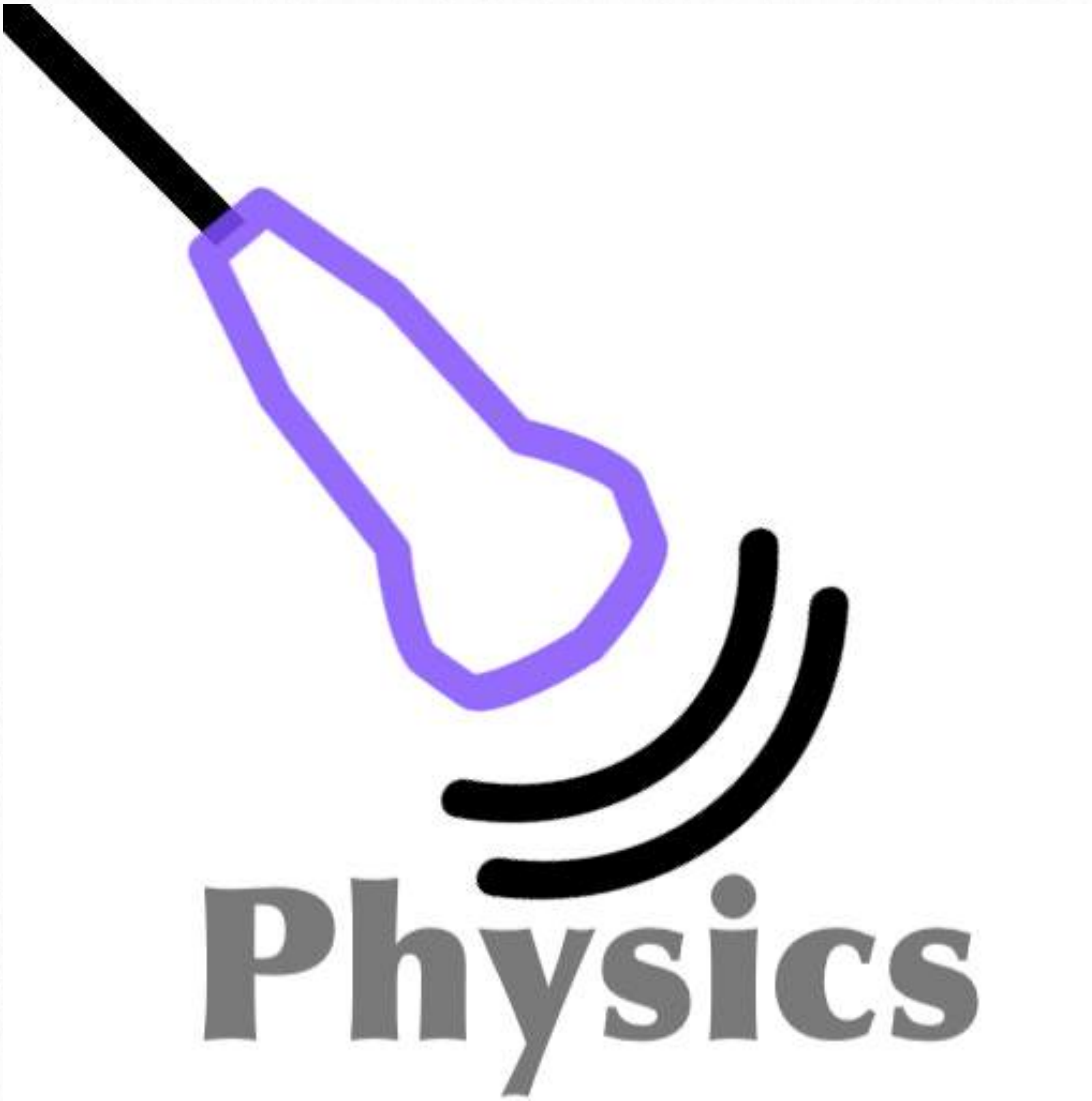
Ultrasound Physics



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 piezoelectric crystal elements. These elements convert electrical energy into a mechanical ultrasound wave and not only produce but can receive ultrasound wavelengths. Ultrasound images are produced from collection of emitted and received ultrasound wavelengths. Sound waves are described in terms of **frequency, velocity, wavelength, and amplitude**.

Frequency: Number of wavelengths per unit time is 1 cycle/ sec = 1 Hz. Frequency is inversely related to wavelength.

Velocity: The speed at which waves propagate through a medium.

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

Amplitude: Height of the ultrasound waves, or "loudness" as measure in decibels (dB).

Velocity = Frequency x 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.

Distance = Velocity x 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 on the display.

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

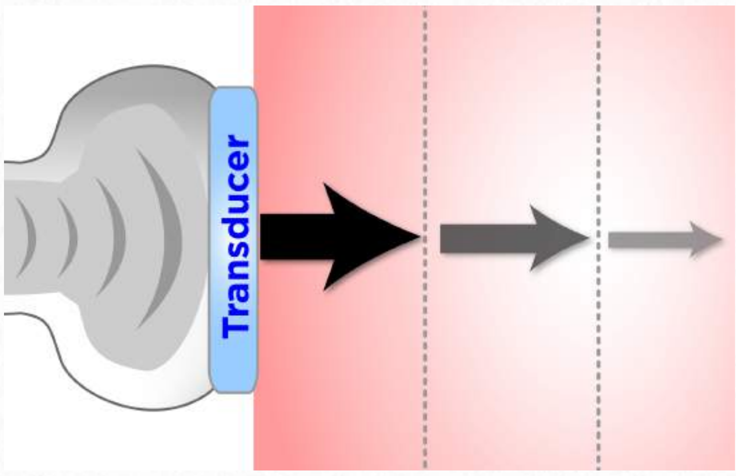
Think of the ultrasound wavelength as a ruler: if one is using a ruler that has only whole inch markings, then they will be *less* precise in their measurement versus using a ruler that has quarter-inch markings as well. Thus a shorter the wavelength allows for a more precise or higher quality image.

Along with this principle is the fact that the longer the wavelength, the more the depth of penetration. This is secondary to the fact that wavelengths will only penetrate a certain number of cycles before they are not enough in 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-points to realize are the following:

- The <u>HIGHER the frequency, the BETTER the resolution</u> (shorter wavelength), but this is at the cost of <u>LESS depth of penetration.</u>

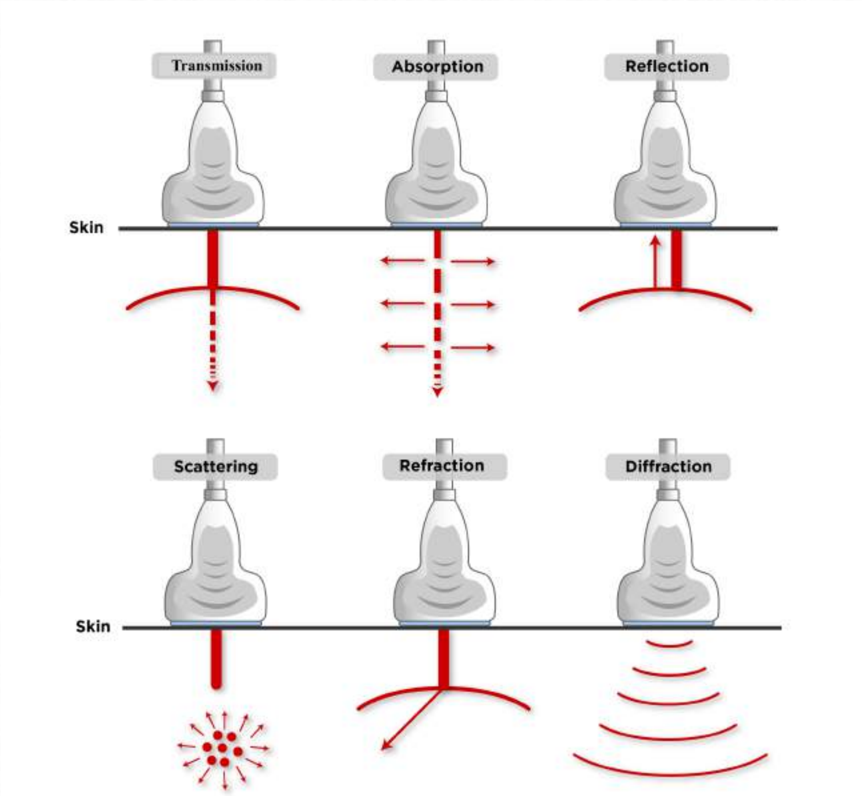
- The <u>LOWER the frequency, the WORSE the resolution</u> (longer wavelength), but the <u>GREATER depth of penetration</u>.

The following figure illustrates the loss of ultrasound signal the further it proceeds from the probe.



INTERACTIONS OF ULTRASOUND WITH TISSUE

When it comes to ultrasound image acquisition, the final fundamental concept to understand is how/why ultrasound devices receive returned 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. *Its important to realize that you will have more attenuation per depth with higher frequency probes vs lower frequency probes*. As ultrasound penetrates tissue 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, and transmission. The additional process of scattering and diffraction are also demonstrated in the following 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 lung tissue well with ultrasound: the majority of the ultrasound waves are reflected at the plane 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 hyper-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 more hypo-echogenic (dark) the structures will appear since less ultrasound waves are reflected back to the probe. *Remember, for 2-D images you want the ultrasound wave to be as perpendicular as possible and for flow assessment you want to be as parallel as possible.*

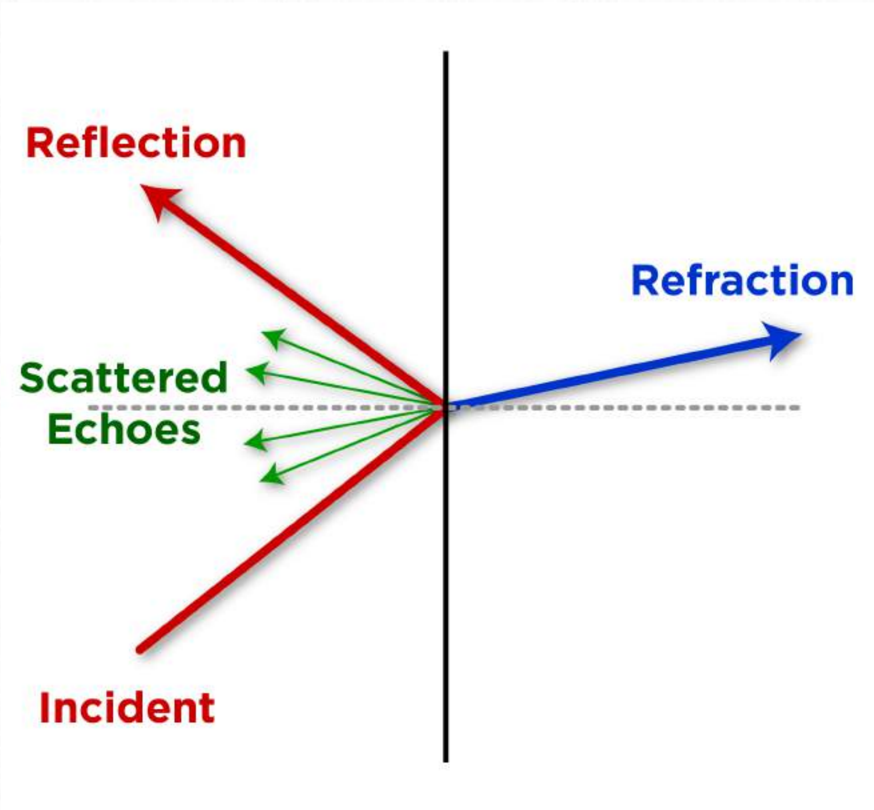
Absorption: At each tissue plane some of the ultrasound waves are absorbed by the tissues and produce heat.

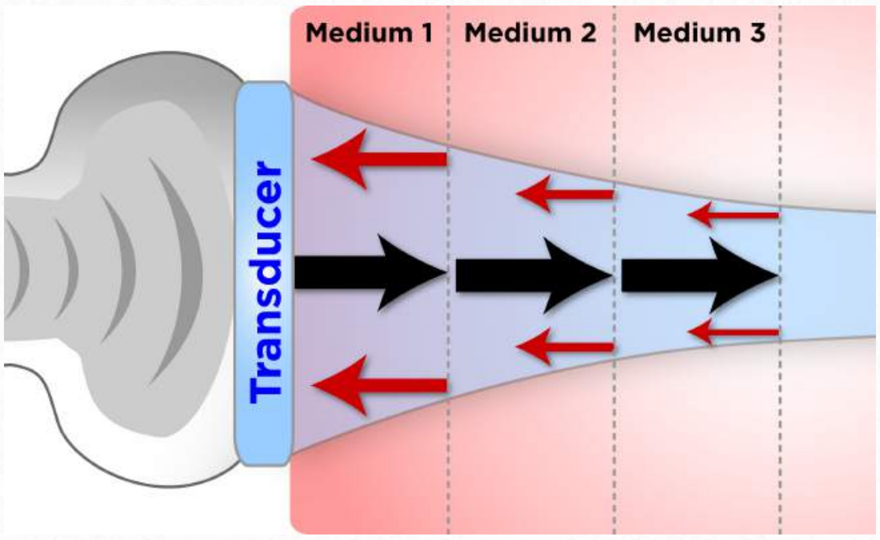
Refraction: This is a change in the direction of the ultrasound wave secondary to a change in density of one medium to another. This phenomena creates artifacts in the ultrasound image.

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.

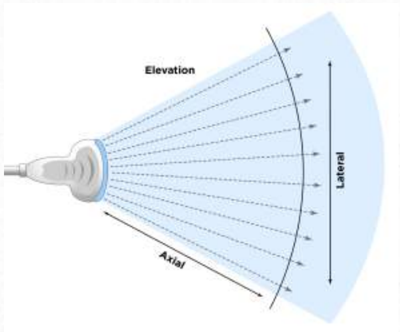
The footprint of the ultrasound probe is important since you have to be able to place the probe over the desired area such that the ultrasound wavelengths can penetrate. This is particularly relevant when it comes to the cardiac exam since the probe has to have a small footprint to allow the probe to 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.

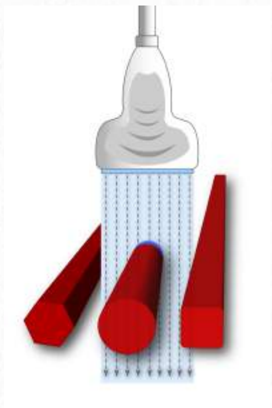
GENERAL PROBE TYPES

Phased Array:
This probe allows for a significantly larger width of image acquisition than 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 rapidly the phases are emitted is related to the *frame rate.*

Curved Linear:
4 to 7 MHz, has a large footprint, ideal for abdominal exam, and a wide image is produced because of how ultrasound waves are emitted (curved).



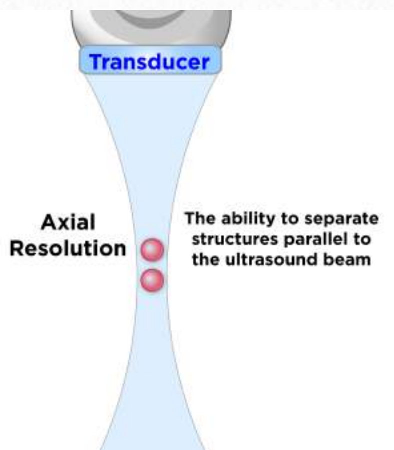
Linear:
10 to 27 MHz, used for superficial structures, and provides the best image resolution.

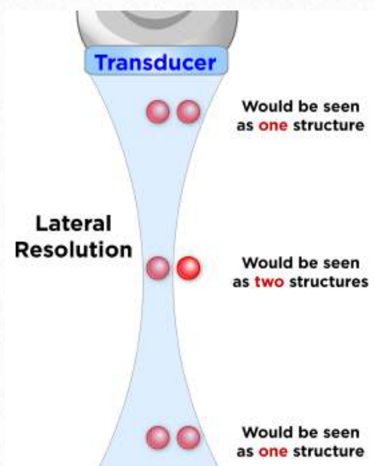


RESOLUTION

Image resolution is defined as the ability to distinguish two points in space and consists 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. Axial resolution is directly related to frequency, pulse length (period of wavelengths), and inversely related to wavelength. *Lateral resolution* is the minimum separation between structures that are perpendicular to the ultrasound beam path. Lateral resolutions is impacted by the ultrasound wave amplitude, the image depth, and the gain intensity.





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, and 4) lower frequency or pulse repetition frequency (PRF).

COMMONLY USED METHODS OF IMPROVING ULTRASOUND IMAGE

Depth: Represents the number of pixels per centimeter 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 resulting in a less echogenic image). One can simply look at TGC as bands of “horizontal gain”.

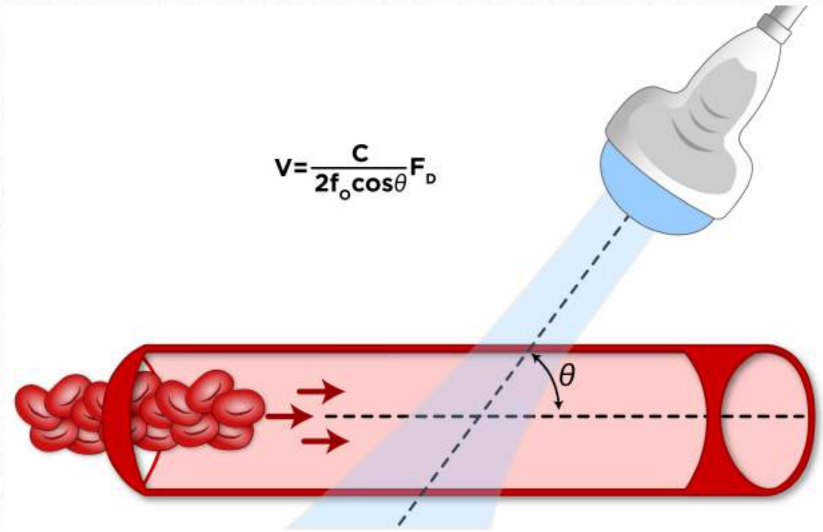
ULTRASOUND MODES

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. Since 2-D images are generated from reflection the best 2-D or B images occur when the ultrasound plane is *perpendicular* to the structure.

M-MODE (motion mode):
This is a graphic B-mode pattern that is a *single line time* display that represents the motion of structures along the ultrasound beam at 1000fps. In this mode the line of ultrasound reflection or returning echoes are shown in the *y*-axis and its change over time is shown in the *x*-axis. This mode allows you to trace motion (i.e. heart wall motion, and vessel wall motion).

PW MODE (pulsed-wave mode):
This mode is a frequency change of reflected sound waves relative to the transducer which is used to detect the velocity and direction of blood flow. This shift in reflection 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. If the blood is moving away from the transducer, a lower frequency is detected (negative shift), and the spectrum appears below the baseline. Conversely, if the blood is moving toward the transducer, a higher frequency (positive shift) is detected and the display is shown above the baseline.

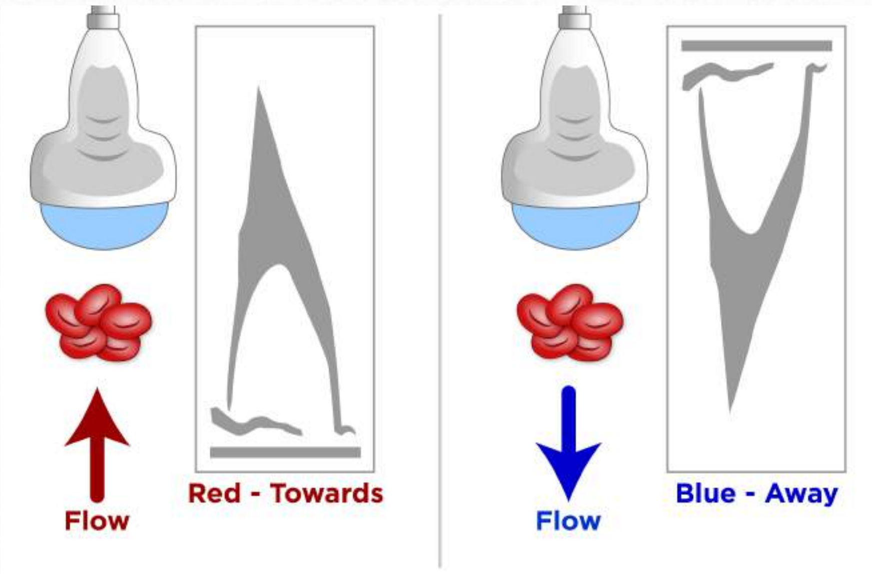
Doppler shift:
This shift is dependent on the insonating frequency, the velocity of blood flow, and the angle between the sound beam and direction of blood flow. It is important to realize that *if the sound <u>beam is perpendicular</u> to the direction of blood flow, there will be <u>no doppler shift</u>*, and consequently no display of flow in the vessel. The angle of the sound beam should be less than 60 degrees at all times.



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

Color Doppler:
Ultrasound images are usually displayed with gray scale brightness corresponding to their intensities. In color doppler, echoes from positive or negative doppler shifts (toward or away from the transducer) *are displayed with corresponding colors to indicate direction of flow*. This is usually overlaid on a B or 2-D image. The color doppler window can be adjusted and represents a window of pulsed wave doppler signals that has been assigned a color representation for its direction and velocity of flow. 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 general rule is 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 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 appear to be worse by *lowering* the Nyquist limit. Important reference measurements include 60 cm/sec to evaluate cardiac valves and 20cm/sec to evaluate atrial or venous flow. Finally its important to realize that the use of color doppler will negatively impact the resolution of the 2-D image directly with the size of color doppler window.



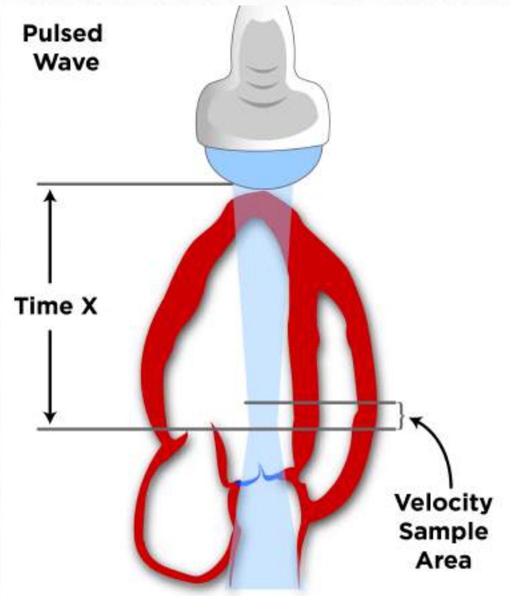
DOPPLER PRINCIPLES

Doppler:
This feature displays the change in frequency of a wave resulting from 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, the angle of the sound beam, and direction of the moving red blood cells.

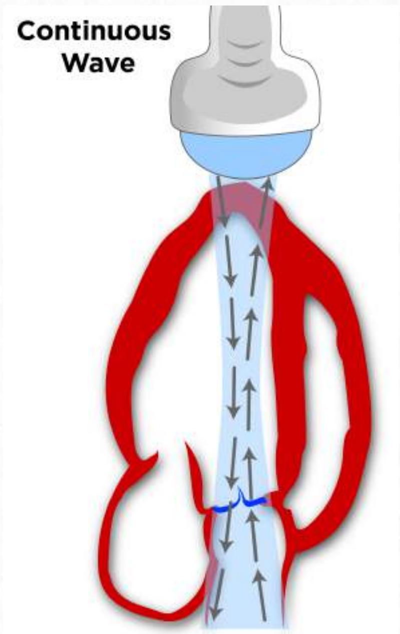
Remember, if the ultrasound beam is perpendicular to the direction of the blood flow, a Doppler shift and potentially incorrect impression of the blood flow velocities may be observed. Therefore, careful consideration should be taken to obtain an angle of less than 60 degrees relative to the direction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

Power Doppler:
This mode depicts amplitude or power of the Doppler signal rather than the frequency shift. Therefore, there is less angle dependence and visualization of smaller vessels with a Doppler shift; however, velocity and directional information are 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. Pulse wave doppler offers the benefit of providing depth discrimination however because one is identifying a velocity sample area one will have a limitation on the ranges that can be assessed with this technique. This range decreases as you move further from the probe (time increases).



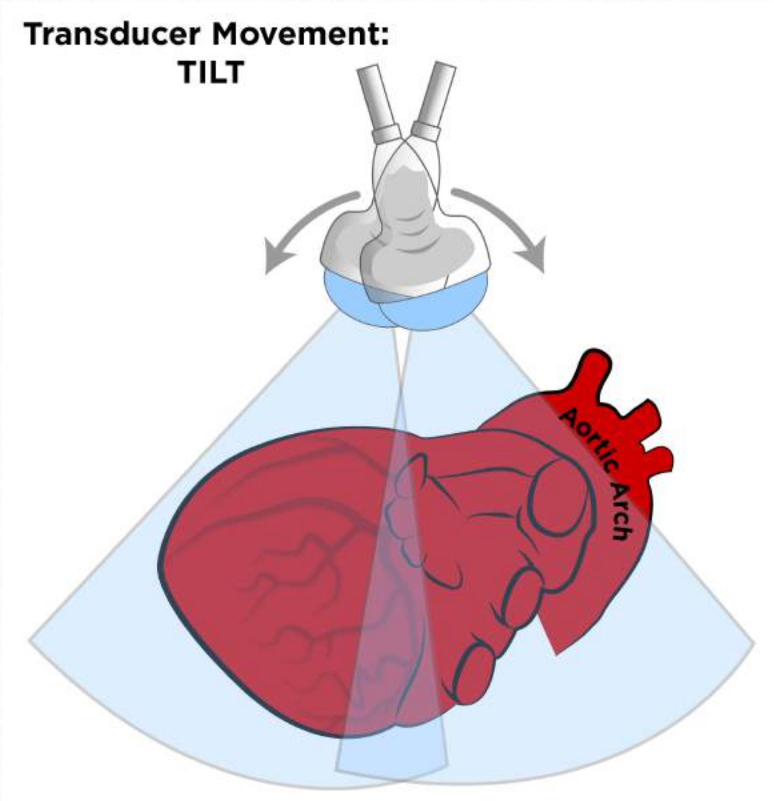
Continuous Wave Doppler:
In this modality, there is a constant ultrasound signal being sent and a part of the piezoelectric crystal that is able to continuously receive the ultrasound signal. The benefit of this is that there are no limitations to velocity measurements. However, the trade-off is a loss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

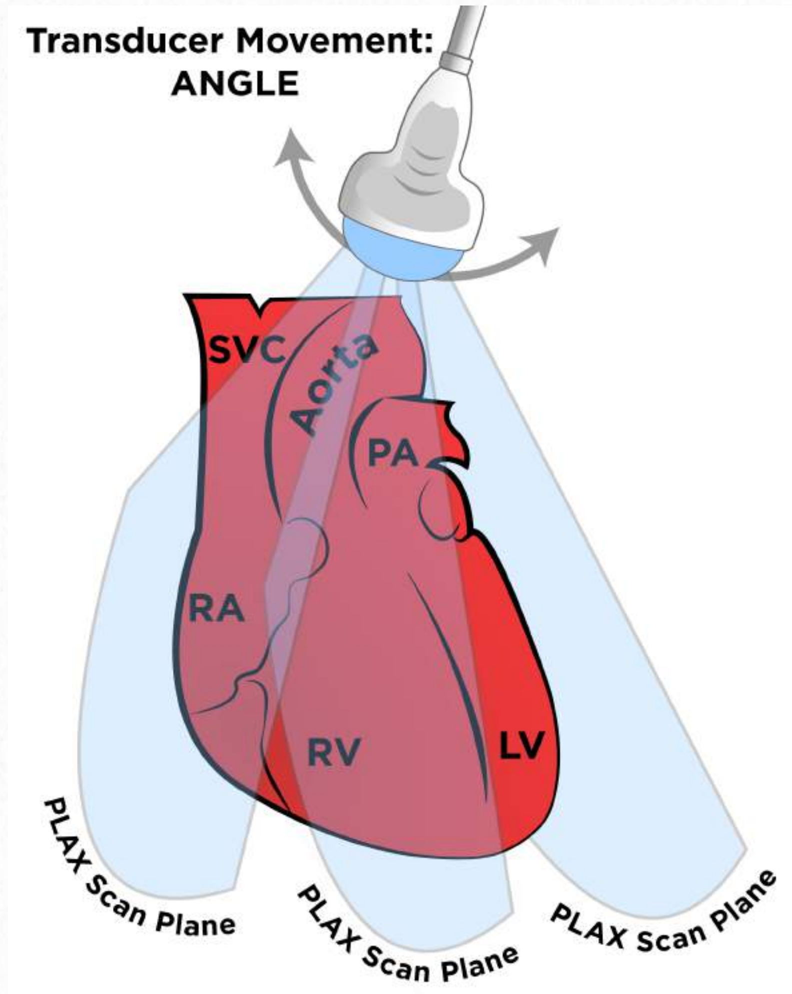


TERMS FOR LABELING

AND SCAN ORIENTATION

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

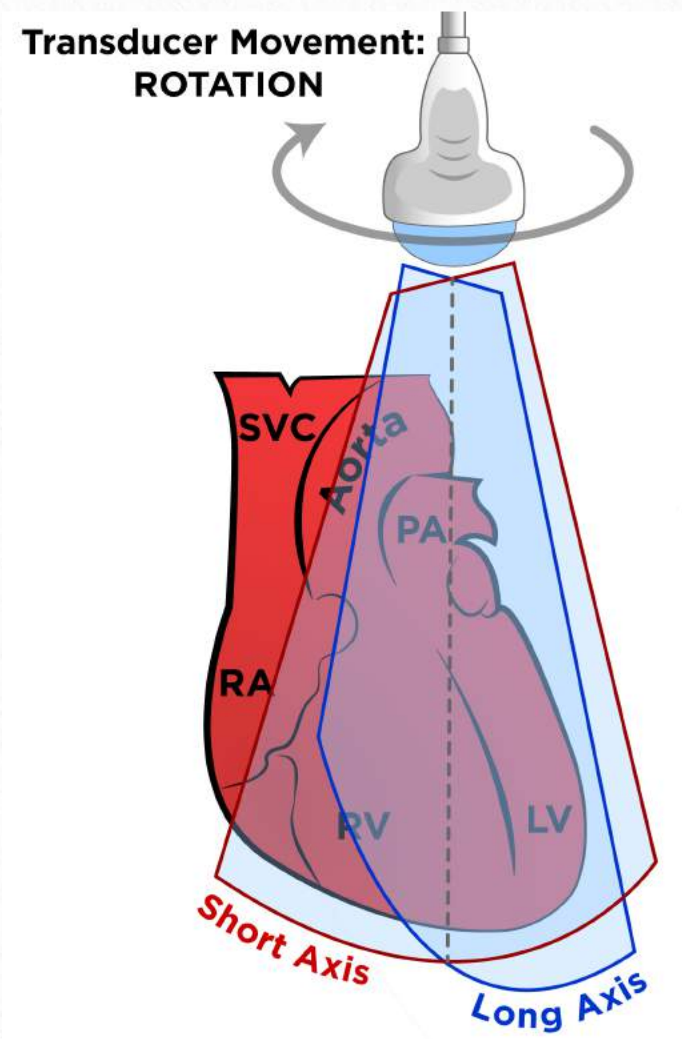


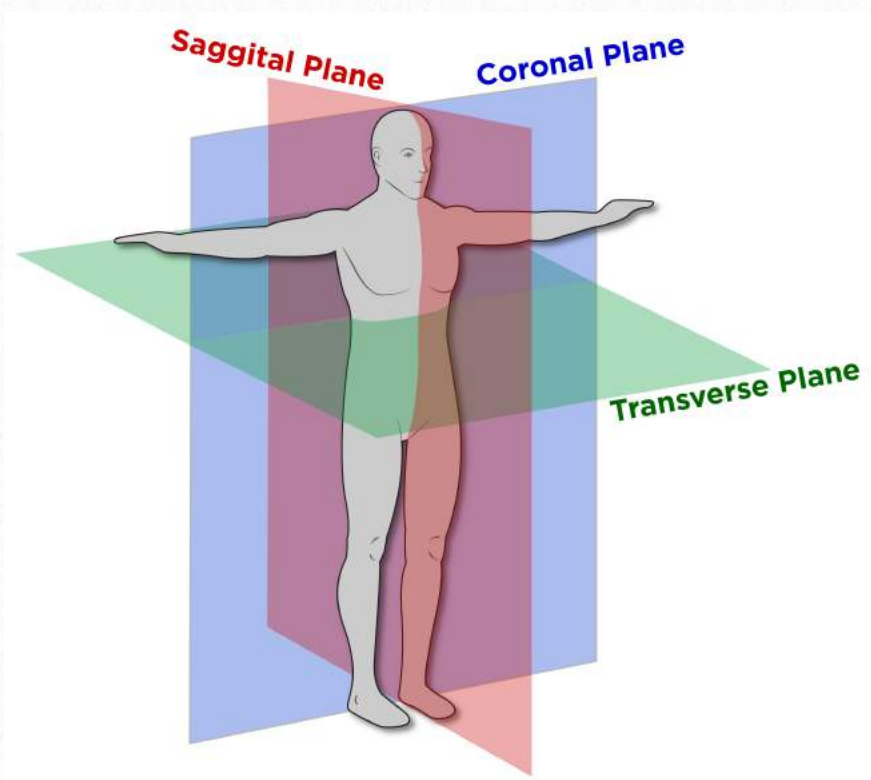


Angle: Scanning in the anterior – inferior direction

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

Rotation: Clockwise, counterclockwise



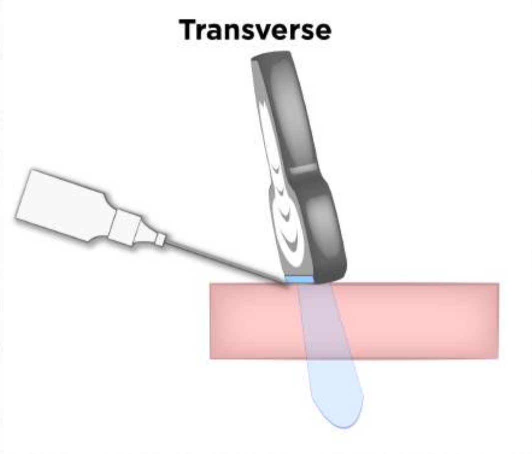


Coronal	The long axis of a scan performed from the subject's side where the slice divides the anterior from the posterior or the dorsal from the ventral in the long axis
Transverse (short axis)	A cross-sectional view
Sagittal (Longitudinal)	The long axis plane
Superior, Cranial, Cephalad, Rostral	Interchangeable 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 the 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 marker 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 presets 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, when 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 usual defaults for the probe and presets used to perform the ultrasound exam.

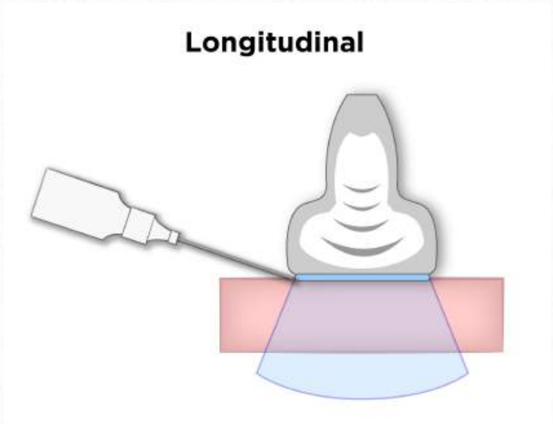
Transverse (Short Axis) Approach



Important Points for the Short Axis Approach

- it provides a cross-sectional view of the needle
- it is known as the out-of-plane technique
- this technique results in the needle being imaged on cross-section that appears as a small dot, which can be difficult to see in real time
- the needle will cross the ultrasound beam only once
- requires frequent probe adjustment (fanning) to maintain continuous visualization of the desired structure (needle) as in penetrates tissue

Long Axis Approach



Important points for the Long Axis Approach

- it provides a view of the entire needle if the ultrasound plan is in the path of the needle
- the operator loses the lateral-medial perspective
- the operator loses the ability to assess surrounding anatomy
- probe is more often fixed in position during a procedure

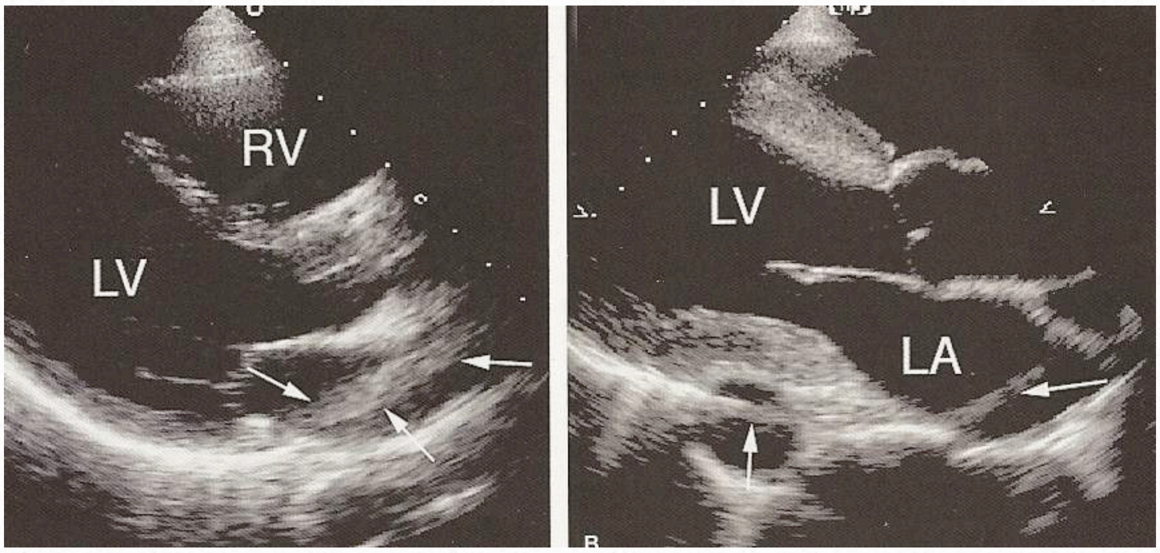
Basic Physics Terms

Absorption	The loss of ultrasound energy by converting to another form of energy (heat or mechanical vibration)
Acoustic Impedance	The resistance to sound transmission through a medium. *It is the difference in acoustic impedances of different tissues that results in reflection and image formation*
Aliasing	Aliasing occurs with any pulsed ultrasound doppler modality (color doppler and pulse wave). All pulsed ultrasound doppler techniques require the machine to have time delays to asses for changes in direction and frequency. This time delay creates a limit or range of velocities that can be assessed. When a velocity is evaluated above this range (Nyquist limit) the phenomena of aliasing occurs in which the flow pattern is reset to the opposite direction. Aliasing can be prevented by using a lower frequency probe, imaging at a shallower depth, and adjusting the pulse repetition velocity scale
Amplitude	The strength of a sound signal
Anechoic	A structure that does not produce any internal echoes
Artifacts	Alterations to the display that can adversely affect ultrasound image acquisition or interpretation
Attenuation	The loss of ultrasound energy due to *absorption*, *reflection*, and *scattering* of sound energy
Axial Resolution	The ability to distinguish two structures as separate when the structures are close to each other along the same axis as the ultrasound plane. Good axial resolution is achieved with short spatial pulse lengths. Short spatial pulse lengths are a result of higher frequency and higher damped transducers. Therefore the higher the frequency the better the resolution
B-mode	A two-dimensional display of ultrasound. The A-mode spikes are electronically converted into dots and displayed at the correct depth from the transducer
Complex	Refers to a mass that has both fluid-filled and solid areas within it
Cystic	This term is used to describe any fluid-filled structure, for example, the urinary bladder
Doppler Effect	The change in frequency as a result of motion between the sound source and the receiver; a movement of the source towards the receiver results in a positive shift and away from each other results in a negative shift
Dynamic Range	The range of echo intensities that are displayed as a gradient of grey values (minimum = black and maximum = white)
Echogenicity	The degree of brightness of a structure displayed on ultrasound. This is influenced by the amount of beam returning to the transducer (reflection) after encountering the target structure
Enhancement (Acoustic)	Sound is not weakened (attenuated) as it passes through a fluid-filled structure and therefore the structure behind appears to have more echoes than the same tissue beside it
Frequency	The number of cycles per second; frequency is the inverse of wavelength; the higher the frequency the shorter the wavelength and the less depth of penetration

Gain	Refers to the amount of amplification of the returning echoes
Gel Couplant	A trans-sonic material which eliminates the air interface between the transducer and the subjects skin
Hyperechoic	Image characteristic of a structure that is highly reflective resulting in a brighter (whiter) image. Examples = bone and lung pleura
Hypoechoic	Image characteristic of a structure that is less reflective than the surround structure resulting in a darker (black) image. Examples = fluid filled structures (vessels and cysts)
Homogenous	Of uniform appearance and texture
Interface	Strong echoes that delineate the boundary of organs, caused by the difference between the acoustic impedance of the two adjacent structures; an interface that is usually more pronounced when the transducer is perpendicular to it
Lateral Resolution	The ability of the system to distinguish two structures as separate when the structures are lying side by side. It is perpendicular to the direction of propagation required to produce separate reflections. Good lateral resolution is achieved with narrow acoustic beams. A narrow acoustic beam is the result of a long near zone and a small angle of divergence in the far zone.
M-mode	The motion mode displaying moving structures along a single line in the ultrasound beam
Noise	An artifact that is usually due to the gain control being too high
Reflection	The mirror like redirection and return of a propagating sound wave
Refraction	A change in the direction of wave propagation when traveling from one medium to another
Scattering	A process by which the ultrasound is forced to deviate from a straight-line reflection and trajectory due to small, localized non-uniformities in the tissue
Spatial Resolution	The ability to distinguish between two structures that lie close to one another
Speckle	The granular appearance of images and spectral displays that is caused by the interference of echoes from the distribution of scatterers in tissue
Temporal Resolution	The ability to distinguish the movement of reflected images (similar to frames per second on movies)
Time-gain compensation	Compensation for attenuation is accomplished by amplifying echoes in the near field slightly and progressively increasing amplification as echoes return from greater depths

Tissue Harmonic Imaging	Standard ultrasound imaging is based on capturing the reflected ultrasound beam from tissue interfaces, which have the same frequency as the transmitted beam. Tissue harmonics imaging is based on the harmonic frequency energy generated as the ultrasound signal propagates through the tissue. These harmonic frequencies result from the nonlinear effects of the interaction of ultrasound with tissues, resulting in new waveforms of higher frequency that are multiples of the baseline frequency. Thus, harmonic imaging reduces near-field artifacts and improves far-field visualization
Transducer	A device which houses the element for transmitting and receiving ultrasound waves. Also referred to as a probe or Scanhead
Velocity (of sound)	The speed at which a sound wave travels. In soft tissue at 37°C sound travels at 1540 m/s
Wavelength	The distance traveled between two consecutive peaks or troughs of a wave

Specific Terms with Images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