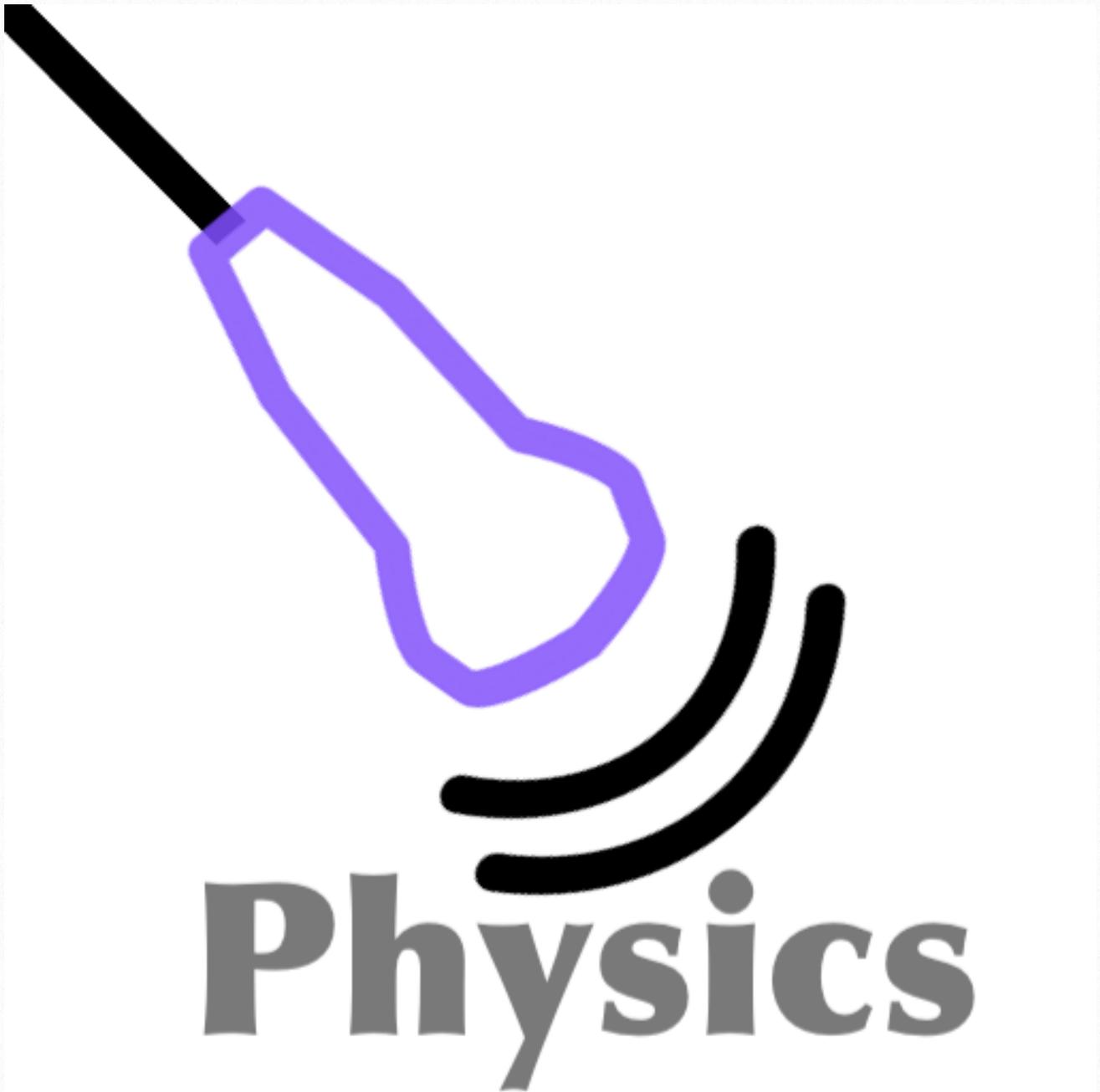


1

Ultrasound Physics



Ultrasound Physics Overview

Basic Principles of Ultrasound

Sound Waves:

Audible sound waves lie within the range of 20 to 20,000 Hz. Clinical ultrasound systems use transducers between 2 and 27 MHz. Ultrasound wavelengths are produced by passing an electrical current through piezoelectrical crystal elements. These elements convert electrical energy into a mechanical ultrasound wave and not only produce but can receive ultrasound wavelengths. Ultrasound image are produced from collection of emitted and received ultrasound wavelengths. Sound waves are described in terms of **frequency, velocity, wavelength, amplitude**.

Amplitude – Height of the ultrasound waves, or “loudness” as measure in decibels (dB)

Wavelength: the distance traveled between two consecutive peaks or troughs of a wave

Frequency: No. of wavelengths per unit time 1 cycle/ sec = 1 Hz Frequency is inversely related to wavelength

Velocity: Speed at which waves propagate through a medium

Velocity = Frequency * Wavelength

It is important to note that the velocity is dependent on physical properties of the medium through which it travels. Ultrasound image productions relies on the assumption that the velocity in tissue is assumed constant at 1540m/sec.

Image Formation:

The returning electric signals produced represent “dots” on the screen. The *brightness* of the dots is proportional to the strength of the returning echoes. The location of the dots is determined by travel time and the assumption that velocity in tissue is constant. Using the below equation each returned ultrasound wavelength is accumulated to produce an image.

$$\text{Distance} = \text{Velocity} / \text{Time}$$

Since the speed in tissue is assumed to be constant and the machine sets the frequency, that is how it identifies the location of each reflected ultrasound wave.

The image is formed from compiling these or scan lines. One image frame consists of many individual scan lines. One alters the image mostly by adjusting the frequency.

The frequency affects the image in the following manner:

The **HIGHER** the frequency, the **BETTER** the resolution (shorter wavelength)

The **LOWER** the frequency, the **LESS** the resolution (longer wavelength)

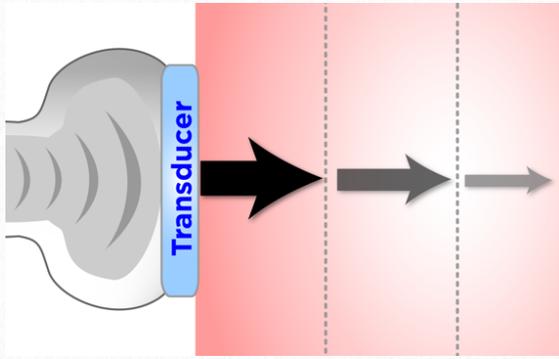
To explain this further one can think of the ultrasound wavelength as a ruler. If one is using a ruler that has only whole inch markings then they will be *less* precise in their measurement than if they used a ruler that had quarter-inch markers as well. Thus the shorter the wavelength allows for a more precise or higher quality image.

Along with this principle is the fact that the longer the wavelength the more the depth of penetration. This is secondary to the fact wavelengths will only penetrate a certain number of cycles before they are not enough quantity to produce an image (see next Figure). Therefore the longer a given wavelength the further it can penetrate before the “signal” is lost. While this is not a complete explanation the key-point is to realize the following:

The **HIGHER the frequency, the BETTER the resolution** (shorter wavelength), but this is at the cost of **LESS** depth of penetration.

The **LOWER the frequency, the WORSE the resolution** (longer wavelength), but this is at the cost of **LESS** depth of penetration.

Figure illustrates the loss of ultrasound signal the further it proceeds from the probe.



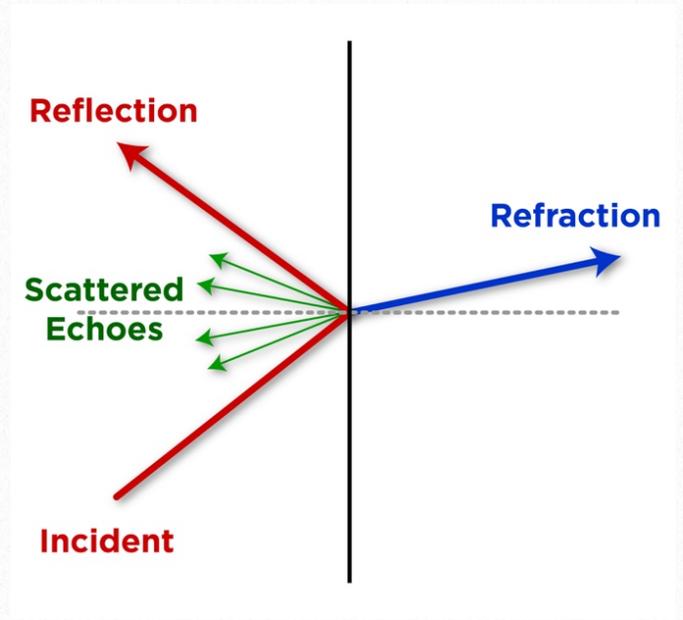
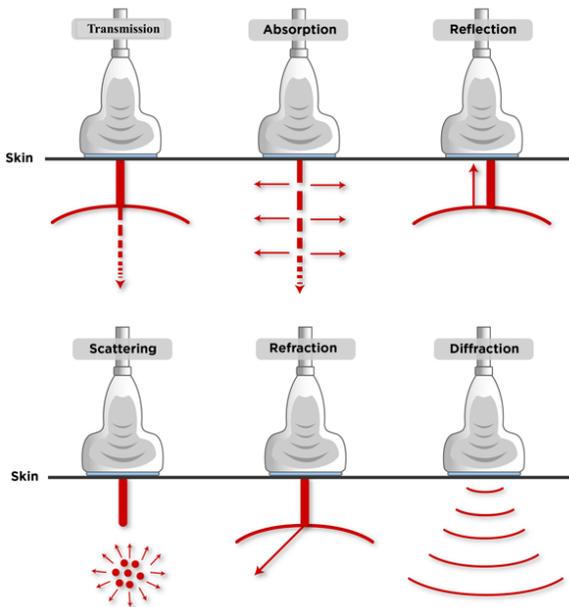
Interactions of Ultrasound with Tissue

The final fundamental concept when it comes to ultrasound image production is to understand how/why ultrasound devices receive return ultrasound waves at different times, which as we stated above represents different depths. An ultrasound wave is “affected” every time it interacts with tissues of different density. In fact this is what produces the ultrasound image. The term **attenuation** is used to describe what happens with the ultrasound wave as it interacts with the tissues. As ultrasound penetrates tissues planes it is attenuated. Attenuation is the concept that the deeper the ultrasound waves travel in the body, the weaker it becomes. This is secondary to 4 *main* processes: reflection, absorption, refraction, transmission. The additional process of scattering and diffraction are also demonstrated in the next figure.

Reflection: This is a mirror-like return of the ultrasound wave to the transducer. Reflections occur at the interface of different densities or acoustic impedances of the tissues. The greater the difference in the density of tissue the greater the amount of tissue reflection. This is why one does not see the lung tissue well with ultrasound, the majority of the ultrasound waves are reflected at the plan between the pleura and the lung. Also it is important to note that the more perpendicular the structure is to the ultrasound wave the more echogenic (or bright) the image will appear since more ultrasound waves are returned back to the probe. Similarly, the more parallel the structure is to the ultrasound probe the hypo-echoic (dark) the structures will appear since less ultrasound waves are reflected back to the probe. **Remember for 2-D images you want to the ultrasound wave to be as perpendicular as possible and for flow assessment you want to be as parallel as possible.**

Absorption: At each tissue plan some of the ultrasound waves are absorbed by the tissues and produces heat.

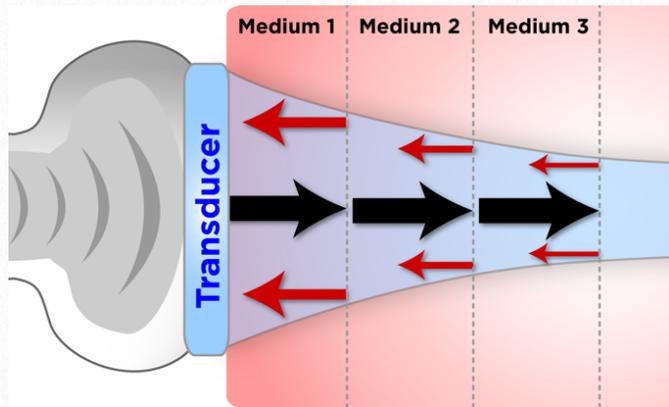
Refraction: This is a change in the direction of the ultrasound wave secondary to a change in density of one medium to another. This phenomena creates artifacts in the ultrasound image.



Transmission: This is necessary for one to see various tissues at various depths.

It is important to remember that one can counteract the loss of signal during the assessment of deeper structures by altering the power/gain/TGC

In addition, it is also important to highlight that ultrasound gel is used between the skin of the subject and the transducer face; otherwise the sound would not be transmitted across the air-filled gap.



Interactions of Ultrasound with Tissue, at each tissue medium the ultrasound is attenuated (waves are reflected, transmitted, refracted, absorbed, etc)

Transducers:

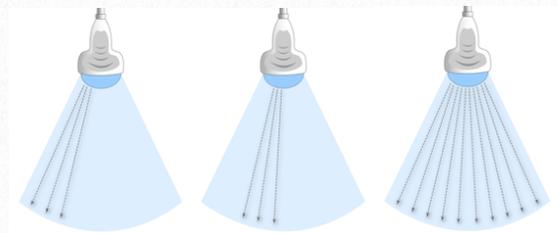
Transducers have three characteristics that help determine if it is the desired probe for image acquisition. These characteristics are: frequency, insonation footprint, and probe design. Most often, the choice of transducer is based on the depth of the structure being imaged since that will dictate the frequency that will be used to insonate. The higher the frequency of the transducer crystal, the less penetration it has, but the better the resolution. So if more penetration is required you need to use a lower frequency transducer while sacrificing some resolution. The footprint of the ultrasound probe is important since you have to be able to place the probe over the desired area such that the ultrasound wavelengths can penetrate. This is particular relevant when it comes to the cardiac exam since the probe has to have a small footprint to allow the probe to be placed in between the ribs (since bone is highly echo-reflective). Finally, the

shape of the probe and its beam is varied and is different for each transducer frequency.

General Probe Types:

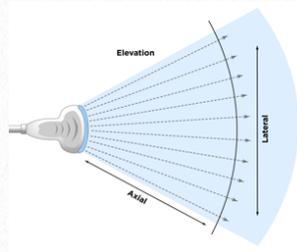
Phased Array:

This probe allows for a significantly larger width of image acquisition then compared to the footprint. This is done by sending directional “phases” of ultrasound wavelengths that are rapidly pulsated and composited together to produce an image. How rapid the the phases are emitted are related to the *frame rate*.



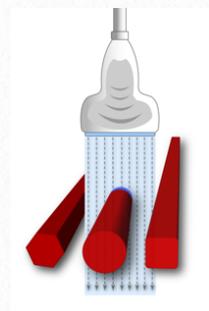
Curved Linear:

4 to 7 MHz, has large footprint, ideal for abdominal exam, wide image produced because of how US waves are emitted (curved)



Linear:

10 to 27 MHz, used for superficial structures, provides best image resolution

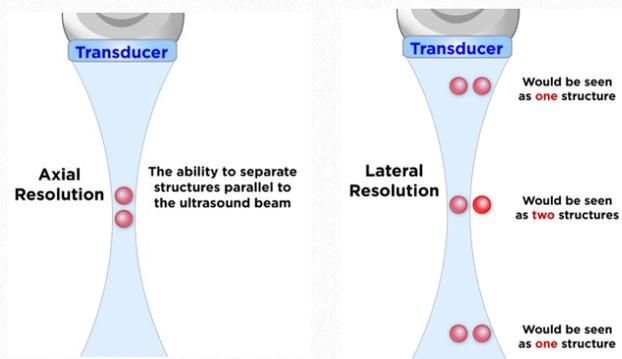


Resolution

Image resolution is defined as the ability to distinguish two points in space and of two components **spatial and temporal**

Spatial resolution is the smallest distance that two targets can be separated for the system to distinguish between them. Spatial resolution consists of two parts – *Axial and Lateral*. *Axial resolution* is the minimum separation between structures that are parallel to the ultrasound beam path. *Lateral resolution* is the minimum separation between structures that are perpendicular to the ultrasound beam path.

Temporal Resolution is the ability of system to accurately track moving targets over time. Anything that requires more time will decrease temporal resolution and includes: 1)Depth, 2)Sweep angle, 3)Line density, 4)PRF =frequency.



Commonly Used methods of Improving Ultrasound Image:

Depth: represents the number of pixels per cm and directly affects the spatial resolution. One should always adjust the depth to the minimum appropriate level in which all relevant structures are visualized since this will result in the highest frequency and thus image resolution.

Gain: adjusts the overall brightness of the ultrasound image. It is important to note that this is a post-processing adjustment so it does not improve differentiation of echogenicity (resolution is the same just brighter or darker). One can improve the image differentiation of echogenicity by adjusting the power.

Power: this relates to the strength of the voltage spike applied to the crystal for each pulse. Increasing power output

increases the intensity of the beam and therefore the strength of echo returned to the transducer.

Focus: There is a fixed, focused region of the ultrasound beam which is indicated on the system with a small triangle or line to the right of the image. This indicates the focal zone of that transducer and is where the best resolution can be achieved with that particular transducer. Effort should be taken to position the object of interest in the subject to within that focused area to obtain the best detail.

Time Gain Compensation (TGC): Equalizes differences in received reflection amplitudes because of the reflector depth. TGC allow you to adjust the amplitude to compensate for the path length differences (it counteracts the fact that fewer wavelengths penetrate to deeper structures that results in a less echogenic image). One can simple look at TGC as bands of *horizontal gain*.

Common Artifacts Seen

Enhancement	Increase in reflection amplitude from reflectors that lie behind a weakly attenuating structure. This is secondary to the large difference in acoustic impedance and examples include cysts and solid masses.
Reverberation	An artifact that results from a strong echo returning from a large acoustic interface to the transducer. This echo returns to the tissues again, causing additional echoes parallel and equidistant to the first echo
Shadowing	Created by strong reflectors, or attenuating structures, i.e. bone, gas, calcifications and air
Speckle	The granular appearance of images and spectral displays that is caused by the interference of echoes from the distribution of scatterers in tissue.
Side Lobe	Side lobe is secondary to the fact that while the main ultrasound beam is central, multiple beams are projected out from the transducer in a diverging manner. These beams are referred to as side lobes and can result in images being placed in the wrong location on the displayed image, since the ultrasound machine interprets all return ultrasound waves to have been emitted from the central beam. Again the result is usually seeing a structure in different location than normally expected. One can determine that this is a side lobe artifacts because the structure does not conflict or interact with surrounding ultrasound image.

ULTRASOUND MODES

B-MODE (brightness mode):

This is the mode used for standard 2-d image creation. There is a change in spot brightness for each echo signal that is received by the transducer. The returning echoes are displayed on a television monitor as shades of gray. Typically the brighter gray shades represent echoes with greater intensity levels. This mode allows you to scan.

M-MODE (motion mode):

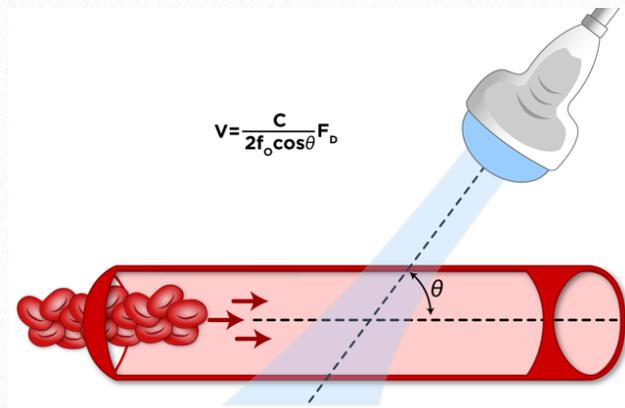
A graphic B-mode pattern that is a **single line time** display that represents the motion of structures along the ultrasound beam, 1000fps. This mode allows you to trace motion i.e. heart wall motion, vessel wall motion.

PW MODE (pulsed-wave mode):

Frequency change of reflected sound waves as a result of reflection motion relative to the transducer used to detect the velocity and direction of blood flow. This reflection shift can be displayed graphically, as well as audibly. During Doppler operation the reflected sound has the same frequency as the transmitted sound if the blood is stationary (we know that blood is not stationary it moves) therefore if the blood is moving away from the transducer a lower frequency is detected (negative shift) the spectrum appears below the baseline. If the blood is moving toward the transducer a higher frequency (positive shift) is detected and the spectral displays above the baseline

Doppler shift:

Dependent on the insonating frequency, the velocity of moving blood and the angle between the sound beam and direction of the moving blood. **THE MOST IMPORTANT THING WITH THIS CONCEPT IS TO REALIZE THAT** if the sound beam is **perpendicular** to the **direction of blood** flow, there will be **no doppler shift** therefore there would be **no display of flow in the vessel**. The angle of the sound beam should be less than 60 degrees at all times.

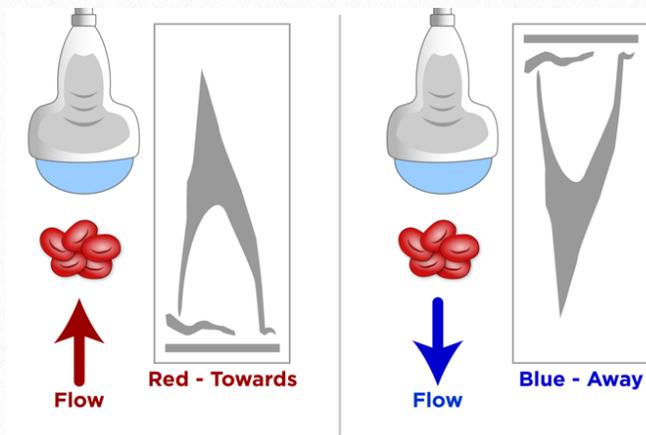


Aliasing:

The production of false doppler shift and blood velocity information when the Doppler shift exceeds a threshold. It appears as if the spectral display is cut off and wraps around and reappears in the opposite region of the display.

Color Doppler:

Doppler echoes are usually displayed with gray scale brightness corresponding to their intensities. In color doppler echoes are displayed with colors corresponding to the **direction of flow** that their positive or negative doppler shifts represent (toward or away from the transducer). The brightness of the color represents the intensity of the echoes, and sometimes other colors are added to indicate the extent of spectral broadening. A good generally rule is that the following: **BLUE COLOR=BLOOD FLOW MOVING AWAY FROM THE TRANSDUCER / RED COLOR=BLOOD FLOW MOVING TOWARDS THE TRANSDUCER - THINK B.A.R.T (Blue-Away/Red-Towards)**. The color range in the color doppler setting represents the range of the velocities. Brighter equals a higher/faster velocity and darker is a slower velocity. The range of the velocities is shown above the color range legend on the top left of the screen. This range of velocities is called the **Nyquist limit**. It is important to always look at the range of velocities (Nyquist limit) when using the color doppler modality. This is because the representation of the color doppler window can be greatly altered by changing the range of the velocities. For example one can make the degree of regurgitation across a cardiac valve to appear to be worse by *lowering* the Nyquist limit. Important references include 60 cm/sec to evaluate cardiac valves and 20cm/sec to evaluate atrial or venous flow.



DOPPLER PRINCIPLES

Doppler:

Displays the change in frequency of a wave resulting in the motion of the wave source or reflector. In ultrasound the reflector is the moving red blood cell. The Doppler shift is dependent on the insonating frequency (transducer frequency), the velocity of the moving red blood cells, and the angle of the sound beam and direction of the moving red blood cells.

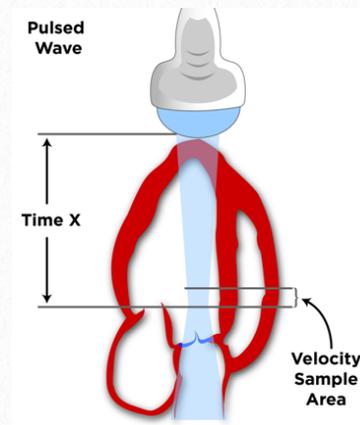
Remember, if the ultrasound beam is perpendicular to the direction of the blood flow a Doppler shift and potentially incorrect impression of the blood flow velocities. Therefore, careful consideration should be taken to obtain an angle of less than 60 degrees to the direction of the blood flow to obtain reliable and accurate results in quantifying the velocity in a certain blood vessel.

Power Doppler:

Depicts amplitude or power of the Doppler signal rather than the frequency shift. Therefore, there is less angle dependence and a visualization of smaller vessels with a Doppler shift, however, velocity and directional information is sacrificed.

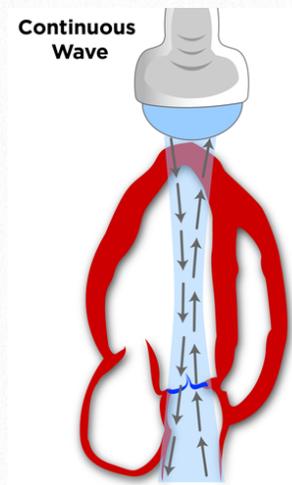
Pulsed Wave Doppler:

This is used with a sample gate or volume, and gives a graphical display of all the velocities within the area sampled. The amplitude of the signal is proportional to the number of blood cells and is indicated as a shade of gray.



Continuous Wave Doppler:

In this modality there is a constant ultrasound signal being sent and there is a constant part of the piezoelectric crystal that is able to receive the ultrasound signal. The benefit of this is that there is no limitations to velocity measurements. However, this is at a trade-off with losing the ability depth (or location) identification. In other words, a continuous wave Doppler will show the highest velocities **anywhere** along the continuous wave ultrasound plane.



TERMS FOR LABELING AND SCAN ORIENTATION

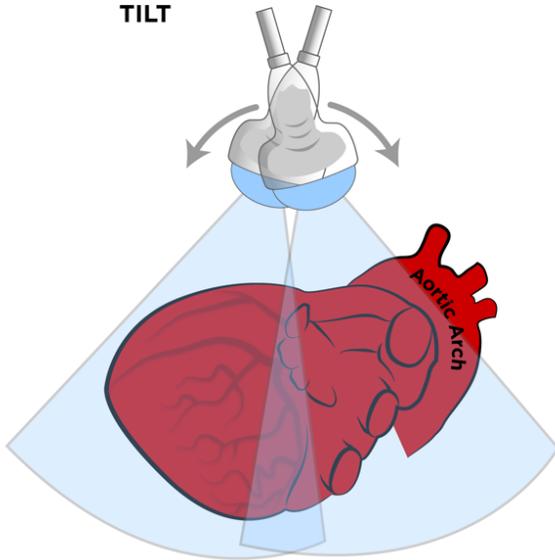
From each transducer position the target structure is focused by three major movements shown below.

Angle: scanning in the anterior – inferior direction

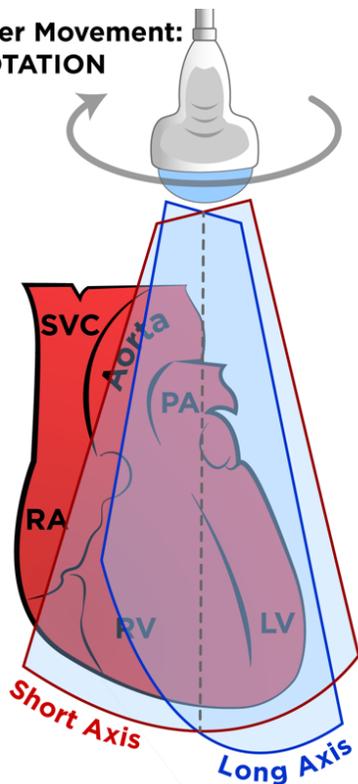
Tilt: scanning in the left – right direction (used to position structures in the middle of the screen)

Rotation: clockwise, counterclockwise

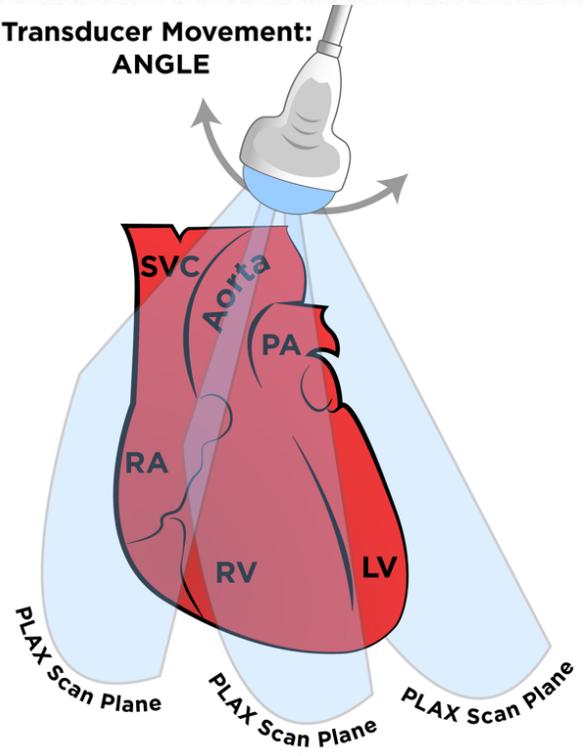
**Transducer Movement:
TILT**



**Transducer Movement:
ROTATION**



**Transducer Movement:
ANGLE**

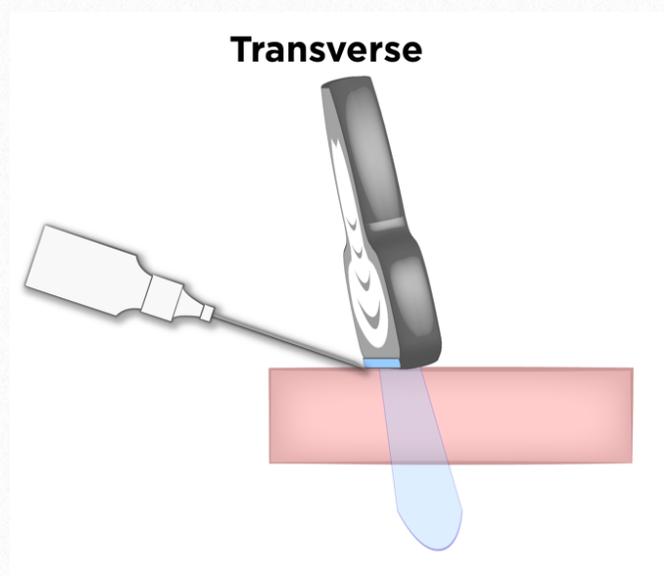


Coronal	The long axis of a scan performed from the subject's side where the slice divides the anterior from the posterior or the dorsal from the ventral in the long axis
Transverse (short axis)	A cross-sectional view
Sagittal (Longitudinal)	The long axis plane
Superior, Cranial, Cephalad, Rostral	Interchangeable terms indicating the direction towards the head
Inferior or Caudal	Indicating the direction towards the feet
Anterior or Ventral	A structure lying towards the front of the subject
Posterior or Dorsal	A structure lying towards the back of the subject

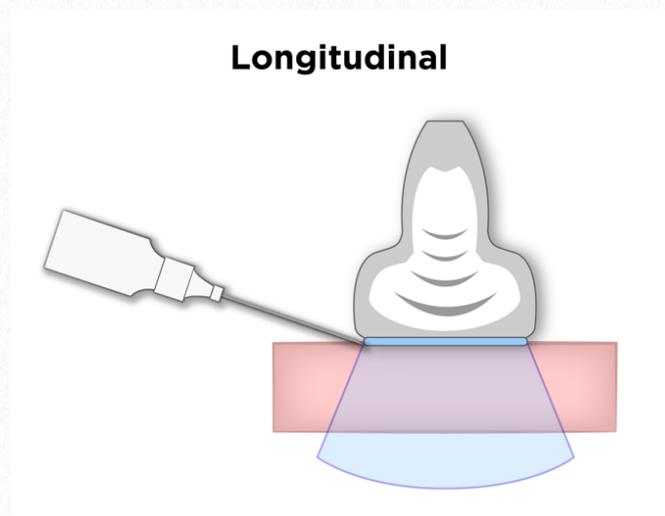
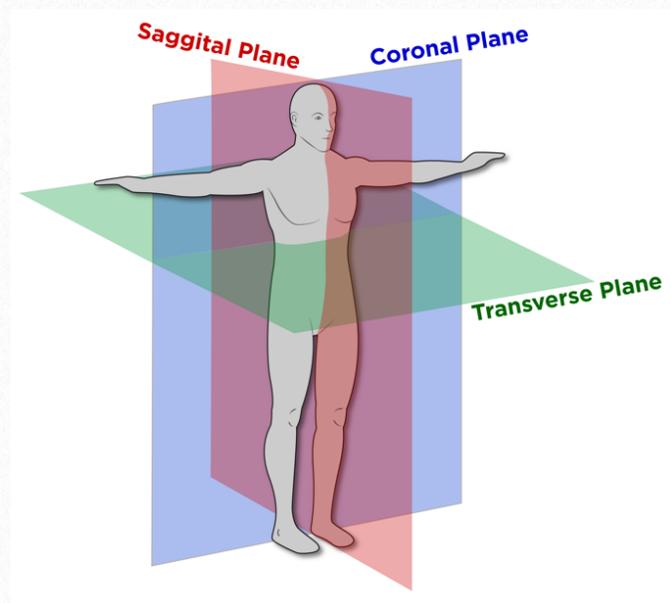
Ultrasound Probe Indicator Marker:

Another important point to become familiar with as one learns about point of care ultrasound is the location of indicator on the probe. All probes will have an indicator mark that can be used to relate the footprint of the probe to the screen (left and right of the probe to the left and right of the screen).

The indicator is marked by a line, bump, or with an led light. One should always identify the indicator of the probe to the maker of the indicator location on the screen. The default location of the indicator for non-cardiac probes and non-cardiac presets is for the indicator to be on the left side of the ultrasound screen. For cardiac presents and the use of the phased array probe the default for most ultrasound machines is to place the indicator on the right of the screen. To summarize this concept to doing an ultrasound exam one should always consider , two key issues regarding the orientation of anatomic structures as they are viewed on the screen: 1)relationship of the probe indicator to the image on the screen (indicator-to-screen) and 2) relationship of the probe indicator to the patient (indicator-to-patient). This eBook will describe probe position based on the usually defaults for the probe and presets used to perform the ultrasound exam



Transverse (Short Axis) Approach



Long Axis Approach