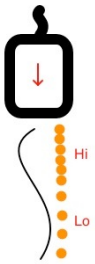
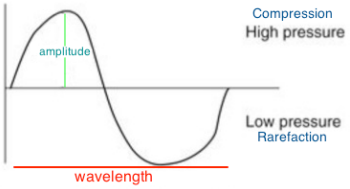
Ultrasound Physics Review

Physics principles (15%)

Properties of sound



Sound is a mechanical, longitudinal wave. Longitudinal means parallel from sound source. Mechanically moves through medium by vibration of molecules or physically changing pressure, compressions (high pressure) and rarefactions (low pressure)
One complete cycle = 1 compression and 1 rarefaction

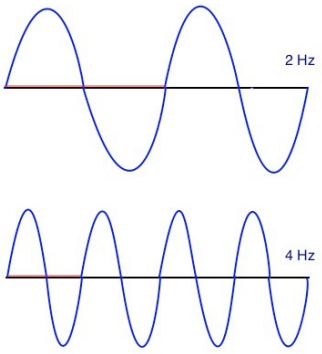


Frequency	# cycles per second	**Hz**
Wavelength	length of one cycle	**mm**
Period	time of one cycle	***μ*s**

$$\lambda = \frac{c}{f}$$

λ = wavelength
c = prop speed
f = frequency

Relationships
Direct: If one increases, the other increases and vice versa (go together)
Inverse: If one increases, the other decreases (opposites)



Wavelength depends on 2 things - frequency (*determined sound source)* and propagation speed *(determined by medium)*

Wavelength and frequency are **inversely related**
Wavelength **directly related** to propagation speed

Mediums with fast prop speed = longer wavelength
Mediums with slower prop speed = shorter wavelength
Propagation speed is NOT affected by either freq or wavelength

Think about the terms! Physics is very literal. If you do not know what something means, think about what it means in everyday language.
Example: frequency means how often something happens in a period of time. So in ultrasound, it means how many waves occur in one second

Different types of sound

- Infrasound < 20 Hz
- Audible sound 20-20,000 Hz
- Ultrasound >20,000 Hz
- Diagnostic US 2-20 MHz

Common unit prefixes

kila(k) = thousand
mega(M) = million
centi(c) = 1/100
milli(m) = 1/1,000
micro(***μ***) = 1/1,000,000

Simply exchange the word with the prefix
Example: 20,000 Hz = 20kHz

Ultrasound Physics Review

Measuring energy

Power- rate of flow of energy (Watts)

Intensity- power/area (Watts/cm^2)

Example: 40 Watt light bulb. That's power. Imagine the 40W bulb in a small closet vs it in a large room. Which appears more intense? The closet = smaller space = greater intensity. Increase the space = decreases the intensity

Amplitude- *height* of pressure wave (MPa megapascals). Hydrophone: used to measure the profile of US beam by measuring the pressure amplitudes (intensities)

These describe the strength of the energy. These are NOT related to frequency/wavelength/period.

Decibels

In US, we use deciBels to describe the relative intensity of our wave.
We only care about what happened to the intensity, not the value.
In other words, to describe HOW much our intensity has changed, we use deciBels.

When we multiply our intensity by 2 = rise of 3 dB (increase or gain)

If we half the intensity = loss of 3 dB (decrease or attenuation)

Half-value layer= when sound reaches 1/2 its original intensity = **-3dB**

Intensity	Decibels
1000	30
100	20
10	10
4	**6**
2	**3**
1	**0**
1/2	**-3**
1/4	**-6**
1/10	-10
1/100	-20
1/1000	-30

Q: A reduction of 6dB means the intensity is reduced by how much?
(we will see more about dB affects us when we look at attenuation)

A: Losing 6 dB corresponds to intensity reduced to 1/4. So if sound attenuated 6dB, that means it is now 25% what is was originally

Q: Adjusting overall gain from 25dB to 28dB will cause what affect to the intensity of the echoes?

A: There was an increase of 3dB which means the intensity was doubled.

Ultrasound Physics Review

Properties of the Medium

Propagation speed

Speed of sound in a medium. **Totally dependent on medium only.**

Before we discuss how sound interacts with the tissue, we have to first understand the properties of our tissue. So forget about sound for a moment.
Propagation speed is a property of the medium. It will only change if the medium changes.

In soft tissue ☞ 1.54 mm/μs or 1540 m/s ALWAYS

It is based on a mediums stiffness (how hard) and density (how packed together) Stiffness is same as BULK MODULUS. Each medium has its own propagation speed.

Elasticity and Compressibility

Opposite to stiffness!
Think of something elastic and compressible.
Ex- marshmallows are very compressible and NOT stiff.
So if elasticity increases > stiffness decreases

⬆ stiffness	⬆ prop speed
⬆ bulk modulus	⬆ prop speed
⬆ compressibility	⬇ prop speed
⬆ elasticity	⬇ prop speed

Propagation speed is NOT affected by frequency or wavelength

$$c = \sqrt{\frac{\text{stiffness}}{\text{density}}}$$

Based on the formula, technically density and prop speed are inversely related. But generally, mediums that are dense are also more stiff, that means prop speed increases.

Medium	Density	Prop Speed
Air	1.2	330
Fat	920	1450
Water	1000	1484
Liver	1060	1570
Muscle	1070	1580
Bone	1800	4080

Increasing propagation speed

Increasing density

Increasing wavelengths

Each medium also has its own **IMPEDANCE** value. To impede means to obstruct or hinder.

∴ Impedance is a measure of resistance (Rayls). It is a property of the medium, so …
It is only dependent on the medium.

Z = pc

Z = impedance
p = density
c = propagation speed

⬆density	⬆impedance
⬆prop speed	⬆impedance

Impedance is NOT affected by frequency or wavelength

Ultrasound Physics Review

HOW DOES THIS AFFECT US?

When sound encounters an interface (tissue change), 2 things can happen: some of the sound can be reflected (bounce back) and the rest continues traveling or is transmitted. There will only be a reflection if there is difference of impedance or impedance mismatch.

REFLECTION = IMPEDANCE MISMATCH

No mismatch (equal impedances) = **NO** reflection = **100% transmission**

Amount of reflection is proportional to the change in impedance levels.
Small change in impedance = small amount reflection
Greater the impedance mismatch, the greater the reflection.

Typical reflection coefficients in soft tissue imaging: < 0.1% and over 99% transmitted. That means the majority of the sound is transmitted with soft tissue imaging. And that's what we want! The more similar they are, the more will transmit

**** Soft tissue to air/lung interfaces = greatest energy reflection****

Think about what that means for you. What happens when you scan on bone or air? What do you see? Not much. Why? Think about how different bone and air are to soft tissue. Big difference in tissue means big impedance mismatch = big reflection and that means nothing left to transmit.

Attenuation

Weakening of sound. Depends on medium, different mediums will weaken the sound differently (as we learned with bone or air)
Average rate of attenuation in *soft tissue 1/2 dB/cm/MHz* (decibels=change in intensity)
Frequency and attenuation are **directly related**. Increase freq = increase attenuation

Attenuation coefficient

How much is the frequency going to attenuate per cm. Simply half the frequency!!

Example:
4 MHz will attenuate 2 dB/cm
8 MHz will attenuate 4 dB/cm
Double the frequency = Double attenuation

Frequency and Attenuation
Directly related

Inc Frequency = Inc attenuation = Less penetration
Dec frequency = Dec attenuation = More penetration

The more sound attenuates, the weaker it gets which means it will not be able to travel as deep

Apply to how you choose frequency. Imagine: You have a 4 MHz, 8 MHz, and 12 MHz to choose from. Do you always choose the highest one you have? No.
Why not? The 12 MHz cannot penetrate or travel as deep as the 4 MHz. All because of attenuation! We choose a frequency that is able to reach the depth we need.

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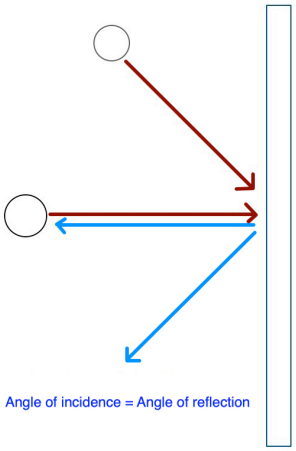
HOW DOES SOUND ATTENUATE?

Absorption: energy is lost as it is converted into heat.

Reflection: Main source of attenuation. When sound encounters tissues with different impedances. Some energy gets reflected back, some is transmitted. The following are different reflector types:

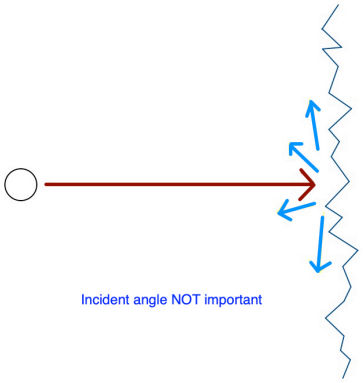
- Specular reflector: *large, smooth interface*
  Reflected back to us if 90 degrees incidence.
  *** Angle of incidence is important! It will determine *where* the reflection will go (not *if* it will occur)



Normal incidence
90°
Right angle
Perpendicular

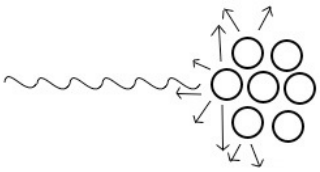
RESULTS : since 100% of reflections come back to transducer when at normal incidence, then boundaries on US appears strong, bright and clear.
(ie- diaphragm, large cyst, renal capsule, etc)

- Diffuse reflector: *large, rough interface.*
  Reflected in all directions, regardless of angle of incidence.
  Angle does not matter

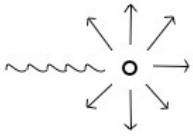


RESULTS : not all reflections return back to transducer, boundaries appear ill-defined, shadowy, and unclear

Scattering: *small interfaces*. Size is equal to one wavelength, reflections are scattered in all directions, creating softer reflections and appearance. Scattering is responsible for the appearance of organ parenchyma. (ie- liver, pancreas, placenta echo texture)



Rayleigh's scattering: when the interface is smaller than one wavelength, the scattered reflections are equal in all directions. (ie- red blood cells)



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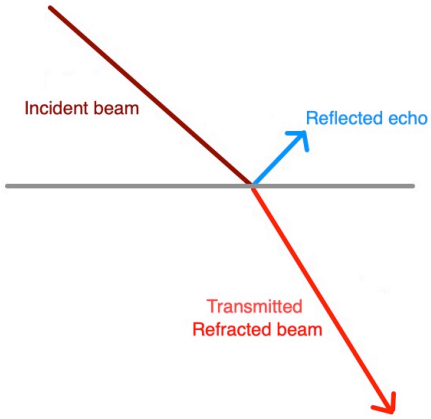
Refraction: when the sound beam changes direction or bends as it transmits from one medium to the next. *Change to the angle of transmission*

2 things are required

Oblique incidence

AND

Different propagation speeds



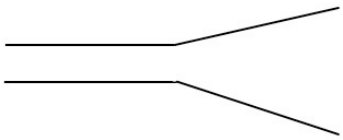
If normal incidence = NO refraction

If identical prop speeds = NO refraction

If NO refraction takes place = angle of transmission is equal to the angle of incidence

If there is an impedance mismatch, then reflection will also take place. But reflection and refraction are very different.
Snell's Law: relationship between the incident angle and refracted angle when the two mediums have different propagation speeds and oblique incidence
Critical angle: When the US beam is extremely oblique, C2 > C1, and the angle of refraction is parallel with medium ∴ NO transmission of sound

Divergence: same power spread over larger area (far field).
Intensity reduction.
Diffraction is a form of divergence and also reduces intensity



Identify the principle. When given a question regarding basic sound principles, first identify what it is asking. Is it about reflection? Transmission? Refraction? Once you know what key principles are involved in the question, then you'll be able to solve what will or will not happen.

Ultrasound Physics Review

Pulsed Ultrasound Parameters

Pulsed US generates pulses of 2-3 cycles only. Pulse echo principle = sends pulse then waits for echo. Uses listening time to know the location of the reflection

PRF: pulse repetition frequency = number pulses in 1s. *Depends on depth* since the machine must wait for the echo before it sends the next pulse (to avoid range ambiguity). The longer the distance the pulse must go, the longer it must wait means less pulses per second. If PRF is too high, machine will not know the location or depth. *Inversely related to depth*

⬆ Depth ⬇ PRF ⬇ Depth ⬆ PRF

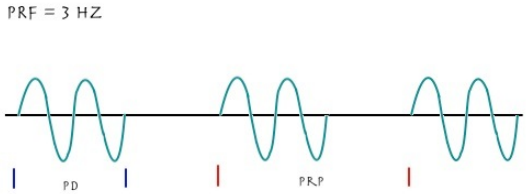
PRP: pulse repetition period = time between beginning of 1 pulse to beginning of the next pulse. Includes listening time or wait time. So *inversely related to PRF and directly related to depth*

⬆ PRF ⬇PRP ⬇ PRF ⬆PRP

SPL: spatial pulse length = length of one pulse. *Depends on frequency*

PD: pulse duration = time for one pulse to occur. *Depends on SPL*

In Diagnostic US- PRF is in kHz



Duty Factor

"on duty"

Fraction of time the machine is actively working and sending pulses. Only things that change the *time* the machine is pulsing will change DF

⬆ PRF ⬆ DF ⬆ PD ⬆ DF

⬆ PRP ⬇ DF ⬇ PRP ⬆ DF

⬆ depth ⬇ PRF ⬇ DF

DF of Pulsed US only 0.1-1.0%
Over 99% of time = listening

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RESOLUTION

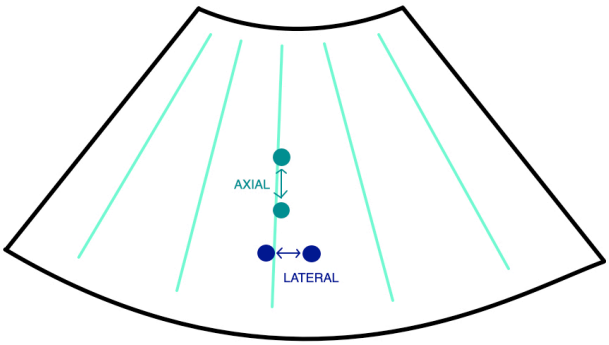
Resolution is the machine's ability to detect and display accurately.

2 main types of resolution: SPATIAL(space) and TEMPORAL(time)

Spatial resolution : the machine's ability to distinguish between 2 closely spaced objects and display them separately. The spatial resolution will be measured in space or distance (mm)

Axial and Lateral

Axial = vertical
Lateral = horizontal

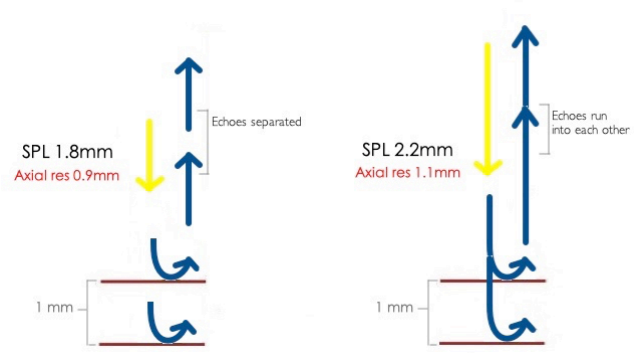


Axial = 1/2 SPL

2 vertical objects *parallel or along axis of pulse*

LARRD (longitudinal, axial, radial, range, depth)

Minimum distance 2 vertical objects must be separated by to be resolved = 1/2 SPL



In this example:

SPL of 1.8mm = Axial res of 0.9mm
The 2 objects are separated by 1mm. They are separated by the minimum distance = resolved!

SPL of 2.2mm = Axial res of 1.1mm
The same 2 objects no longer meet the requirements = blurred together vertically

Even though 2 echoes are produced, the echoes are blended because the pulse is longer

GOAL: shorten the pulse

- Increase frequency
  Decreases wavelength = decreases pulse
- Damping/backing material
  Reduces ringing of crystal = shortens the pulse
- Wide Bandwidth = shorter pulse (lo Q)

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Trade off

When you gain something by giving something else up. All resolutions have a trade off

Main way to improve axial = increase frequency. Do you always choose the highest frequency you have? NO. Because you will not be able to scan deeper

Now think about when you choose a lower frequency… what do you gain? imaging depth or penetration… what do you give up? axial resolution

Axial resolution for penetration

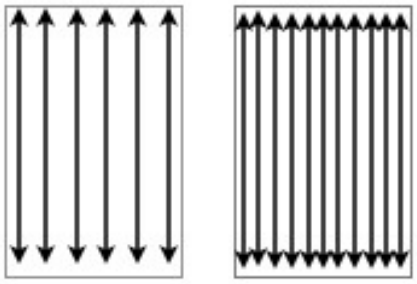
How to choose? The highest possible frequency with adequate penetration

Lateral = Beam width

2 horizontal objects *perpendicular* to beam

LATA (lateral, azimuthal, transverse, angular)

Two objects must be separated by a distance greater than the beam width



As long as the 2 objects are hit by their own beam, then they will produce separate echoes and then machine will display both of them. Not resolved = blurred horizontally

The smaller the cuts are through the tissue, the more likely they will be seen separately. Notice what happens when line density increases (increase the # of scan lines) = the beams are smaller. Closer lines = better lat res

GOAL: narrow the beam

- Focusing : Position and Number
  - At the area of interest (target within near field)
  - Multiple focal zones = overall beam narrowing
- # Scan lines / scan line density
  - Scan lines = beams. Increase line density = smaller beam size
- Sector angle
  - Decreasing sector size = increases line density
- Transducer choice
  - Sector FOV (field of view) = lower line density in far field, lat res worsens

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Temporal = Frame Rate

Determined by time it takes to make the frame (# frames per second)

Adequate FRAME RATE in order to visualize 2 separate events (frames) in time. Basically the machine needs to 'keep up' with whatever is going on in the body so that it can display the events accurately. If the frame rate is poor, the images appear to be blurred together giving a slow motion effect.

Frame rate is determined by the amount of work the machine has to do or time it needs to produce the frame. Anything that will add more work or more time = slower frame rate

GOAL: Faster frame rate

- PRF/depth
  - Higher PRF = faster FR. Decrease depth to increase PRF
- Reduce # transmit focal zones
  - Multiple pulses per scan line = more work
  - Reduce # focal zones to improve FR
- # Scan lines / scan line density
  - Scan lines = work. More scan lines = slower FR
  - Reduce scan lines/line density to improve FR.
- Sector angle
  - Decreasing sector size = reduces # lines and smaller frame
  - Less work = faster FR and better lat res

<u>Trade off</u>

Lateral resolution is improved by more information, more detail. Temporal resolution is worsened by more info, more detail. When we improve one, the other is degraded

Lateral resolution for temporal

How to choose? Optimize your lateral resolution without sacrificing the frame rate.

Some exams require faster frame rates.

Cardiac = highest frame rates since heart is constantly in motion. MSK and small parts usually have minimal motion = frame rate can be lower and lateral resolution optimal
** More motion involved, the faster the frame rate needs to be.

Ultrasound Physics Review

Transducers (16%)

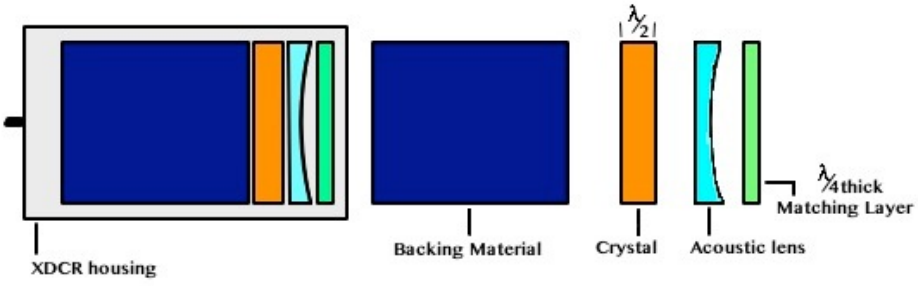
⇔ Act as both transmitter and receiver ⇔

Transducer element converts one form of energy into another electrical ⇄ mechanical

Piezoelectric **(literally pressure-electric)**

When electric voltage is applied, crystal vibrates (becomes mechanical) >> produces pressure
When pressure is put onto crystal >> crystal produces electricity (converts back to electric)

Crystal materials : PZT - lead zirconate titanate (man made ceramic crystal) or Quartz
Curie temperature/point: @ 400°C the point the crystal loses its piezoelectric properties

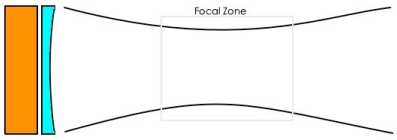


Operating frequency is determined by the <u>thickness</u> of the crystal (typically 0.2- 1.0mm)

Crystal thickness = 1/2 wavelength

Since wavelength and frequency are inverses, then crystal thickness and frequency are also inversely related
Thinner the crystal, higher the frequency

<u>Lens</u>
Mechanical means of focusing to reduce divergence.
Mechanical focus = lens, curved element, or mirrors
Fixed focal point with all mechanical ways to focus
(Fixed means we cannot control)



<u>Impedance Matching Layer</u>
A *layer* at the transducer face that *matches* the *impedances*. We need to "match" the two impedances so that most of the beam can be transmitted easily into the body. The Z value of the matching layer is halfway between the Z of the crystal and the Z of soft tissue.

Purpose of the matching layer is the same as the coupling medium or gel.
Aids transmission of sound into the body by reducing reflection.

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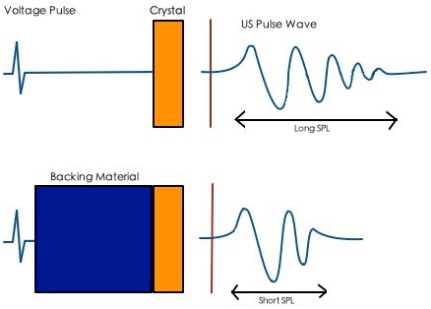
Backing/Damping material

When the crystal is hit with electricity it rings like a cymbal on a drum set. If nothing is done, the cymbal will ring on and on. The stop the ringing you can put your hand on the *back* of the cymbal. That is what *backing* does, it stops the ringing and shortening the pulse. We do not want long uncontrolled pulses.

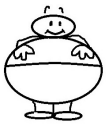


For Pulsed US : we want 2-3 cycles only

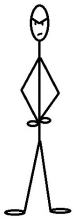
Backing and damping shortens the pulse

Bandwidth

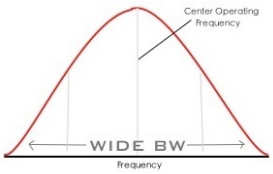
The range of frequencies.
The size of the pulse determines the bandwidth.

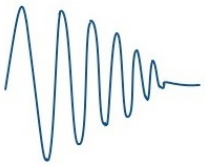


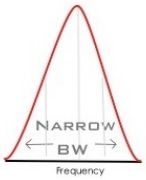
Short and Fat
Short pulse/wide BW



Tall and Skinny
Long pulse and narrow BW







* Center operating frequency = MAIN operating frequency

***Benefits of wide BW*- since larger BW means shorter pulses. Wide BW = better axial res**

Quality Factor or Q-Factor: quality of *frequency* of the transducer. Does NOT mean quality image!

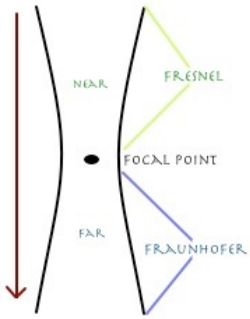
$$\text{Q-factor} = \frac{\text{resonant freq}}{\text{bandwidth}}$$

Bandwidth and Q factor are inversely related.
Narrow BW = Hi Q
Just main frequency= clean
Wide BW = Lo Q
Multiple frequencies and good axial res

Do we want Hi Q transducers?
Think about this. If we choose Hi Q : hi Q = narrow BW and that means longer pulses. Longer pulses have poor axial resolution. So we prefer Lo Q

Ultrasound Physics Review

Beam Characteristics



Fresnel Zone: Near field
The point from the transducer face to the point of divergence. If it is a focused transducer, then the beam is converging in the near field.

Fraunhofer Zone: Far field
Beam divergence.

Focal zone/point
The area the beam reaches its smallest diameter

What influences beam shape in single element transducers?

Crystal size or diameter Smaller diameter gives a narrower beam, but shortens the near field. Larger diameter = longer near field

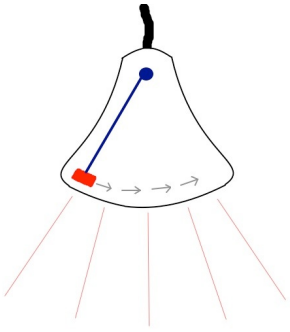
Frequency Increasing freq ⇒ lengthens the near field ∴ less divergence.

Both are directly related to the length of the near field (depth of focus)

Longer near field = larger diameter and higher frequency

Transducer Types

The whole idea of real-time imaging transducers is to send multiple cuts or scan lines through the medium in order to produce a frame. There are mechanical and electronic (array) transducers. All modern day transducers are arrays.



Mechanical: "moving parts". The piezoelectric crystal is mechanically moved from side to side, sending out scan lines across the face of the transducer. Since the whole transducer is mechanical, the focusing is only done mechanically (fixed focus).

Rotating or oscillating mechanical transducers produce a sector field of view (swinging or pendulum like motion)

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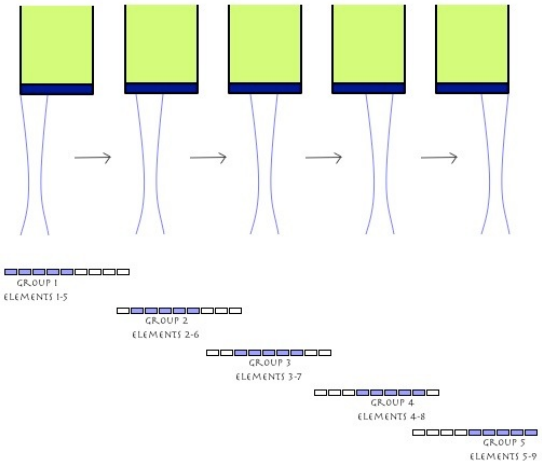
Array (electronic): Imagine the inside of a digital watch, no moving parts, computerized or programmed. The goal is the same as the mechanical, to fire off a sequence of scan lines across the transducer face. But the crystals do not move. Instead there are multiple of crystals lined up in a row: 128-256 crystals. These crystals are electronically fired or set off in a series individually or in groups across the face of the transducer in a sequential manner.

Beam Former sets the order and timing of the sequence



Notice in the diagram to the left. The elements are organized into sequential groups. Each group is one scan line/one beam. Together these elements in a group form the aperture.
Increase aperture = increase beam size

Huygens' Principle

Basically states that each wave produced by the elements will combine or link together to form a wavefront. The wavefront is a single beam of sound. This is what allows us to manipulate the beam shape electronically by focusing and/or steering.

Electronic Focusing and Steering

In addition to mechanical focus (lens), array transducers can also do electronic beam focusing. Some arrays can also do electronic steering. Both work by using ***time delays***. Since all the elements in a group will be linked together to become a wavefront, they affect each other. Just as a marching band can be guided in different shapes and directions by timing the actions of the people, the shape and direction of the beam can be manipulated by changing the timing or sequence of the elements. This is done by the beam former

Electronic Focusing
Time delays on the center elements >> shape of the beam becomes U shaped Beam converges or get smaller as it travels. Adjustable focal position
Focal depth/position determines timing. Change position = change timing
Multiple focal zones: One pulse is needed for each focal point. Mult focal points means we will need multiple pulses
(ie- **3** focal points = **3** pulses per scan line)

All **array transducers** can do dynamic / electronic / transmit focusing because they all have a series of elements.

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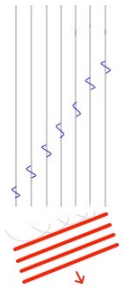


Electronic Steering / Phasing
Same principle as focusing except the *time delays* are now across the group of elements to guide it in that direction = phasing. The beam direction will go towards the side the delay is on.
Not all array transducers are capable of electronic steering.
ONLY PHASED ARRAYS

The beam goes in the direction of the delay.

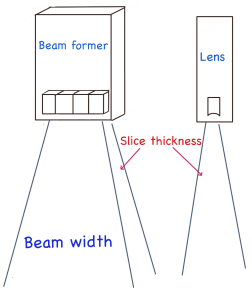
Focusing : delay in center, beam focuses towards the center

Steering : delay on side, beam steered to the side

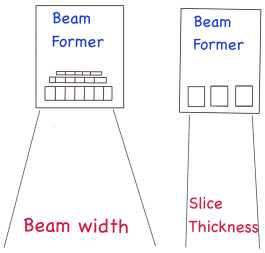
Slice thickness AKA elevational dimension

Thickness of the beam.
Beam is 3 dimensional. Like beam width, the narrower the better.

Like a sharp knife, a thin slice thickness is able to "slice" through tissue clearly, especially small echo free structures. When the elevational resolution is poor (thicker): unable to clearly display small cystic objects, blends surrounding echoes into structures.



1 row of elements **1D**
Typical array transducers have one row of elements.
One row = mechanical focus = fixed (curved element, lens, or mirror)
Unable to control elevational resolution



Multi rows **1.5D and 2D**
Transducers capable of 3D or 4D imaging, several rows of elements. Having multiple rows, dynamic elevation focusing is possible and better elevational resolution. 2D has more rows than 1.5D = better beam control, thinner slice, and better field of view. 2D can also do 3D/4D imaging.

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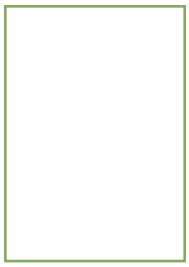
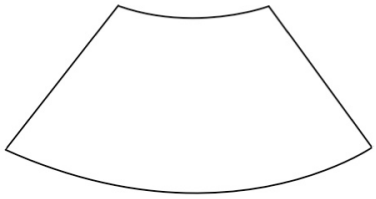
Linear : High frequency >7MHz Small parts, Vascular, MSK



Aka Linear sequential array. When scanning superficial structures that require high resolution imaging but do not require penetration. Higher frequencies provide improved axial resolution but reduced penetration. Line density is maintained in the far field. Rectangular display

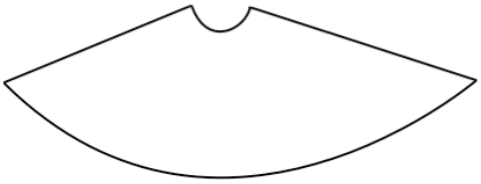
- Linear phased array
  Looks the same as linear probe. Capabilities of electronic beam steering (phased). Gives option of wider FOV as a trapezoid display.

Curvilinear : 2-6 MHz Abdomen, OB, Gyn, Pelvis

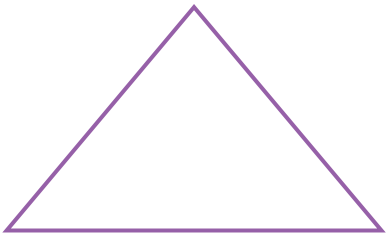


When exam requires larger FOV and penetration. Usually lower frequencies since large depth is normally required. Always choose the highest possible frequency but with adequate penetration.
Sector display (elements arranged in curve. *Does NOT steer*)

- Endocavity probes AKA tightly curved linear
  6-8 MHz (Transvaginal, Transrectal) Allows scanning closer to the area of interest, higher frequency transducer can be used, resulting in superior spatial resolution. Very low line density in far field. Lateral resolution degrades with depth.



Phased Array : 2.5-4 MHz Echo



Small footprint with wide FOV. Chosen for echo exams since views are obtained intercostally and heart is larger organ which requires wide FOV.
Pie shaped display (sector). Obtains FOV by phasing (steering)

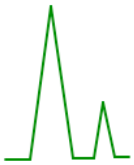
Annular array: no longer used but here's what you need to know:
Concentric rings of elements (target sign) produces a symmetrical beam shape (cone or cylinder). Very poor elevational resolution. Electronic focusing but mechanical beam steering. Sector FOV

Think about which transducer and frequency you choose for each exam type.
What? When? Why?
Example: Why would you choose a low frequency curved for an abdomen exam on a large patient? Why would you not choose a linear? How would you choose what frequency within the range?

Ultrasound Physics Review

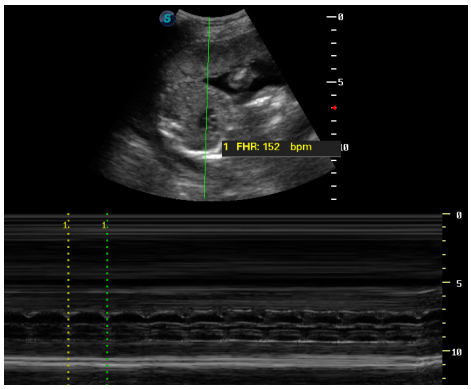
Imaging Principles and Instrumentation (28%)

Pulse echo principle: When a sound wave encounters an interface of 2 different impedance levels, part of the pulse is reflected and the rest is transmitted. The machine is able to *determine the distance* of the reflector based on the time the echo takes to return to the transducer. 1st use of pulse-echo principle was with SONAR (SOund NAvigation and Ranging) in WWI. 1st contact form of US- B scanner.



A-mode (*amplitude* mode)- Displays reflections as height of the spikes. Strong reflections (signal amplitudes) would be plotted as a tall peak, low intensity as smaller peaks, and no echoes as a flat line. Graph of received voltages representing the echoes and plots them according to their received time is plotted by oscilloscope.
Time corresponds to distance = distance measurements can be made.
No longer used on modern machines.

B-mode (*brightness* mode)- A-mode info converted into dots of varying brightness and displayed on video screen. The higher the amplitude, the brighter the dot. Tall spike = bright dot … Small spike = dark dot … Flat areas = echo-free. Uses pulse echo principle, distance can be measured.
Originally bi-stable (only black and white) now grey scale (shades of grey)



M-mode (*motion* mode)- Detects the location of all structures along a single scan line (line of sight) and displays it according to time. If location changes with time = MOTION. Displays stationary objects as well as moving objects. The purpose is to see the motion of the moving targets.
Distance can also be measured

Range Equation

Allows us to use the "time of flight" or round trip time to calculate the distance travelled.
Speed and time needed

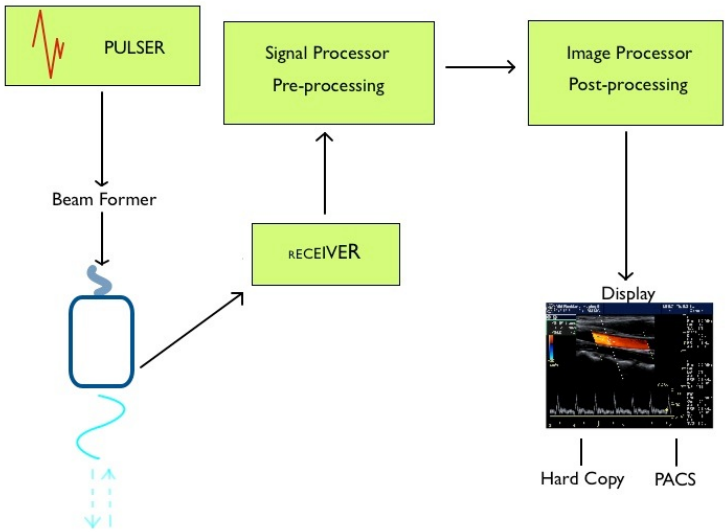
$$\text{Distance} = \frac{\text{RT time} \times \text{prop speed}}{2}$$

13 microsecond rule

For every 13μs of RT time = reflector is 1cm deeper

Ultrasound Physics Review

Pulse Echo Processing



PULSER controls the electric voltage that will be sent to transducer. *Power* and *Rate*

Power

Adjusting the **Output Power** will adjust the power of the voltages used. Increasing the strength of the voltages will in turn increase the intensity of transmitted US pulse. Result to image = increases overall intensity of the echoes (brighter image)

To increase brightness of image… do we always increase output power first? Why not?

Rate

Pulser also controls the rate that pulses are sent. Adjusted when tech changes imaging depth = changes PRF. In order the change PRF, rate of voltages must also be changed.

BEAM FORMER receives these pulses of voltage and programs order and timing of sequence. Controls beam shape, focusing and direction of beam (by time delays) Anything that changes shape of beam or scan lines will be accomplished using the beam former. Example: line density, sector angle, multiple focal zones, steering.

TRANSDUCER converts voltage into pressure. Sound transmitted into body, echo produced. Echo returns to transducer as a pressure wave. When hits crystal, pressure is converted back into electric signal. Sent to machine for processing!

What naturally occurs as sound travels through tissue? It attenuates. It loses energy. When the echo is produced, that echo (which is still a sound wave) now has to travel through the same tissue. Echo also attenuates. VERY WEAK!

Ultrasound Physics Review

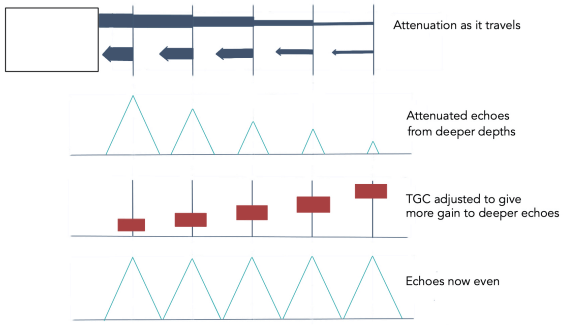
PRE-PROCESSING

RECEIVER receives the returning signals and knows that they have been weakened by attenuation and compensates by amplifying the received echoes.
Compensation, amplification, gain all refer to this same process

How do we control?

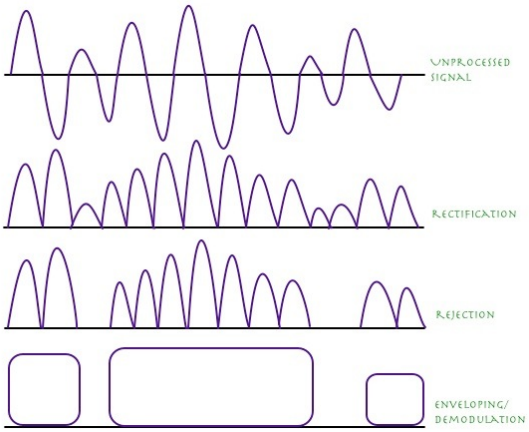
Overall gain- Increases overall brightness of ALL echoes (received signal amplitudes)

TGC (time gain compensation)- attenuation worsens with depth. TGC allows us to compensate for loss with increasing depth ⇉ RESULT: even brightness level across the screen



Q: How would your image appear if you had no TGC??
A: Brighter at top with gradual darkening down the screen.
Why? Because attenuation increases with depth

Remember decibels?? Let's bring it full circle.
Say your current gain setting is at 25 dB and you increase it to 28dB. What is the overall effect to the *intensity* of the echoes? Doubles (3dB gain = double intensity) pg 2
When you make that change, what does increasing the gain actually do? Only increases received info = nothing changes in the transmitted sound = SAFE!

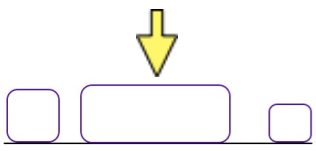


The SIGNAL PROCESSOR is going to clean up the signal and turn it into something machine can display. Like a processing plant, we start with raw material. Goal is to have a clean digital signal ready to be displayed

Rectification Turns all negative waves into positive. Not operator adjustable

Rejection Filters or eliminates noise or low level echoes. Operator adjustable

Enveloping/demodulation Turns signals into a "package" of a video signal. Not operator adjustable



Compression After enveloping, the signal is a value too large for the machine to display. Signal information is compressed into a value within the dynamic range and decreases difference between largest and smallest signals. Operator adjustable

Ultrasound Physics Review

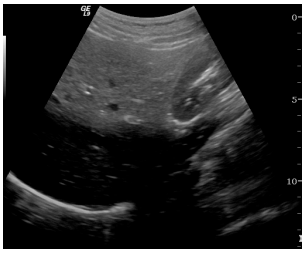
Dynamic Range

Number of shades of grey. Shades of grey represent the signal intensities. So dynamic range can also be defined as the minimum(black) to maximum(white) displayed intensities or the ratio of the smallest to the largest signal amplitudes.

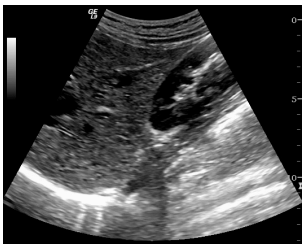
Decreasing DR = less shades of grey = higher contrast

Increasing DR = more shades = softer image/less contrast

Make it practical!
Imagine yourself in the following scenarios



Imaging the liver: Anteriorly appears normal echogenicity but distinct darkening in the far field. What should be adjusted? Gain or TGC? Why?



Entire image appears to be very black and white = high contrast. What do you change and how? Would overall gain help? Output power? Why not? Dynamic range?

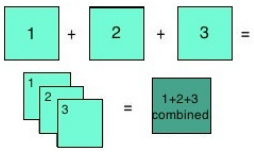
Contrast Resolution

The ability to distinguish similar structures with slightly varying grayscale.
GOAL: subtle changes in shades of gray, smoother imaging

Improved by Dynamic Range, Persistence, Compounding, Grey scale maps

<u>Additional pre-processing functions</u> (all of the following are operator adjustable)

Edge Enhancement: applies filters to emphasize changes in brightness in the area around the edge. Increases contrast at the boundary ∴ appears sharper



Persistence: Frame Averaging. Echo info is accumulated over a longer period of time and combined. Allows for subtle tissue texture differences. Improves *contrast resolution* but reduces frame rate. Should be turned off or low when need high frame rate.

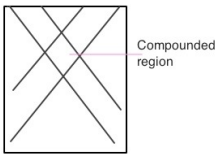
DOPPLER/COLOR: subtle doppler shifts enhanced. Inc to enhance slow flow

Ultrasound Physics Review

Image Compounding to enhance image quality

Frequency Compounding (common names: SRI, XRES, MView, SCI, SonoHD)
Speckle Reduction Imaging. Identifies strong and weak signals pixel by pixel. Eliminates the speckle leaving cleaner, smoother image. Improves contrast resolution

Spatial Compounding (SonoCT, CrossBeam, XView, SonoMB, CRI)



Scan lines are directed in multiple directions by phasing (beam steering). Views tissue from multiple angles, reducing artifacts such as shadowing and enhances edges. Improves contrast resolution
Reduces frame rate.
When imaging a structure that a shadow is expected such as a stone, spatial compounding must be turned off

Zoom: to magnify areas of interest and small structures. Write and Read zoom

- *Write* (real-time) is pre-processed. Improves image quality: resolution and line density. Best way to zoom.
- *Read* is post-processed. Can be done on frozen image. Only enlarges stored data/ larger pixel size. Image quality is degraded

Extended field of view
Enables a panoramic image by moving probe across the patient. Multiple image frames are captured and matched by location. (just like taking a panoramic with your iPhone). It's able to track probe motion and reconstructs the composite image. Allows for better visualization and measurement of larger structure that cannot fit in the traditional field of view

POST-PROCESSING

Image Processor takes the value of the signal and assigns it to a location (pixel=picture element) and displays it as a level of brightness at the correct depth and location. Grey scale maps are used to display levels of grey. Can be chosen by operator.

Image Memory/Scan converter stores the sequentially acquired and processed image frames. Rapidly sent to the display for real-time imaging.
> 30 FPS (frames per second) is optimal for real-time imaging. > 15 FPS to be flicker free.
Freeze image: 1 frame is frozen and displayed for permanent storage of still images.
Digital video clips of multiple frames can also be acquired and stored. Real time clips can be saved and stored. Used for dynamic studies such as echo.

CINELOOP Numerous frames are temporarily stored in image memory. On frozen image, you can "rewind" to find the desired frame and permanently store.

Ultrasound Physics Review

DISPLAY frames in memory sent to display

CRT Cathode Ray Tube Made of 525 horizontal scan lines. Signal must be converted back to ANALOG. (Digital to analog converter) Uses electron gun that shoots a stream of electrons to "paint" the image on the screen. When the electrons hit the phosphor coating on the inside screen, they glow

Modern day Digital scan converter. We use computer screens or flat screen monitors (LCD monitors). Digital is based on binary system.
8 bits = 1 byte = 1 pixel (grey scale image)

STORAGE

Hard copy: film, paper
Optical: CD, DVD, blue ray (greatest capacity)
Digital Storage: PACS network

PACS Picture Archiving and Communication Systems
Easy management of workflow. Physicians can almost instantly access exam images and documentation from remote locations. Not relying on hard copy = reduces loss of images and repeat exams. Study intergraded with all other associated data and images with report.

Format: DICOM (Digital Imaging and Communications in Medicine)
DICOM is the protocol standard for communicating imaging data between the US machine and workstations. PACS is the network and DICOM is how it communicates

Additional PACS components:

Query - search for pt on US machine

Worklist - allows you to select pt and will automatically populate pt info into US machine

QA workstation: ✓ pt info (tech to review)

⬇

ARCHIVES

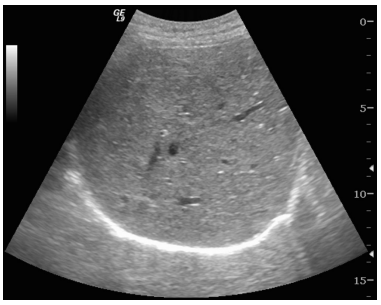
⬇

Reading workstation (Radiologist)

Ultrasound Physics Review

Console Settings and Image Optimization

This section is to help you be prepared for SIC questions on the ARDMS. It will also aid you in applying your knowledge to best optimize your images. The key is recognizing the problem and knowing how to use your controls to improve the situation. Remember only change 1 setting! To be safe, change them to the 'middle' option

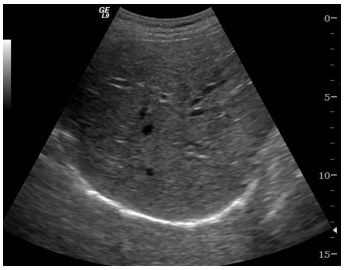


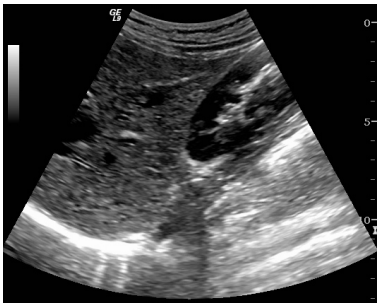
Problem: Entire image appears too bright.

Current control settings:

Output Power	50%
TGC	normal curve
GAIN	100%
Frequency	4MHz

Goal: darken the image (decrease the echoes)
Solution: Decrease the GAIN to 50%



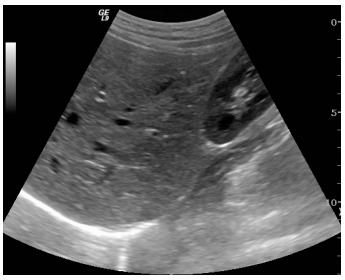


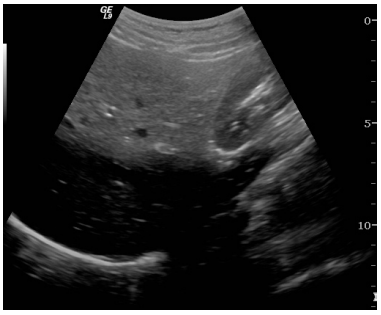
Problem : High contrast image

Current control settings:

GAIN	50%
Focus position	LOW
Dyn Range	40dB
Output Power	60%

Goal: Normal appearing liver texture
Solution: Softer grey-scale by increasing DYNAMIC RANGE to 60dB



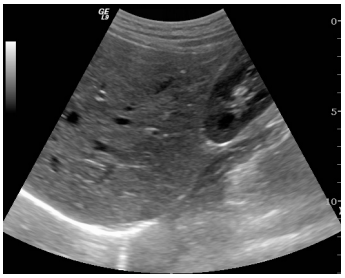


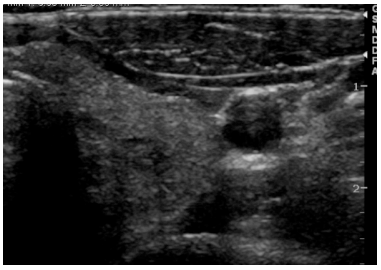
Problem : Uneven brightness level

Current control settings:

Dyn Range	70dB
Depth	14cm
Focal number	1
TGC	last 3 knobs to left (off)

Goal: Homogeneous texture
Solution: Adjust TGC to be even brightness

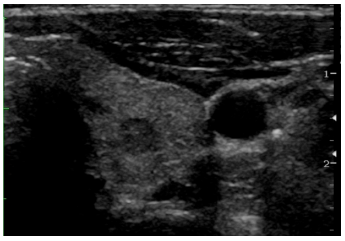




Problem : Poor lateral resolution

Gain	50%
Focal number	2
Focal position	High
Frequency	10MHz

Goal: Improved resolution
Solution: Lower the focal position to low or middle



Ultrasound Physics Review

Tissue Harmonic Imaging

Signal processing technique. Only changes how the machine will "listen" to the echoes.

What is a HARMONIC?

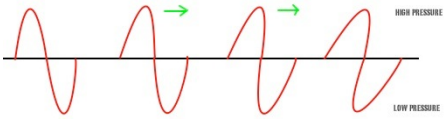
Basically, it is a multiple of the fundamental frequency (operating freq of transducer)
When echo is created, it vibrates at different frequencies in multiples of the original freq
Example: Transmitting at 4 MHz, results in echo freq of 4 MHz, 8 MHz, 12 MHz, and so on... 4 MHz would be the 1st harmonic, 8 MHz would be the 2nd harmonic, etc.

Harmonic Imaging uses the 2nd harmonic frequency for signal processing

By processing the 2nd harmonic, it allows the machine to be "picky" with the echoes it processes. For 2 reasons

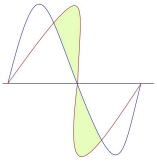
1. Only real reflectors vibrate at harmonics. Noise is easily ignored.
2. Most harmonics are produced in the center of the beam, where non-linear sound propagation occurs

Non-linear Sound Propagation



As an US pulse travels, it changes shape or distorts. Remember sound is a wave of high (peaks) and low (troughs) pressures. High pressure travels faster than low pressure. Pulse distortion occurs at the center of the beam where the signals are the strongest (smaller beam interrogation) > improved lateral resolution

All weaker signals are filtered. These new peaks are the basis for the processed image. Only the distorted harmonic signals remain.



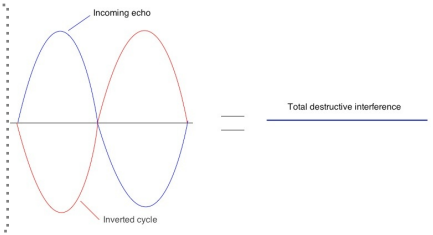
Filtering techniques must be used to get rid of the fundamental frequencies. In other words, all echoes received at operating frequency are thrown out

Pulse Inversion An inverted fundamental frequency is simultaneously applied to incoming frequencies. Any matching frequency would be out-of-phase and canceled out. This is called destructive interference

Interference principle

Constructive:
When the wave is in-phase, the peaks and troughs (compressions and rarefactions) are in line with each other. The 2 waves combine to form a new wave with higher intensity. Resulting wave is BIGGER

Destructive:
When the cycles are out of phase, the peaks line up with the troughs. They destructively cancel each other out (when perfectly out of phase)



Pulse Encoding Codes or marks the fundamental frequency. Anything coded will be filtered, anything uncoded will be processed
CODED EXCITATION (improves the signal to noise ratio)

RESULTS : less artifacts, less noise, crisper images,
improved lateral resolution

Ultrasound Physics Review

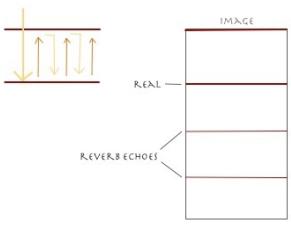
Pulse-echo Imaging Artifacts

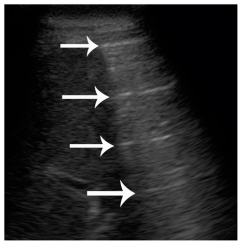
An artifact is anything that does not match with the actual tissue being scanned. Could be something that's not real, missing objects, or in the wrong location.

What you need to do …. *IDENTIFY*, know the *CAUSE*, and *HOW TO FIX* it if possible

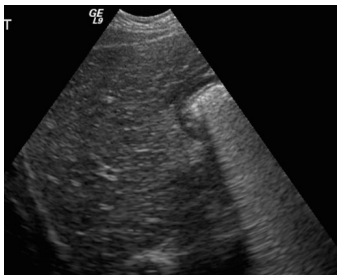
Reverberation

Multiple false echoes at regular intervals deep to a *highly reflecting objects*.
Cause = 2 interfaces with a high impedance mismatch.
Beam gets 'trapped' between the two causing several false reflections.
To reduce reverb: change scanning angle or transducer



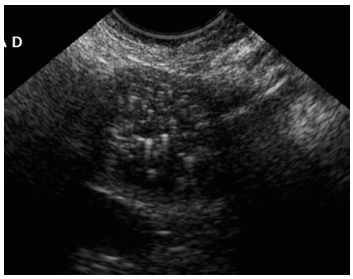


- RING DOWN and COMET TAIL are forms of reverb



Ring down
Several false echoes that just keep "ringing" down screen. Unable to count them

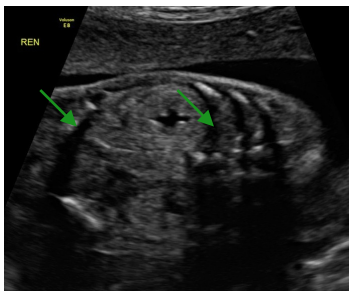
Caused by larger strong reflectors such as by the diaphragm or bowel gas



Comet tail
Multiple false echoes that gradually fizzle out.

Caused by small highly reflecting objects such as microcalcs and tiny air bubbles

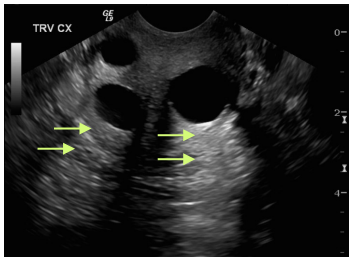
Posterior Shadowing



Severe attenuation of beam. Dark band posterior to highly reflecting object.
Large impedance mismatch = large reflection = little transmission.
Example: stones, ribs, bowel gas. Calcified material gives a clean shadow. Bowel gas gives a dirty shadow which appear hazy

Shadowing is a helpful tool since it tells us when we have a structure that is calcified.
To enhance the shadowing = *Increasing frequency increases shadowing* because it increases attenuation.
Spatial compounding removes/reduces

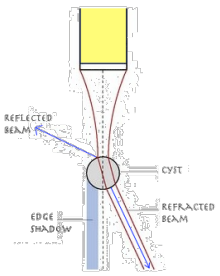
Posterior Enhancement

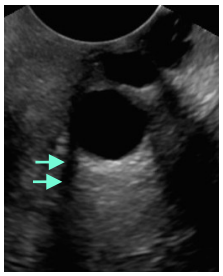


Opposite to shadowing. Caused by *lack of attenuation* and produces brighter echoes posterior to fluid filled object. The machine assumes attenuation is the same in all tissues. The echoes posterior to fluid-filled structure appear to have greater intensity. Beneficial for diagnosis to differentiate cyst vs solid.

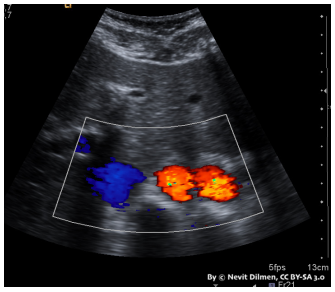
Ultrasound Physics Review

Edge shadowing
Dropout or shadowing at the lateral edges of a round structure. Caused by *refraction*. Curved surface at edge (oblique incidence) and different prop speed
NOT helpful artifact. Drop out limits imaging of borders
How to fix: change angle, spatial compounding

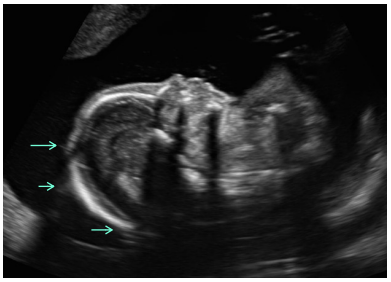




Double Image
Produces 2 of same object side by side. Caused by *refraction* usually through rectus abdominus muscles in transverse plane. Single structure is evaluated by 2 separate refracted beams. 2 separate sets of echoes returned to machine and displayed as 2. Most commonly seen ML TRV aorta. Aorta appears to be duplicated, 2 side by side.
How to fix: move the probe

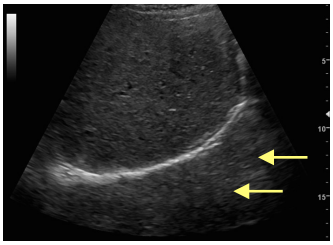


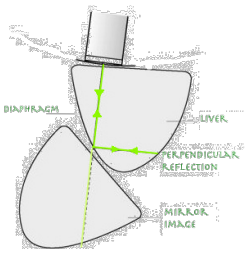
Beam Width Artifact
Cause: *Loss of lateral resolution* along the beam width. Echoes in a sense 'overlap' or as seen as horizontal echoes instead of dots. Lateral splaying of echoes may be noted. Often seen in the edges of an echo free area
How to Fix : Improve lateral resolution: Increase line density, decrease sector angle, check focal position, Harmonics ON



Slice Thickness Artifact
Beam's elevation dimension or slice thickness causes echoes to blend into smaller anechoic structures. Will show as low level echoes across the screen seen within normally echo free structure or echoes filling a small cystic structure. Easily seen when gains are too high
How to fix: lower gain, adjust TGC, Harmonics,

Mirror Image
Produces a mirror or copy of the real echoes posterior or deep to a curved *specular reflector.*
Commonly seen with the liver (diaphragm = round specular reflector)



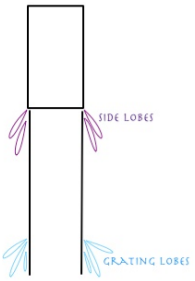


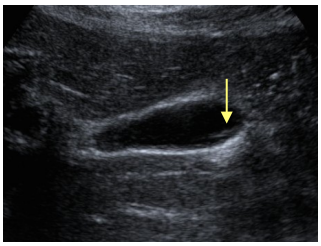
Part of beam is reflected perpendicularly at the interface, but not back towards the transducer. It is reflected again traveling along same path. Machine assumes all echoes come from straight beam. Reflected echoes are displayed in a straight line as if originating from main beam.
How to fix: Change scanning angle

Ultrasound Physics Review

Side Lobe/Grating lobe Artifact

Side lobes are small bits of sound energy that escape from the transducer face. Grating lobes are also escaping energy but they come from the beam itself. Each lobe is like a tiny US beam and has the same characteristics as the main beam. And can generate echoes just like the main beam. When they produce echoes, machine does not know they come from a side lobe and assumes all echoes come from main beam. Machine plots info according to depth along the main beam ∴ echoes will be misplaced on display.





Commonly seen as echoes/septation in cystic structures.
How to fix: Change angle of insonation. Spatial compounding, Harmonics

Apodization is the technique used to reduce side lobes by varying the voltages across the elements

Propagation Speed Errors

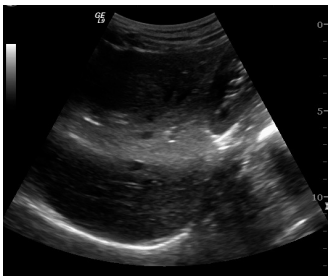
Echoes appearing at incorrect depths because the medium's propagation speeds is not 1540m/s. The range equation will not be calculated accurately = wrong depth location

Range Ambiguity Artifacts

Echoes placed at incorrect locations due to PRF being too high

Equipment Generated

Improper use of control settings such as gain/TGC
Overall gain too high results in amplifying noise and increase in artifact echoes.
TGC inappropriately set leads to vertical non-uniformity of echoes.
CHECK settings!



Why do we care?
They can tell us a lot about what we are looking at. Posterior shadowing and enhancement are diagnostic tools we use to confirm pathology. Know how use them to your benefit and you will improve the sensitivity of your exams
The others we need to be aware of to avoid pitfalls of misdiagnosis. For example, if you do not know about side lobes, you could image a cyst with an appearance of a septation instead of just a simple cyst. Know how to identify and avoid them

Ultrasound Physics Review

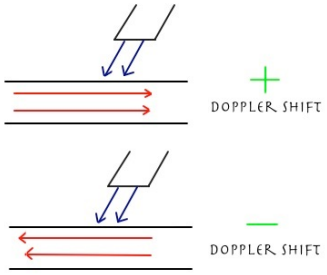
Doppler Instrumentation and Hemodynamics (31%)

The DOPPLER EFFECT

When there is a difference in motion between the sound source and the reflector, the echoes come back at a slightly different frequency than what was sent out.

If moving TOWARDS the sound source = Received frequency will be HIGHER
If moving AWAY from sound source = Received Frequency will be LOWER

The change in frequencies is called the Frequency Shift or Doppler Shift.
A shift is a *slight change,* the difference between the received and transmitted frequencies.
If the received freq is greater than the transmitted, it's a positive shift.
If the received freq is less than the transmitted, it's a negative shift



- Based on +/- and magnitudes we can determine:
  Presence of flow, direction, and velocity

Presence: If there *is* a shift, there *is* flow

Direction: If it's **+** or **-**, we will know if it's moving away or towards us

Velocity: The magnitude of shift helps to determine velocity

Critical thinking…
Two doppler shifts are received. Vessel A is +3kHz and vessel B is -4kHz. Which vessel has the higher velocity? Hint: what does the + or - tell us about the signal?

THE DOPPLER EQUATION

$$\text{DOPPLER SHIFT} = \frac{2 \times \text{FREQ} \times V \times \cos\theta}{C}$$

3 things will affect the Doppler shift:

Velocity	Directly related. Inc velocity = inc shift / Slow velocity = small shift
Frequency	Directly related. Inc freq = inc shift / Dec freq = dec shift
Angle	Inversely related. 0 degrees is the greatest shift. 90 degrees = NO shift Increasing doppler angle = closer to 90° = decreasing shift Decreasing doppler angle = closer to 0° (same as 180°) = increasing shift

Know these relationships!

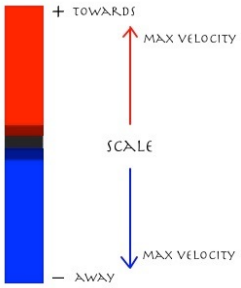
Ultrasound Physics Review

Color Doppler Imaging

Doppler shift info colorized and superimposed or 'pasted' onto B-Mode image (duplex). The color box is made up hundreds of scan lines. Each scan line is divided into sample volumes. In order to be sensitive to moving blood, multiple pulses are needed.

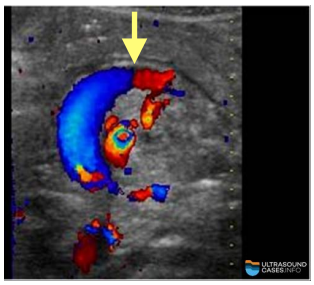
PACKET SIZE or ENSEMBLE LENGTH = number of pulses per scan line (8-10 typical)
Increasing packet size will enhance quality and sensitivity but reduces frame rate.

Doppler shifts are received from sample volumes.
PHASE QUADRATURE DETECTION determines direction by detecting positive or negative.
AUTOCORRELATION assigns a color for direction (ie- red for positive, blue for negative) depending on color map chosen. Then assigns a shade or hue of that color to represent avg velocity.



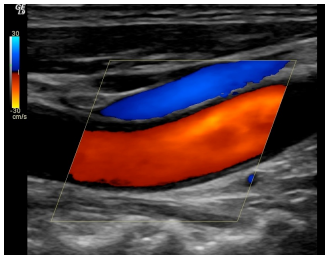
Our color scale display shows us what color is assigned for positive and for negative. The color on top is always positive.
Scale also represents our PRF (displayed doppler shift freq) and the range it's able to detect (maximum velocity)

The scale should be set to the type of flow you are evaluating in order to be displayed accurately
Slow flow = Low scale Fast flow = High scale



This images shows well how the difference in brightness and color are affected by angle. Closer to parallel = higher doppler shift and therefore, brighter color. Perpendicular (as shown by arrow) = NO doppler shift and so black. Any vessel that loops or curves will show both red and blue as part of the flow moves towards the transducer and then away as it loops around.

How to correctly use Color Doppler
Steer the box in the direction of the vessel angle. Color box angle should be steered so that the scan lines are closer to parallel to the flow. The closer it is to perpendicular means lower doppler shift or no shift. The size of the box should just cover area of interest. Adjust the scale to fit the type of flow you are evaluating. Adjust color gain so color fills in vessel but does not 'bleed' out of the vessel walls.



What is the direction of flow of the vessel in red?

First, notice the scale. What is red? Negative or positive? Away or towards?
It is negative, so away. Box is steered to left, so flow is going away from us (downhill) to the LEFT. The negative color is always going towards the side the box is steered. The positive color is the opposite.

Ultrasound Physics Review

Pulsed Doppler

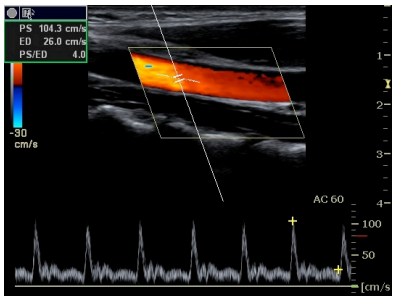
Applies same principles as color except now evaluate flow over one small area called our sample volume or range gating. PW pulses have more cycles per pulse than B-Mode imaging. Normally 6-10 cycles. Triplex when using all 3 modes
Benefits: We decide position (where to sample) and size (how much to sample).
Information will be specific and velocities can be measured

Processing of doppler shift into spectral waveform:

SPECTRAL ANALYSIS which breaks down the signal into separate components according to velocity(magnitude of shift) and time(location).
Wall filters and *High Pass filters* are used to cut out low frequency noise/clutter. Removes LOW FREQUENCY/HIGH AMPLITUDE. Reduces the display of low frequency shifts whether it is real or not. Increasing the filter will get rid of more. If the filter is too high, it will get rid of low velocity flow that is real.

Imagine the flow you are looking at produces a low frequency shift of 300 Hz and the Wall Filter is set at 350 Hz. It will erase all information 350 and lower including the real flow. Fix? Decrease the wall filter

Fast Fourier Transform displays the processed data as velocity vs time at a rate of 100-200 lines of data/second.

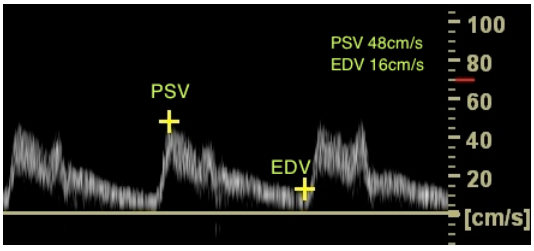


How to correctly use PW doppler
Sample at center of flow/vessel with sample angle steered in direction of vessel and parallel to vessel walls. Since most vessels run perpendicular to transducer, ideal angles are 45-60 degrees. If the angle is not estimated correctly, velocity measurement will be inaccurate. Sample gate should be approximately 1/3 the size of the vessel

Benefits	*Limitations*
More specific evaluation of sampling	Subject to aliasing
Detailed velocity info	Angle dependent
Calculations of velocity and other measurements	Only samples where tech places gate

Basic measurements
Peak Systolic Velocity (PSV) and End Diastolic Velocity (EDV) can be measured as shown in the waveform

Using these measurements, Resistance Index (RI) and Pulsatility Index (PI) can also be calculated



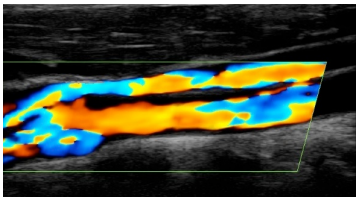
Ultrasound Physics Review

NYQUIST LIMIT = 1/2 PRF

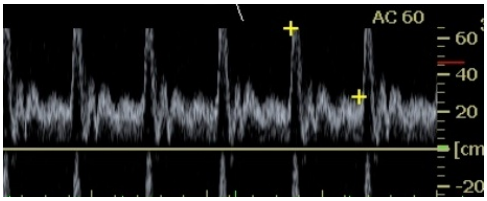
ALIASING occurs when the doppler shift EXCEEDS the Nyquist Limit.

When the frequency shift is greater than 1/2 the PRF, aliasing will occur.

The aliased color pattern is mosaic and appears to be turbulent. The color overflows into the other color on the scale. Reds turn to orange to yellow to white to light blue



The aliased spectral waveform appears to wrap around the baseline. The peaks are cut off and appear on the other side



How to eliminate aliasing

The problem simply is that the shift is to big for the scale. So *increase the scale (or PRF)*
If you can increase the scale, the shift will no longer exceed it.
With spectral waveform, you can also *lower the baseline* to help 'unwrap' the waveform
What if you cannot do either?
The other option you have is the decrease the shift. The Doppler equation. Frequency and angle affect the doppler shift (pg 27)
Decrease frequency will decrease the shift.
Increasing doppler angle will decrease the shift

Eliminating aliasing
- Increase scale/PRF
- Lower baseline
- Decrease frequency
- Increase Doppler angle

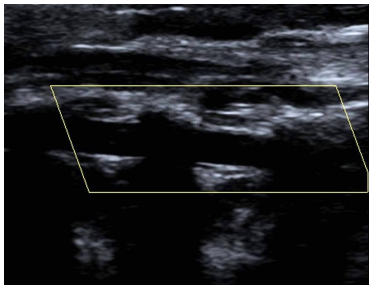
Q: What would be the effect to aliasing if the Doppler angle was reduced or frequency was increased?

A:There would be more aliasing. Decreasing angle or increasing freq = increased doppler shift

Sensitivity to SLOW flow

Now we have the opposite problem. Low velocity flow will produce a small doppler shift.
The opposite to aliasing.
Simply the problem is the shift is too small to see.

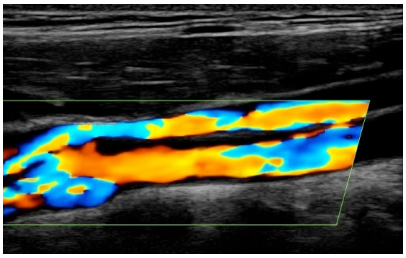
- Decrease the *scale* so the machine looks for lower velocity flow
- Decrease *Wall filter* to allow the display of low frequency shifts
- Increase the shift by increasing *frequency*
- Decreasing doppler *angle* by steering color box or rocking probe
- Increase color *gain* to strengthen the returning Doppler shift
- *Persistence*: Increasing will accumulate multiple color frames
- Increase packet size



Ultrasound Physics Review

Console Settings and Image Optimization
Color and Doppler Images

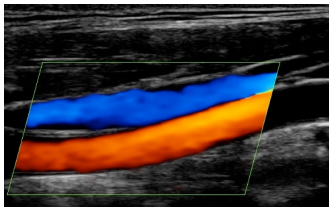
The key to optimizing your images is recognizing the problem and knowing how to use your controls to improve the situation

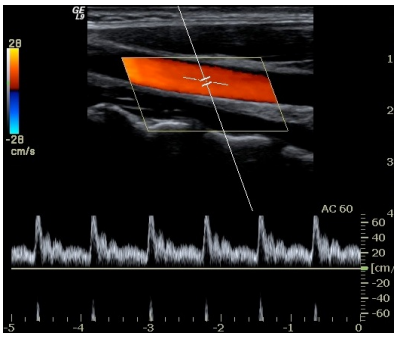


Problem: Color aliasing
Current control settings:

Color Gain	50%
Scale/PRF	30/-30
Color box angle	LEFT

Goal: Accurately display the normal color flow
Solution: Increase the SCALE

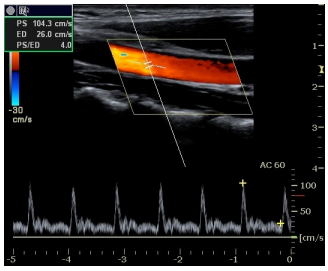


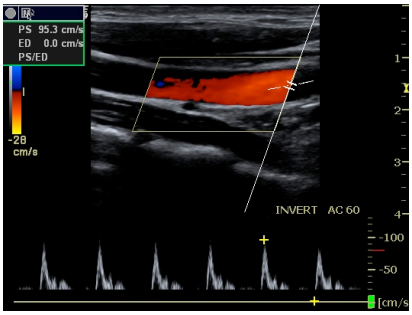


Problem : Aliasing of spectral waveform
Current control settings:

Doppler gain	50%
Scale/PRF	60/-60
Baseline	Center
Doppler angle	60 degrees

Goal: Eliminate artifact, visualize entire waveform
Solution: Adjust baseline to LOW

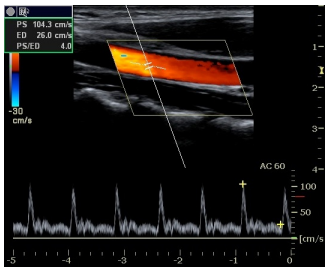


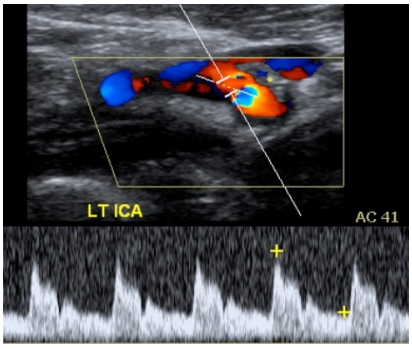


Problem : Disappearance of diastolic flow
Current control settings:

Baseline	Low
Scale	140/-20
Doppler gain	50%
Wall Filter	750 Hz

Goal: Visualize entire waveform
Solution: Decrease the wall filter to 250Hz

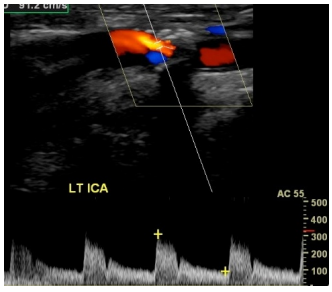




Problem : Spectral box is filled with echoes
Current control settings:

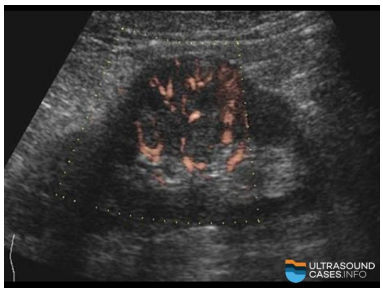
Doppler gain	80%
Wall Filter	250 Hz
Frequency	9 MHz
Sample size	2mm

Goal: Accurately display waveform
Solution: Decrease doppler gain to 50%



Ultrasound Physics Review

Additional Doppler Modes



Power Doppler

AKA energy doppler, amplitude doppler

Only one color, usually yellow or orange.
** Maps magnitude/power/amplitude of doppler signal (not velocities) Only detects and displays the presence of flow. NO direction or velocity info. NO aliasing
Benefit: Very sensitive to slow flow

Continuous Wave Doppler (non-imaging)

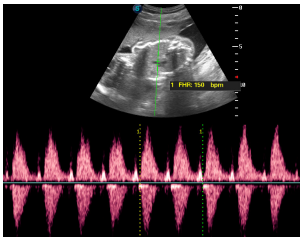
Requires 2 separate crystals side by side: 1 transmitting & 1 receiving
NO PULSES = NO PRF = No Nyquist Limit ∴ no limit of max velocities ∴ no aliasing

Only used as flow detector or to measure severely elevated velocities.
Range ambiguous: unable to determine depth or location. *Cannot choose a location*. Will sample ALL vessels in its path.

Doppler Artifacts

Aliasing of color and PW
Problem: Color appears to be turbulent mimicking disease. PW waveforms are cut off not allowing the peak velocities to be measured.
Cause: Doppler shift exceeds Nyquist limit or scale
Solution: Increase scale/PRF, adjust baseline, decrease frequency, increase angle

Doppler Mirror aka Ghosting
Problem: Spectral mirror or crosstalk produces exact copy of waveform appears below the baseline. Flow appears reversed. Color mirror will show color copy below real flow.
Cause: When gain is too high, presence strongly reflecting objects, or angle is close to 90
Solution: Decrease doppler gain or decrease angle



Flash
Cause: Large movements or respirations, cause flash of color to fill box. Sometimes occurs when settings are too sensitive
Solution: Reduce motion if possible. Reduce gain, increase scale

Ultrasound Physics Review

Hemodynamics

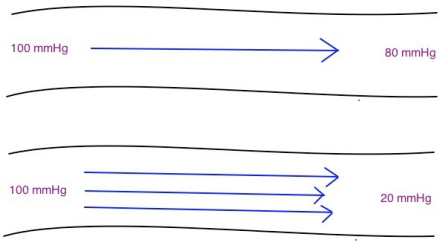
The study of blood moving through the circulatory system

Blood flow depends on 2 main things:
Pressure gradient and Resistance

$$\text{Flow rate} = \frac{\text{pressure gradient}}{\text{resistance}}$$

Greater pressure gradient "push" = more flow (directly related)

Increased resistance = less flow (inversely related)



Pressure gradient The driving force behind flow

Pressure gradient = difference in pressure from high to low

Greater the gradient = =greater amount of flow

Arterial flow is *pulsatile* because it is driven by the pressure gradient from cardiac cycle.

Systole LV contracts (hi pressure) creating pressure energy that pushes blood into aorta (low pressure)
Diastole Heart relaxes. Blood continues to flow through arterial tree because it is already in motion (kinetic energy). How much flow will continue during diastole will depend on resistance

Venous flow is *phasic* because it is moved by respiration. This means that flow comes and goes depending on the phases of respiration.
Inhalation increases abdominal pressure and lowers chest pressure. Hi abdominal pressure stops legs from flowing. Low chest pressure allows arms to flow
Exhalation reduces abdominal pressure allowing lower extremities to flow up and increases thoracic pressure so arm flow stops
Valsalva maneuver stops ALL venous flow because it increases chest and abd pressures

Hydrostatic (gravitational) energy: weight of column of blood (pull of gravity)

Supine: all same level as heart = *0mmHg at ankle*
Standing: increases to *100mmHg at ankle*
Hand raised above head: negative gravity = *-50mmHg*

Resistance

Increased resistance will decrease flow
Resistance is determined by

Vessel size length and diameter/radius
Thickness of blood (viscosity)
Outside forces upon vessel (elasticity of walls)

Biggest effects to resistance occur when there is a change of vessel diameter or radius

Ultrasound Physics Review

Poiseuille's Law = relationship of *resistance, pressure gradient* and *volume flow (flow rate)*

$$Q = \frac{\Delta P \pi r^4}{8 \eta l}$$

Q = volume flow
ΔP = pressure gradient
r = radius
η = viscosity
l = length

Increase pressure gradient = Increase volume flow

Increase resistance = Decrease volume flow

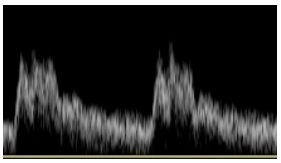
Decreasing diameter would increase resistance and decrease flow

Flow volume directly proportional to diameter. Notice how radius is to the 4th power.
That means small changes in radius result in big changes to flow.
Decreased radius = increased resistance = decreased volume
Flow is inversely related to length and viscosity

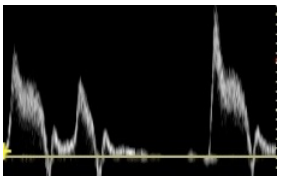
Resistance and US

Resistance is determined by *where the flow is traveling to*. The body regulates flow by changing the resistance of the arterioles. If an organ needs constant forward flow, it will have a vaso-dilated vascular bed. That means the arterioles are bigger. Bigger means lower resistance. If a body part does not require constant perfusion, then its vascular bed will be vaso-constricted. That means smaller and smaller means higher resistance.
We can tell resistance by how much diastolic flow there is.
Hi resistance = little or no diastolic flow. Possibly even flow reversal
Lo resistance = more diastolic flow. Constant forward flow

Examples:
ICA feeds the brain. Brain needs constant flow. It's arterioles are dilated (bigger) to reduce resistance. Notice waveform from the ICA. Lots of diastolic forward flow= Low resistance



ECA feeds the face and neck. Does not require constant flow. It has a constricted (smaller) vascular bed. Waveform has very little if any diastolic flow = High resistance



In the case of obstruction

Arterial flow volume comes from cardiac output (how much heart pumps) so it cannot change. We can't tell the blood to slow down or stop when we have obstruction

$V = \frac{Q}{A}$

This is described by the Law of Conservation of Mass

When vessel size decreases and volume is constant = Velocity must increase

Hi Velocity = Low Pressure
Decrease velocity = Pressure increases

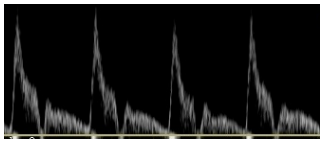
Ultrasound Physics Review

Bernoulli Effect describes the relationship of pressure and velocity at the location of a change in vessel radius or diameter. Pressure and velocity are inversely related.

Example:When there is a decrease in radius (stenosis), the velocity increases and so pressure (at the stenosis) decreases

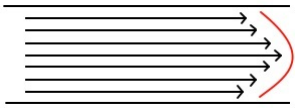
Types of blood flow

Laminar
Normal flow that moves in concentric streamlines or layers. Organized. We can see laminar flow by the quality of the spectral waveform.

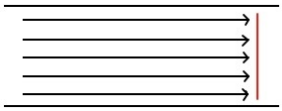


The flow in this waveform is laminar because it has a **spectral window**. The PW is sampling one, neat layer which moves at its own speed. So the waveform displays a neat, organized flow pattern

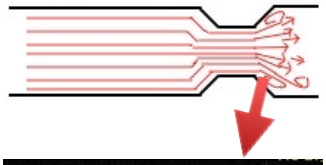
Parabolic: most common type of flow. Highest velocities found in the center of vessel and lowest next to wall. Parabolic shaped flow

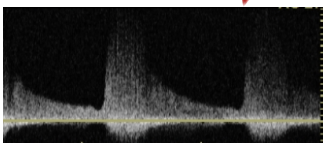


Plug: Found at origin of vessels. All layers move at the same velocity



Turbulent
Abnormal, disorganized flow. Flow patterns become disturbed and form eddies or swirling patterns. Occurs when we have a sudden change in resistance and elevated velocities. Often seen distal to stenosis or tortuous vessels. Loss of spectral window





Reynold's #
Predicts when flow becomes disorganized or turbulent

CRITICAL VALUE = >2000

The 2 main factors are radius and velocity.
Both are directly related to Reynold's#

$$R\# = 2rV\frac{p}{n}$$

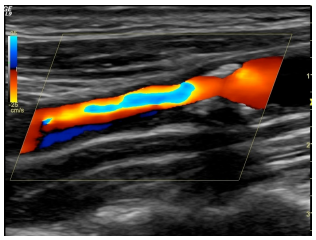
r = radius
V= velocity
p = blood density
n = blood viscosity

The larger the vessel and higher the velocity will increase the Reynold's # and more likely there will be turbulent flow… "post-stenotic" turbulence

Ultrasound Physics Review

Ultrasound and Hemodynamics

In cases of stenosis, increased velocities will appear as aliasing since they will exceed the PRF settings for the normal vessel.

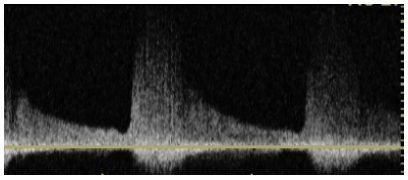


In color, we will see aliasing (mosaic) at the location of stenosis and post-stenotic turbulence. In this case, aliasing can be used diagnostically to locate turbulent patterns.

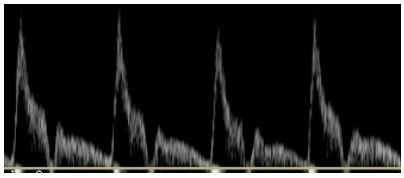
In PW spectral analysis, we will find elevated velocities. (Now is the time to increase PRF in order to accurately display and measure peak systolic velocities.)

Since all our layers are squeezed into reduced space, sample volume will pick up multiple velocities at once. The spectral waveform will lose its clean spectral window and will fill in with echoes. It broadens. Notice the difference between laminar and turbulent flow

Spectral broadening = turbulent flow

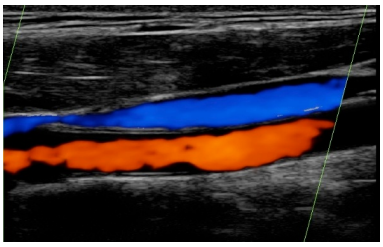


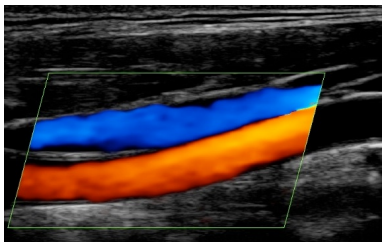
Spectral window = laminar flow

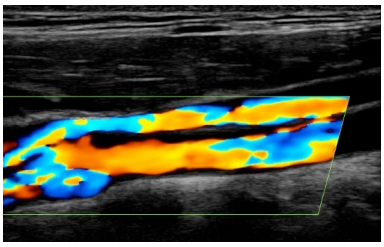


Warning Your settings can either hide or create disease

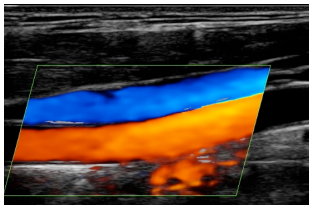
Color Scale
In a normal vessel, if the scale is too low, it will appear as aliased. Aliasing appears to be turbulent flow. Increase the scale to demonstrate normal flow in a normal vessel.
When there is a stenosis, you want to show the turbulent flow. In this case, do not increase the scale so much that it appears normal.







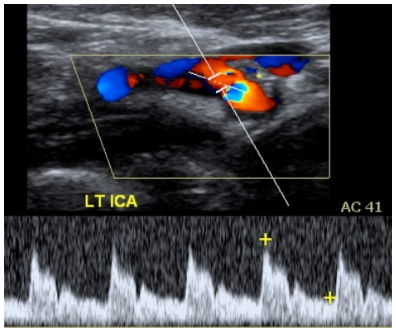
Color gain
Gain too high will make color 'bleed' out of vessel and can underestimate disease.
Gain too low makes the vessel not filled in as if there is disease



Ultrasound Physics Review

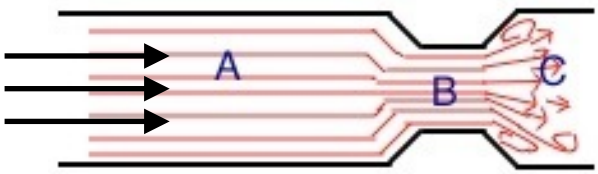
Doppler sample gate
The PW gate should be kept at approximately 1/3 the vessel size. If the gate is too large for the vessel, the waveform will have spectral broadening even if the flow is really laminar. This will happens because a large gate will sample all of the shifts that occur in the vessel. It will display all of these shifts 'filling' in the waveform.

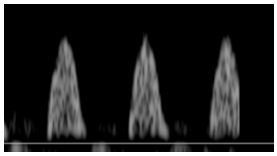
In this example, the gate is too large and the doppler gain is too high
Waveform appears to have spectral broadening. Doppler gate should be made smaller and doppler gain should be decreased



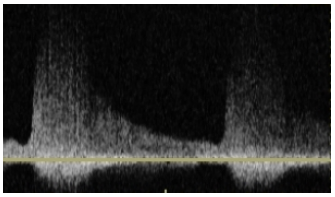
Stenosis profile

How stenosis affects blood flow. You can apply Pouseuille's Law, Bernoulli Effect, and Reynold's number to understand the hemodynamics of a stenosis

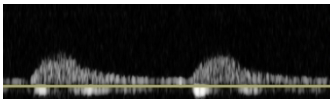




A.**Proximal to stenosis**. Decrease in diameter upstream = increase in resistance. Hi resistance waveform (less diastolic) is noted



B. **At the stenosis.** Elevated PSV and EDV through the narrowed section. Velocity must increase when area decreases to maintain volume flow. Bernoulli effect says that lowest pressure is found here



C.**Distal to stenosis.** Turbulent flow patterns. According to Reynold's number, the larger radius with the elevated velocities will increase the likelihood of turbulent flow patterns. We call this region 'post-stenotic turbulence'. Lo resistance waveforms since vessel widened. Flow may also be dampened distal to severe disease

Ultrasound Physics Review

Clinical Safety 10%

ALARA As Low As Reasonably Achievable
We keep power settings and acoustic exposure to a minimum to reduce risk of bioeffects

Possible Bioeffect Indices : *measures risk or likelihood*. NOT if it's actually happening

Mechanical AKA cavitation

Change in pressure due to sound wave microbubbles form, grow, and can collapse causing damage to cells. During rarefaction: expansion phase where bubbles are likely to form

Mechanical Index (MI)
Measure of likelihood of cavitation

Thermal

Tissue heating when sound is absorbed. Absorption converts pressure into heat causing rise in tissue temperatures

Thermal Index (TI)
Risk of tissue heating indicated by TI
TI of 1 = rise of 1°C

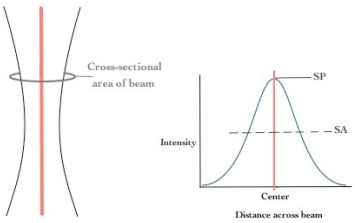
Maximum allowable intensities

Unfocused 100 mWatts/cm²
Focused 1 Watt/cm²

Intensities are measured based on machine settings

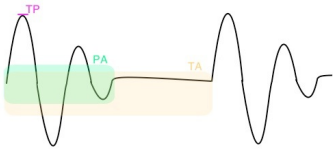
Spatial intensities. Intensity is power/area so intensity will vary depending on size of beam and location within the beam.

Spatial Peak	**SP**	Center of the beam
Spatial Average	**SA**	Average intensities across the beam



Temporal intensities. We use pulsed US, so intensity changes with time.

Temporal Peak	**TP**	Highest intensity found at peak of the pulse
Pulse Average	**PA**	Average intensity over the pulse itself
Temporal Avg	**TA**	Average intensity over the whole time (including listening time)



Combined intensity measurements
Highest to Lowest

SPTP
SATP
SPPA
SAPA
SPTA
SATA

To calculate MI and TI, machine uses these intensities based on current power and control settings

SPTA is used to calculate TI SPPA is used to calculate MI

What control settings that you control would also change the risk of bioeffects?
Think about if the following settings would change MI or TI and how

Output power Depth Multiple focal zones Gain Doppler modes

Ultrasound Physics Review

Safe environment for you and patient

Preventative maintenance is part of clinical safety. Like routine check ups and cleaning on car (oil change, check tires, etc) are important for safe driving.
Preventive maintenance includes keeping machine and XDCR's clean, cleaning air filters, keeping XDCR cords from being tangled or run over. Check control panel and inspect probes for wear.

Protect patient
Cleaning and disinfecting probes with approved disinfectants. Probes *cannot* be sterilized since that requires extreme heat and will damage crystal. Disinfect with solution containing Gluteraldehyde (ex- Cidex or T-spray). When contact with bodily fluids: 1st rinsed, then soaked 15min. NO bleach, needs to be approved disinfectant or hydrogen peroxide
Universal precautions include hand washing between patients, changing gloves. Masks and gowns when necessary

"Time-Out" take time to make sure you have the correct patient and correct exam before beginning exam

Sterile Technique
Touch only the outside wrapper, not the sterile supplies with ungloved hands.
Do not to reach over the sterile supplies when doing the procedure
Unfold the sterile paper wrapper of the kit or tray. Always open the flap away from you. If you need to add sterile dressings or other items to your tray, open the package. Holding the outside of package, drop the item so it lands near the center of your tray. Throw the outer wrapper away. When something non-sterile comes in contact with sterile tray, all becomes non-sterile.

Protect yourself

Use ergonomic techniques while scanning to prevent injury and muscle strain.
Basic rules of ergonomics:

Shoulder abduction <30 degrees

Wrist 20 degrees most extended angle and <40 deg for max flexion

Try to use a palmar grip for the majority of each exam. Allows for neutral wrist position

Adjust the height of your exam table and your chair. Avoid twisting or bending

Get closer to your patient

Position monitor in front of you at eye level

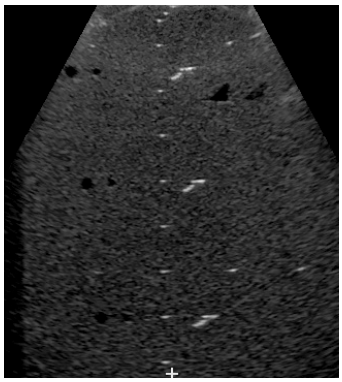
Ultrasound Physics Review

Quality Assurance

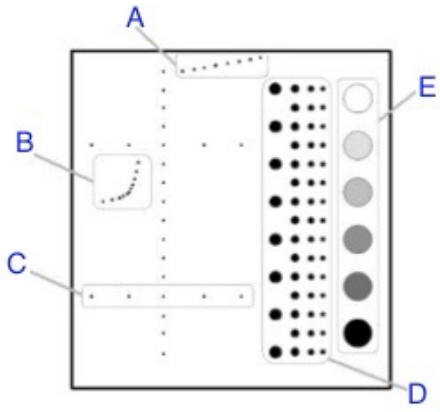
QA is medically and legally necessary, must be done periodically and routinely.
GOAL: to ensure all equipment meets and performs up to standard, maintaining optimal image quality.

Performance Testing

AIUM's 100mm test object
Fluid-filled tank with same propagation speed as soft tissue but without attenuation (doesn't look like tissue). Stainless steel pins strategically placed to produce reflections. To test distance and accuracy of system: caliper accuracy, spatial resolution, dead zone.
Cannot test grey scale properties



Tissue Equivalent Phantom (TEP)
Similar properties as soft tissue including propagation speed of 1540m/s and attenuation rate of 1/2dB/cm/MHz. Looks the same as soft tissue. Contains nylon wires and objects to mimic simple cysts and solid masses. Ability to evaluate grey-scale, focal zones, spatial resolution, caliper accuracy, depth calibration, dead zone, elevational resolution, sensitivity



A Dead Zone The dead zone is the space close to XDCR face that cannot detect echoes. The first pin detected in section A is the depth of the dead zone

B Spatial Resolution Made up of pins closely spaced horizontally and vertically.
Vertical pins = axial resolution
Horizontal pins = lateral resolution

C Horizontal Caliper Accuracy The TEP doesn't lie. So if calipers on image give a different measurement, they need to be calibrated

D Slice Thickness and Elevational Resolution Section of cystic spaces of differing sizes and different depths. The cysts that appear clear and echo-free tell us the elevational resolution thickness

E Grey Scale Accurate and uniform presentation of cystic to solid looking masses.

Depth calibration (or depth measurement accuracy) evaluated by measuring objects along vertical axis at 1cm intervals. If off, can be recalibrated

Ultrasound Physics Review

Doppler Phantom
Device within TE phantom that propels fluid in a tube used to evaluate doppler instrumentation accuracy such as velocity measurements, caliper accuracy, scale, etc

No test object can test for temporal resolution (frame rate)

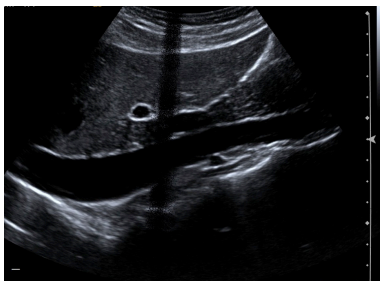
Sensitivity
Ability of machine to detect and display low level echoes. No variance (change over time)

Minimum sensitivity	The weakest echo that can be found in far field. TGC are set flat and gain is increased until deeper rods appear
Normal sensitivity	The setting that all pins are displayed. Should not change over time
Maximum sensitivity	Power and gain is set to max levels. Max visualized depth can be determined

Malfunctions
Malfunctions may be found during QA or PM's or during day to day imaging as an artifact.

All dysfunctional equipment should be recorded and repaired as soon as possible.

Black shadow from the transducer face indicates broken or cracked crystal



Gold Standard

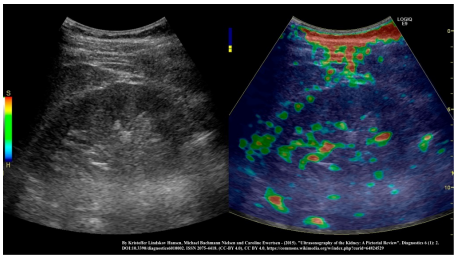
Gold standard testing is basically statistics, checking the accuracy of the non-invasive test (like ultrasound) against whats considered the "truth" or gold standard which would be the test that is more accurate and usually the more invasive exam.

Sensitivity is how good the test is at detecting disease. Ex - In 10 patients with gallstones, only 9 were detected with US. The sensitivity would be 9/10
Specificity is how good the test is at detecting normal. Ex - In 20 normal patients, 18 accurately were found to be normal by the ultrasound. The specificity would be 18/20

Ultrasound Physics Review

New Technologies

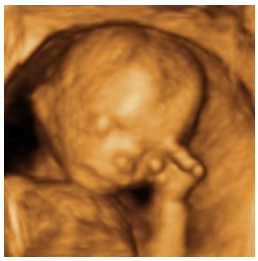
Elastography
Maps the elasticity or stiffness of tissue. Helps to distinguish between benign or malignant tumors and other conditions that affect tissue density. Commonly used in breast and abdominal imaging



3D and 4D imaging
Volumetric data acquisition, volume data analysis, and volume data display. The 3rd dimension is the coronal plane. 4D is the addition of time (real time 3D)
Requires a volume of tissue to be scanned and reconstructed

Electronic 3D probe has over 2,000 elements. Collects volume data from pyramid shaped US beam and processes simultaneously. Able to do 4D since it all simultaneous. Display rate of > 20 vol/s Measurement accuracy due to automated sweep

Traditional probes with 3D capabilities require a sweep to acquire the 3rd dimension. These are not as accurate as electronic 3D/4D probes. Tech dependent



Display modes
Multi-planar- 3 orthogonal planes (SAG, TRV, and Coronal) and/or volume rendering can be displayed. Able to sweep through any of 3 planes simultaneously or rotate volume. Or display each separately.

Volume rendering will show the surface of the volume and constructs and image with color, texture, shadows. Able to produce “photographs” of baby in the womb. Can be done off-line = post-processing

All machines controls can be used to optimize 3D image same as 2D (depth, gain, TGC, FR, focal point, etc.)

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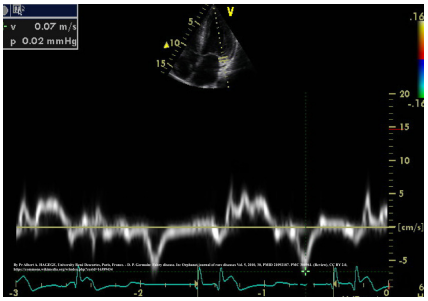
Contrast Agents

Microbubbles trapped in a shell that can be injected intravenously. The tiny bubbles are highly reflective and will appear very bright on the image. The purpose is to 'light up' blood chambers or vessels. Not like contrast of MRI or CT. It is only bubbles in a saline solution. No dye, safe for all patients
Main use now is for Cardiac to see LV function.

Must use low MI settings. Higher output and increased cavitation causing bubble destruction. Harmonics may still be used to increase echo intensity, Doppler signals also may be improved due to increased amplitude echoes.

Tissue doppler
Used in echo for cardiac function by measuring the velocity of the moving heart muscle during cardiac contraction.
AKA myocardial motion.
Uses doppler just like for blood flow, except detecting the movement of the muscle. Wall filter or high pass filter is turned off as we want to see the high amp/low freq shifts



Ultrasound hybrid imaging
aka fusion imaging. A combo of ultrasound with either CT or MRI. One probe that will scan with ultrasound and a CT image at the same time. Primarily used for diagnosis, staging of tumors and cancers. Also during ablation procedures. Combining both modalities allows for more accurate reading.
Contraindications = pt who cannot have CT or MRI due to allergies or metal within body.