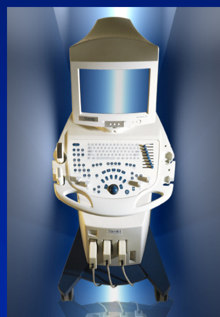
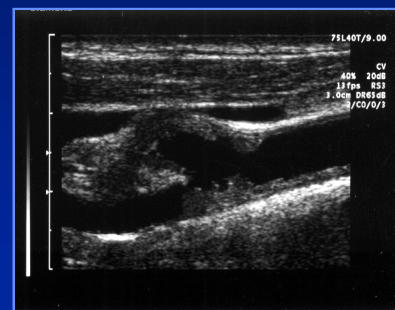
Basic Ultrasound Imaging Principles
Extra material- Not contained in Techniques.



How is this image generated?



Slide note

Definition of Sound

- Sound is a mechanical, longitudinal wave produced by a vibrating source.
  - Travels in a straight line
  - Needs a medium
  - Sound waves transfer energy from the source to the receiver
  - *If a tree falls down in the woods and no one is around to hear it- does it make a sound?*

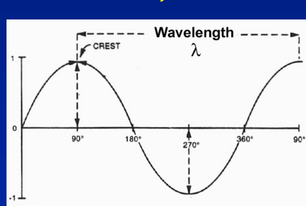
Slide note

Sound versus Ultrasound

- Audible sound (humans)
  - Frequency range between 20 cycles/sec (20 Hz) and 20,000 cycles/sec (20 kHz)
- Ultrasound
  - Wave frequency > 20 kHz
  - Frequency is too high to be heard (humans)
  - Typical diagnostic ultrasound frequency
    - 2 MHz - 15 MHz
- Infrasound- Freq. less that 20 Hz

Wavelength - ⌊

- **Distance between two peak compressions in a wave (peak to peak)**
- **Measured in mm, or m**

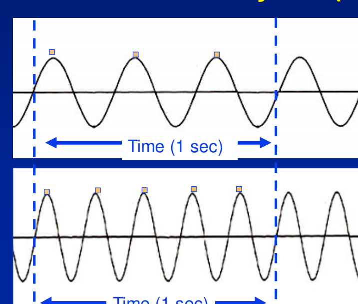


⌊ = "lambda"

Slide note

Frequency

- **Number of wave cycles (Hz) per second**

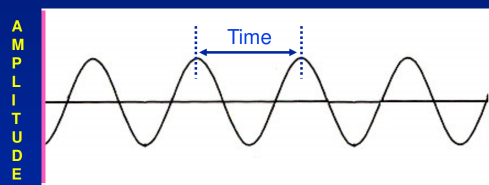


Frequency = 3 Hz

Frequency = 5 Hz

Period

- Time interval between peaks



- Waves are hitting shoreline every 4 seconds
- Wavelength?
- Period?
- Frequency?
- Amplitude?

Slide notes

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Propagation Speed

- The rate at which a wave moves through a medium
- Speed depends on the characteristics of the medium (density)
- Not related to the frequency of sound
- Propagation speeds: C
  - Soft tissue 1540 m/sec
  - Air 330 m/sec
  - Water 1480 m/sec (temp dependant)
  - Bone 4080 m/sec

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Acoustic Impedance- Z

- The resistance of a sound wave as it travels through a medium.
- Impedance (Z) is density of the medium (p) x propagation speed (C)
  - Z= p x C
- Impedance units are called RAYLS

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Acoustic Impedance

- Impedance increases if density of medium increases
- Impedance increases if propagation speed increases
- An acoustic impedance *mismatch* is necessary for ultrasound reflection to occur.

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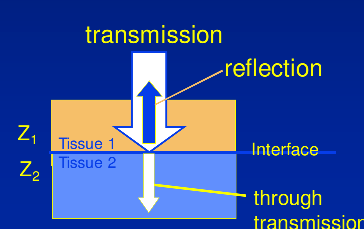
Acoustic Impedance

- If a strong impedance mismatch occurs between tissue layers, a large reflection occurs.



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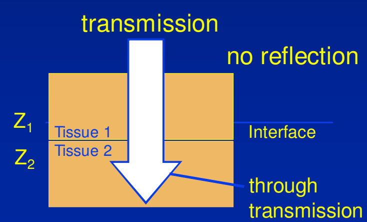
Acoustic Impedance

- If a small or absent impedance mismatch occurs, there is 100% through transmission and no reflection: no reflection = no ultrasound image



Reflection

- Must be an impedance mismatch for reflection of the sound wave to occur at tissue interfaces.
- Intensity Reflection Coefficient (IRC)
  - % of incident sound intensity reflected back, versus energy that passes through.
- Intensity Transmission Coefficient (ITC)
  - % of incident sound intensity that passes through the interface.

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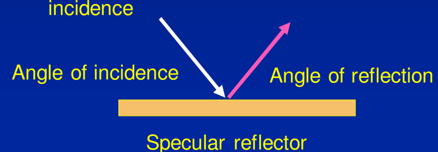
Reflection

- IRC + ITC should equal 1 (or 100%)
- Specular Reflection
  - Reflected sound waves from a large, flat surface or interface
  - The angle of reflection equals the angle of incidence



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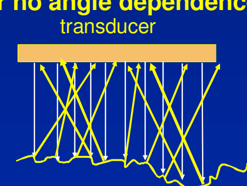
Reflection

- Back Scattering (non-specular reflection)
  - Reflection that occurs from rough, irregular surfaces of interfaces
  - Little or no angle dependence



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Refraction

- A change in direction of a sound wave (bending of the beam) as it passes through an acoustic interface
  - Propagation speeds of the two mediums must be different
  - Sound wave must hit the interface at an oblique angle (not 90º)
  - Refraction can cause lateral position errors in the ultrasound image!

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Refraction or broken oar?

Slide note

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Absorption

- Sound wave energy conversion to heat in tissue
- Higher the frequency, the higher the absorption
- Increased intensity = increased absorption

Therapeutic Ultrasound relies on absorption to create heat

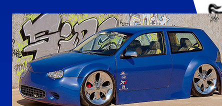
Attenuation

Attenuation

- A decrease in sound intensity and amplitude as sound moves through a medium
- Factors that affect attenuation:
  - Tissue path length
  - Tissue or medium type
    - soft tissue 0.5 dB per cm
    - blood 0.125 dB per cm
    - muscle 1.0 dB per cm
  - Transmitted frequency
    - The higher the frequency, the greater the attenuation.

Frequency vs. Depth

- Inversely proportional
  - The lower the transmitted frequency, the greater the depth (distance) penetration



Is he hearing the bass, or treble?

Attenuation Coefficient dB/cm

- The amount of attenuation (expressed in decibels) occurring per centimeter of tissue path
- Attenuation calculation in soft tissue:

Attenuation (dB) = 1/2 Freq. (MHz) x path length (cm)

Attenuation for a 5 MHz transducer at a depth of 10 cm.
dB =1/2 x 5 MHz x 10 cm

dB = 2.5 x 10

Attenuation = 25 dB

Depth Gain Compensation (DGC) aka, Time Gain Compensation

Without DGC, image is not uniform in appearance.
Near field is bright, far field too dark

Slide notes

The World of Ultrasound: Terminology

- B-mode
- Grayscale
- Echogenicity
- Contrast resolution
- Attenuation
- Enhanced through transmission
- Time-gain compensation TGC
- Reverberation
- Scanlines
- Power Doppler
- Angle theta
- Nyquist limit
- PRF
- Autocorrelation
- Packet size

Transducer Design

- Linear array
- Curved linear array
- Phased array
- Mechanical Sector
- Annular array
- Also Matrix, 2-D and 3-D

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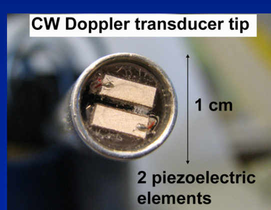
Doppler Devices

- Continuous-wave (CW) Doppler
  - 2 piezo-electric crystals: one transmitting, one receiving
  - No aliasing artifact
  - Not specific for depth



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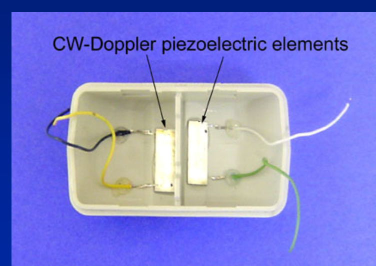
Mechanical fixed element

Continuous wave Doppler- two fixed piezoelectric elements



Slide notes

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Piezoelectric Material

- Natural
  - quartz
  - rochelle salts
  - tourmaline
- Man-made
  - Ceramic material- most prevalent

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Natural Resonance or Frequency

$$\text{Frequency (MHz)} = \frac{\text{material's propagation speed (mm/}\mu\text{s)}}{2 \times \text{thickness}}$$

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Bandwidth

- Piezo electric element, and consequently transducers, emit a range of frequencies, not a single note. (think musical chord versus single note)

A piano musical chord

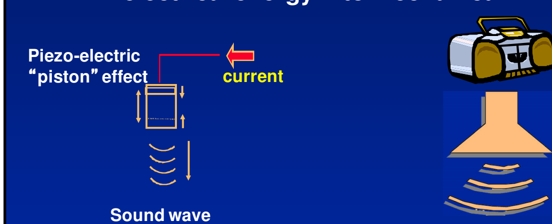
Bandwidth

- The difference between the highest and lowest frequencies found in a pulse is called the bandwidth.
- Examples:
  - Linear Array L12-5 (5-12 MHz bandwidth)
  - Curved array C3-6 (3-6 MHz bandwidth)

Piezo-electric Effect

- Similarities exit between transmit-echo ultrasound principles and hearing.

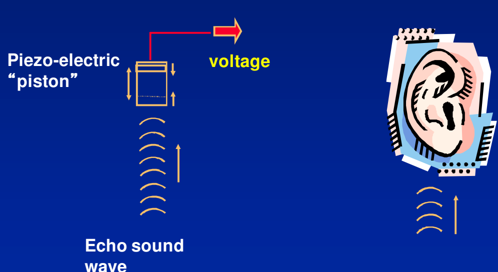
Piezoelectric elements vibrate when voltage is applied, ie., convert electrical energy into mechanical



Conversion of Electrical energy → Mechanical energy

Slide note

Mechanical energy (sound) vibrates the piezo elements and converts to electrical energy



Mechanical energy → Electrical energy

Note included

Signal Processing

- Ultrasound echoes are converted to voltage
- Signals are amplified and digitized
- Digitized signals are stored, then displayed on CRT or LCD monitor.

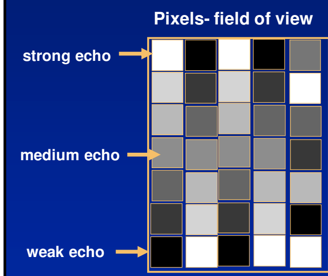
B- Mode ultrasound aka “2-D”

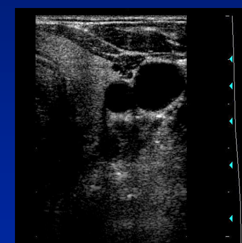
- Diagnostic ultrasound is “echo” ultrasound.
- B= “Brightness” mode
  - Different tissues reflect ultrasound with varying intensity
  - Reflected intensity is graded and assign

Note included

Image pixels(0.5 mm) are assigned a shade of gray.

Pixel shade assignment depends on the strength of the echo.



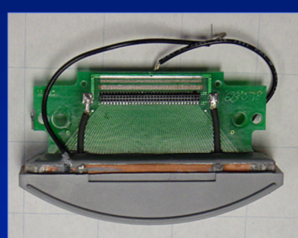


grayscale = 254 shades

Note included

Piezoelectric linear array transducers may be flat or curved

Flat 38 mm linear array

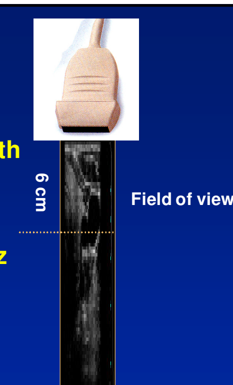


Curved linear array- 66 mm radius

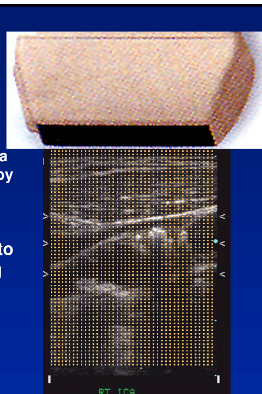
Slide note

Flat Linear Array Transducers

- Good to about 6 cm in depth
- Footprint length dictates field of view
- Frequency range 4 -12 MHz
- Beyond 6cm, FOV width is too narrow



Slide note

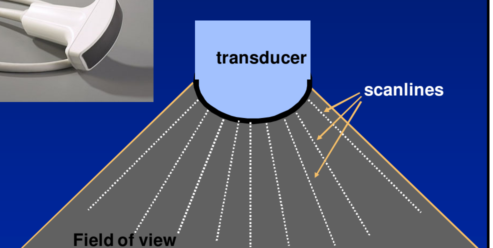


An image “frame” consists of a number of scan lines created by the transducer elements.

Multiple frames are linked to provide a real-time moving picture.

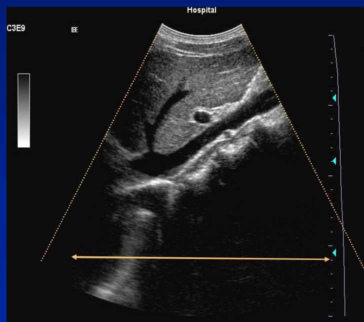
Slide note

Curved Linear array transducer



Slide note

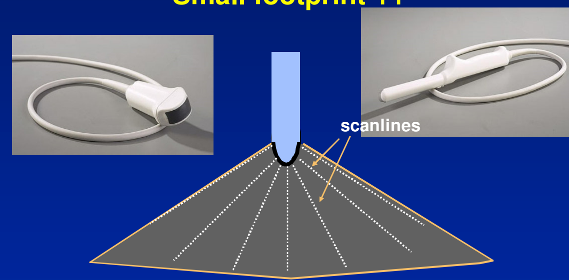
Curved array- increased field of view at depth



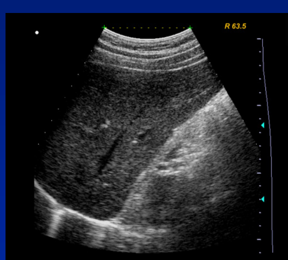
Slide note

Tightly Curved Array

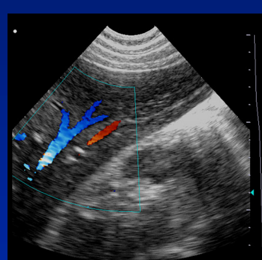
Small footprint ++



Curved Array



Standard curve radius 63.5

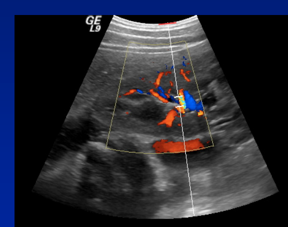


Tightly curved array, radius 19.5

Slide note

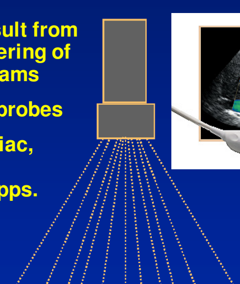
Curved Array Doppler

- The Doppler beam is unsteered in curved array technology
- It' s angled in the image due to the curve of the array.



Phased Array

- Scan lines result from electronic steering of ultrasound beams
- AKA - Sector probes
- Good for cardiac, OB/Abd and transcranial apps.

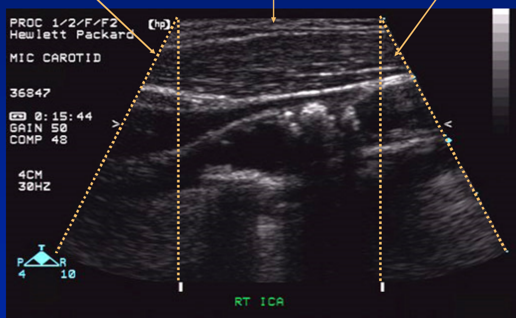


Trapezoidal Imaging:

Flat linear array,but elements near the transducer ends are phased to provide a larger field of view.

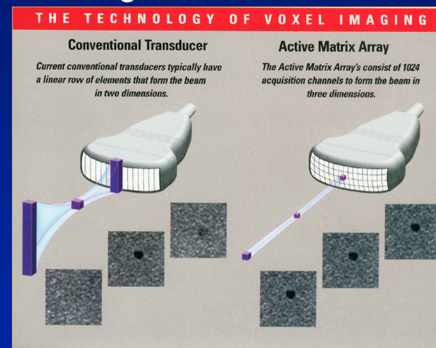
Trapezoidal Imaging

Phased section | Straight linear section | Phased section



Note included

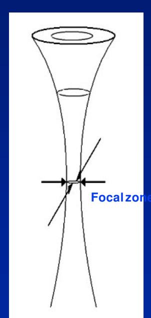
Matrix Transducers- focusing in the third dimension



Courtesy of GE Ultrasound

Annular Array Transducers

- Multiple concentric rings used to focus beam
- Focusing in axial, lateral and elevation planes
- Must be mechanically oscillated



Slide note

New annular array applications

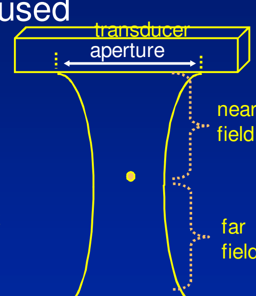
- HIFU- High intensity Focused Ultrasound
- Therapeutic applications
  - Prostate cancer
- A total of 3 annular HIFU phased arrays (capable of electronically focusing in depth, but requiring mechanical linear and sector motors to place lesions in longitudinal and transverse directions, respectively) were designed, built, characterized, and tested

Sound Beam Characteristics

- Beam diameter affects resolution
  - The smaller the beam at the point of interest in the tissue, the better the resolution

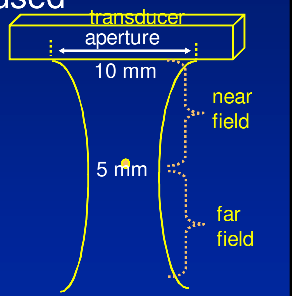
Beam Characteristics Unfocused

- As the sound beam moves from the transducer, the diameter changes
- At some point it narrows, then it diverges
- Beam diameter decreases in the NEAR FIELD or Fresnal Zone
- Beam diameter increases in FAR FIELD or Fraunhofer Zone



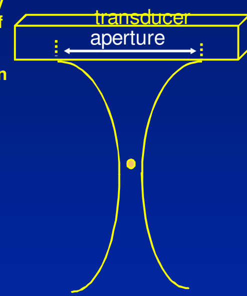
Beam Characteristics- Unfocused

- At the end of the near zone, beam width is about 1/2 aperture width
- Near zone length increases with higher frequency and larger aperture size



Beam Focusing

- Focusing improves resolution by narrowing beam width at point of interest in tissue
- Focusing can be achieved only in the near zone
- Focusing can be done with:
  - Acoustic lens
  - Internal focusing (shaping the piezoelectric elements)
  - Acoustic mirrors
  - Electronic focusing -phasing



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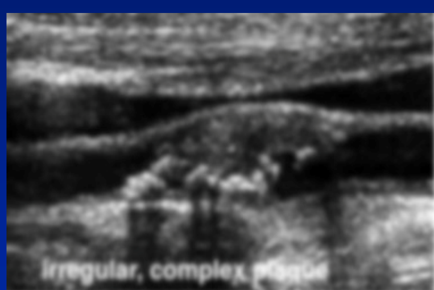
Resolution



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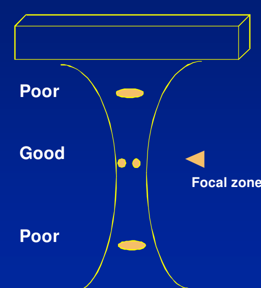
LATERAL RESOLUTION.



Lateral resolution.
The ability to distinguish two closely spaced objects in the horizontal plane

Improved by focusing the ultrasound beam

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Lateral Resolution

- AKA, angular, transverse, Azimuthal
- Measured in mm, the smaller the number, the better
- Varies with depth, focal point is adjustable
- Dynamic focusing provided multiple focal zones and a large zone of lateral res.

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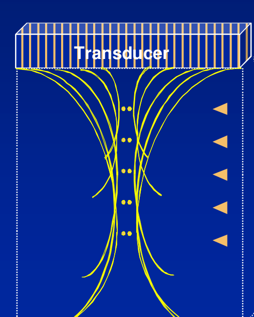
Dynamic Focusing



Multiple focal zones improve lateral resolution at multiple depths.

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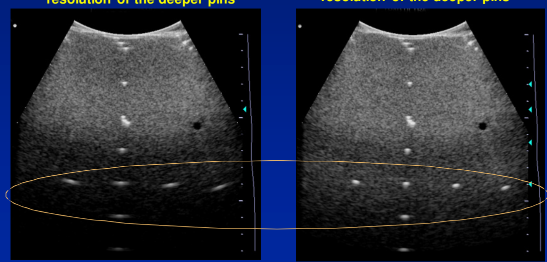
Lateral resolution depends on beam focusing

Single focal zone at 4.5cm. Note the poor lateral resolution of the deeper pins

Multiple focal zones at 4 -9 cm. Note the improved lateral resolution of the deeper pins



Pin phantom with 3.5 MHz transducer

Slide note

Axial Resolution

- AKA, axial, range, depth, longitudinal
- The ability to distinguish 2 separate objects along the beam path
- Axial res doesn't vary along beam path
- The higher the transducer frequency, the higher the axial res.

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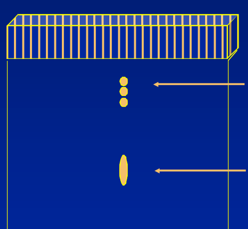
AXIAL RESOLUTION



Good axial resolution: the ability to distinguish adjacent structures in the vertical axis

Poor axial resolution

Axial resolution is determined by spatial pulse length

Slide note

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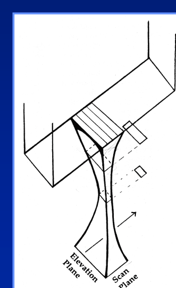
The third dimension- the elevation plane



- AKA – slice thickness
- "slice thickness" varies with depth.
- focal point is fixed and determined by transducer design and frequency

Slide note

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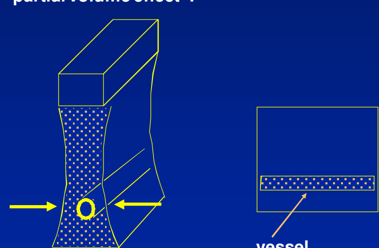
If the slice thickness is wider than the object, the surrounding tissue may be displayed along with the object of interest. This is sometimes referred to as "partial volume effect".



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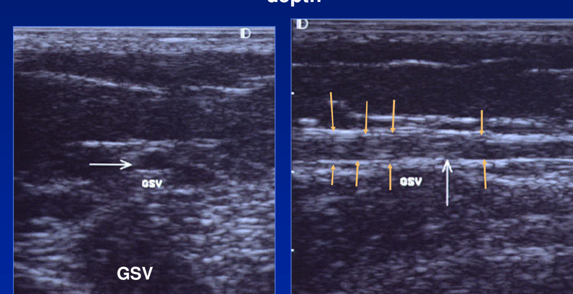
5 MHz transducer with mid elevation focal depth



Partial volume effect

Note included

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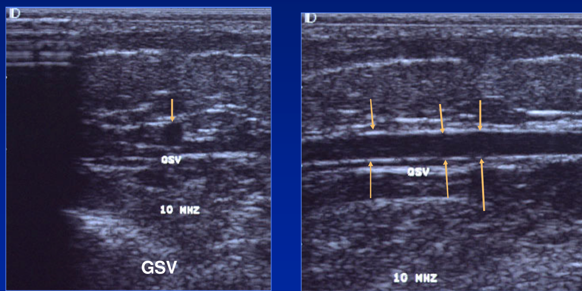
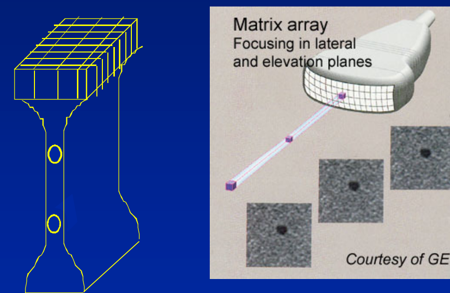
High frequency transducer with short elevation focus minimizes partial volume effect



Note included

"Matrix" array transducers can provide a more uniform elevation focal zone.



Contrast Resolution

- The ability of the gray-scale display to distinguish subtle differences in echogenicity, or brightness, of adjacent tissues.

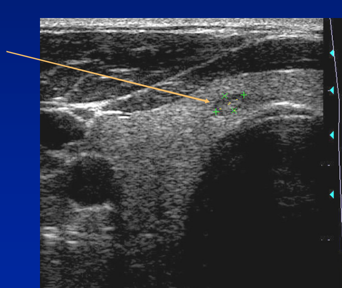
Con rast
Res lution

Contrast resolution not very good; Letters missing against the background

Co trast
Res lution

Better contrast resolution; all letters are seen.

Good contrast resolution! Small, subtle thyroid nodule



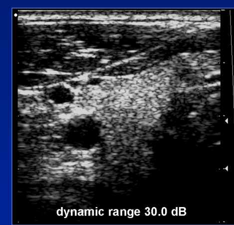
Slide notes

Good axial, lateral, elevation, and contrast resolution = Good resolution

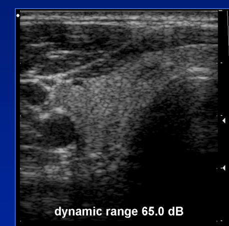
Dynamic Range (DR)

- Range of gray shades shown in image
- Lowest DR - black to white (bi-stable image)
- Highest DR- highest # of shades
- Expressed in dB

Dynamic Range



Low dynamic range
Few gray shades-more contrast



High dynamic range
More gray shades- less contrast

Probe versus clinical application

- Flat Linear
  - most peripheral vascular, small parts imaging, breast ultrasound etc
- Curved Linear (convex array)
  - Abdomen, Obstretrics (OB), Cardiac
- Phased array
  - Cardiac, Abdomen, Transcranial Color Doppler imaging, OB,

Duplex Ultrasound aka, color duplex imaging

- Originally two, now three modalities
  - Real-time B-mode image
  - Pulsed wave (PW) Doppler
  - Color Doppler
- Doppler used for:
  - Determine if flow is present or absent.
  - Estimate velocity
  - Demonstrate normal or abnormal hemodynamic flow patterns