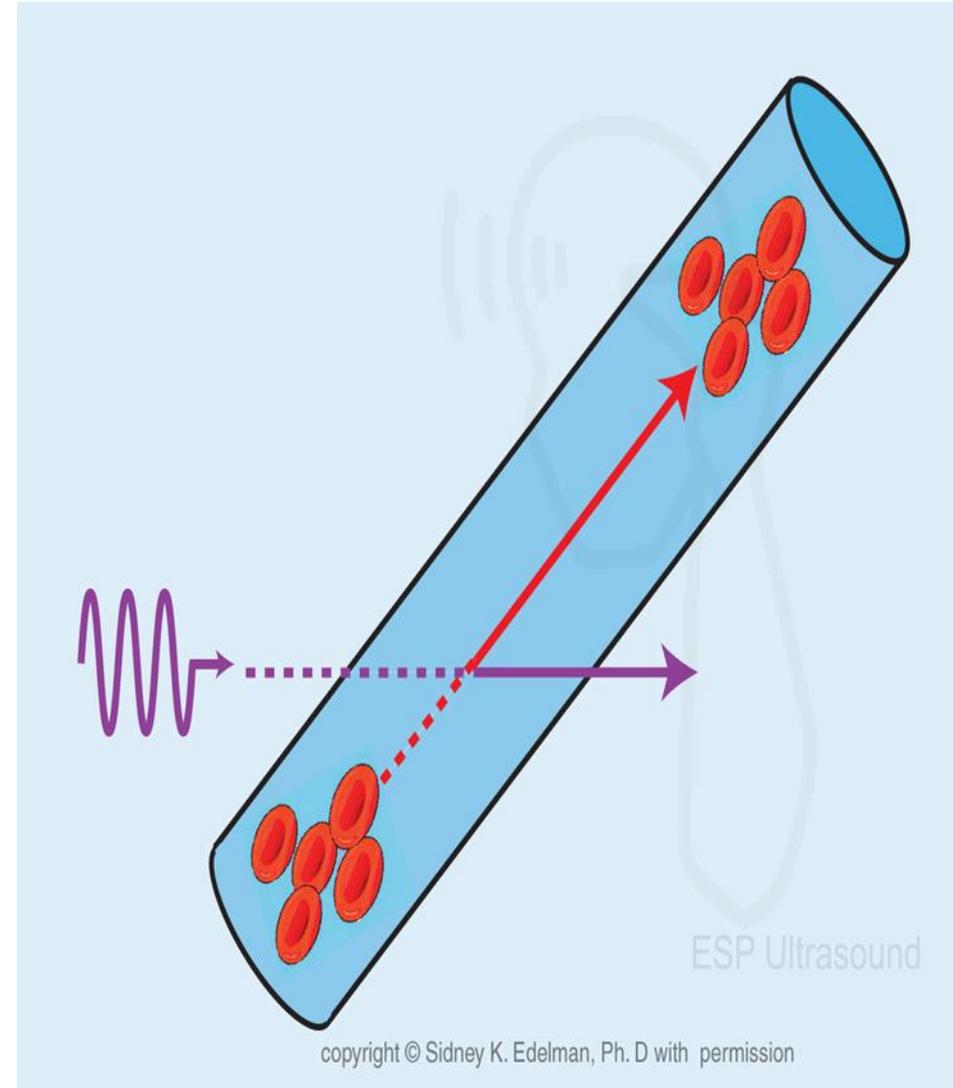
# Sound Beam Direction vs. Flow Direction

- When RBC move parallel to the beam (either towards or away)
  - **Entire Doppler shift is measured**
  - **Velocity is 100% accurate**



# Sound Beam Direction vs. Flow Direction

- When angle exists between direction of flow and sound beam
  - **Measured velocity is less than the true velocity**



# Sound Beam Direction vs. Flow Direction

- Cosine  $\theta$ 
  - Angle between sound beam and direction of motion
  - % of true velocity depends on the angle
- **Measured velocity = true velocity x  $\theta$**
- As the Doppler angle increases, the cosine of the angle decreases
  - Doppler angle and frequency shift are inversely proportional
- Doppler angle must be known to calculate velocities....in echocardiography, a 0-degree angle is always assumed

# Sound Beam Direction vs. Flow Direction

- The most accurate Doppler shift (and therefore the most accurate velocity) will come from a  $0^\circ$  angle
  - **For the boards, the most accurate angle is  $0^\circ$  or  $180^\circ$**
  - **Flow is parallel to the beam**
  - **Measured velocity = True velocity**
  - **$0^\circ$  indicates flow towards the transducer**
  - **$180^\circ$  indicates flow away from the transducer**
- No Doppler shift is obtained at a  $90^\circ$  angle
  - **The cosine of  $90$  is  $0$ , and therefore, the Doppler shift is  $0$**

$$F_D = \frac{2 v f \cos \theta}{c}$$

# Sound Beam Direction vs. Flow Direction

- Cosine of  $60^\circ$  is 0.5
  - **Measured velocity =  $\frac{1}{2}$  true velocity**

- If RBC's travel @ 2 m/s @  $60^\circ$

Then velocity is reported as 1 m/s

$$F_D = \frac{2 v f \cos \theta}{c}$$

# Sound Beam Direction vs. Flow Direction

Angle (°)	Cosine of the Angle
<b>0</b>	<b>1.0</b>
<b>30</b>	<b>0.87</b>
<b>45</b>	<b>0.71</b>
<b>60</b>	<b>0.5</b>
<b>90</b>	<b>0</b>
<b>180</b>	<b>-1.0</b>

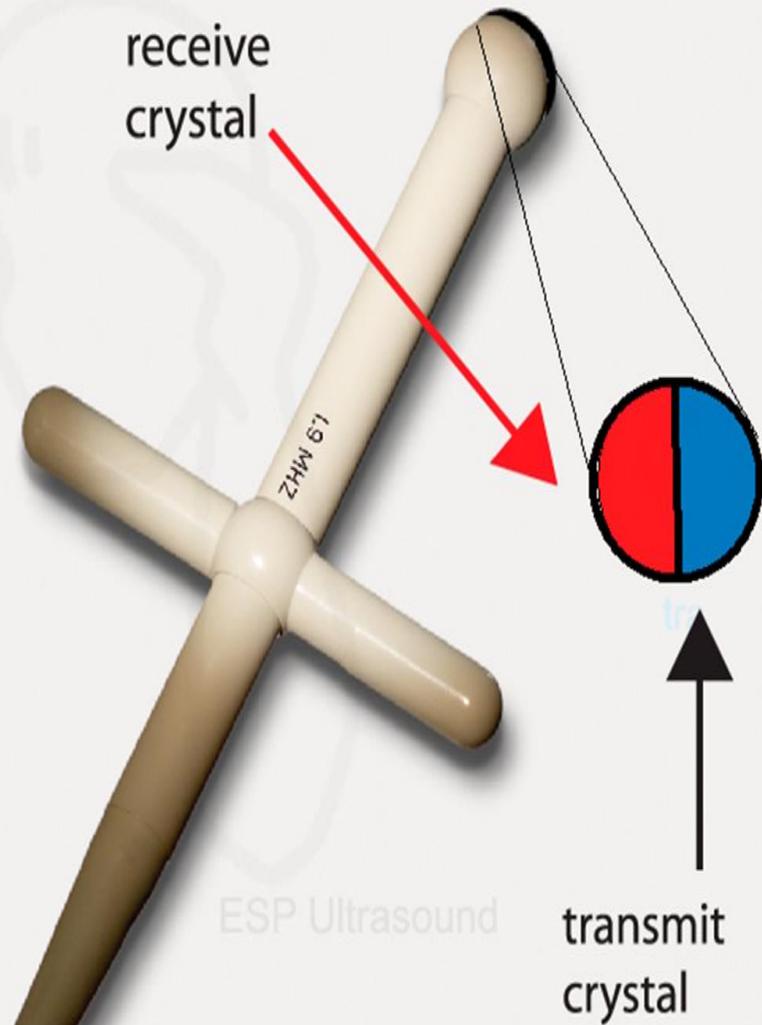
# The Doppler Effect

- Some Doppler devices are nondirectional
  - Unable to distinguish between positive or negative Doppler shifts
- Some Doppler devices use phase quadrature to determine whether there is a positive shift or a negative shift
- Phase quadrature permits bidirectional Doppler, which displays positive versus negative shifts
- There are two ways of obtaining a Doppler signal: continuous-wave (CW) and pulsed-wave (PW)

# Continuous Wave Doppler

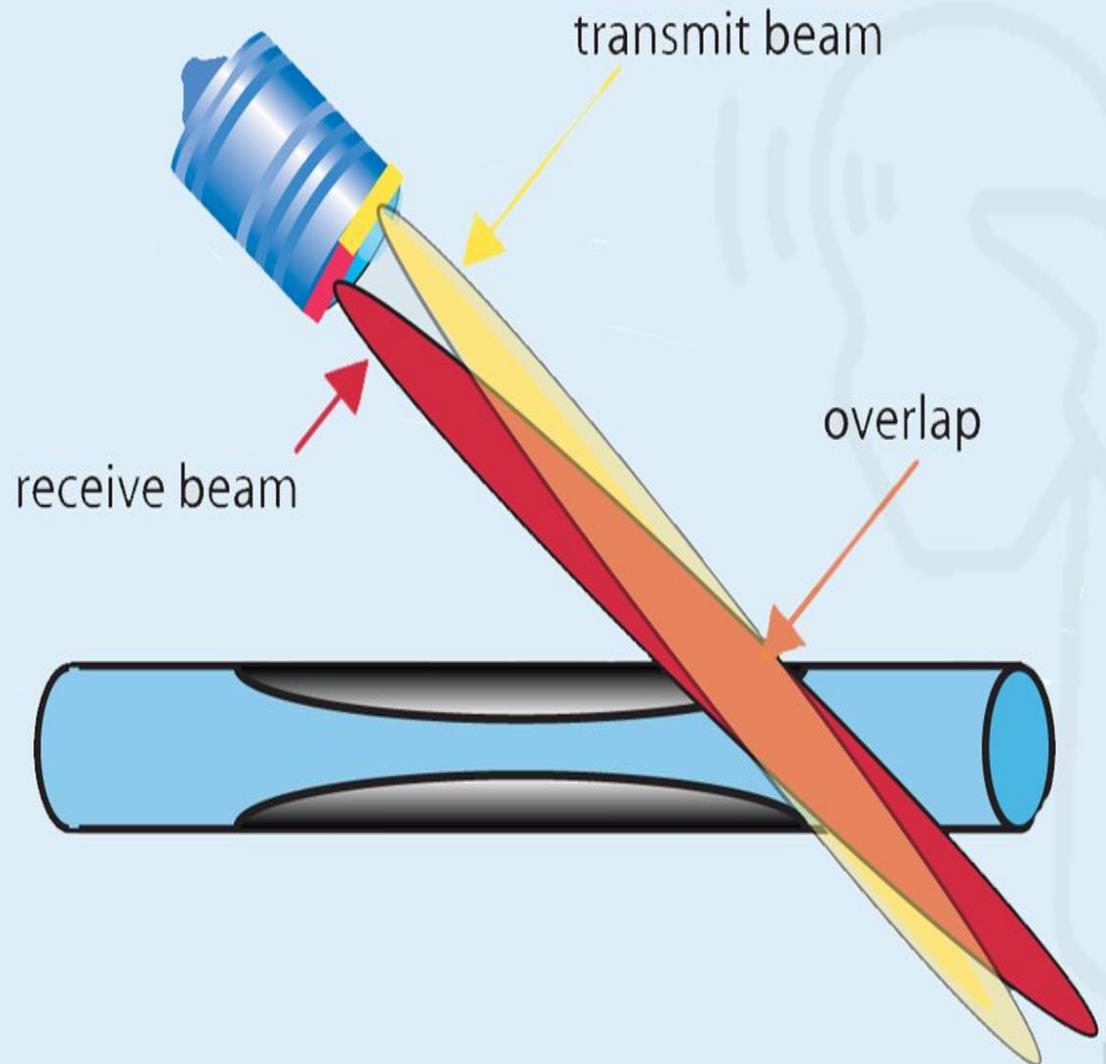
- A continuous-wave (CW) Doppler device consists of two elements
  1. **One element is used by the system to constantly transmit sound**
  2. **One element is used to constantly receive sound**
- With CW devices, the piezoelectric elements used by the system to create ultrasound cannot send and receive at the same time
  - Do not pause to listen for return echoes
  - Cannot calculate how long it takes for echo to return
- **CW devices have no range resolution and cannot produce a 2D image**
  - **Only able to produce a spectral Doppler waveform**

# Continuous Wave Doppler



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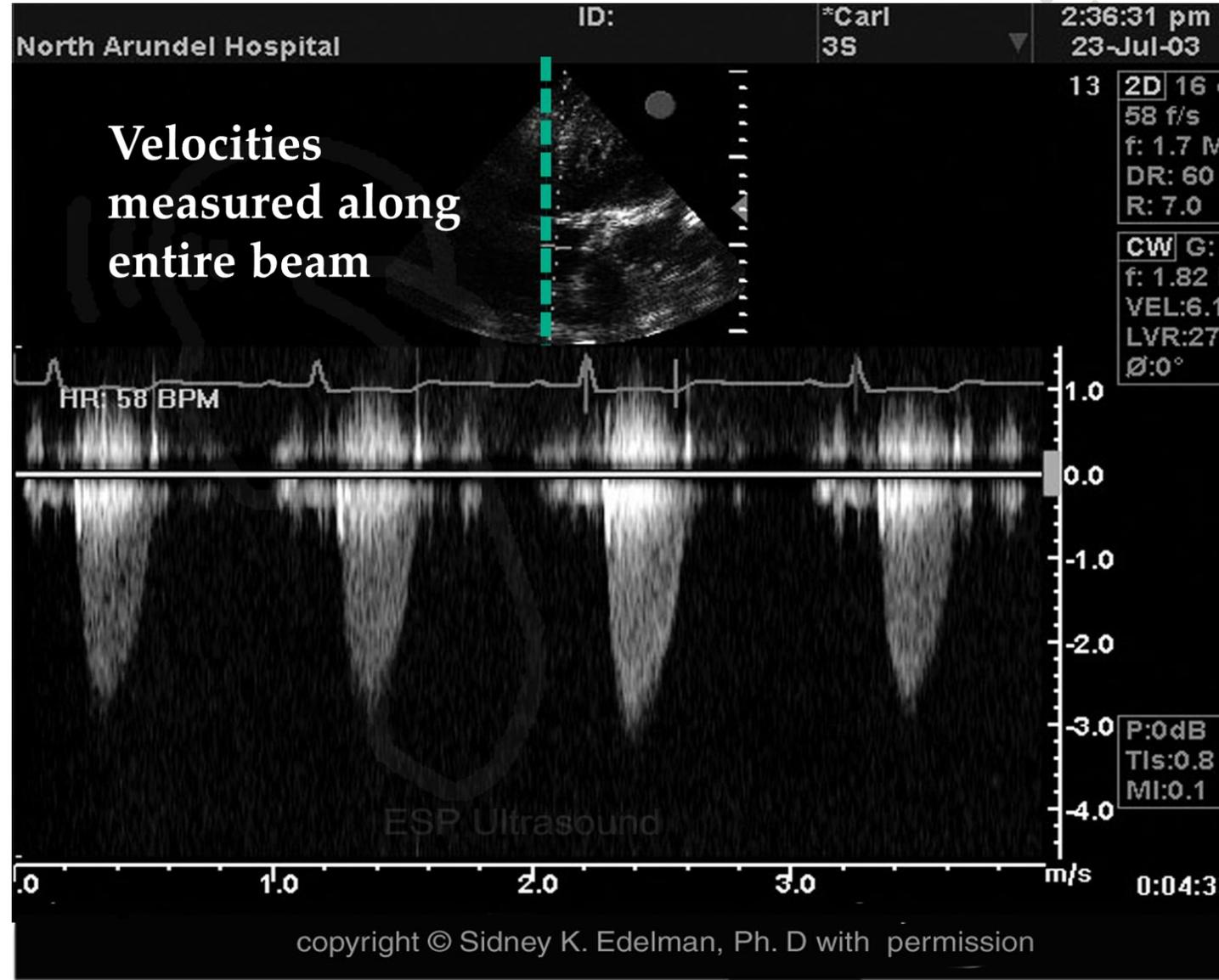


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# Continuous Wave Doppler

- The sample volume, or region that is being measured by Doppler, is very large with CW Doppler
  - **Any blood vessel that lies within the sample volume will be measured and displayed in the signal**
  - **The operator is not able to select a specific vessel which creates problems when there are several vessels within the sample volume**



# Continuous Wave Doppler

- **With CW transducers, the oscillating voltage is equal to the operating frequency**
  - If the oscillator vibrates at 3,000,000 times per second, the CW transducer operates at 3 MHz
- **Advantages of using CW:**
  - **Accurately measures very high velocities**
  - **No aliasing with CW**

# Continuous Wave Doppler

- **Disadvantages** of using CW:
  - Inability to determine exact location
    - **Range ambiguity** (picks up all RBC's in overlap region during both transmit and receive)
  - **Lack of TGC**
    - Reflections from deeper depths will have lower amplitude than from shallower
    - Doppler shift by deeper RBC's may be incorrect as having been created by fewer RBC's

# Continuous Wave Doppler

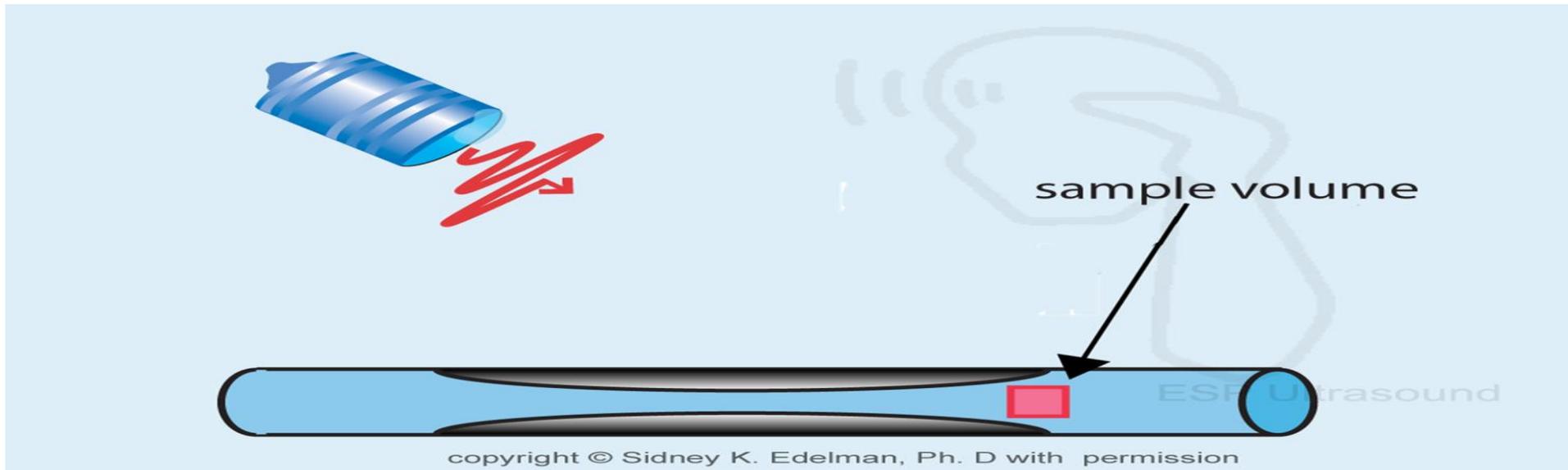
- Less complicated
  - **Does not contain backing material**
    - Which has the following effects:
      - Un-dampened transmitted signal
      - Narrow bandwidth
      - High quality factor
      - Higher sensitivity
        - Detect low amplitude and small Doppler shifts

# Continuous Wave Doppler

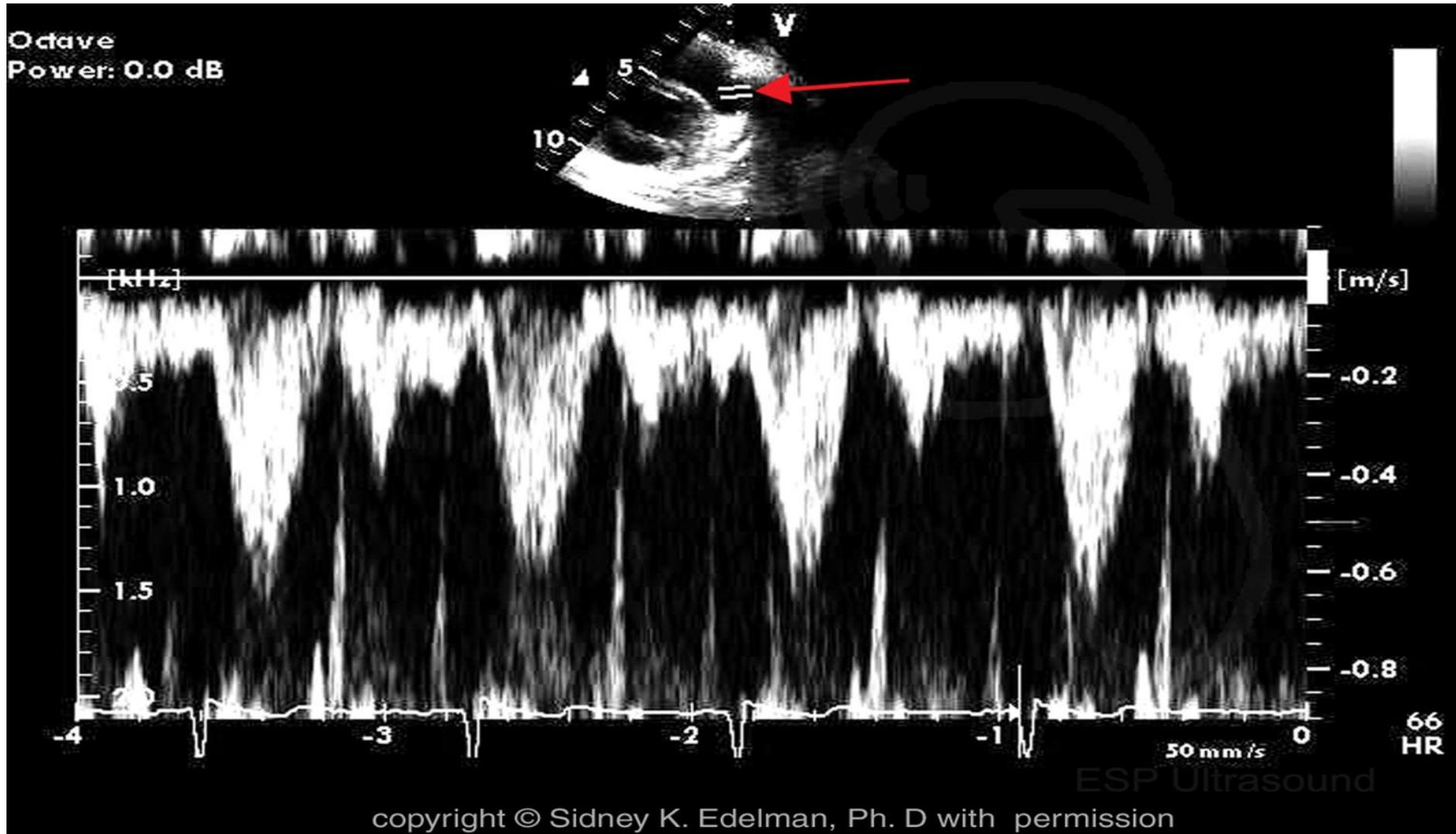
- There is no damping with a CW transducer
  - **Because the sound is being transmitted continuously, damping is not needed**
- The continuously transmitting CW device has a 100% transmit time
  - **Therefore, the duty factor of a CW device is 100%, or 1**

# Pulsed Wave Doppler

- One crystal
  - **Alternates between sending and receiving sound**
- Sample volume or "gate"
  - **Positioned within center of the vessel**
  - **Calculates time-of-flight corresponding to depth of sample gate**

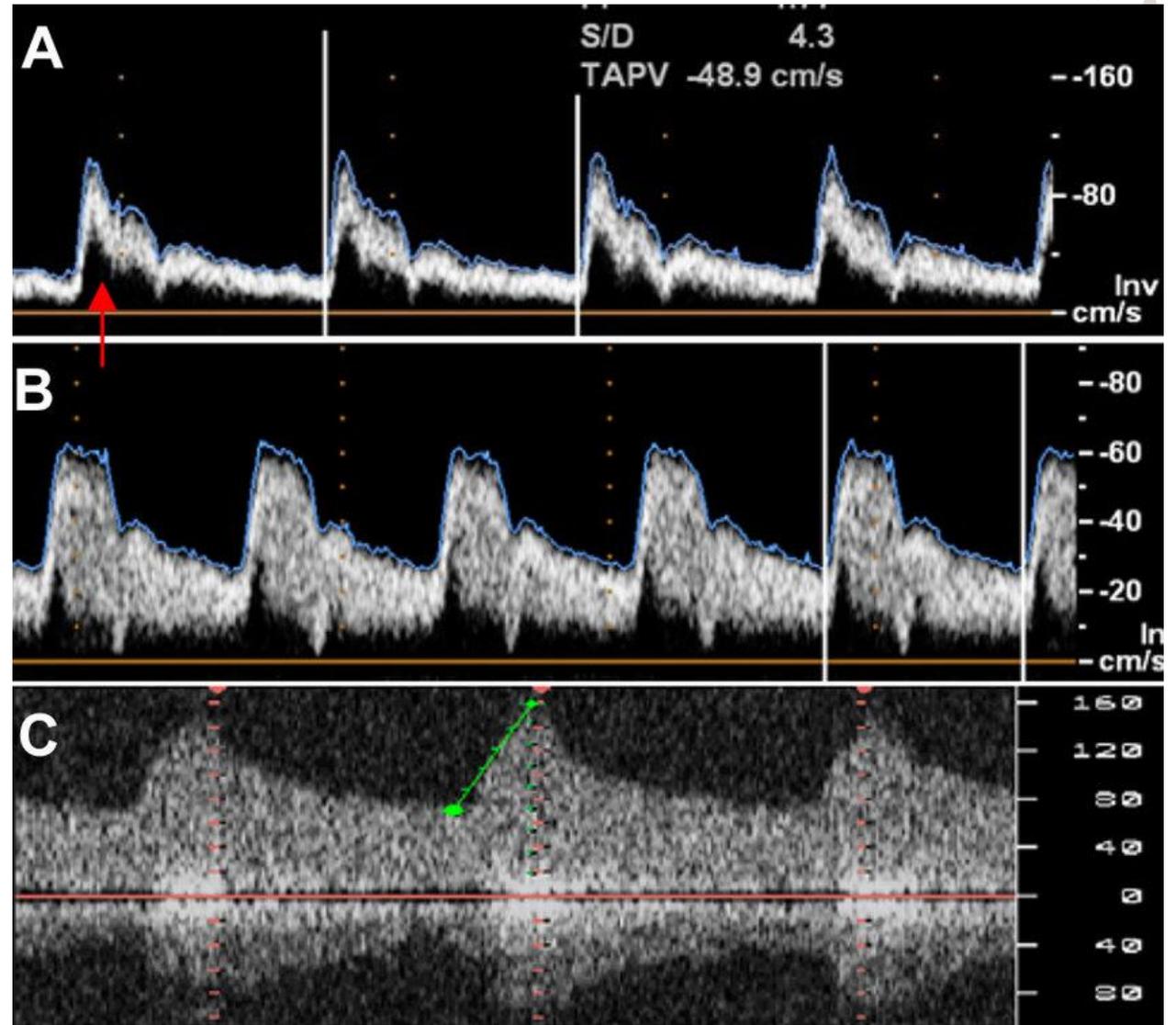


# Pulsed Wave Doppler



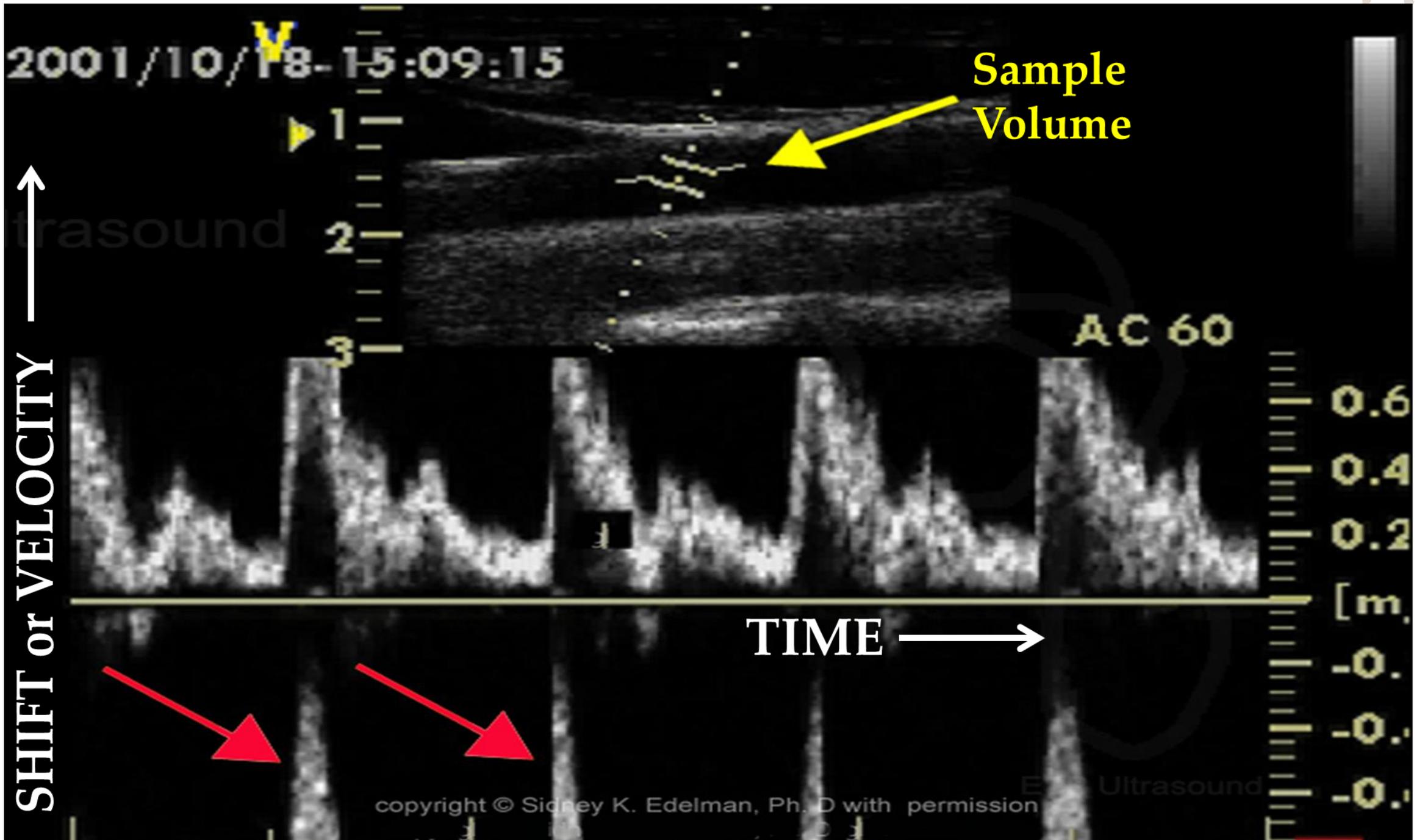
# Pulsed Wave Doppler

- Sample volume or "gate"
  - **Smaller gates**
    - Create larger, cleaner envelopes
  - **Larger gates**
    - Create smaller envelopes (spectral broadening)



# Pulsed Wave Doppler

- Advantage:
  - **Exact sample location is known**
  - This is called:
    - Range Resolution
    - Range Specificity
    - Freedom from range ambiguity artifact
- Disadvantages:
  - **Inaccurate measurement of high velocities**
    - Super high velocities are displayed as traveling in the opposite direction, aka "aliasing"



# Pulsed Wave Doppler

- More complicated
  - **Contains backing material**
    - Which has the following effects:
      - Dampened transmitted signal
      - Wide bandwidth
      - Low quality factor
      - Lower sensitivity
  - **Duplex imaging**
    - Simultaneous imaging and Doppler

# Analyzing the Spectral Waveform

- The signal that is received by the transducer is a complex mix of frequency shifts and time
  - Spectral analysis dismantles the complex signal and breaks it down by frequency
  - **The mathematical technique used to break down the signal and produce a spectral waveform is called Fast Fourier Transform (FFT)**
    - FFT produces accurate velocity measurements that are needed to quantify the level of disease
  - **The spectral display provides the following information: time, velocity, frequency shift, flow direction, and amplitude**

# Analyzing the Spectral Waveform

- Time is displayed on the spectral display along the x-axis
  - Tick marks represent seconds, making it possible to calculate events as they occur
  - The time displayed can be adjusted by changing the sweep speed of the Doppler instrument
- Ultrasound machines measure the frequency shift and convert it to velocity information (more relevant for our use)
  - Relies on angle correction to reduce operator variability
  - Measures PSV and EDV to quantify disease in a vessel

# Analyzing the Spectral Waveform

- Mean velocity can be derived by tracing the spectral waveform from end diastole of one wave to end diastole of the next wave
- Other relevant measurements include the Resistive Index (RI) and the Pulsatility Index (PI)
- RI quantitates the resistiveness of the distal vascular bed
  - Great for analysis of kidneys in cases of hydronephrosis
- PI determines how pulsatile a vessel is over time
  - Great for OB in the evaluation of fetal brain and umbilical cord

# Analyzing the Spectral Waveform

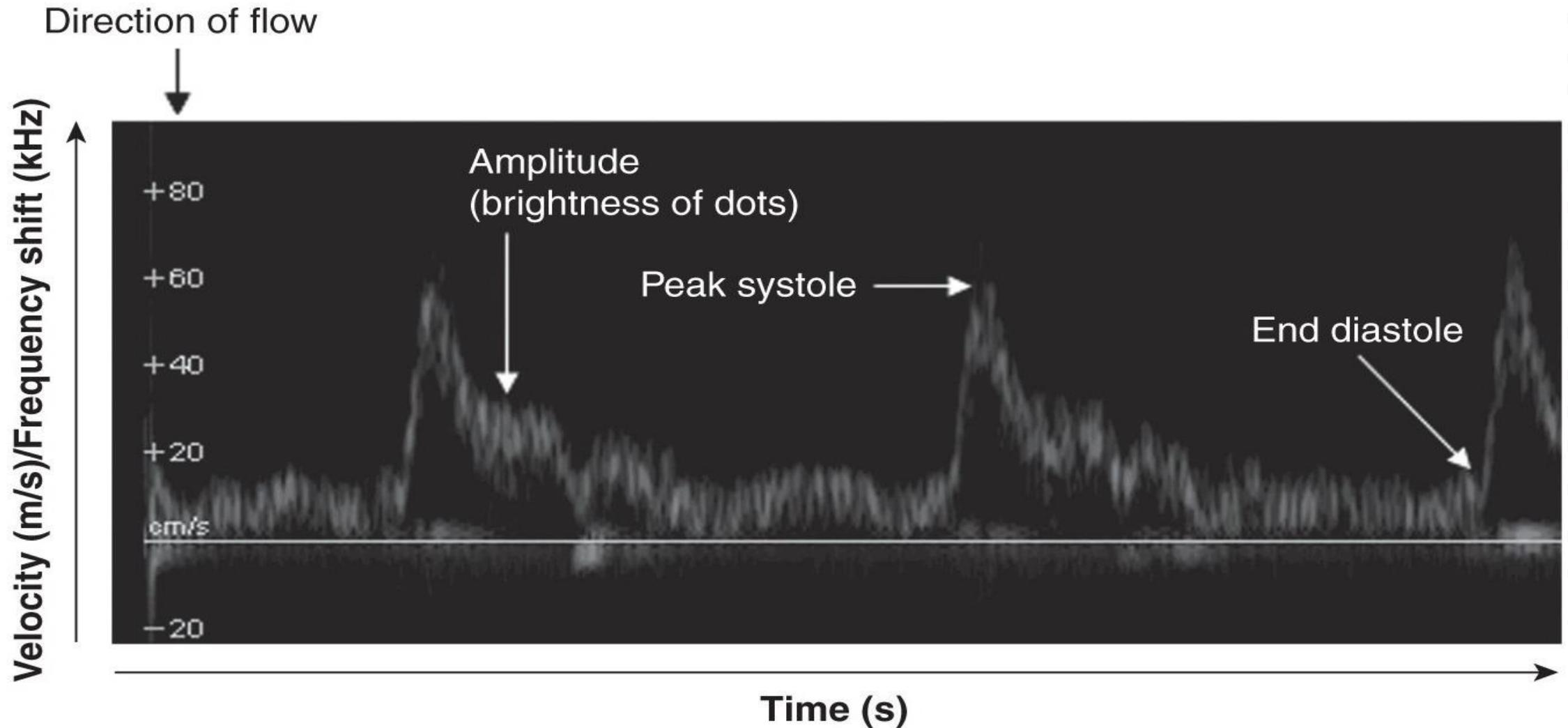
- **Resistive Index:**

$$RI = \frac{\text{Systole} - \text{Diastole}}{\text{Systole}}$$

- **Pulsatility Index:**

$$PI = \frac{\text{Systole} - \text{Diastole}}{\text{Mean}}$$

# Analyzing the Spectral Waveform



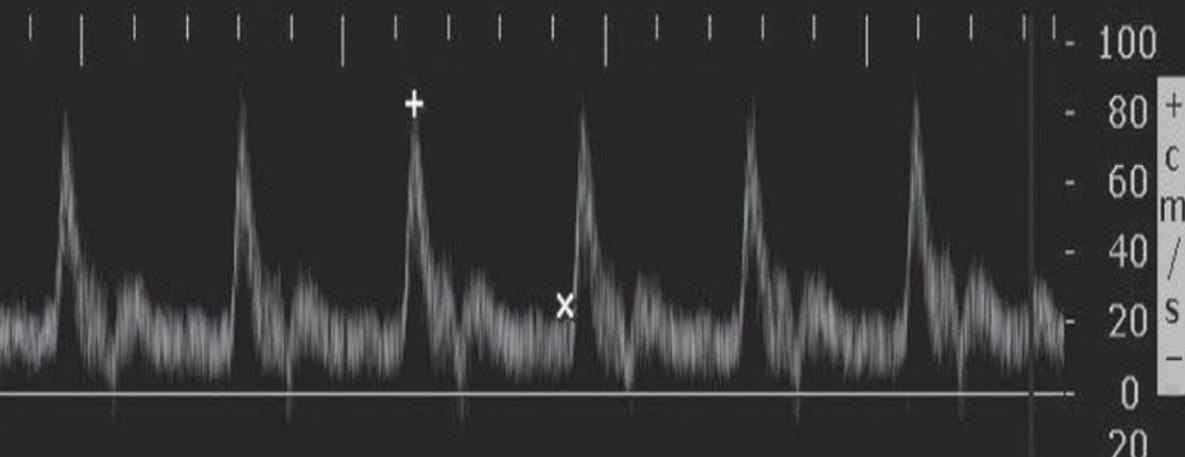
Right P

RI 0.697

+ SV 83.8 cm/s

x DV 25.4 cm/s

G  
P  $\triangle$   $\odot$  R  
3.8 7.6

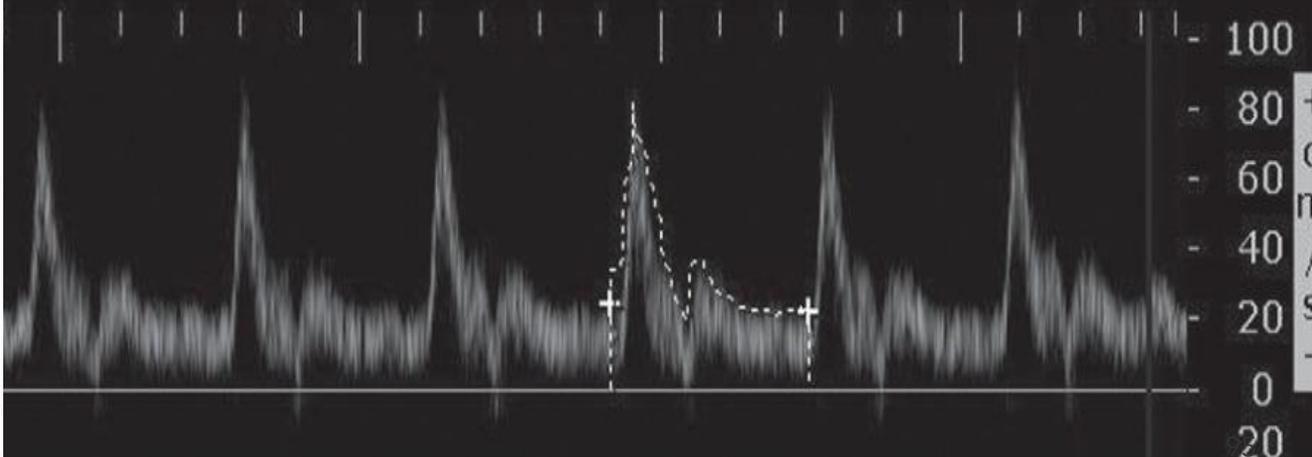


Right P

PI 1.68

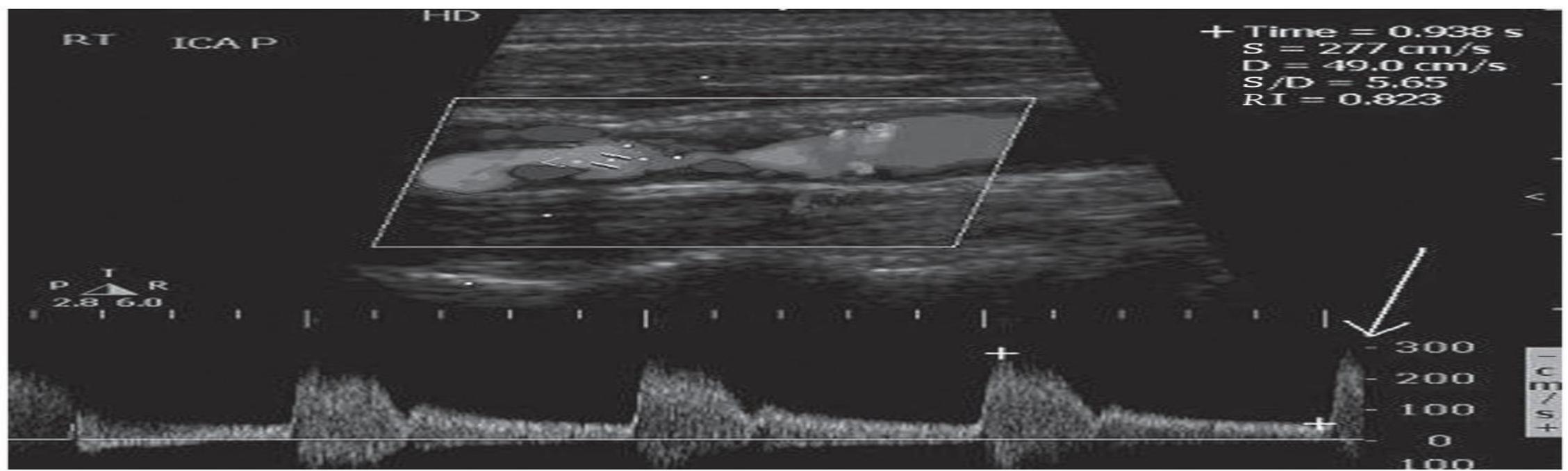
TAVP (PI) 34.7 cm/s

G  
P  $\triangle$   $\odot$  R  
3.8 7.6

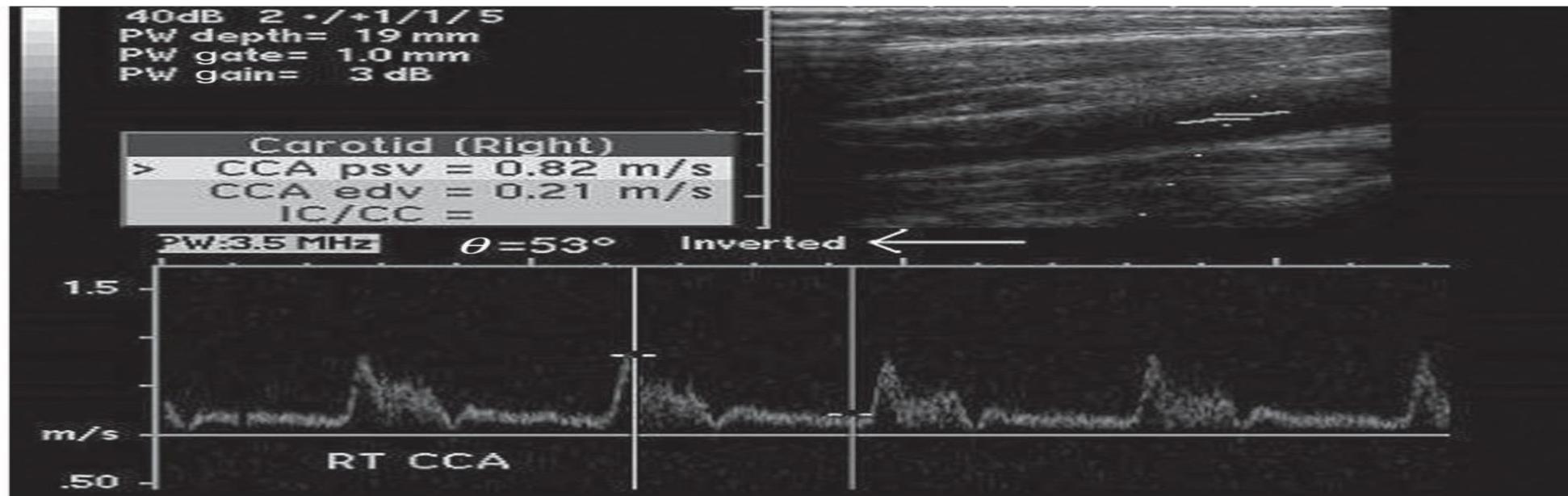


# Analyzing the Spectral Waveform

- Flow direction:
  - Displayed above or below the baseline
  - Positive or Negative shift
  - Flow can be inverted by sonographer; this may hide pathological reversal of flow
    - Always pay attention to the screen indicators
      - Some machines have a minus (-) sign in front of the velocity
      - Some machines use the word "INVERT" instead



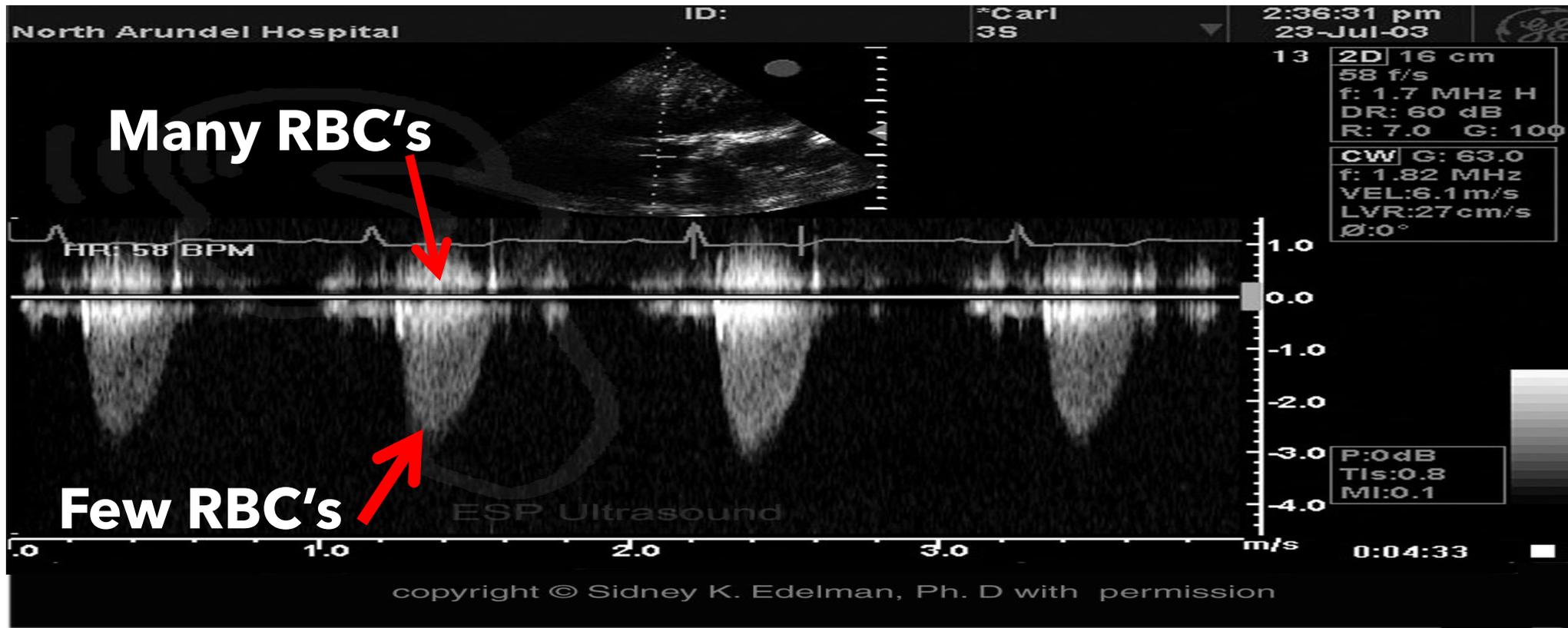
**A**

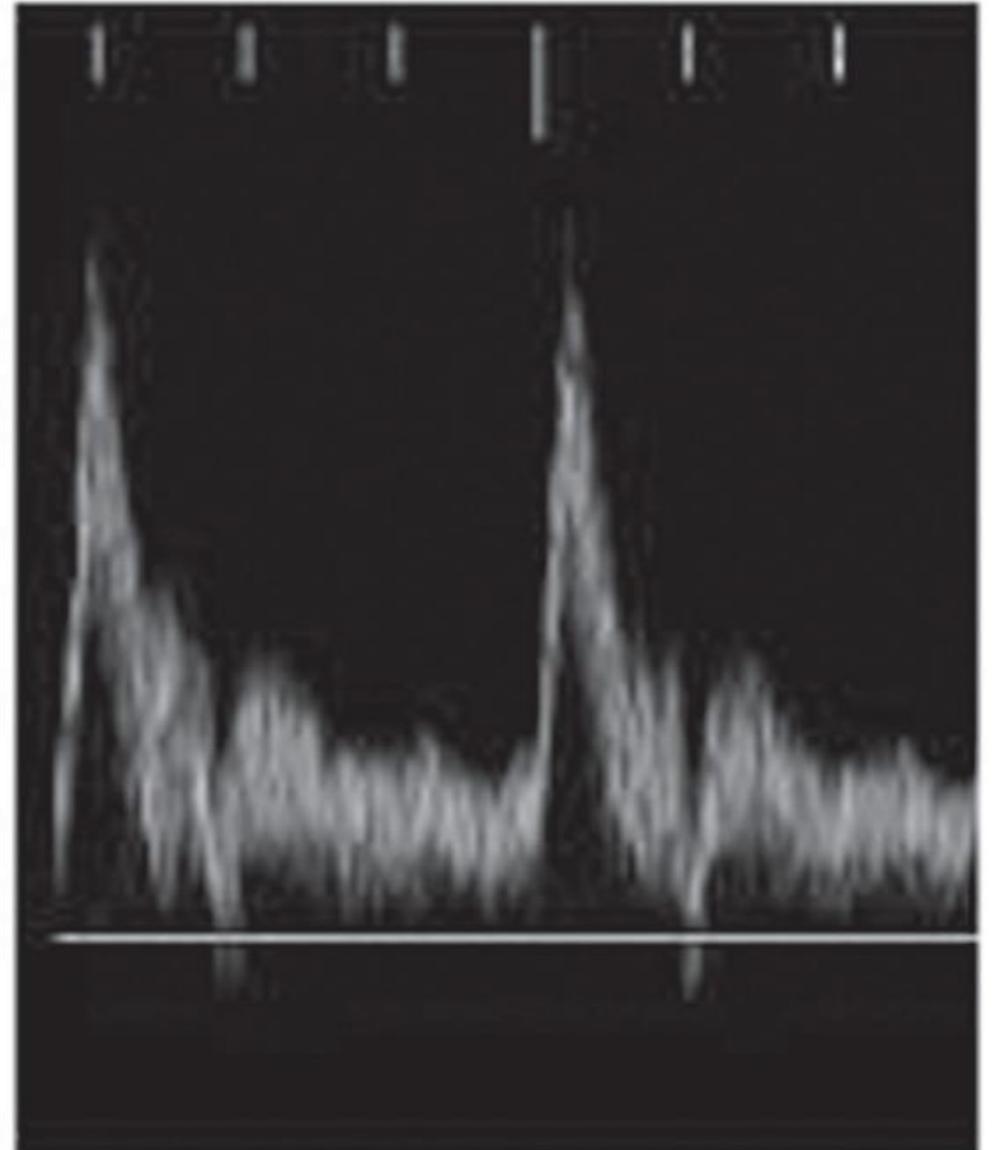
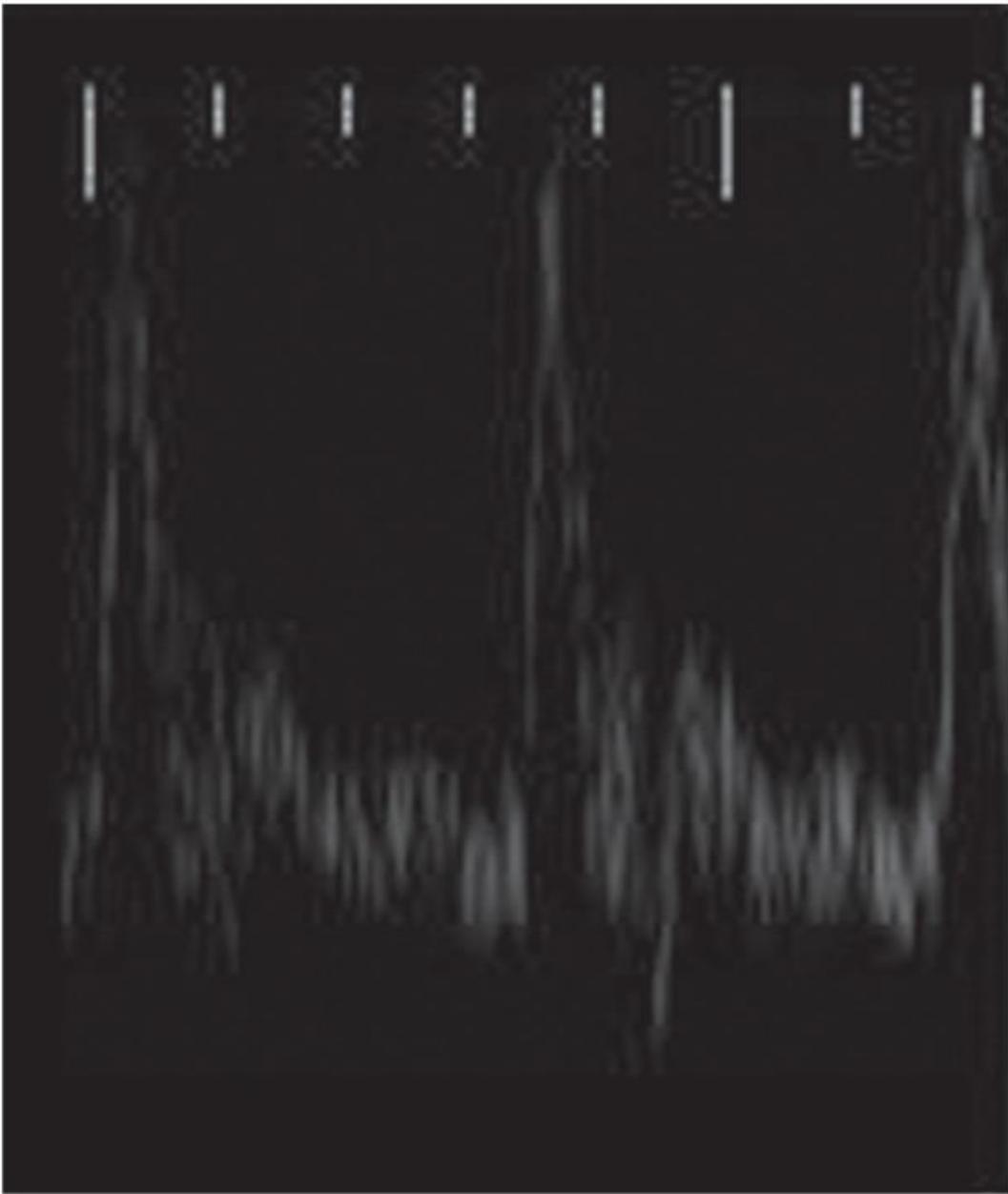


**B**

# Analyzing the Spectral Waveform

- The gray shades of the spectral waveform are related to:
  - **Amplitude of the reflected signal**
  - **Number of RBC's creating the reflection**



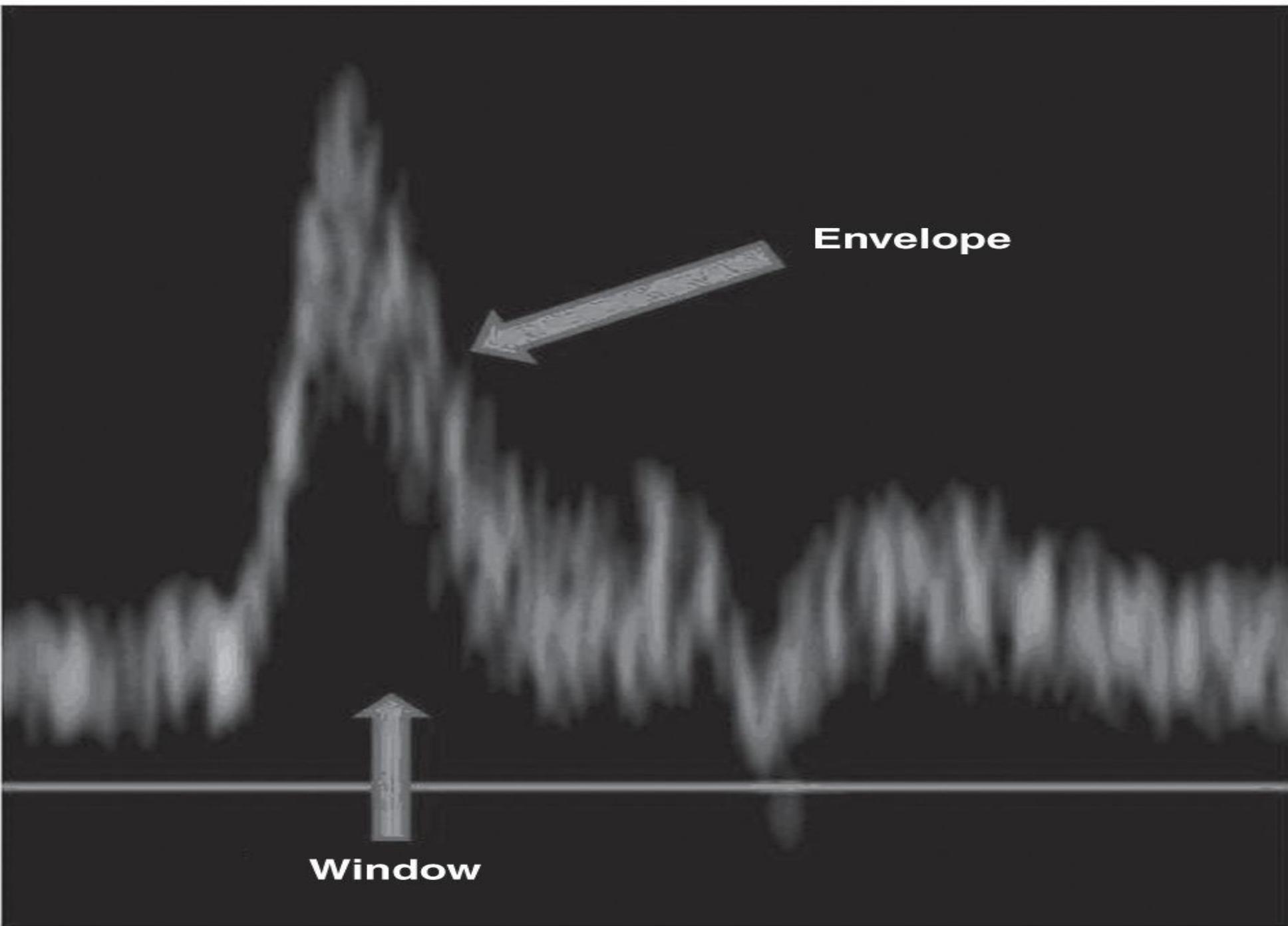


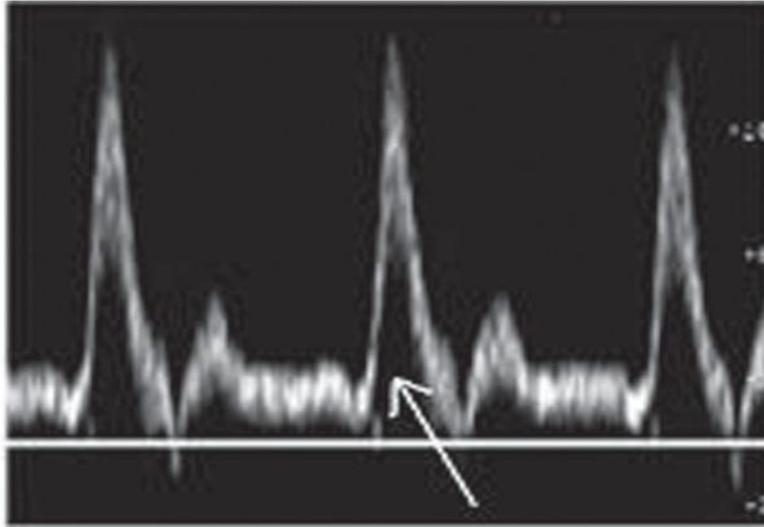
**A**

**B**

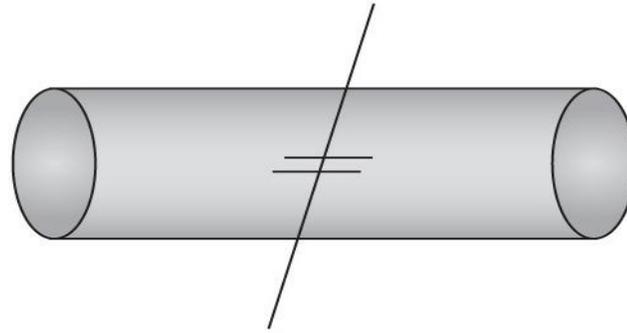
# Analyzing the Spectral Waveform

- The **envelope** of the waveform represents how many RBC's are traveling at the same velocity at a specific time
  - **The more velocities occurring during a specific time, the thicker the envelope will be**
- We use a small sample volume to record only the highest velocities in the center of the vessel
- Using a large sample volume that encompasses the entire lumen will represent many different velocities
- The area under the envelope is called the **spectral window**

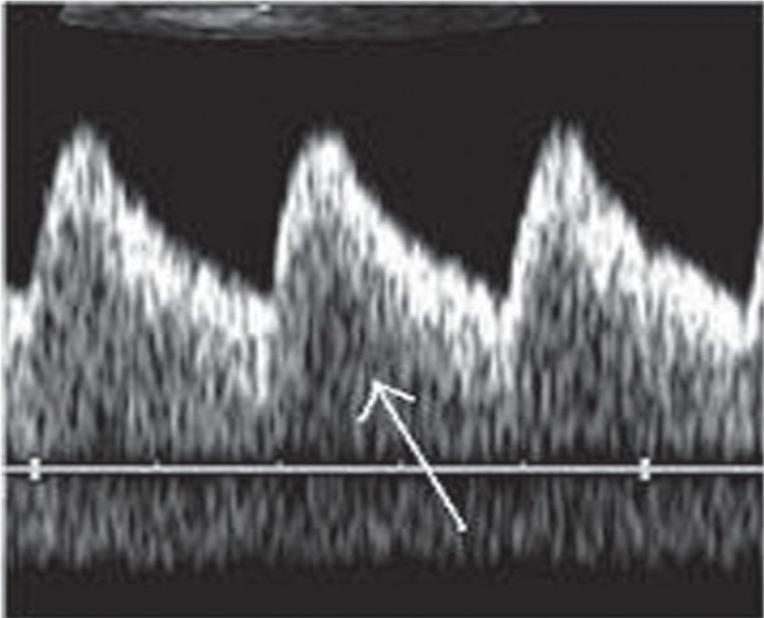




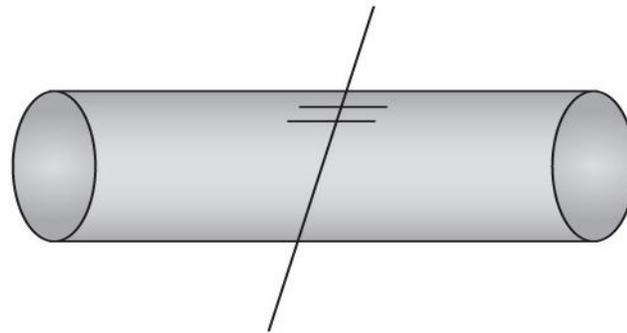
**A**



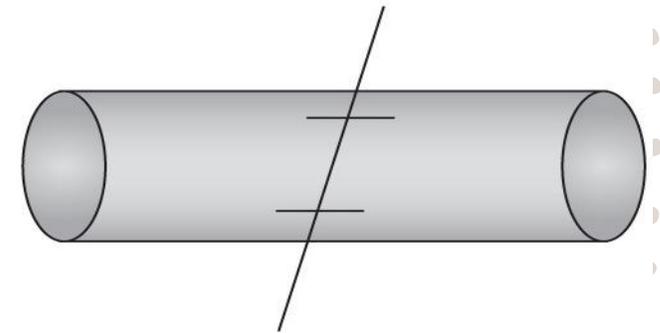
Keep the cursor in the center of the vessel (fastest flow for clear window)



**B**



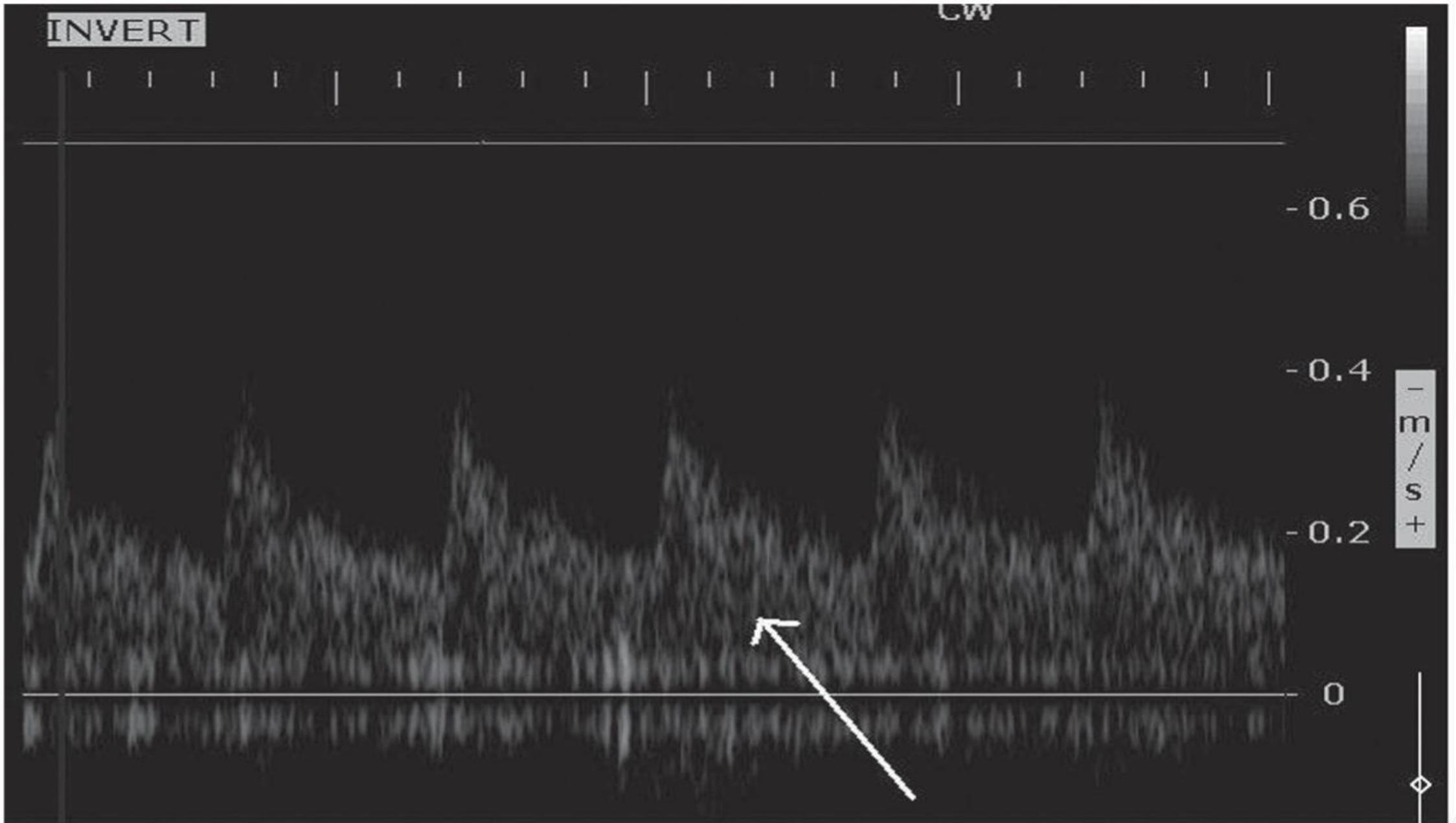
or



Cursor toward the edge (boundary layer) or gate too wide open results in broadening (no window)

# Analyzing the Spectral Waveform

- When RBC's are moving at almost identical speeds, as seen with laminar flow, the spectral waveform will demonstrate a thin envelope
- When turbulent flow is present, or when a large sample volume is used, a wide range of velocities will be present
  - This creates filling-in of the spectral envelope termed **spectral broadening**



# Analyzing the Spectral Waveform

- Turbulence is not always pathologic
  - **Carotid bulb**
  - **Tortuous vessels**
- If laminar flow is expected and turbulence is seen, then further investigation is warranted
- CW flow uses a large sample volume and samples many vessels at the same time
  - **It is expected to spectral broadening when CW is used**

# Pulsed-Wave Doppler

- PW Doppler functions much like PW grayscale
  - Transmits a pulse of sound and waits for the sound to return
  - Calculates depth of the returning echoes
- PW Doppler allows the sonographer to select the depth at which the Doppler measurements will be taken
  - Sample volume or "gate" is placed where the PW Doppler signal is obtained
  - Can also change the size of the "gate" or sample volume

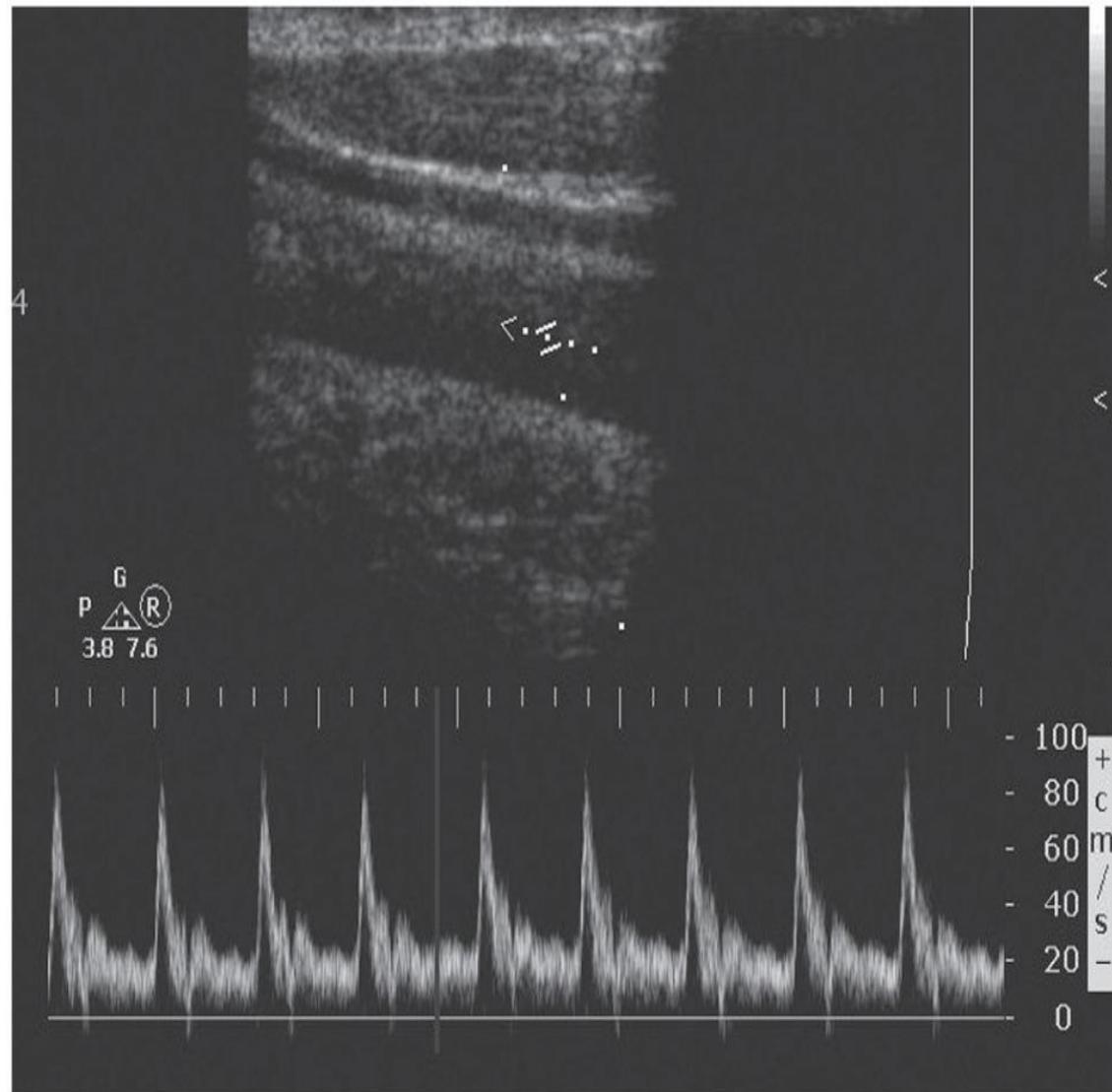
# Pulsed-Wave Doppler

- Regular grayscale imaging uses 2-3 cycles per pulse to produce a B-mode image
- PW Doppler uses 5-30 cycles per pulse
  - More cycles (longer pulse length) provides a more accurate sampling of the RBC's
- PW Doppler also uses angle correction
  - Calculates velocities from the frequency shifts

What is the Doppler Shift equation?

# Pulsed-Wave Doppler

- PW Doppler devices also permit duplex imaging
  - **B-mode image is on the display at the same time as the Doppler signal**
  - **Duplex imaging allows for real-time adjustment of the sample volume and angle while observing the grayscale image**



# Pulsed-Wave Doppler

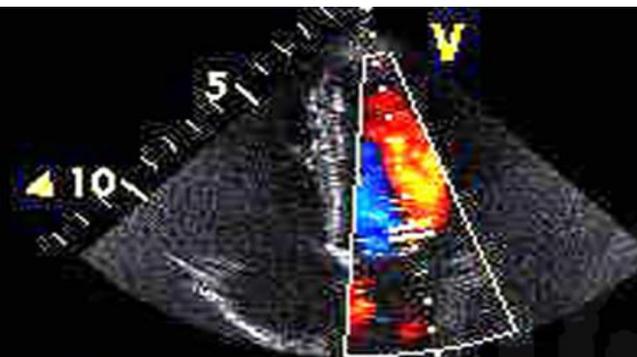
- With duplex imaging, the acquisition of the grayscale information alternates with obtaining the Doppler information
  - This switching back and forth occurs very fast but does affect the frame rate in a negative way, because it decreases the temporal resolution
- Triplex imaging is combined grayscale, spectral, and color Doppler information on the screen

# Pulsed-Wave Doppler

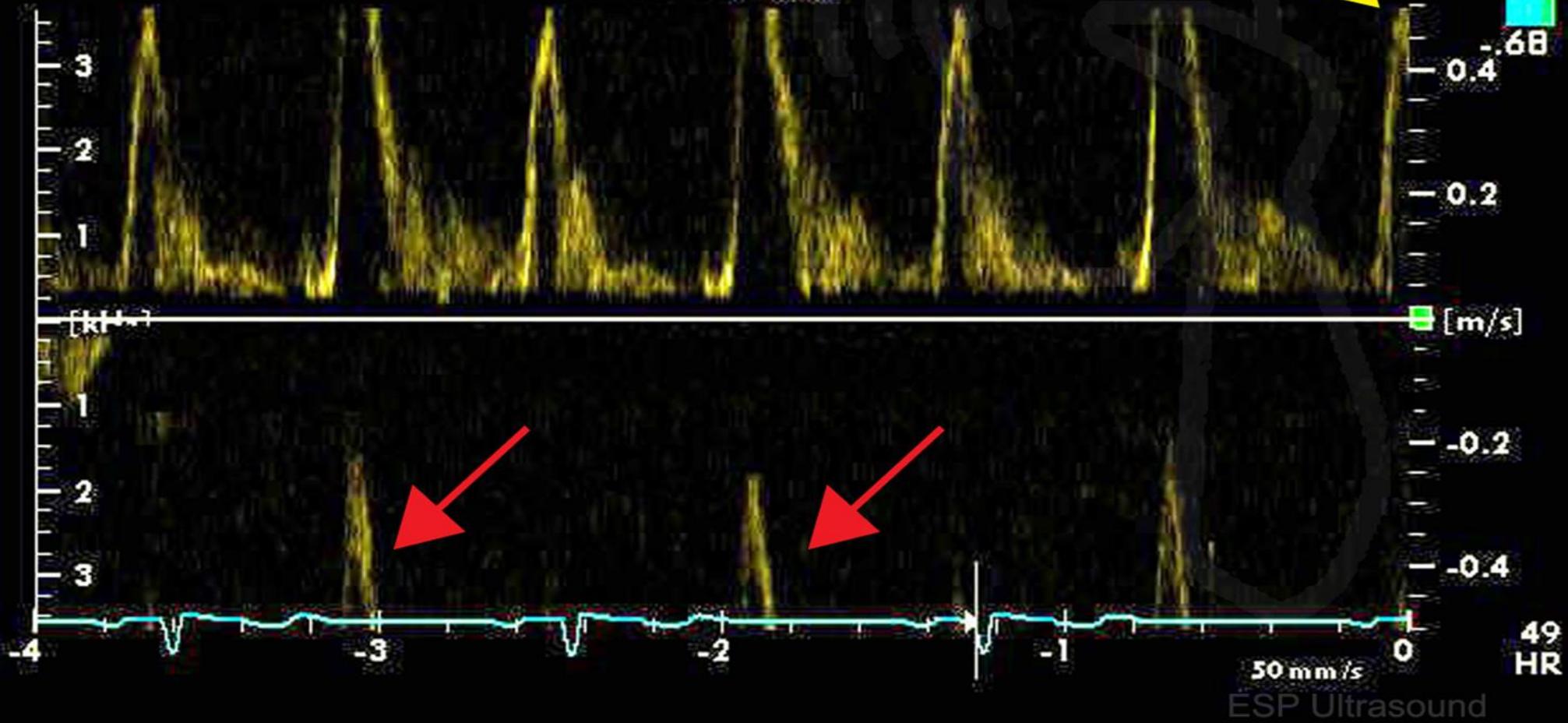
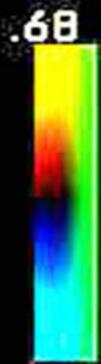
- Limitation of PW Doppler is ***aliasing***
  - **Wrap around of the Doppler signal that makes positive shifts appear as negative shifts**
- The highest frequency shift that can be measured is equal to  $\frac{1}{2}$  the Pulse Repetition Frequency
  - **This is called the Nyquist Limit**

$$\text{Nyquist Limit} = \frac{\text{PRF}}{2}$$

Octave  
Power: 0.0 dB



Nyquist Limit



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# Aliasing

- Exists when Doppler sampling rate is too low in comparison to velocity
  - RBC's moving at high velocities are displayed as moving in the wrong direction
- Exists **only** with PW Doppler
- Never happens with CW Doppler

# Aliasing

- **Deeper samples volumes create more aliasing**
- **When sample volume is deep**
  - PRF and Nyquist limit is low
  - Velocity is estimated fewer times each second
- **When sample volume is shallow**
  - PRF and Nyquist limit is high
  - Velocity is estimated many times each second

# Aliasing

- Higher frequency transducers create:
  - **More aliasing (more likely to occur)**
  - **Higher Doppler shifts**
    - More likely to exceed Nyquist Limit
- Lower frequency transducers create:
  - **Less aliasing**
  - **Lower Doppler shifts**
    - Less likely to exceed Nyquist Limit

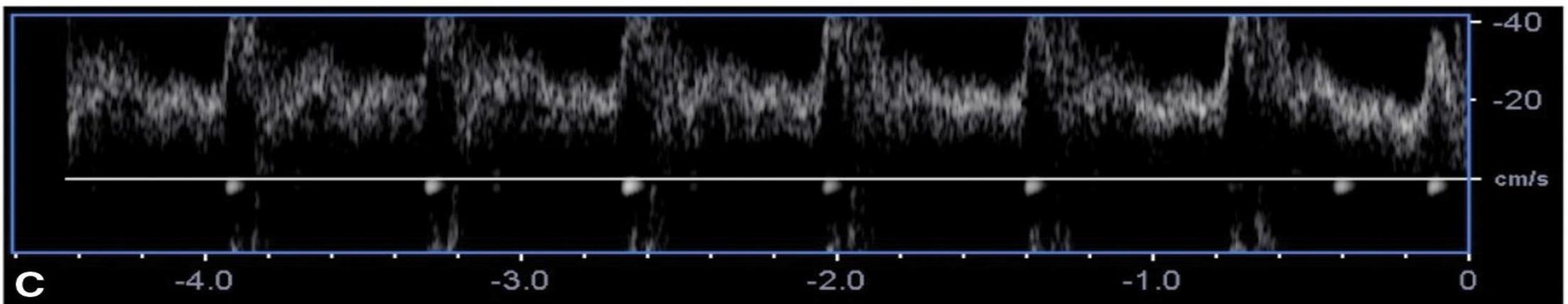
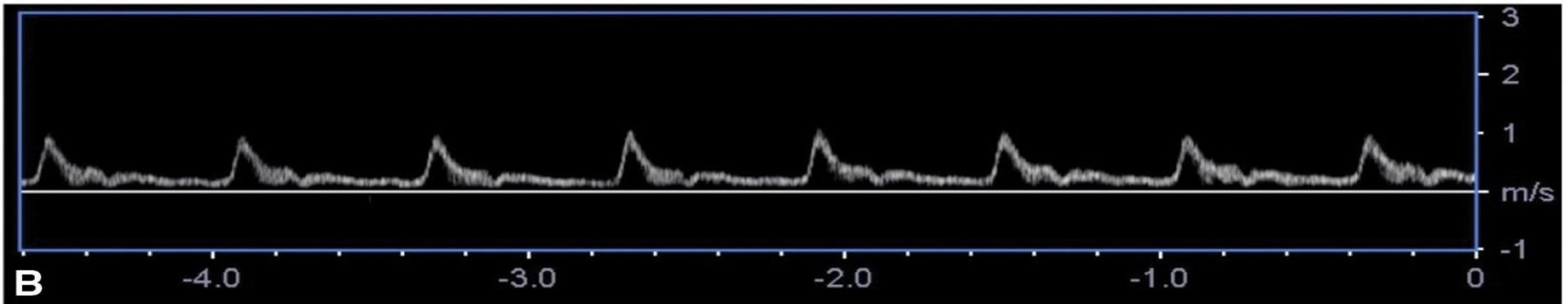
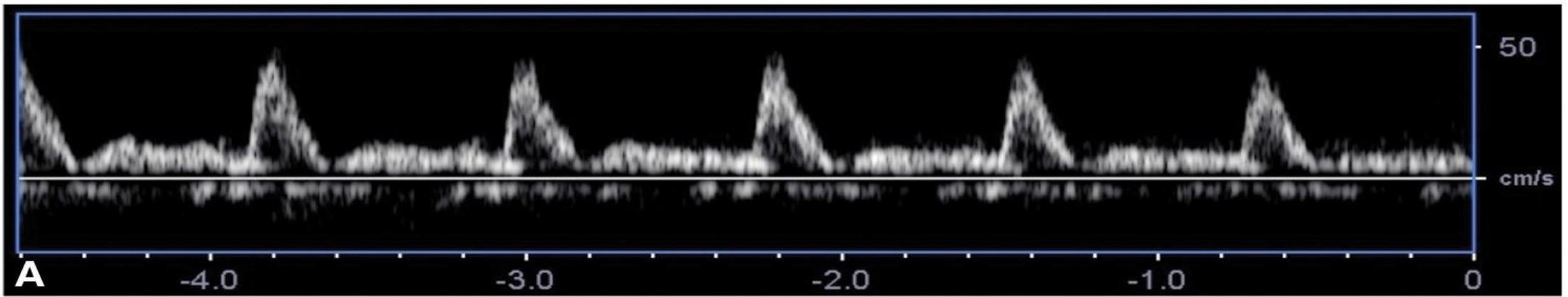
# Aliasing

<b>Less Aliasing</b>	<b>More Aliasing</b>
<b>Slower blood velocity</b>	<b>Faster blood velocity</b>
<b>Lower frequency transducer</b>	<b>Higher frequency transducer</b>
<b>Shallow gate (high PRF)</b>	<b>Deep gate (low PRF)</b>

# Aliasing

- Things to try to avoid aliasing:
  1. Adjust scale (PRF) to its maximum
    - **Advantage:**
      - Maximizing PRF raises Nyquist limit; aliasing less likely to occur
    - **Disadvantages:**
      - Higher PRF reduces sensitivity to low velocities

\*\*\* Aliasing persists with very high velocities even when scale is maximized \*\*\*



# Aliasing

- Things to try to avoid aliasing:
  2. Select lower frequency transducer
    - **Advantage:**
      - With lower frequency transducer RBC's produce lower Doppler shifts
      - Lower Doppler shifts are less likely to exceed the Nyquist Limit
    - **Disadvantage:**
      - Lesser quality real-time image is produced when using Duplex imaging

# Aliasing

- Things to try to avoid aliasing:
  3. Select new "window" with a shallower sample volume (i.e. decrease the sample depth)
- **Advantage:**
  - PRF and Nyquist limit is increased
- **Disadvantage:**
  - None really; reliant on sonographer's skill level

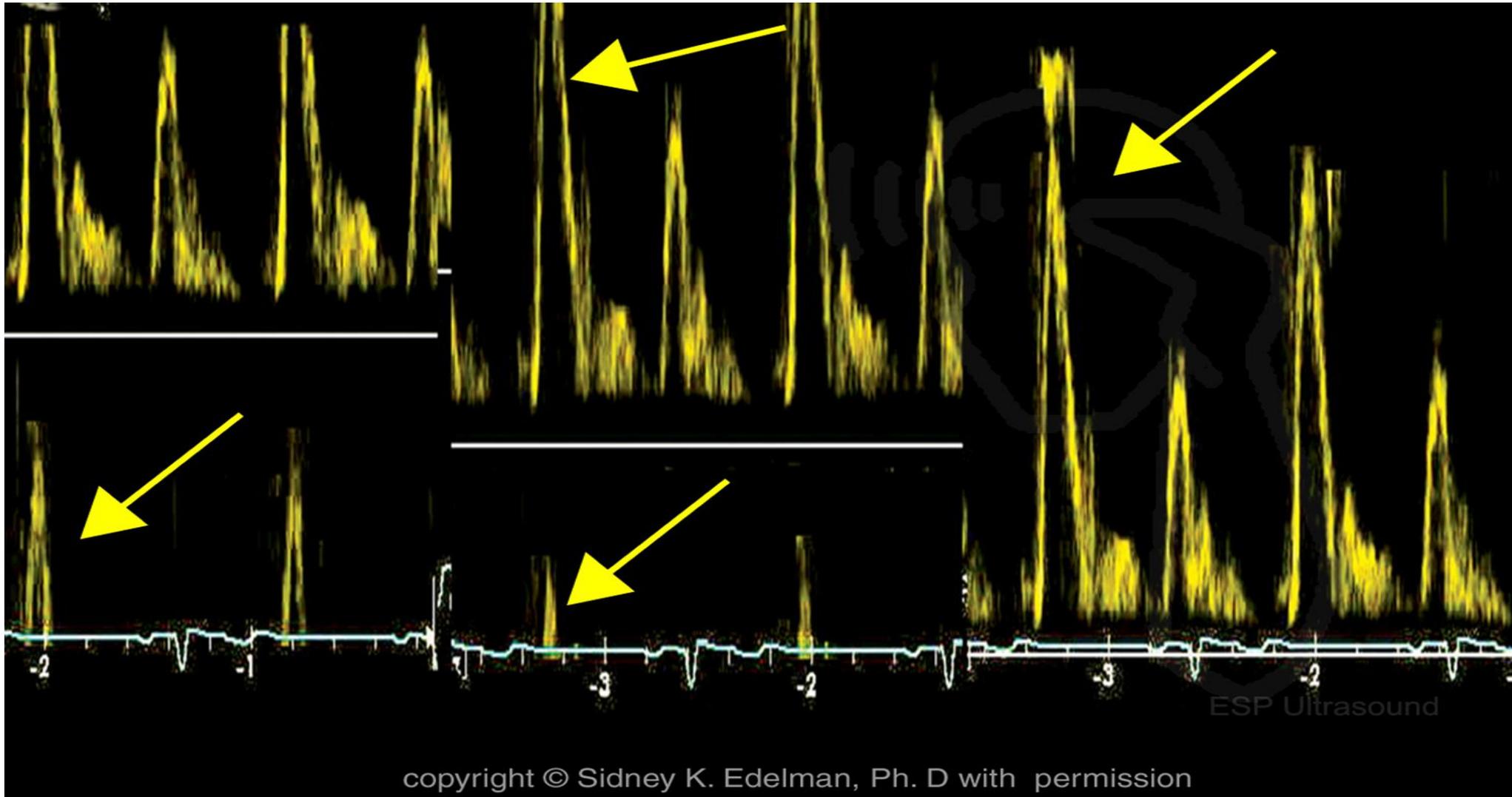
# Aliasing

- Things to try to avoid aliasing:
  4. Use CW Doppler
    - **Advantage:**
      - Aliasing never occurs with CW Doppler
    - **Disadvantage:**
      - Range ambiguity
      - Velocities along region overlap and blend together

# Aliasing

- Things to try to avoid aliasing:
  5. Use baseline shift
    - **Advantage:**
      - Simply slide baseline down so the entire velocity scale is going in one direction
      - Not anymore accurate, just makes display more pleasing to the eye
    - **Disadvantage:**
      - Just changes the visual appearance; nothing else
      - Baseline shift will be ineffective when the Doppler shift is too high and the signal wraps around itself

# Baseline Shift



# Review of Doppler Controls

- Numerous controls are used to manipulate the spectral waveform to aid in diagnosis and interpretation
- The range gate, already mentioned in previous sections, is the cursor used in PW Doppler that is placed in the vessel where sampling is desired
  - The size of the sample volume may be controlled by changing the size of the gate

# Review of Doppler Controls

- Angle correction is used with PW Doppler to accurately calculate the velocities from the frequency shifts
  - The higher the Doppler angle, the greater the degree of potential error in the measurement
  - **Angles greater than  $60^\circ$  exhibit a very high rate of velocity measurement error, and therefore should be avoided**
- When using a linear transducer, the Doppler cursor can be steered to either the left or the right

# Review of Doppler Controls

- Steering permits the operator to keep the angle correction at or below  $60^\circ$  by changing the steer angle
  - When steering cannot be adjusted, the operator may have to “heel” or “toe” the transducer in order to angle correct
- The operator must avoid a  $90^\circ$  angle to flow when sampling a vessel
  - **Cosine of  $90^\circ$  is 0...no Doppler shift can occur** (need to steer your angle correction, heel/toe, or find a different window)

# Review of Doppler Controls

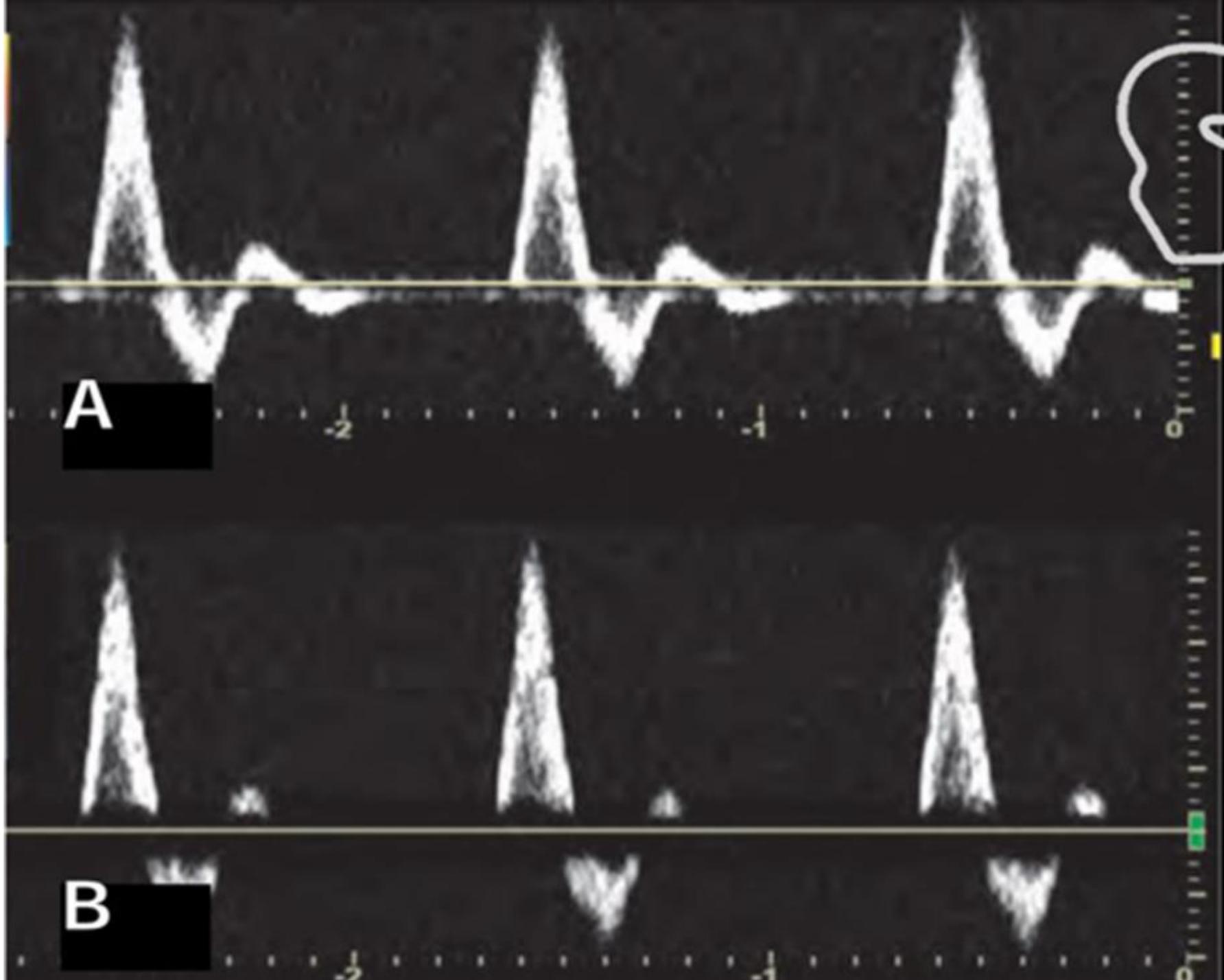
- The scale, or PRF setting on the machine, is the sampling rate of the Doppler
  - The sampling rate must be fast enough to accurately plot the frequency shifts or aliasing will occur
- The PRF is determined by the depth
  - The deeper the vessel, the lower the PRF
  - Occasionally, when a deep vessel needs to be imaged the PRF cannot sample at a sufficient rate
    - Some ultrasound systems solve this dilemma with the use of a high PRF (HPRF) setting
    - HPRF uses multiple sample gates, and this will signify the lack of depth information

# Review of Doppler Controls

- **The wall filter eliminates the low-frequency signals caused by vessel wall or heart valve motion**
  - These motions appear on the spectral display as low-level acoustic noise, or clutter
  - Noise takes away from the image and does not contribute useful information and is therefore filtered out with the wall filter
  - Increasing the wall filter will increase the amount of signals that are eliminated

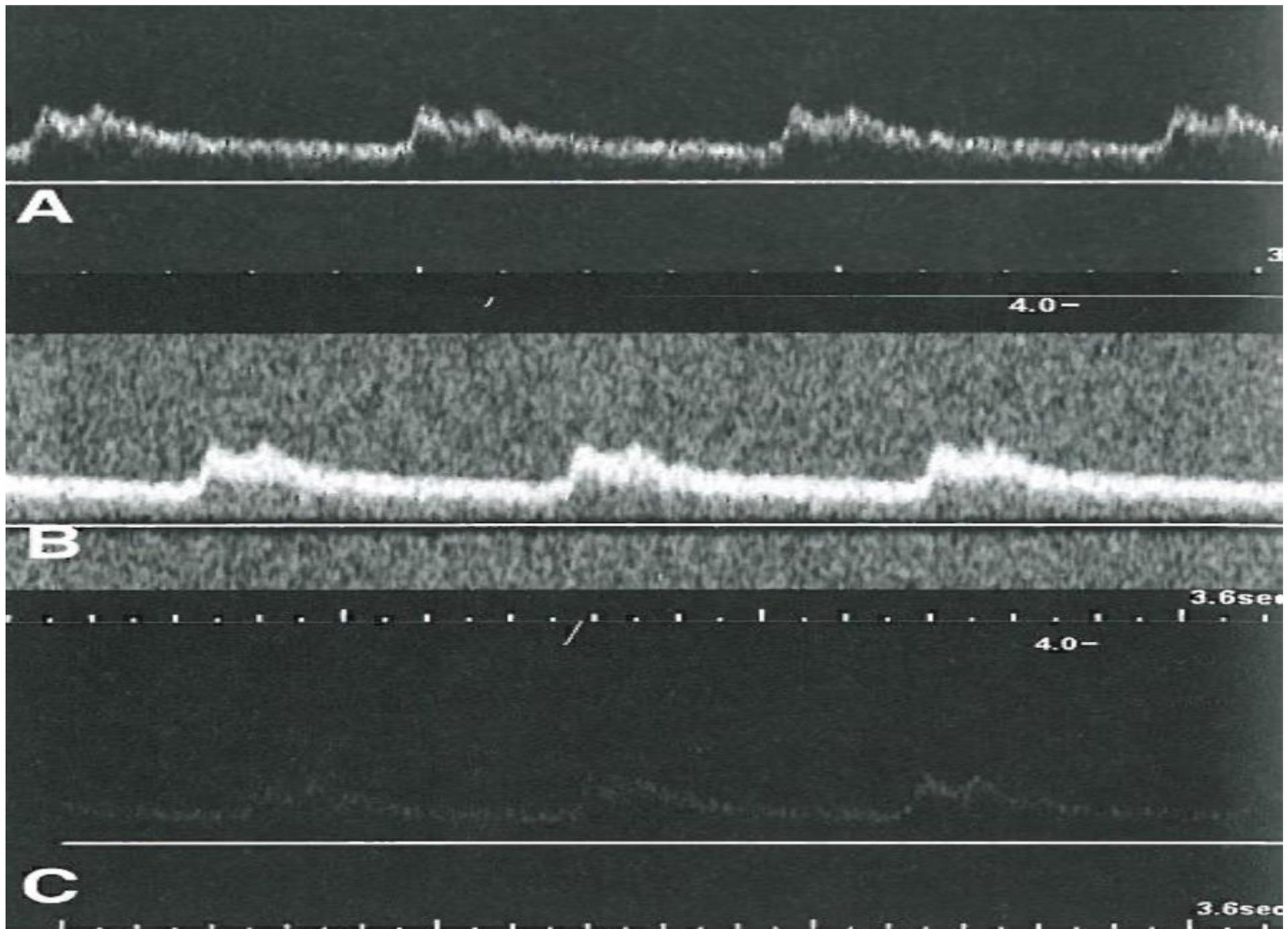
# Review of Doppler Controls

- Other names for the wall filter are **high-pass** and **wall-thump filter**
- In both general and vascular imaging, wall motion is not a concern, so the wall filter is kept low
- In cardiac imaging, a high wall filter is used to counteract the signal coming from the movement of the myocardium and valves
- Caution should be used when applying the wall filter so that useful diastolic information is not removed from the spectral display



# Review of Doppler Controls

- Spectral Doppler gain can be set independent of the grayscale gain
- The brightness of the dots of the spectral display corresponds to the amplitude of the Doppler shift
- If the spectral signal is weak, the gain can be increased to improve visualization of the signal
- If the spectral gain is too high, it may cause over measurement of the spectral waveform, so it is imperative that the gain be set to an appropriate level



# Color Doppler Imaging

- Color Doppler imaging (CDI), a PW technique, is a color representation of the Doppler shift information superimposed on the grayscale image
- **Provides information to the direction and mean velocity of the flow**
- Autocorrelation is the processing technique use to obtain color flow
  - Extremely fast processing but not as accurate as FFT (hence, why only the mean velocity is recorded and not the maximum)

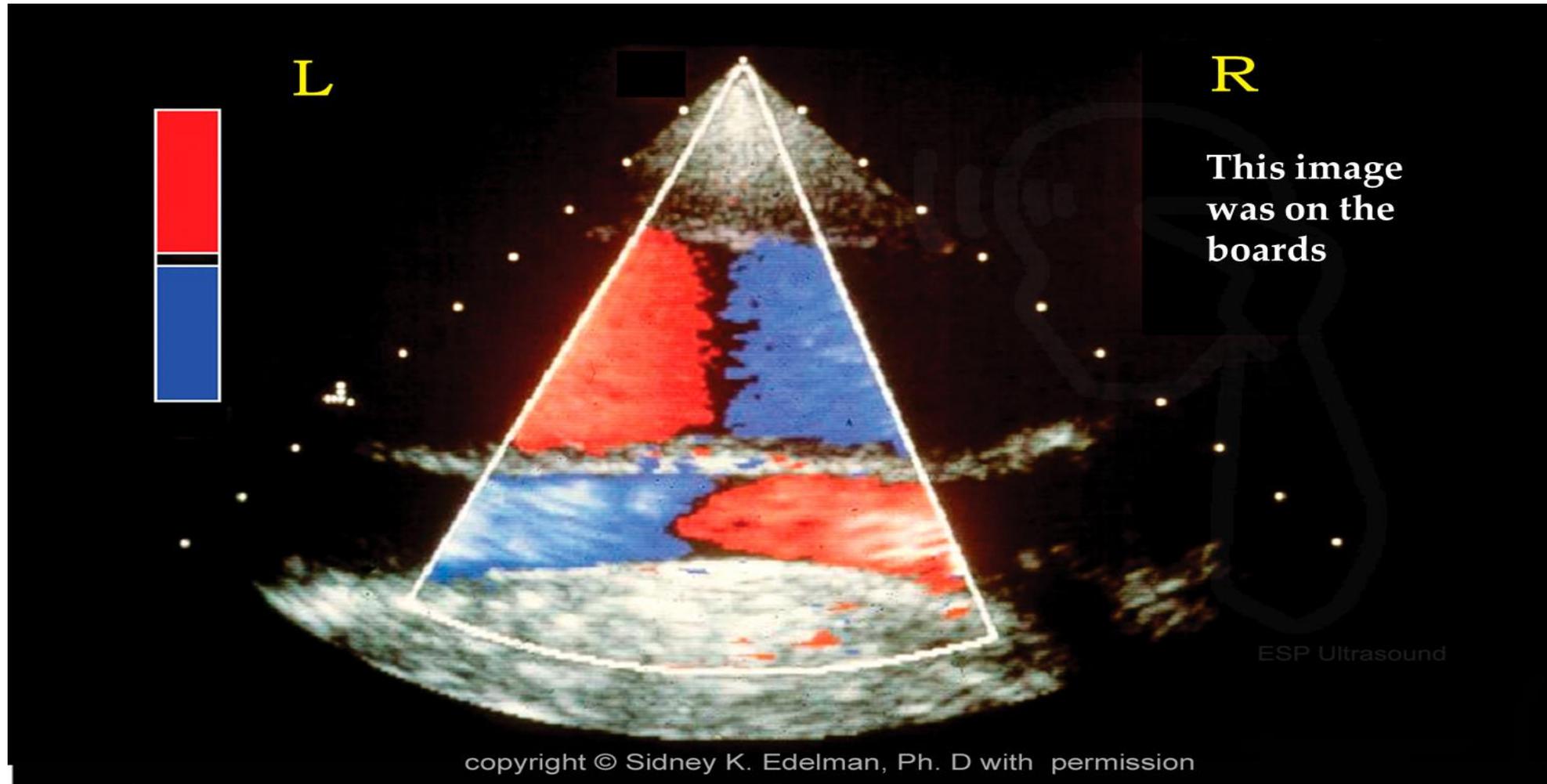
# Color Doppler Imaging

- With CDI, your color box is your “sample gate” and is made up of many scan lines that equate to the width of the box
- The **ensemble length**, AKA **packet size**, is the number of pulses per scan line within the color box
  - The higher the ensemble length, the more sampling points along each scan line, and therefore, the higher the sensitivity of the color signal
  - High ensemble lengths increase the ability to detect slow flow and offer a more accurate mean velocity
  - The trade off is with frame rate, which is very low with high ensemble lengths

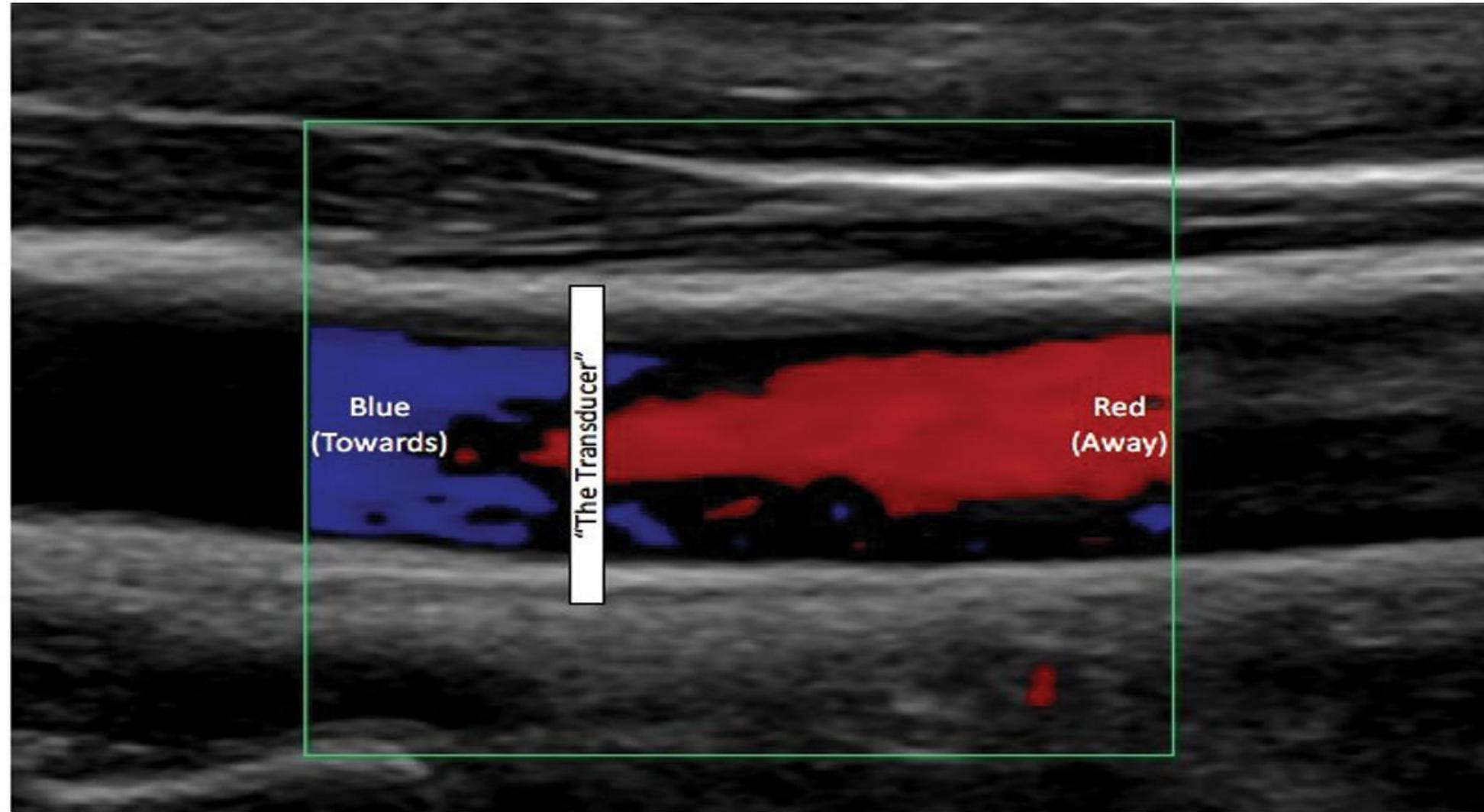
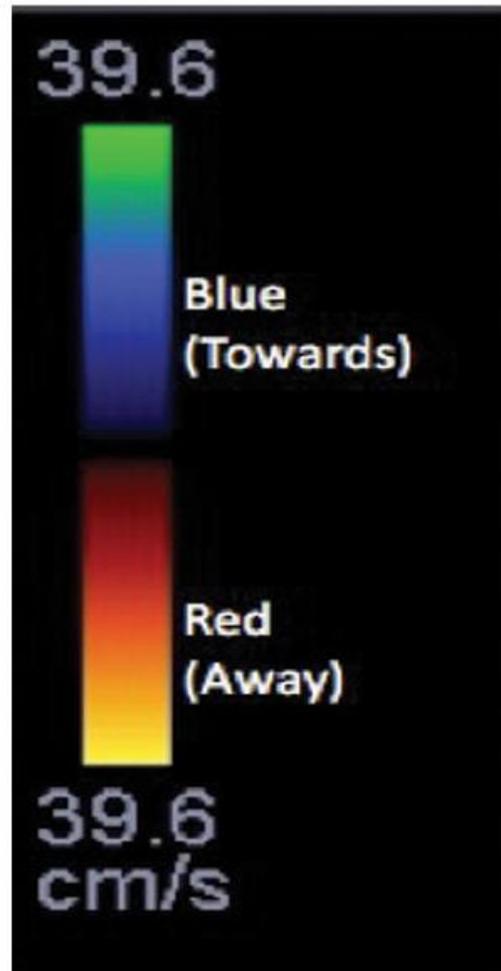
# Color Doppler Imaging

- The ensemble length can be as low as 3 pulses per scan line but is typically around 10 to 20 pulses per scan line
  - **CDI is inherently slow, and large gates and/or high ensemble lengths slow it down even further**
  - **For the best frame rate, the smallest color gate should always be employed**
- Color Doppler scale shows direction of flow as a color or range of colors on each side of a black baseline
  - **Black within a color display means that either there was no Doppler shift present in that location (as a result of either a 90° angle to flow or no flow), or the shift was so low that it was eliminated by wall filters**

# How to determine which direction blood is flowing....

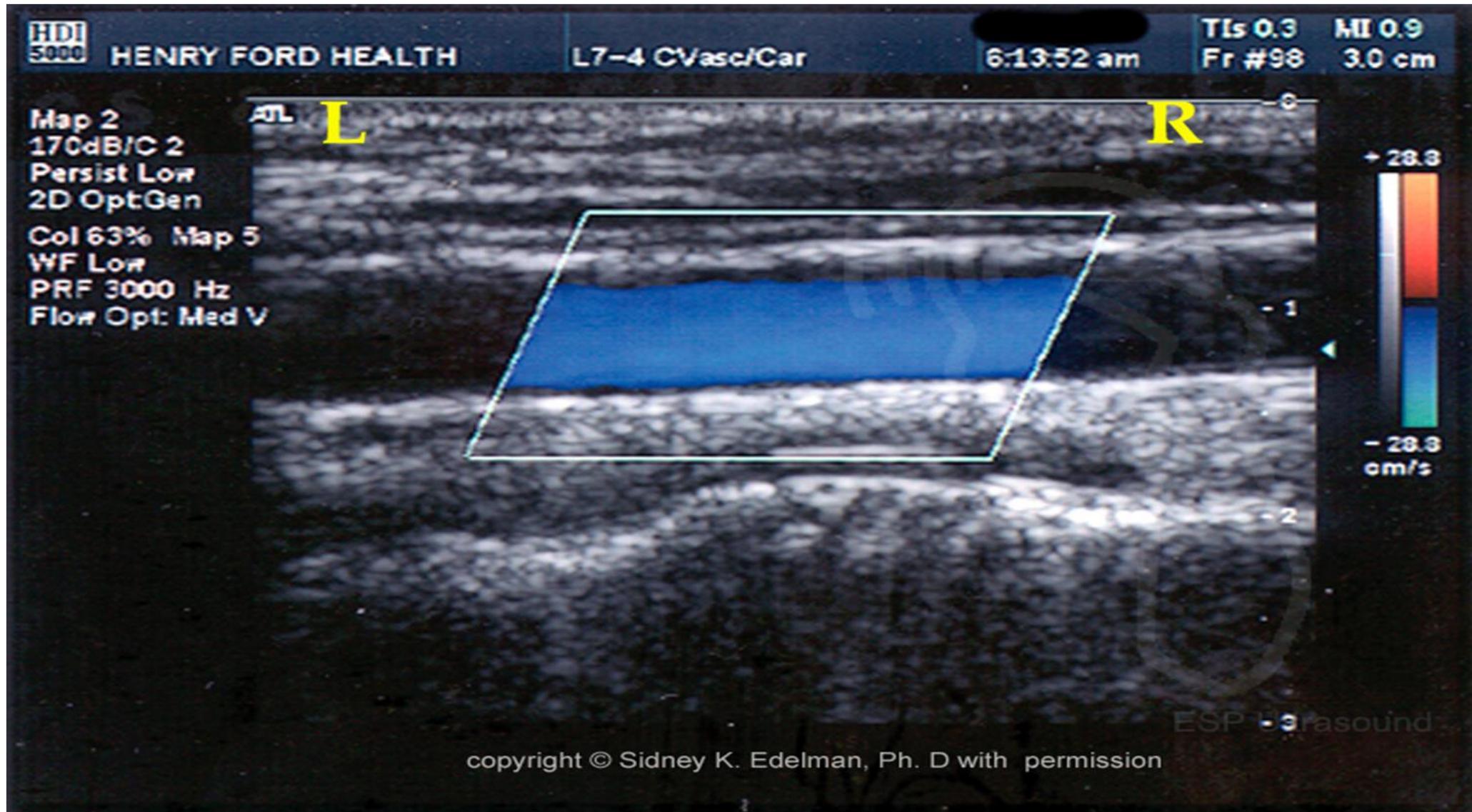


# Which direction is blood flowing?

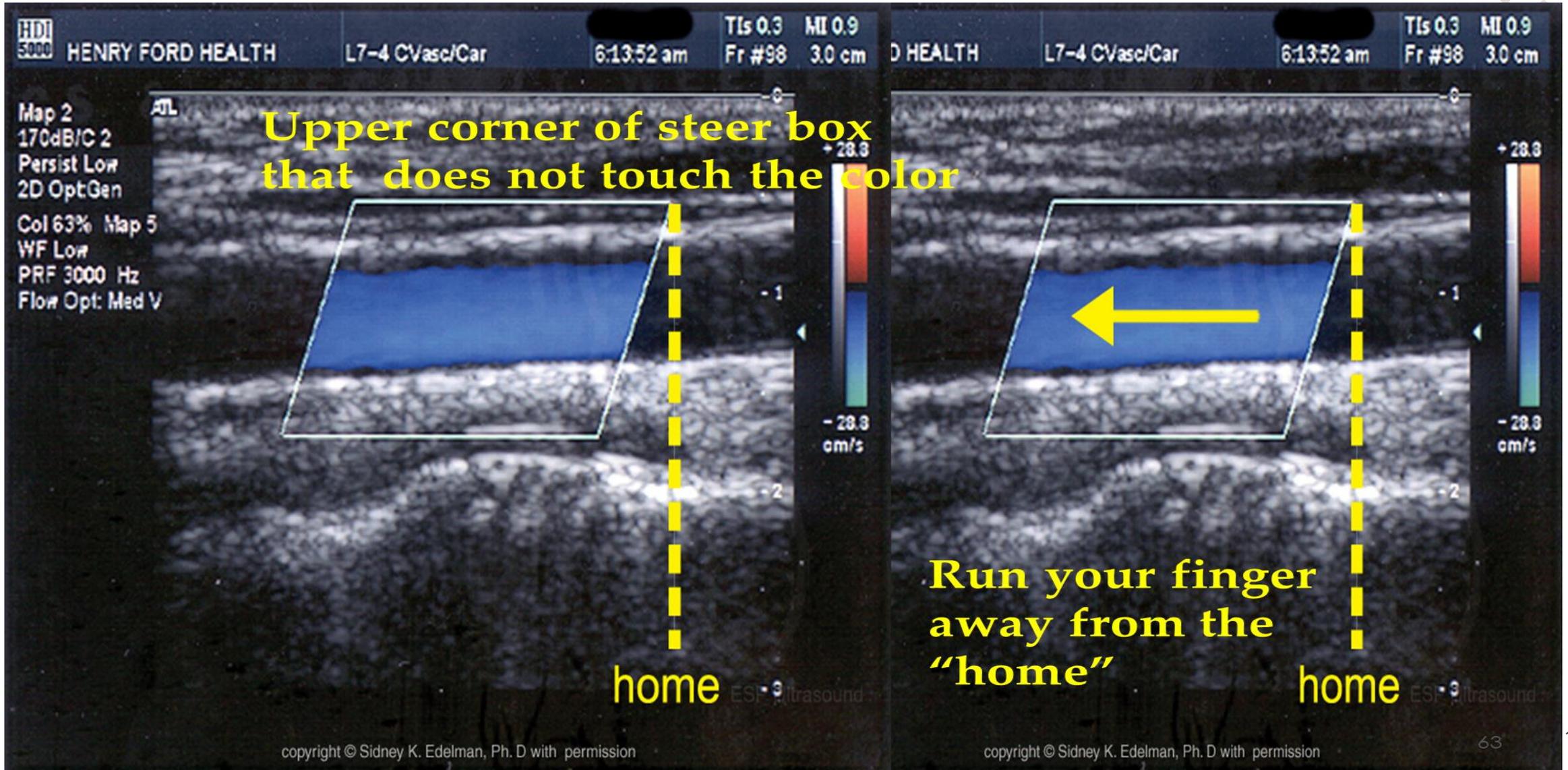


B

# Which direction is blood flowing?



# Which direction is blood flowing?

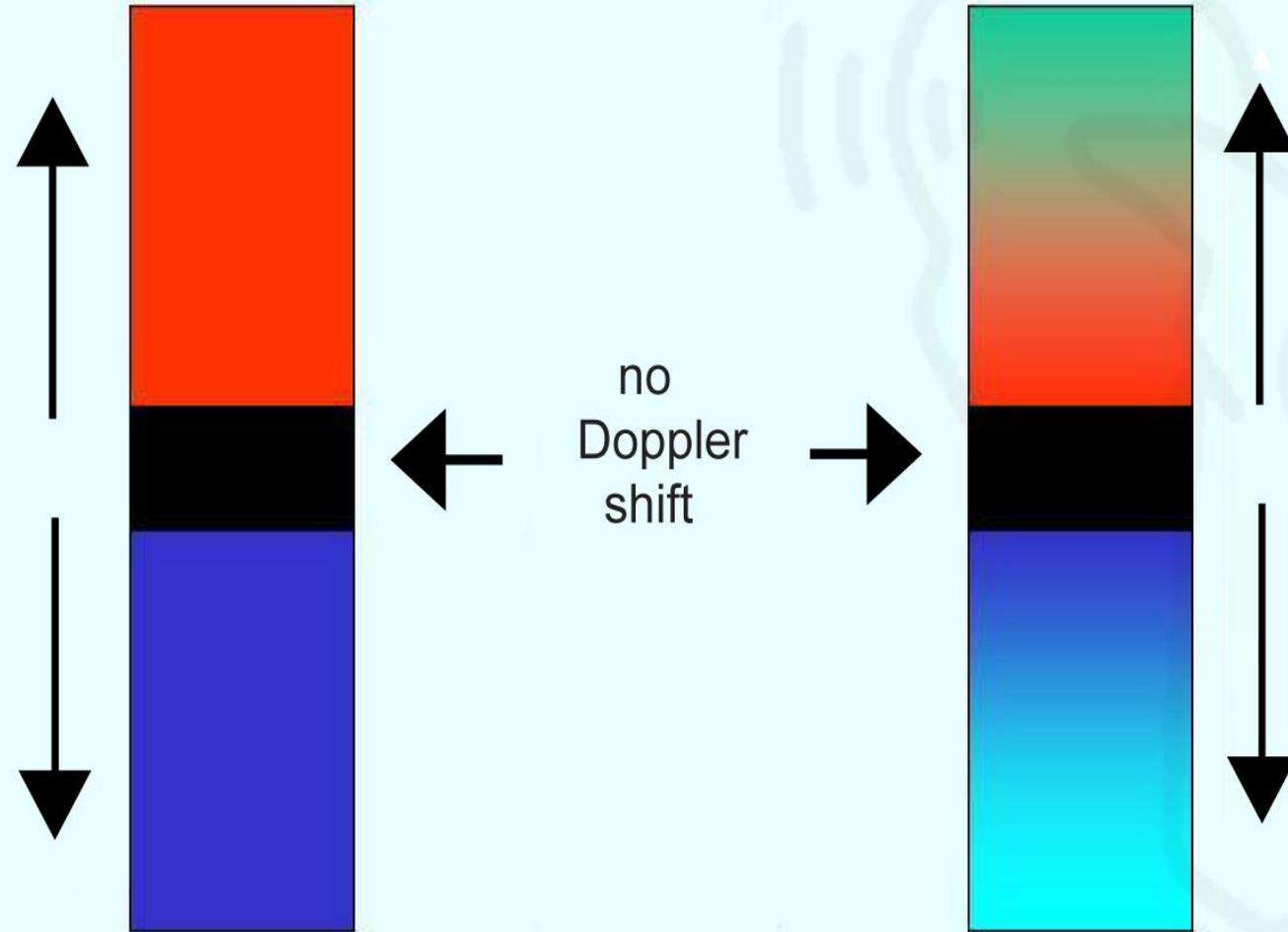


# Color Doppler Imaging

- In general and vascular imaging, the color scale is often set by convention, so that red represents arteries and blue represents veins
- In cardiac imaging, the color scale is thought of as BART: blue away, red toward
- However, the color scale can be inverted, so that blue is toward and red is away
- The preferred color scale setting may vary from lab to lab

# Velocity Mode

Higher Velocities



map1

map2

ESP Ultrasound

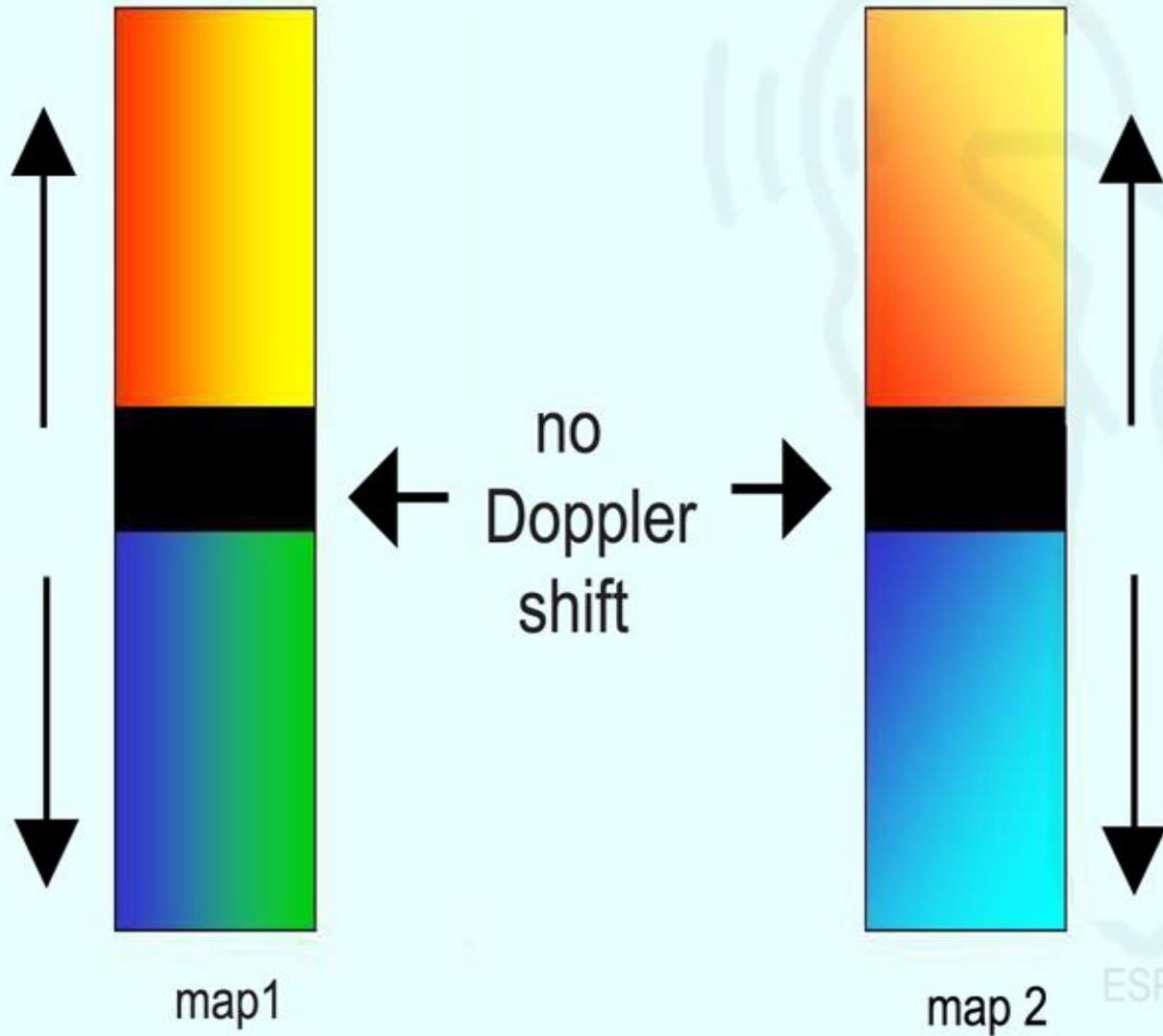
Higher Velocities

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# Color Doppler Imaging

- The color scale is most commonly presented in velocity mode, where the colors are vertically oriented for positive/negative shifts
- Another mode, associated with hemodynamic imaging, is variance mode
  - **Distinguishes laminar flow from turbulent flow**
    - Laminar flow is on the Left side of the map
    - Turbulent flow is on the right side of the map

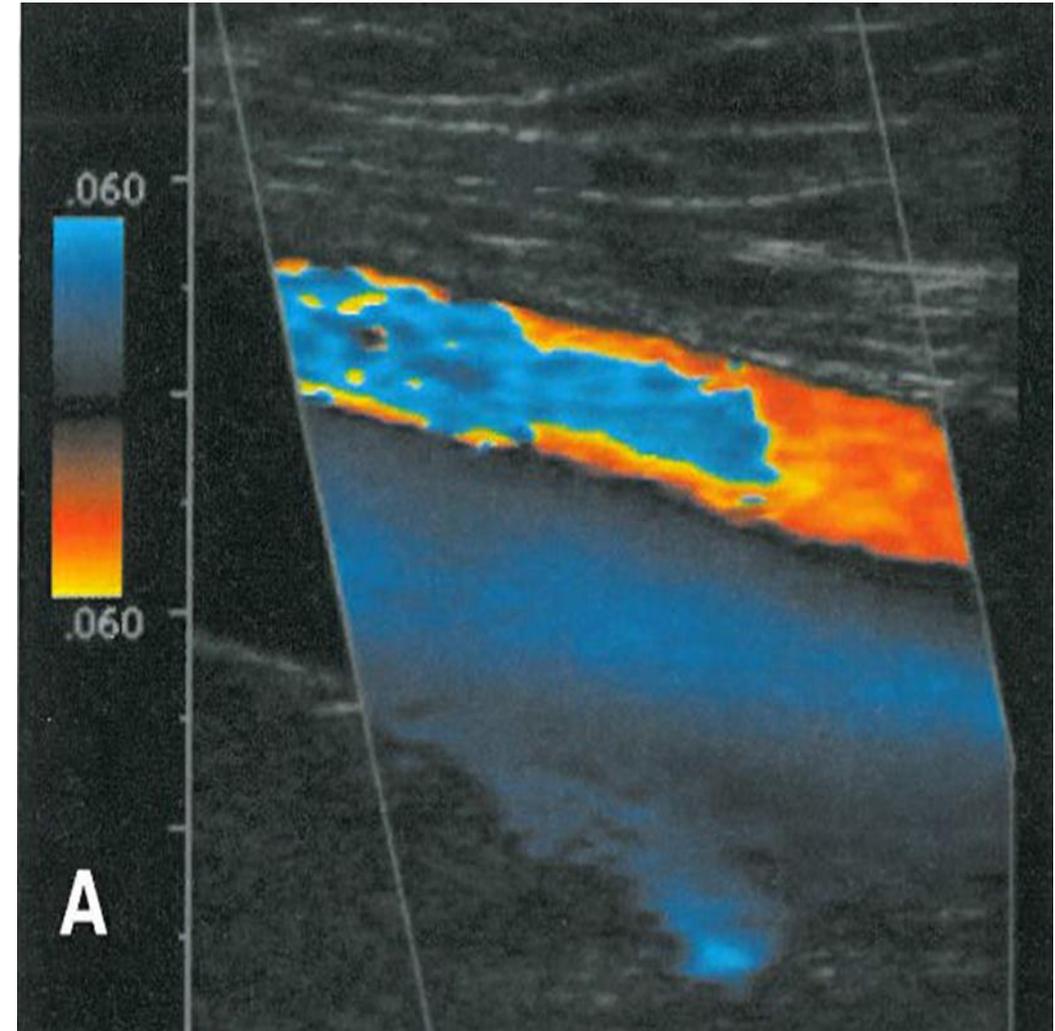
# Variance Mode



ESP Ultrasound

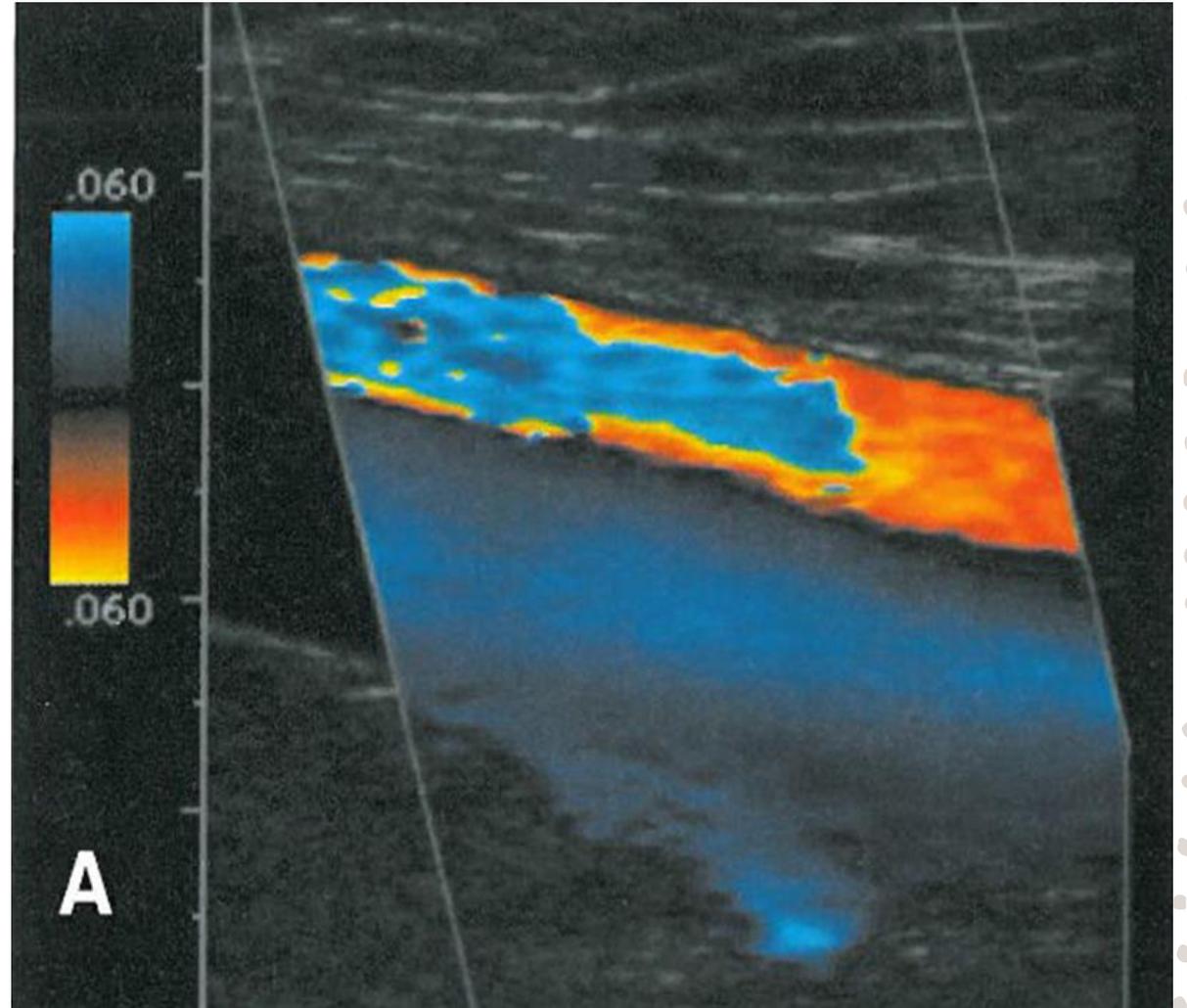
# Color Aliasing

- As a PW technique, CDI is bound by the same limitation as PW spectral Doppler
- Aliasing can occur and is represented by a wraparound of the color scale
- CDI aliasing can be eliminated by increasing the PRF/scale



# Color Aliasing

- The central flow stream is blue, but the flow near the vessel wall is red
- Unlikely that there is bidirectional flow within this vessel
- Always consider aliasing as a possibility when you see this color change

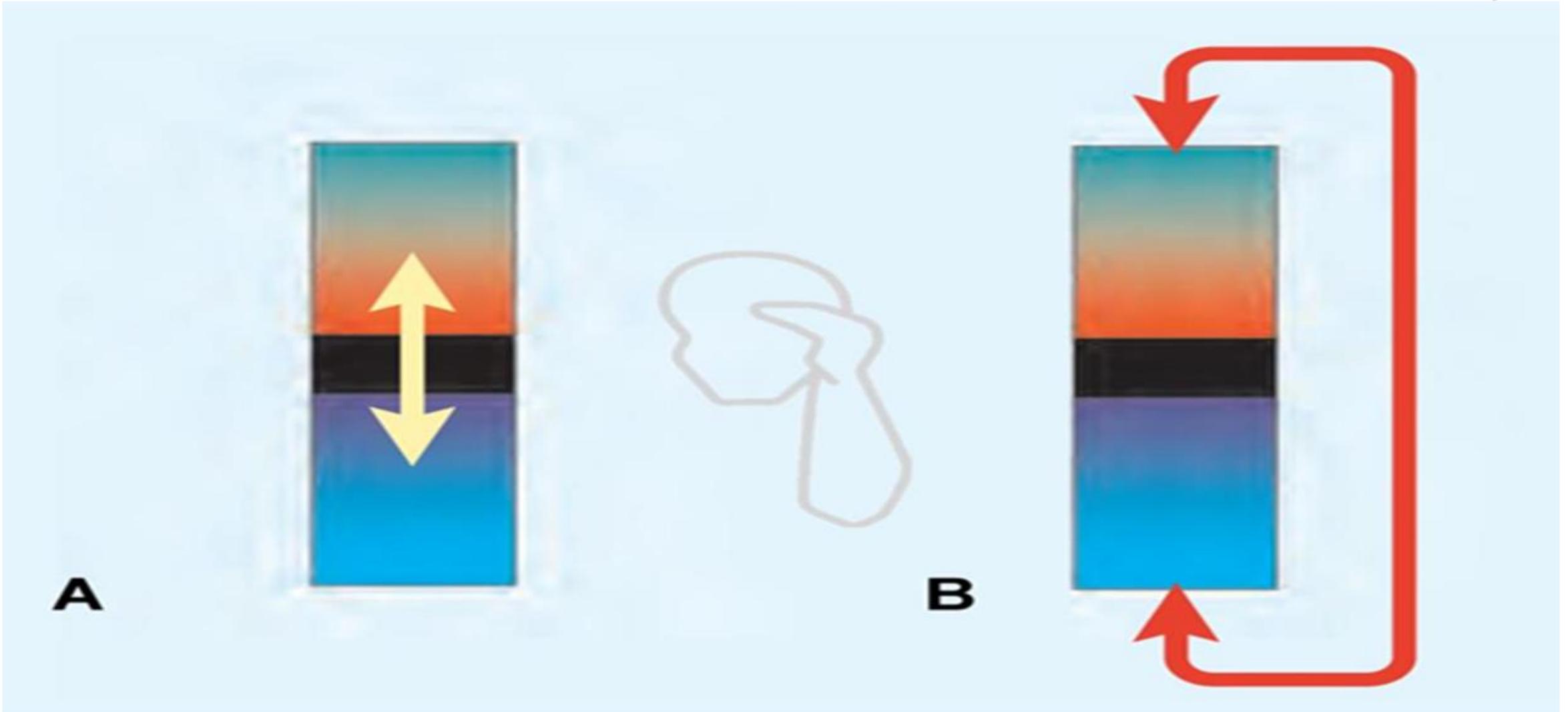


# Color Aliasing

- Bidirectional flow and aliasing appear differently!!

The key is in the color map:

- If the colors that touch each other in the image go through the map's middle, it is flow reversal
- If the colors that touch each other go around the outside of the map, it is aliasing



**A**

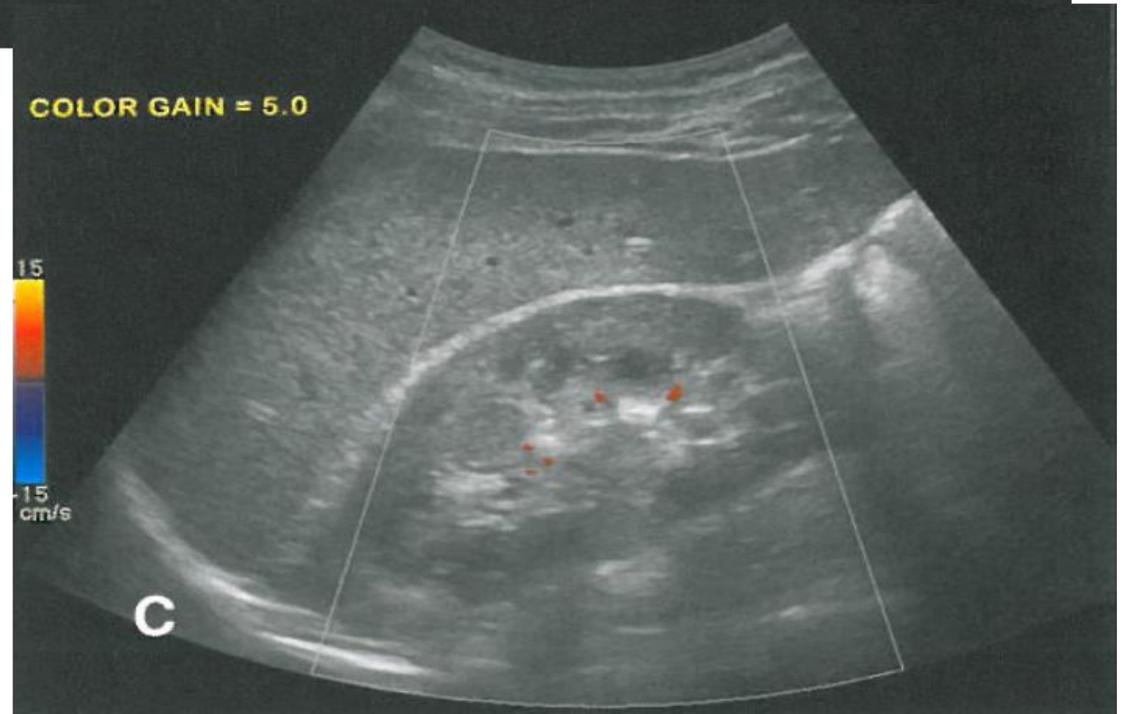
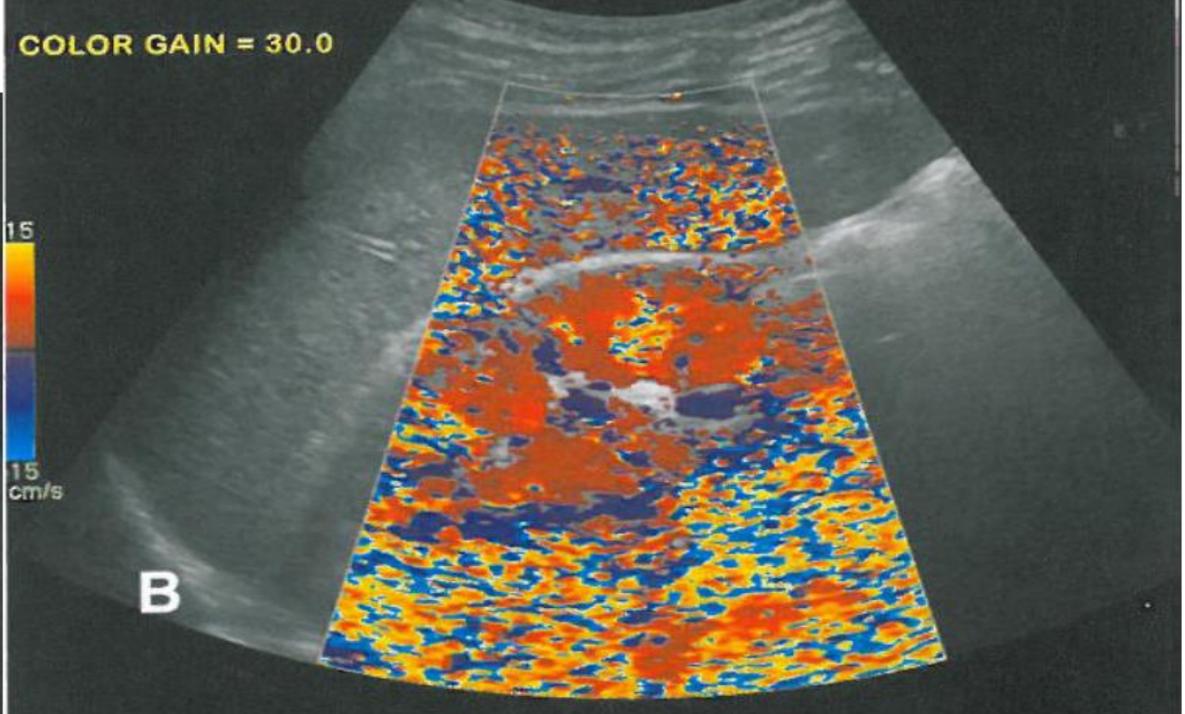
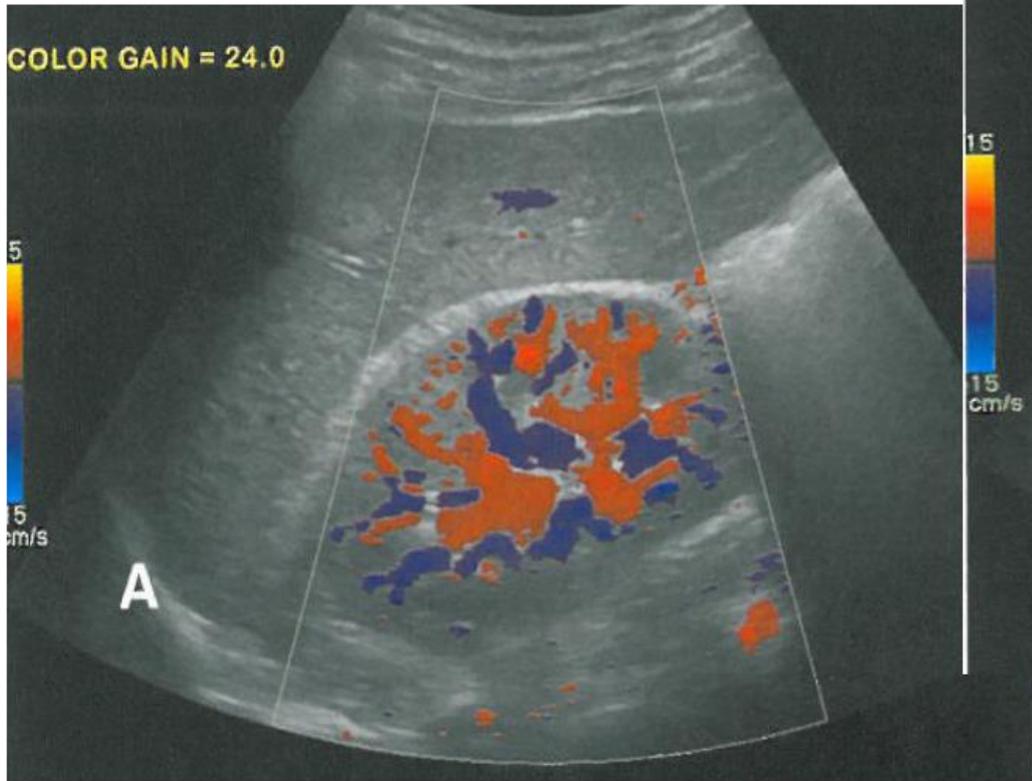
**B**

Flow Reversal -  
through the middle

Aliasing - around  
the outside

# Color Aliasing

- Appropriate setting of the color PRF allows for setting the proper sensitivity to flow
  - Low PRF color settings are used for slow or difficult-to-demonstrate flow
  - High PRF settings are used for fast flow or to eliminate aliasing
- In addition to PRF, color Doppler also has a gain setting
  - If color gain is set too high, the result is color noise throughout the color gate
  - If color gain is set too low, the vessel will not be adequately filled with color



\* Which is the best diagnostic image?

# Color Aliasing

- **Persistence**, when increased, is a control that reduces the effect of noise and makes it easier to follow small vessels
  - In the presence of very slow flow, or if small vessels are being analyzed, it may be helpful to **average multiple frames instead of displaying only one frame of color information at a time**
  - *The trade-off of high persistence is a decrease in the frame rate*

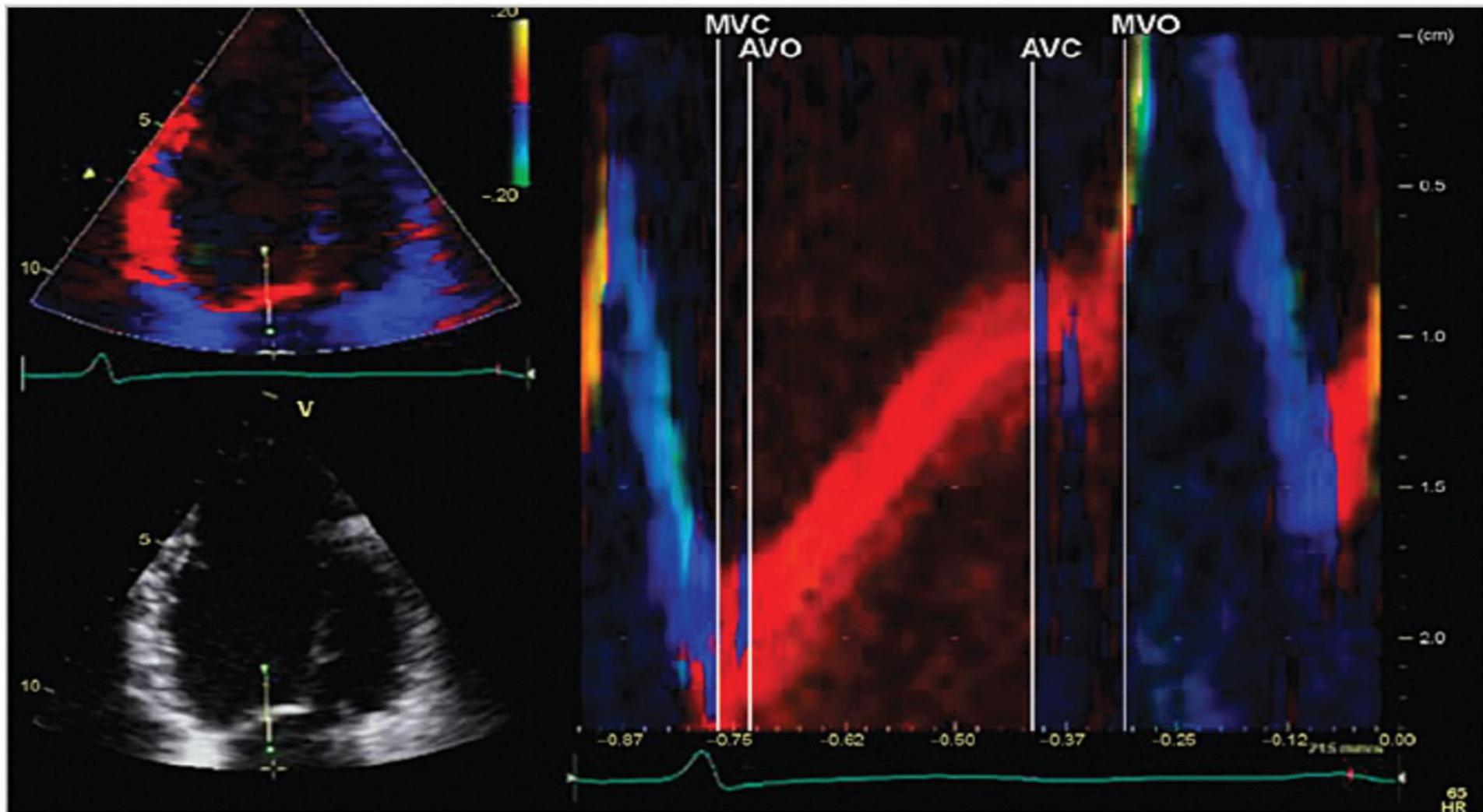
# Color Aliasing

- When both grayscale and color information are present within the same pixel, **color priority** is a setting on the machine that allows the operator to set a threshold for displaying color pixels instead of grayscale pixels
  - Remember, a pixel can only be one shade of color (or gray) at a time
  - Priority sets the threshold (or brightness of gray) that will have to be exceeded for grayscale pixels to be displayed rather than color pixels
    - If the threshold is set too low, then only grayscale will be seen and not color
    - A higher priority setting is useful when trying to fill in a vessel with color

# Tissue Doppler Imaging

- Specifically used for cardiac imaging, tissue Doppler imaging (TDI) is another CDI technique
- Flowing blood typically produces a low-amplitude, high-velocity signal
- However, myocardial wall motion produces a high-amplitude, low-velocity signal. Instead of using a high-pass filter to filter out the signal from the wall motion, TDI uses a low-pass filter to eliminate the signal from the blood and only show color information representing the wall motion

# Tissue Doppler Imaging



# Power Doppler

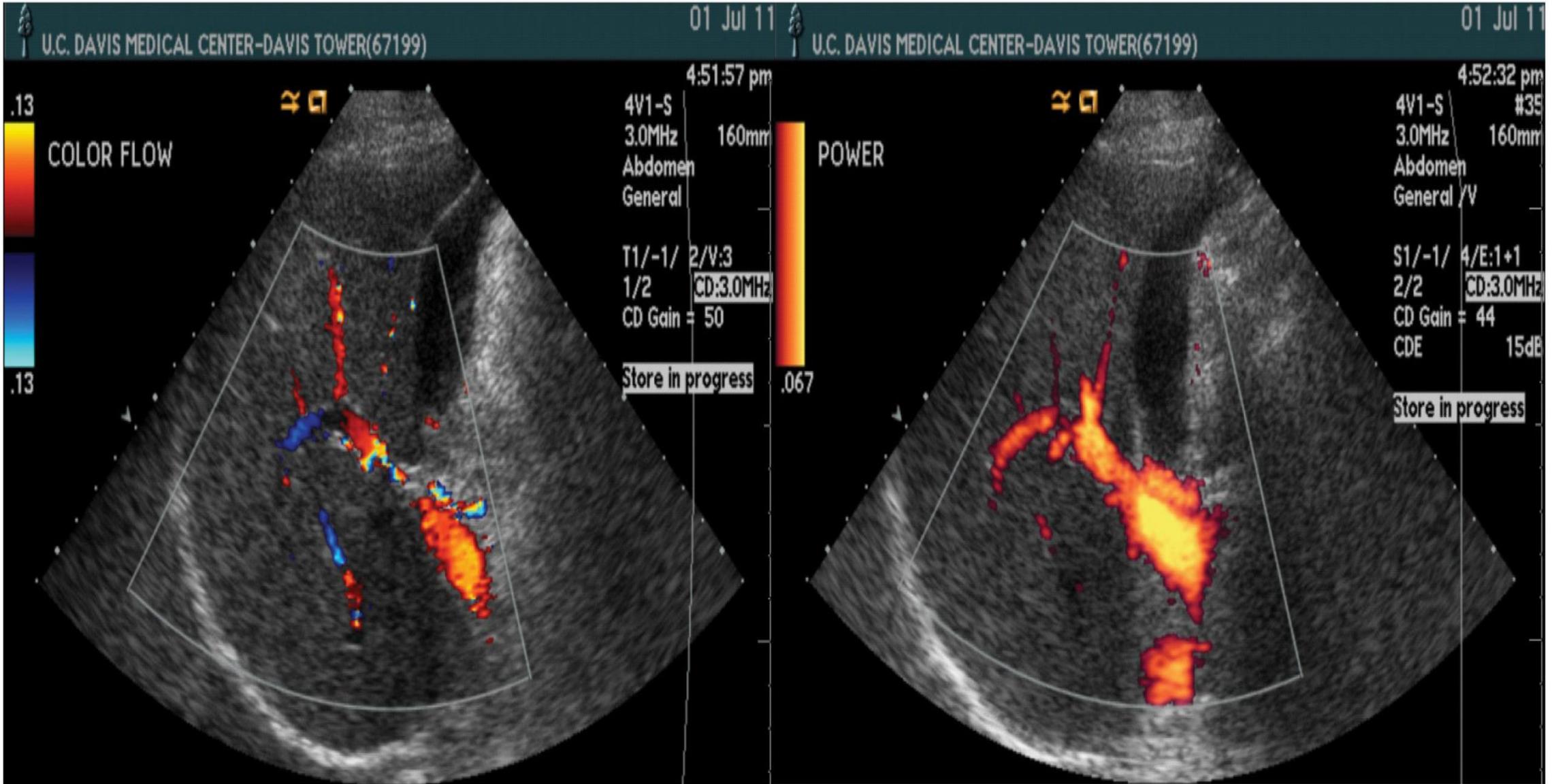
- Power Doppler, also termed color Doppler energy or power angio, ignores the frequency shift information and focuses only on the amplitude, or strength, of the shift
- Power Doppler is only able to display amplitude information and does not provide information on velocity or direction of flow
  - **i.e. Power Doppler tells me if there is blood flow present in that vessel/organ, but I do not know if it is an artery or a vein**

# Power Doppler

- Power Doppler is almost completely independent of angle, which makes it quite functional for evaluating slow flowing and/or tortuous vessels
- Both an advantage and a disadvantage of power Doppler is its sensitivity
  - Since power Doppler is very sensitive, it is ideal for slow, small vessels, but it also makes it more susceptible to patient or organ motion
  - Flash artifact occurs when power Doppler is being used and inadvertent motion interrupts the quality of the signal

# Color Flow

# Power



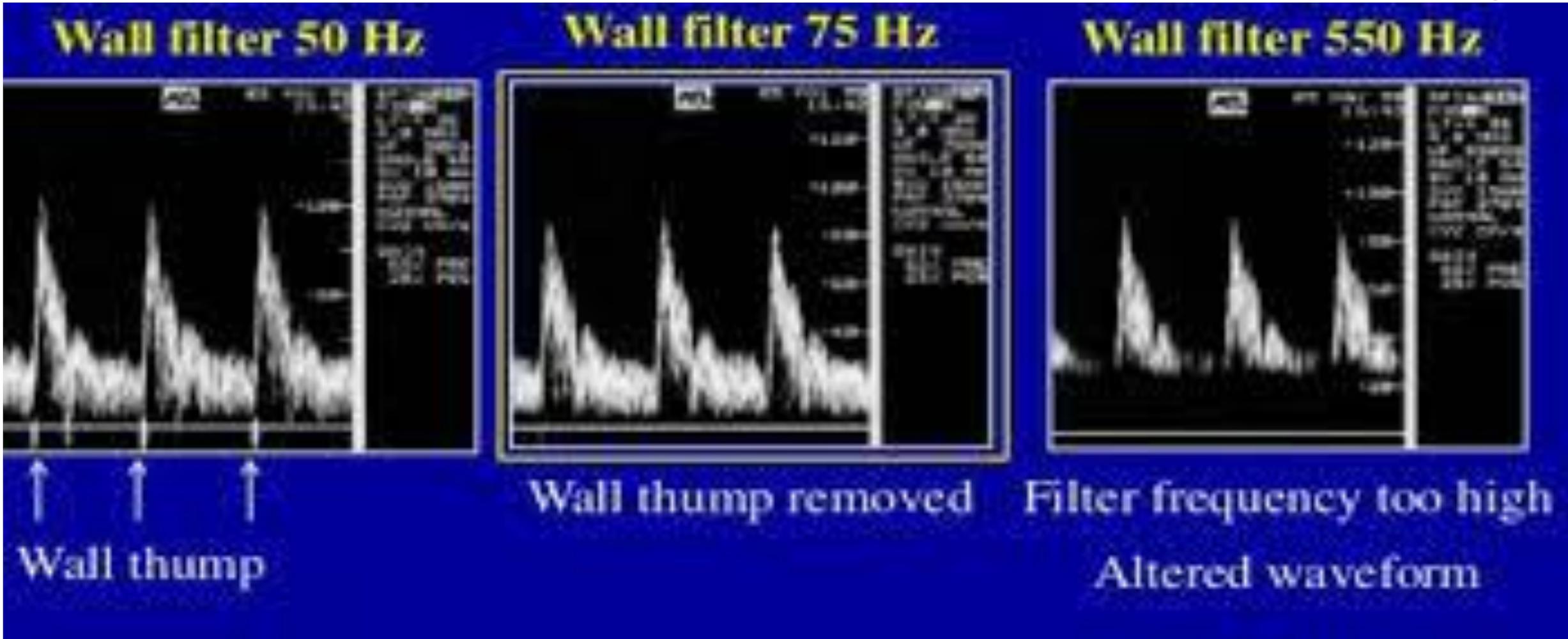
# Cardiac Strain and Strain Rate

- Cardiac strain and strain rate are used for measuring myocardial function
  - **Strain is the changing of the shape of the muscle as it lengthens and contracts**
  - **Strain and strain-rate analysis analyzes the deformation of the cardiac wall to evaluate for ventricular function**
- Speckle tracking is the method used to obtain the strain information
- By observing the “dots” that represent the myocardial tissue, the machine can measure the movement of the tissue all axes

# Doppler Artifacts

Artifact	Definition	Quick Fix
<b>Clutter</b>	Acoustic noise eliminated with high-pass wall filters	Increase wall filter
<b>Aliasing</b>	Pulsed-wave artifact caused by insufficient sampling of flow	Increase PRF; decrease frequency shift, or use CW
<b>Mirror image</b>	Reproduction of spectral or color information opposite a strong reflector	Decrease color/spectral gain or angle (must be $<90^\circ$ )
<b>Color bleeding</b>	Over-gained color or spectral waveform causing signal to be larger than it should be	Decrease gain or transmit power
<b>High PRF (depth ambiguity)</b>	HPRF setting in PW Doppler means the PW is emulating a CW probe and is unsure of where echoes came from	Change depth or Doppler angle
<b>Flash artifact</b>	Excessive color signal in surrounding tissue caused by movement during power Doppler	If possible, eliminate source of motion (e.g., with a breath hold)

# Clutter

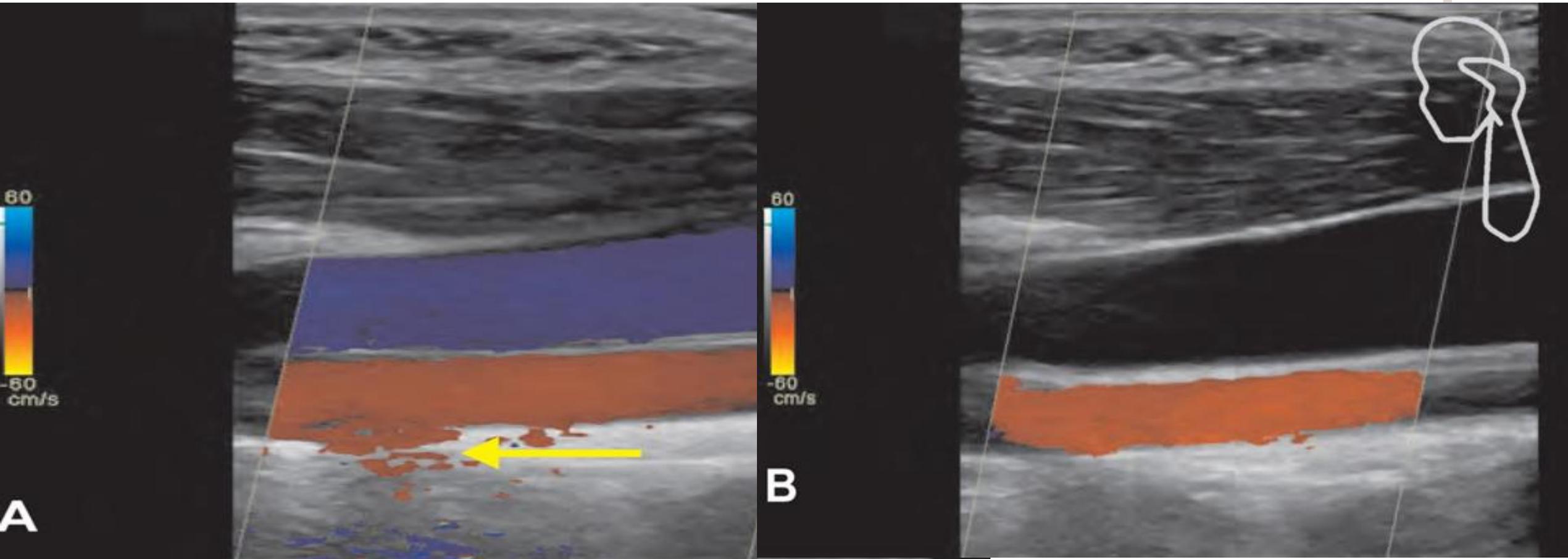


**\*\*\*Increase Wall Filter**

# Ghosting (aka color clutter)

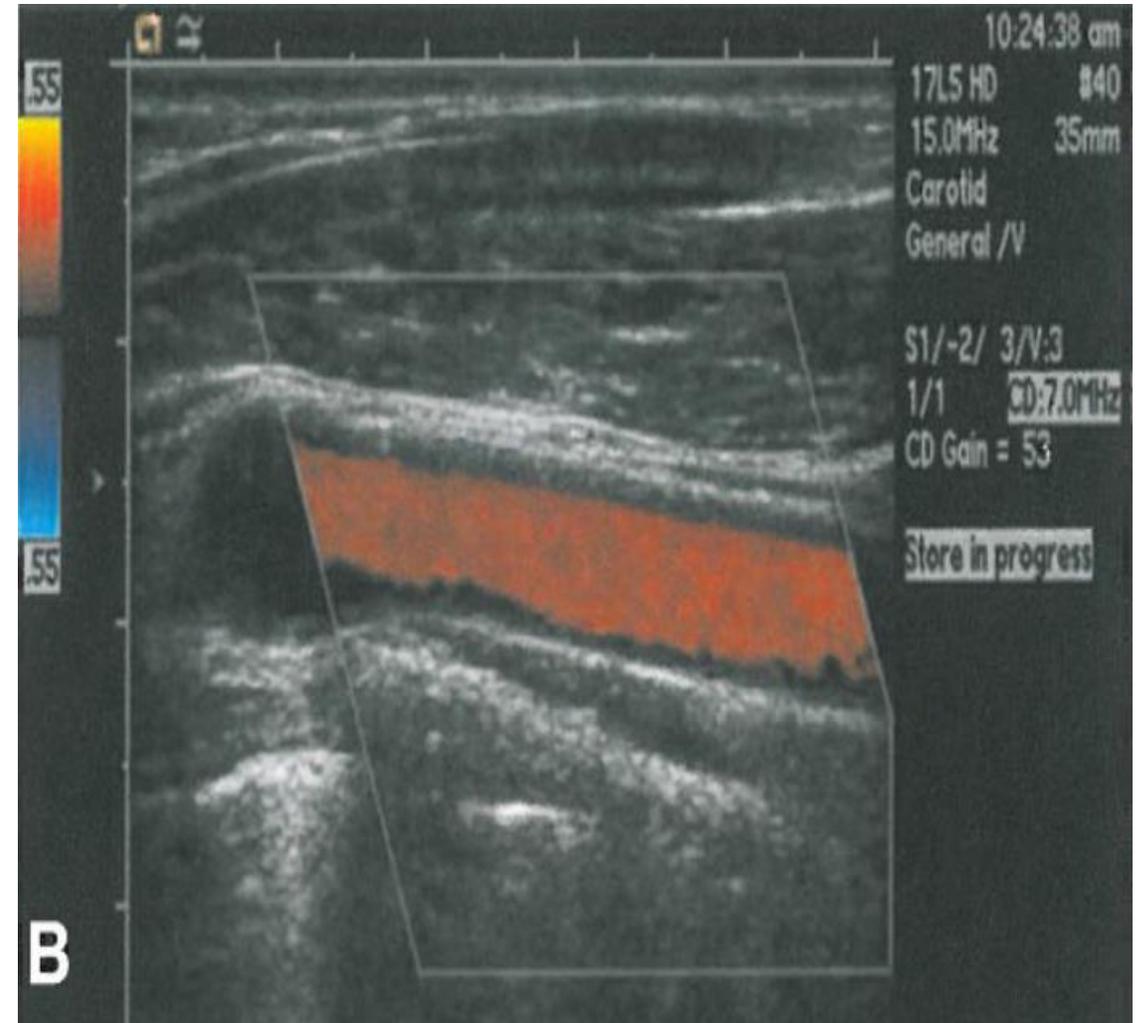
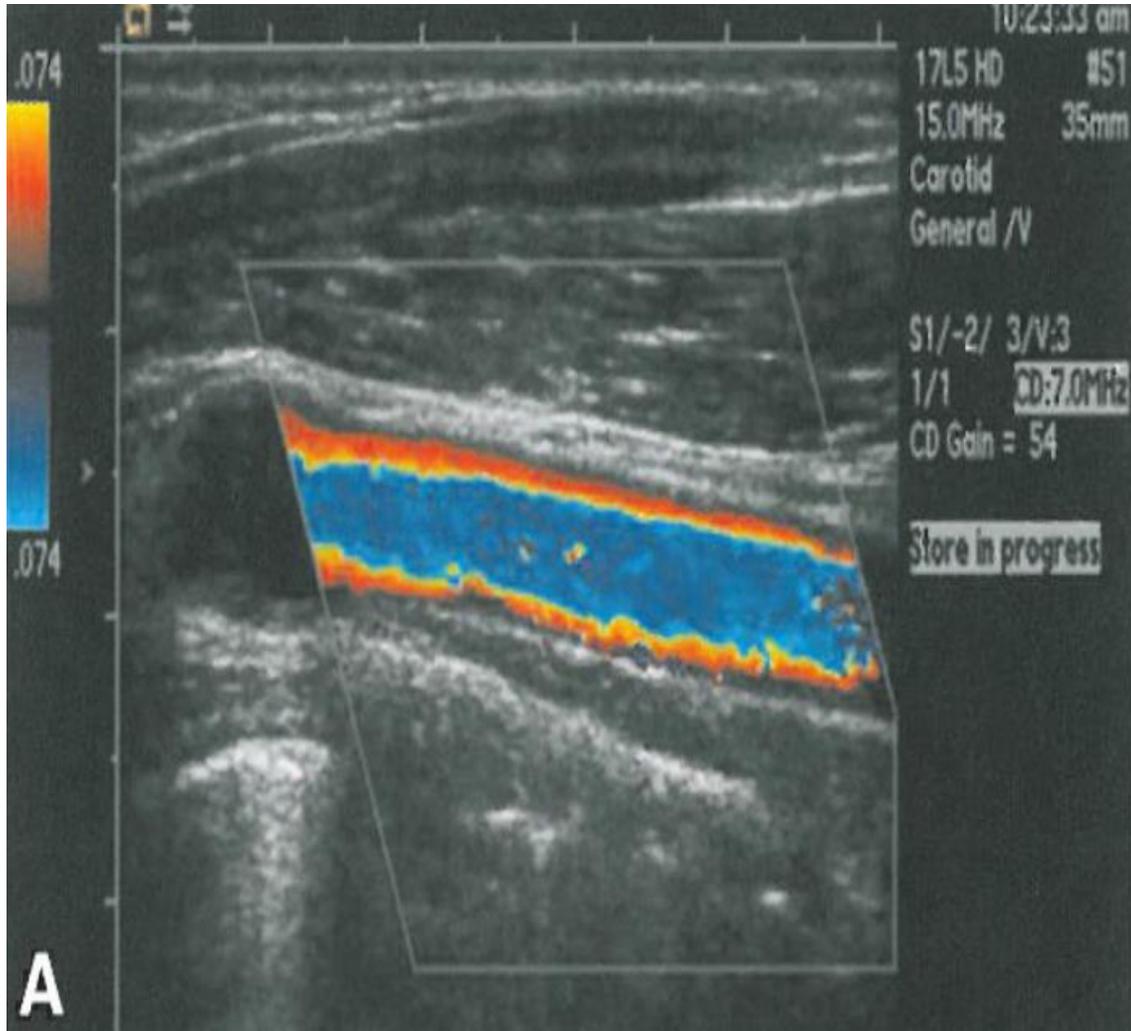
- Before

- After



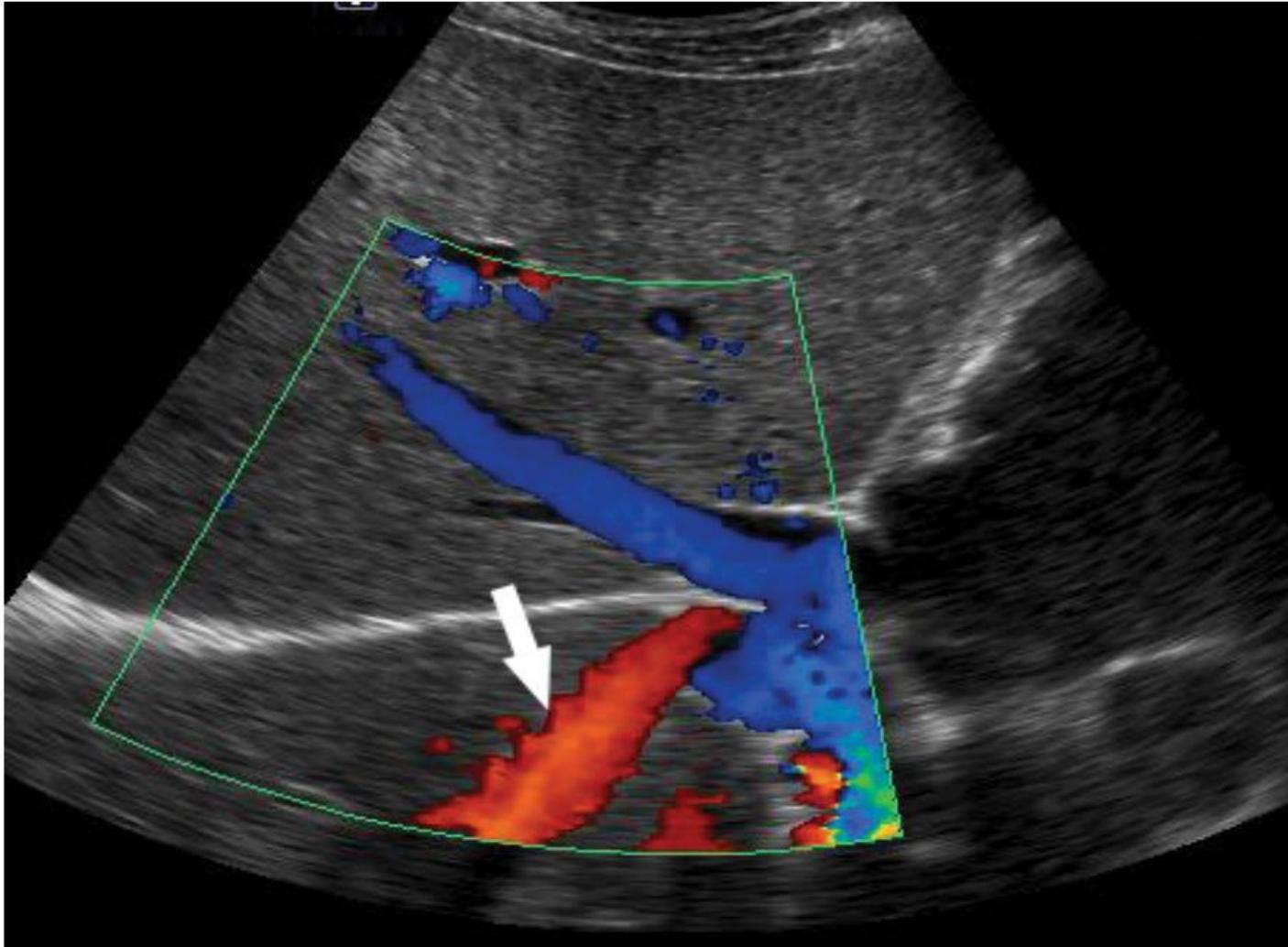
**\*\*\*Increase Wall Filter**

# Aliasing



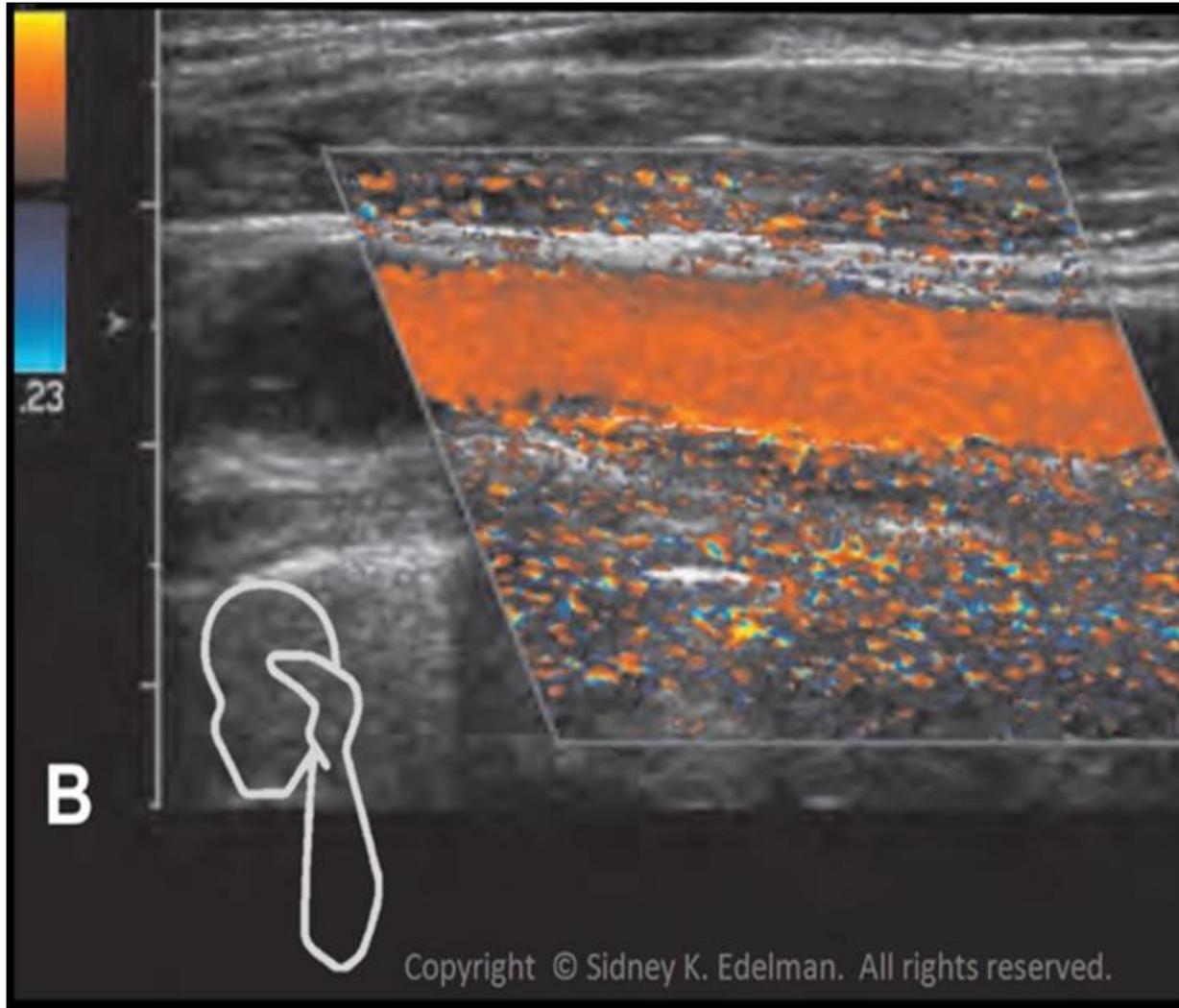
\*\*\* Increase PRF (color scale)

# Mirror Image



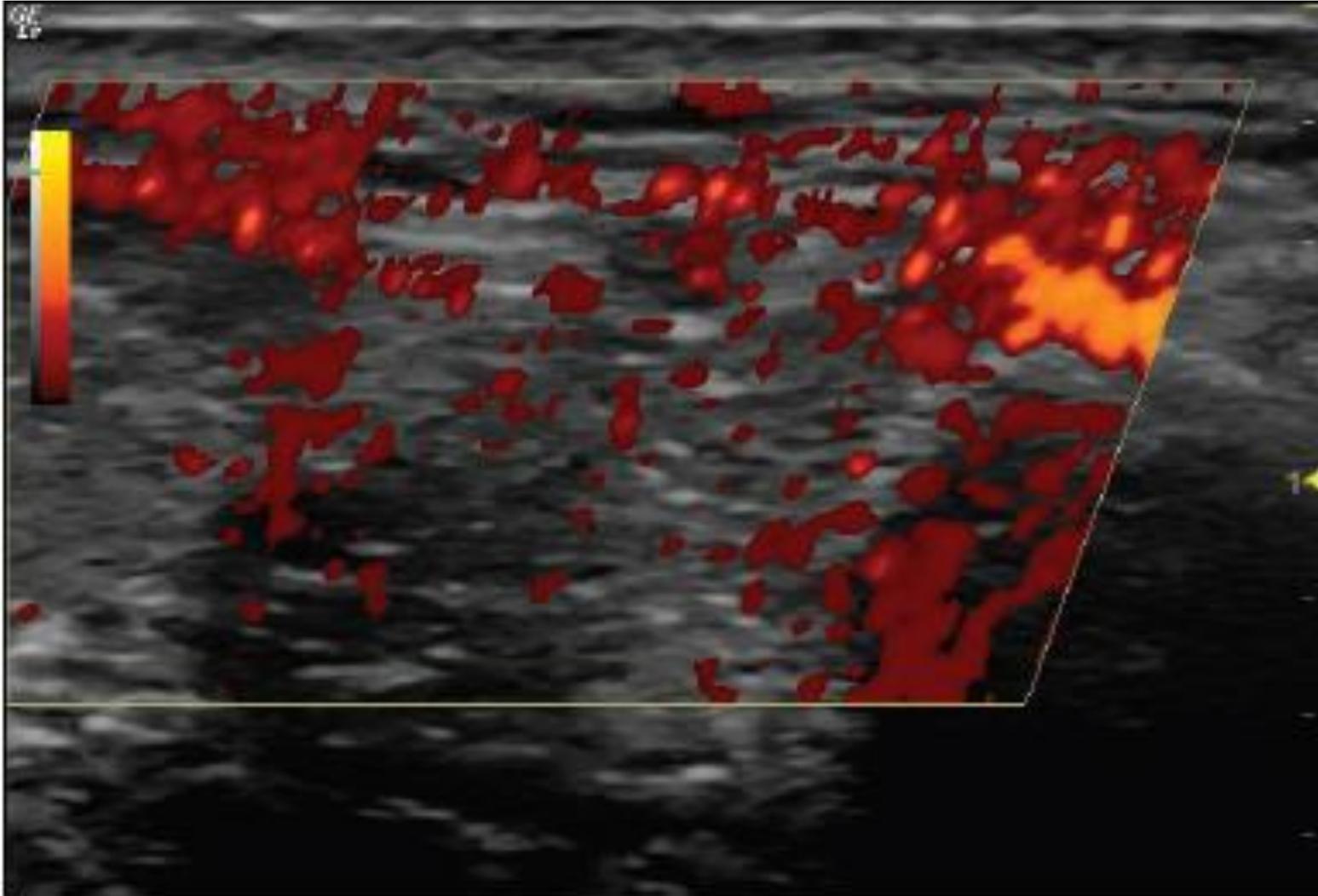
**Decrease spectral gain or adjust scanning window to get away from a 90° incident angle**

# Color Bleeding



**Decrease color gain to remove "color confetti" and create a smooth, uniform color fill-in within the vessel walls**

# Flash Artifact



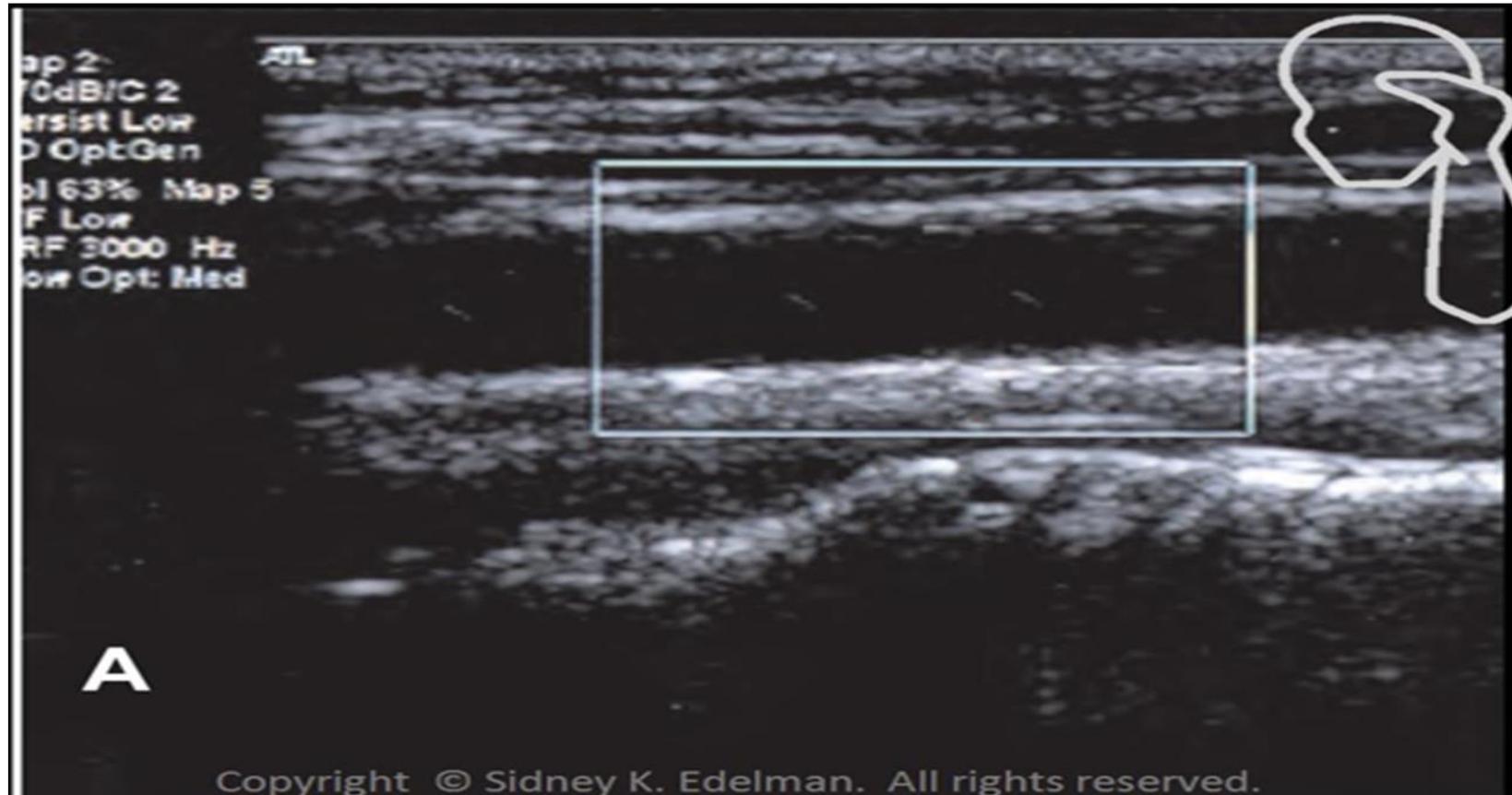
(A)

**Remove unnecessary background noise caused by motion: Have patient hold their breath or keep scanning arm steady**

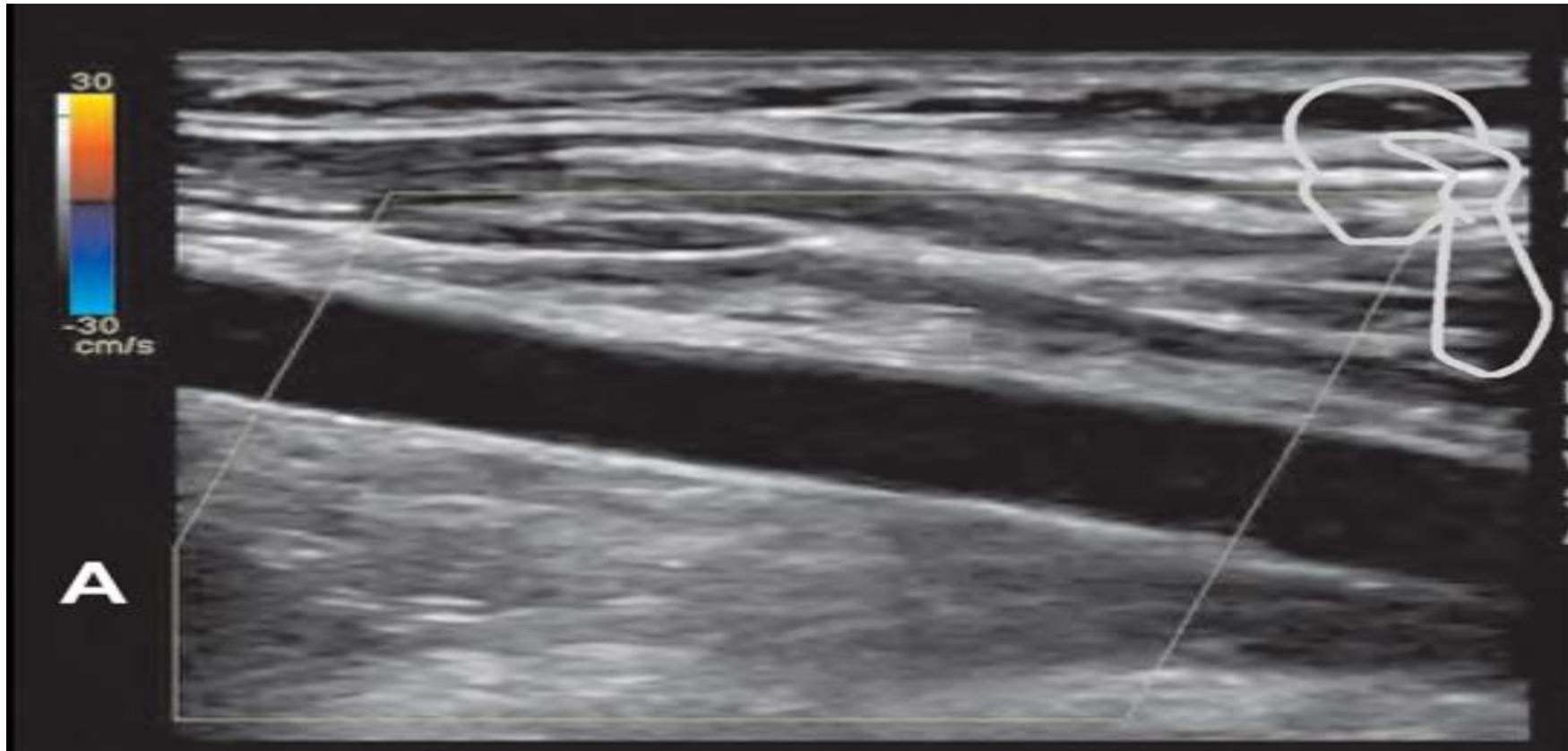


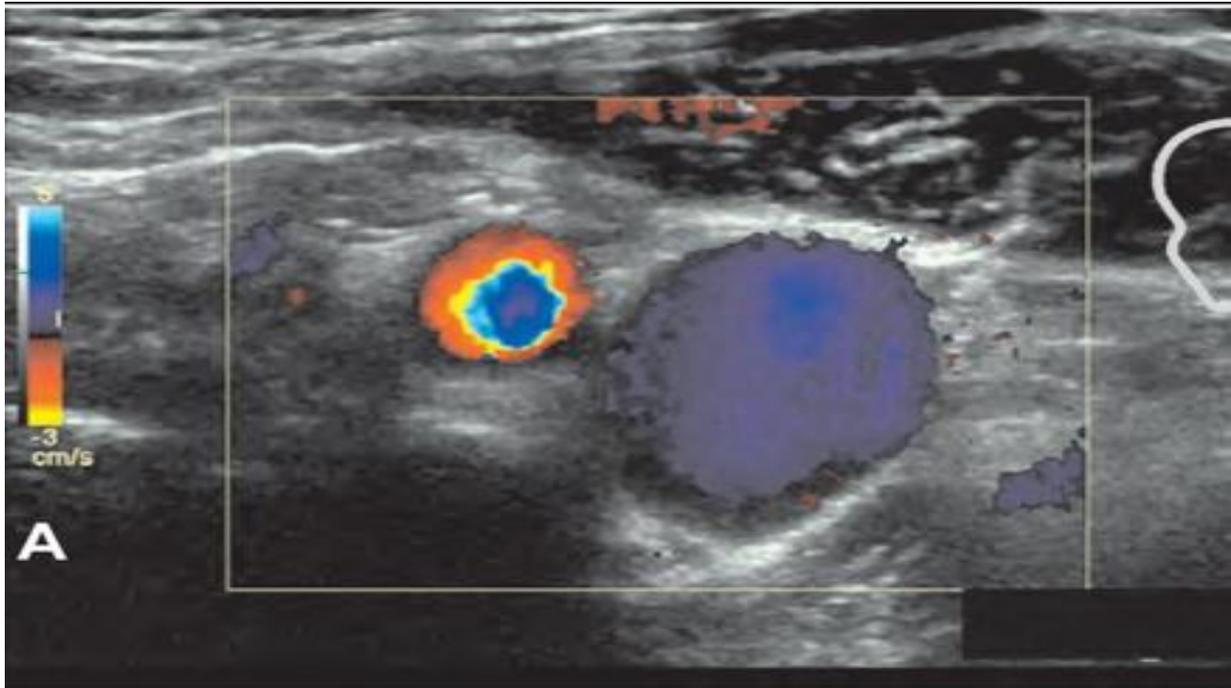
*Questions??*

# Why is the vessel not filling in with color?

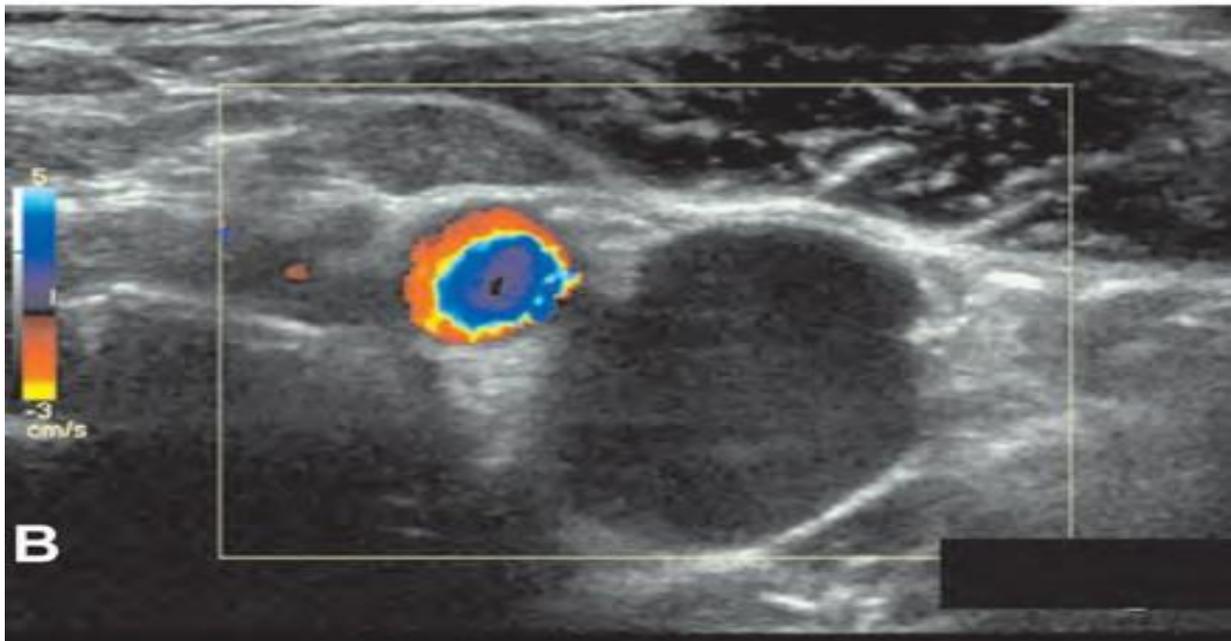


# Why is the vessel not filling in with color?

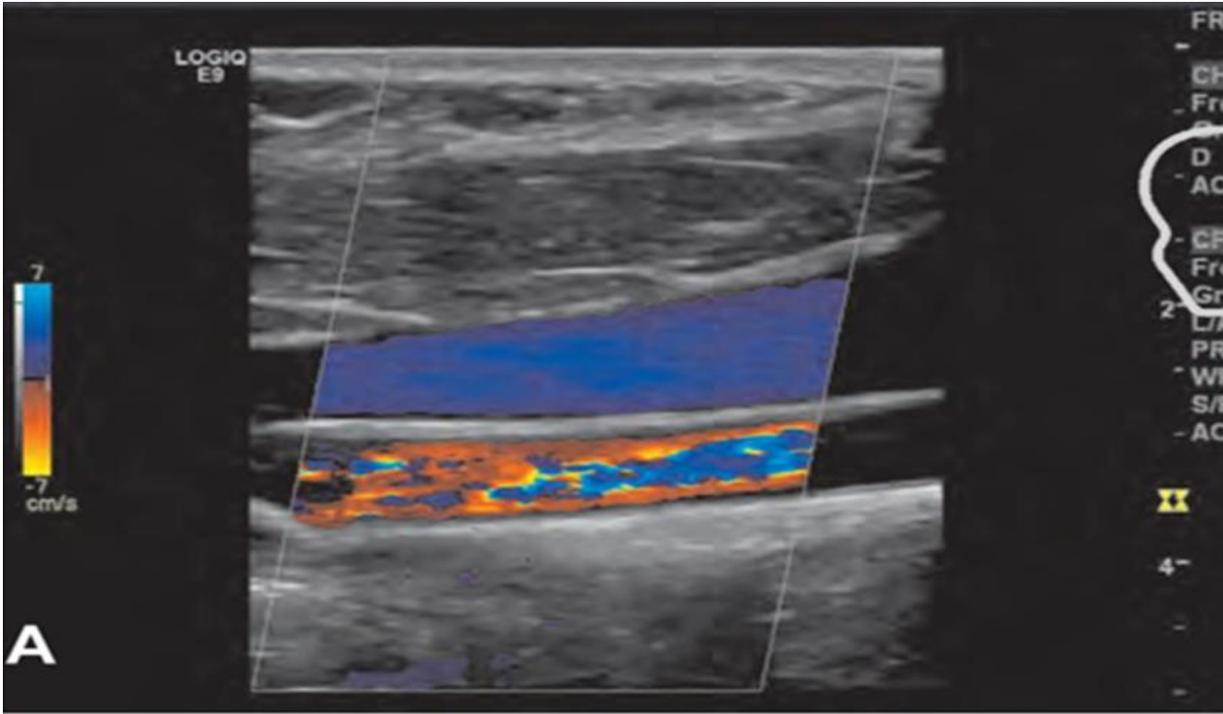




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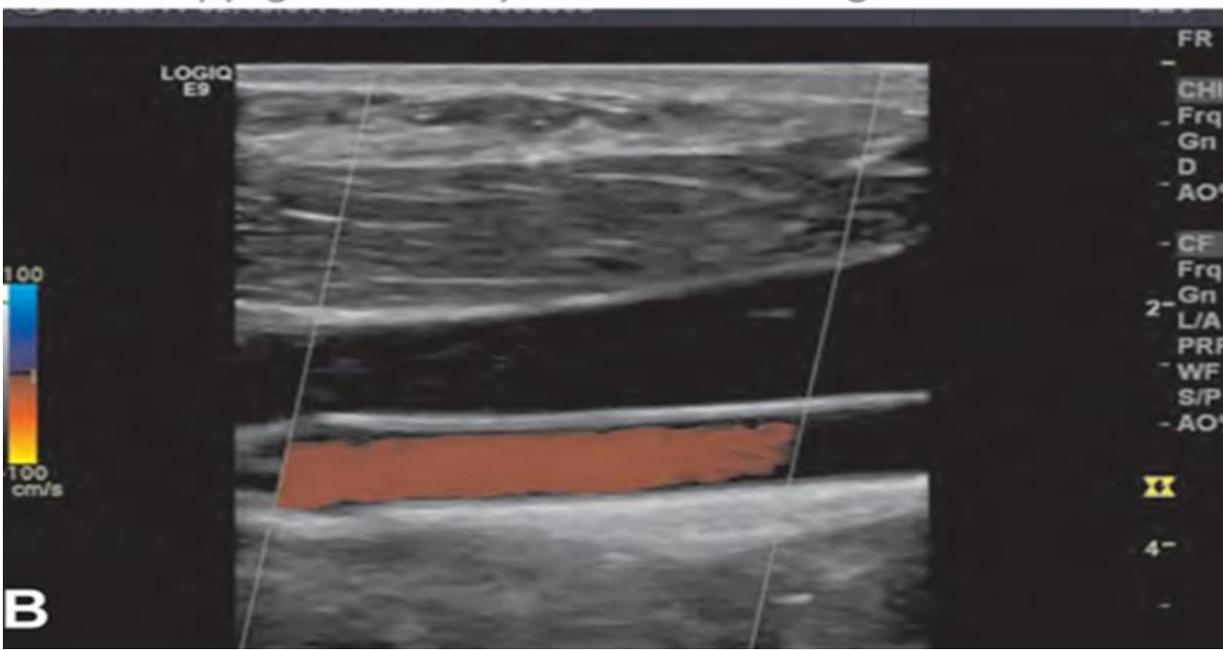


Was the change in images (A to B) due to an increased wall filter or an increased color scale?



Was the change in images (A to B) due to an increased wall filter or an increased color scale?

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# Wall Filter vs. Increasing Scale

- Both increasing the wall filter and increasing the color scale will eliminate slow moving blood flow seen in veins
- Look for a change in arterial flow:
  - A wall filter will alter low velocity flows, leaving high velocities alone (and the aliasing that accompanies it)
  - Increasing the scale removes low velocity flows AND corrects for aliasing

Arterial blood pressure measured in a supine patient's arm is 140 mmHg. What is the arterial pressure at the knee of this patient?

- A. 110 mmHg
- B. 140 mmHg
- C. 190 mmHg
- D. 215 mmHg

Normally, what happens to venous flow in the legs during inspiration?

- A. Increases
- B. Decreases
- C. No change

*At what angle between the sound beam and the direction of motion will the Doppler shift be the highest?*

0° or 180° (The sound beam and the direction of motion should be parallel)

At what angle between the sound beam and the direction of motion will the Doppler shift be closest to zero?

90° No Doppler frequency exists because the cosine of 90° is zero

An 8 MHz transducer with a pulse repetition frequency of 5,000 Hz is imaging to a depth of 7 cm. What is the Nyquist limit?

- A. 4 MHz
- B. 3.5 MHz
- C. 2.2 kHz
- D. 2.5 dB
- E. 5 kHz

*A successful Doppler exam cannot be performed on a severely anemic patient.*

- A. True
- B. False

*Which technique is used to perform spectral analysis on color Doppler data?*

- A. Autocorrelation
- B. Demodulation
- C. Fast Fourier Transform
- D. Pulse Inversion

Which of the following terms is synonymous with spectral broadening?

- A. Plug flow
- B. Parabolic flow
- C. Turbulent flow
- D. Laminar flow

*Which of the following is an advantage of a large packet size?*

- A. Less aliasing
- B. Increased frame rate
- C. Improved lateral resolution
- D. Increased Doppler accuracy

# Why are dedicated continuous wave transducers so sensitive?

- A. Absence of the matching layer
- B. Increased electrical impedance
- C. Absence of back material
- D. Inclusion of demodulator