Ultrasound Imaging: Basic Physics

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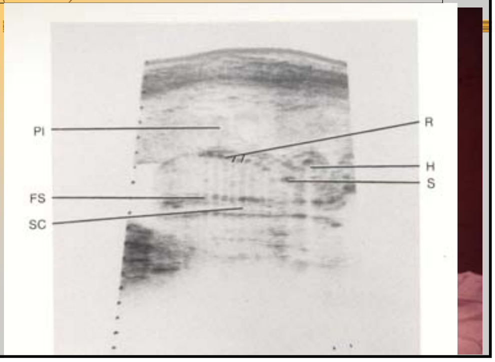
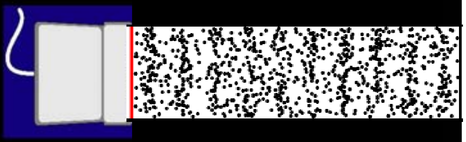
Physics Honor's Lectures
November 3, 2006

First Generation Scanner (1971)

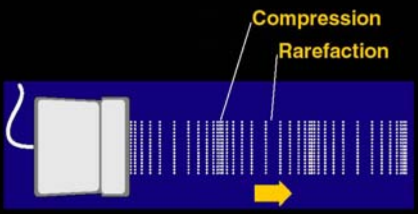


Present Day Scanner

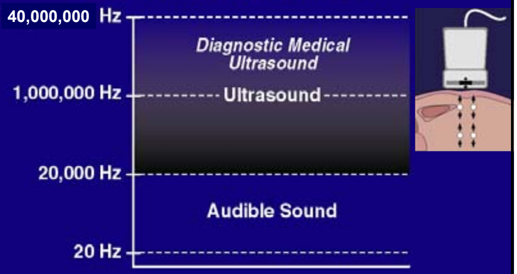
Producing compressional waves

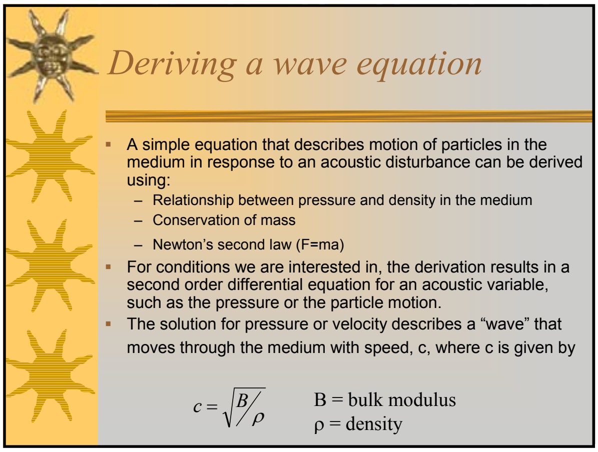


Pressure waves; compression and rarefaction



FREQUENCY RANGE



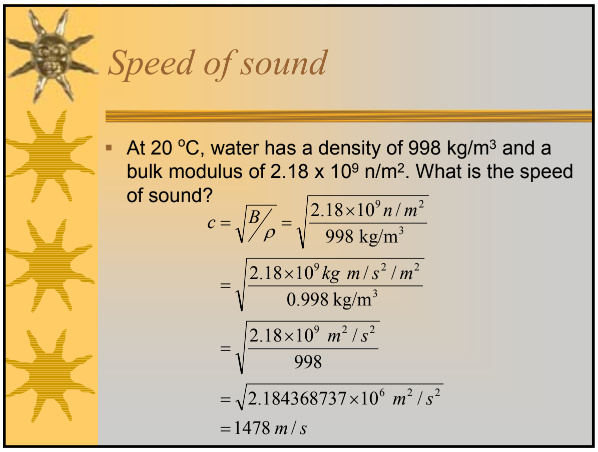


Deriving a wave equation

- A simple equation that describes motion of particles in the medium in response to an acoustic disturbance can be derived using:
  - Relationship between pressure and density in the medium
  - Conservation of mass
  - Newton's second law (F=ma)
- For conditions we are interested in, the derivation results in a second order differential equation for an acoustic variable, such as the pressure or the particle motion.
- The solution for pressure or velocity describes a "wave" that moves through the medium with speed, c, where c is given by

$$c=\sqrt{B/\rho}$$

B = bulk modulus
ρ = density



Speed of sound

- At 20 °C, water has a density of 998 kg/m^3 and a bulk modulus of 2.18 x 10^9 n/m^2. What is the speed of sound?

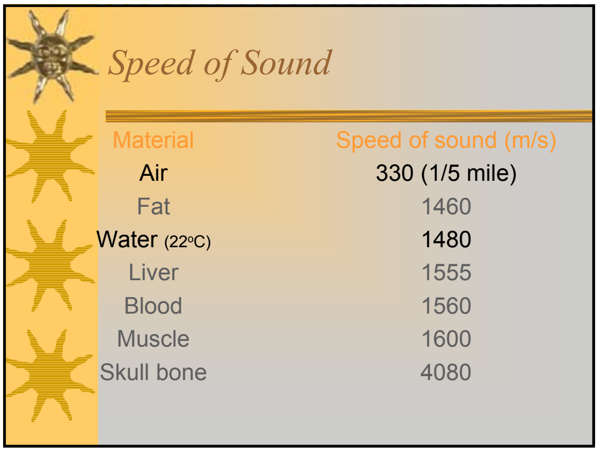
$$c=\sqrt{B/\rho}=\sqrt{\frac{2.18\times10^{9}\,n/m^{2}}{998\ \text{kg/m}^{3}}}$$

$$=\sqrt{\frac{2.18\times10^{9}\,kg\ m/s^{2}/m^{2}}{0.998\ \text{kg/m}^{3}}}$$

$$=\sqrt{\frac{2.18\times10^{9}\ m^{2}/s^{2}}{998}}$$

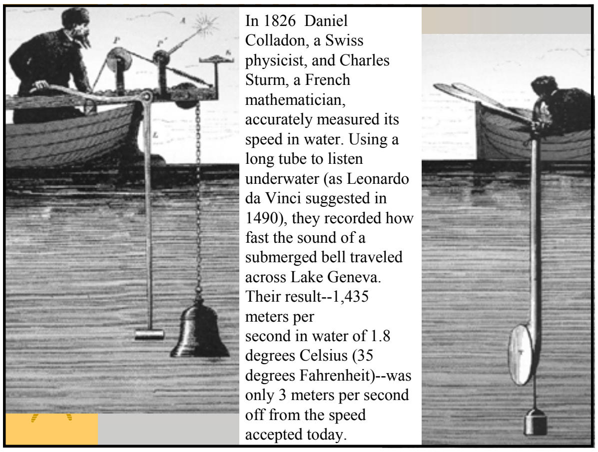
$$=\sqrt{2.184368737\times10^{6}\ m^{2}/s^{2}}$$

$$=1478\ m/s$$

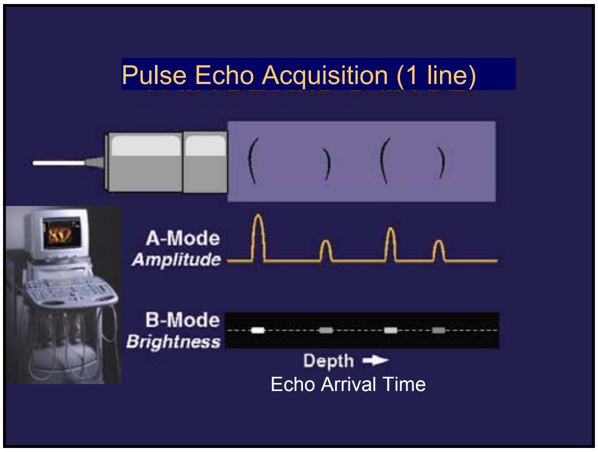


Speed of Sound

Material	Speed of sound (m/s)
Air	330 (1/5 mile)
Fat	1460
Water (22°C)	1480
Liver	1555
Blood	1560
Muscle	1600
Skull bone	4080

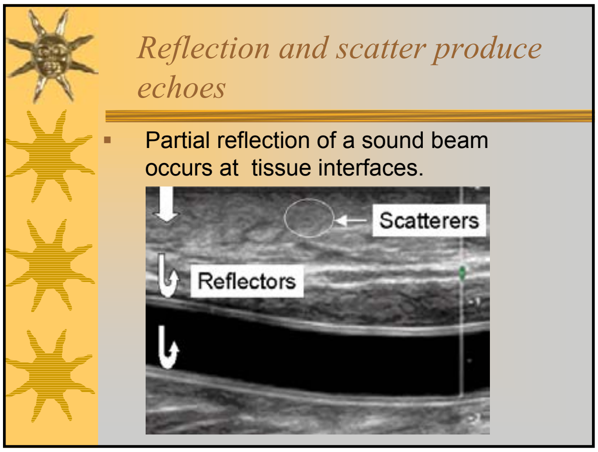


In 1826 Daniel Colladon, a Swiss physicist, and Charles Sturm, a French mathematician, accurately measured its speed in water. Using a long tube to listen underwater (as Leonardo da Vinci suggested in 1490), they recorded how fast the sound of a submerged bell traveled across Lake Geneva. Their result--1,435 meters per second in water of 1.8 degrees Celsius (35 degrees Fahrenheit)--was only 3 meters per second off from the speed accepted today.



Pulse Echo Acquisition (1 line)

Echo Arrival Time



Reflection and scatter produce echoes

- Partial reflection of a sound beam occurs at tissue interfaces.

Acoustic Impedance (Z)

- Important in reflection
- A property of the tissue
- Given by the speed of sound (c) times the density ρ

$$Z = \rho c$$

- Unit is the rayl, 1 rayl = 1 kg/m^{2}s

Acoustic Impedance

Tissue	Impedance (Rayls)
Air	0.004×10^6
Fat	1.34×10^6
Water	1.48×10^6
Liver	1.65×10^6
Blood	1.65×10^6
Muscle	1.71×10^6
Skull bone	7.8×10^6

Note, the range of impedances of soft tissues (that do not contain air) is relatively narrow.

Reflection

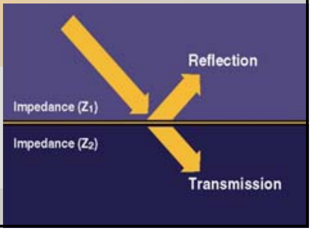
- Partial reflection of a sound beam occurs at tissue interfaces.
- Interfaces are formed by tissues that have *different impedances*.
- Examples:
  - Muscle-to-fat
  - Bone-to muscle
  - Red blood cell-to-plasma

Reflection Coefficient, R

R is the ratio of the amplitude reflected to the incident amplitude.

A bigger R means more reflection, less transmission.

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$



Reflection Example:

liver (1.65 x 10^6 Rayls)-to-muscle (1.71 x 10^6 Rayls)

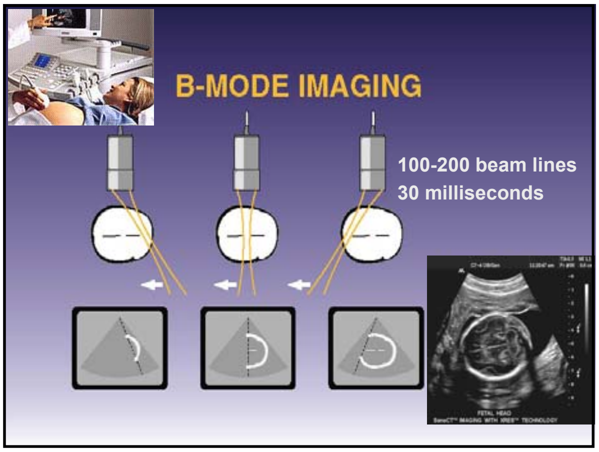
Z2 = 1.71 x 10^6; Z1= 1.65 x 10^6

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{1.71 - 1.65}{1.71 + 1.65} = .018$$

Amplitude Reflection Coefficients

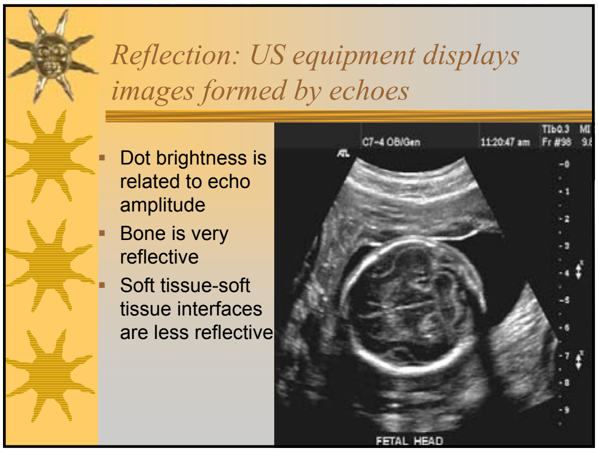
Muscle-liver	.02
Fat-muscle	.1
Muscle-bone	.64
Muscle-air	.99

Note, the reflection coefficient between soft tissues is relatively weak; reflection at interfaces between soft tissue and bone is much stronger. Reflection at interfaces between tissue and air approaches 100%.



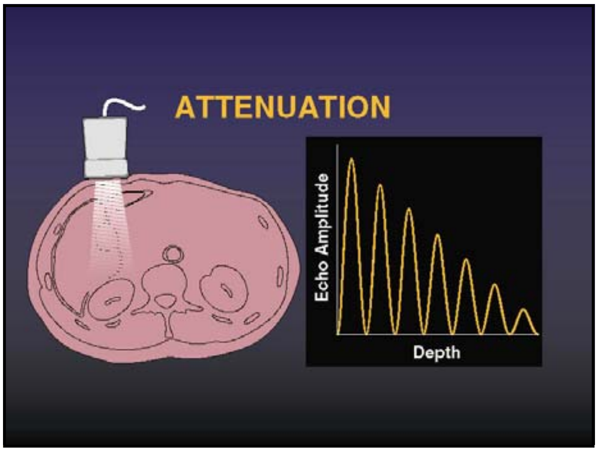
B-MODE IMAGING

100-200 beam lines
30 milliseconds

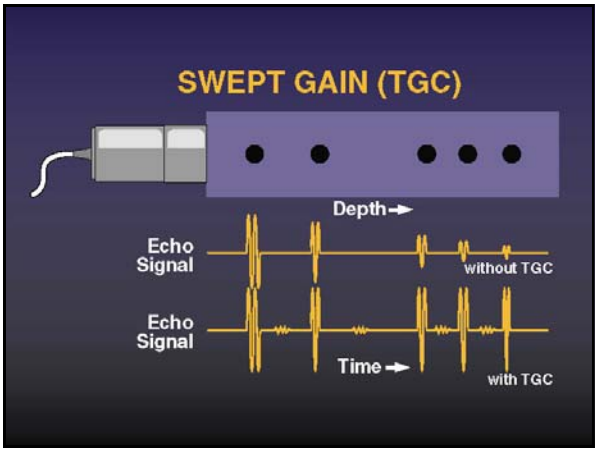


Reflection: US equipment displays images formed by echoes

- Dot brightness is related to echo amplitude
- Bone is very reflective
- Soft tissue-soft tissue interfaces are less reflective



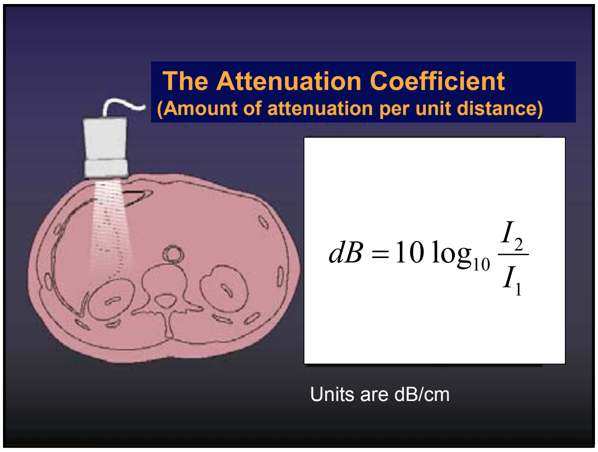
ATTENUATION



SWEPT GAIN (TGC)

Causes of Attenuation

- Reflection and scatter at interfaces
  - Very small contribution within organs
  - Can be significant at calcifications, stones
- Absorption
  - Beam energy converted to heat
  - Diagnostic beams usually cause negligible heating

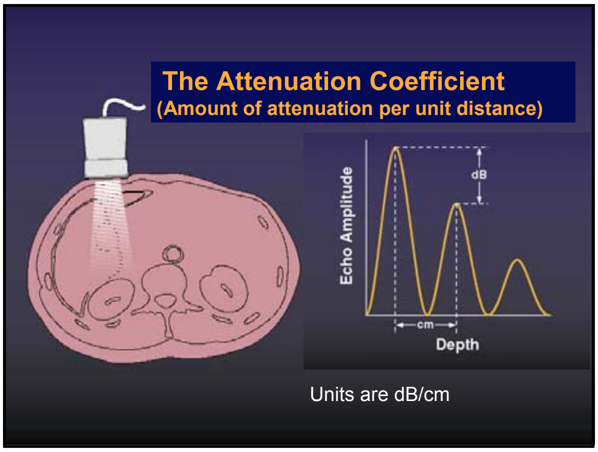


The Attenuation Coefficient

(Amount of attenuation per unit distance)

$$dB = 10 \log_{10} \frac{I_2}{I_1}$$

Units are dB/cm



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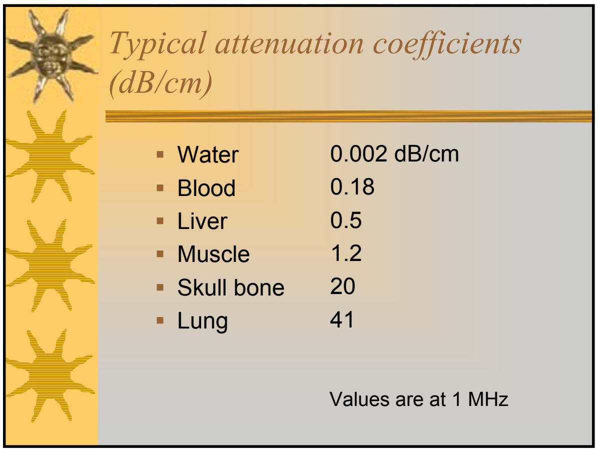
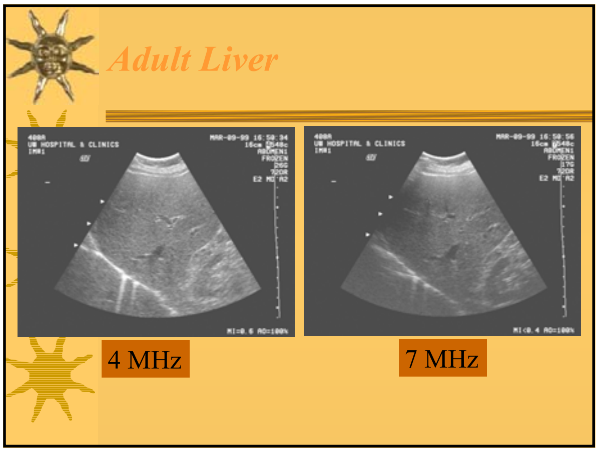


Typical attenuation coefficients (dB/cm)

Water	0.002 dB/cm
Blood	0.18
Liver	0.5
Muscle	1.2
Skull bone	20
Lung	41

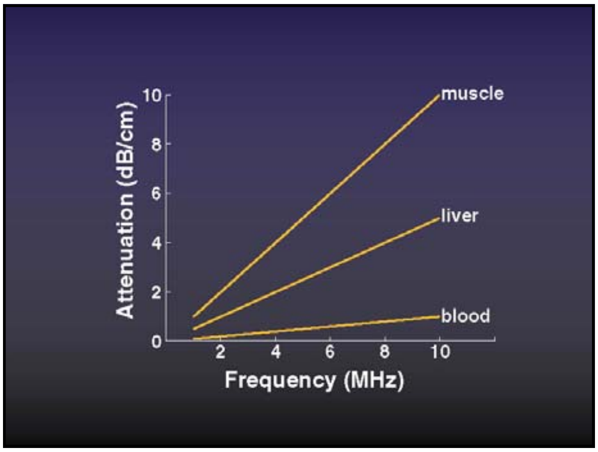
Values are at 1 MHz

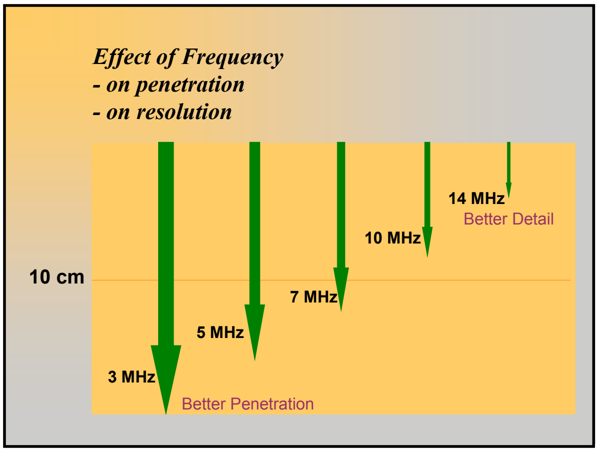


Adult Liver

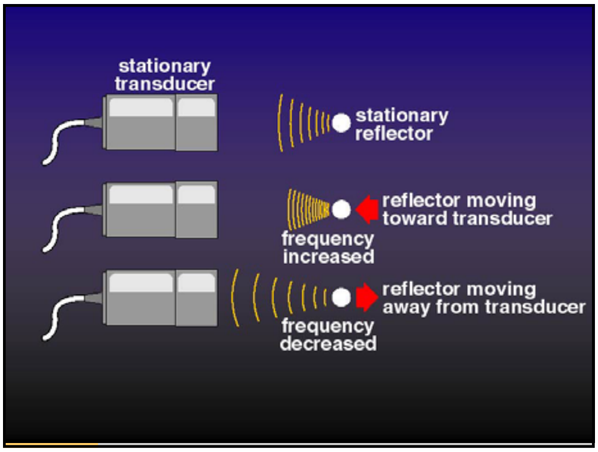
4 MHz

7 MHz





Effect of Frequency
- on penetration
- on resolution



Doppler equation

- Relationship between Doppler shift (or just Doppler) frequency, F_D and reflector velocity, v:

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

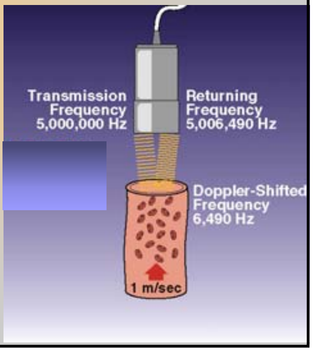
- f_o is the ultrasound frequency, or the transmitted beam frequency.

Doppler Shift for 5 MHz, 1 m/s, 0 degrees:

$$F_D = \frac{2f_o v \cos\theta}{c} = \frac{2x\ 5{,}000{,}000/s \text{ x } 1\text{m/s}}{1{,}540\text{m/s}} = 6{,}493/s$$

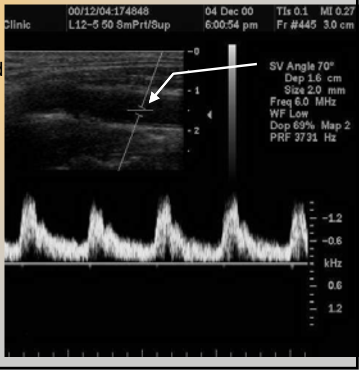
Doppler shift

- Doppler shift is the difference between the transmitted and received frequencies.
- Transmitted and received frequencies are in the MHz range
- Doppler shift frequencies often in audible range

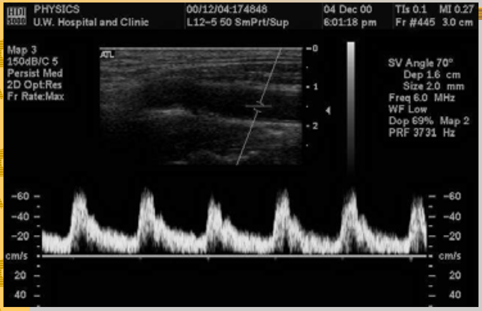


Angle Correct Cursor

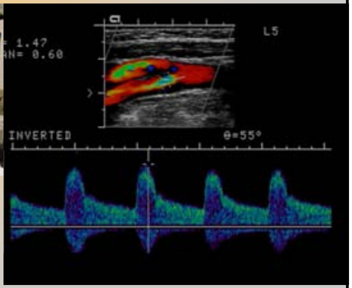
- Angle correct is needed to convert the Doppler frequency to a reflector velocity
- Operator adjusts the cursor parallel to the flow direction
- Machine then computes the Doppler angle



Spectral Display (velocity)



Scanning the carotid artery

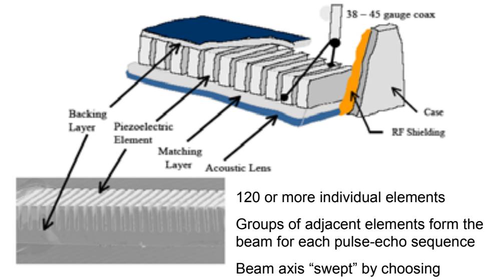


Color flow image (top) and spectral display

Modern Ultrasound Transducers

- Nearly all transducers contain an array of PZT elements (120 or more)
- Advantages of arrays:
  - Electronically controlled, “real-time” imaging, sending beams into many different directions
  - Individual beams can be focused
  - Focusing can be controlled electronically

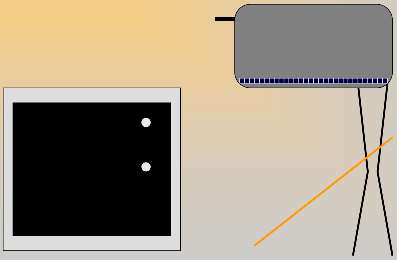
Probe Construction: linear array

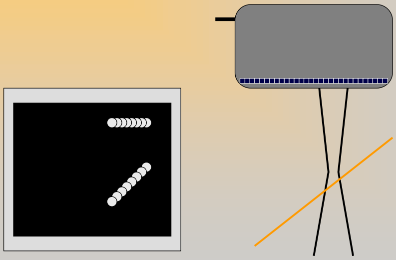


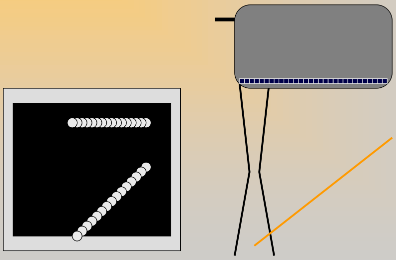
120 or more individual elements

Groups of adjacent elements form the beam for each pulse-echo sequence

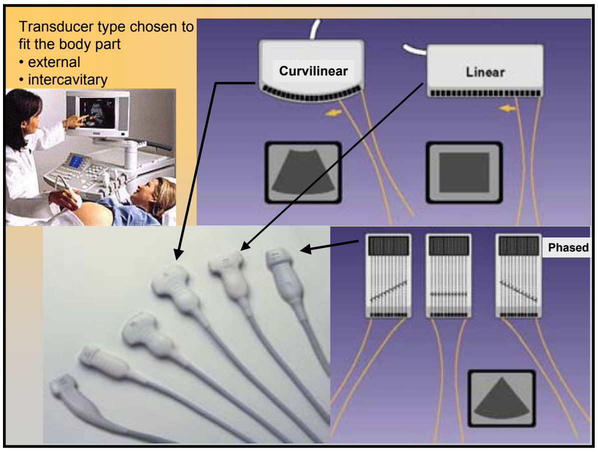
Beam axis “swept” by choosing different element groups.







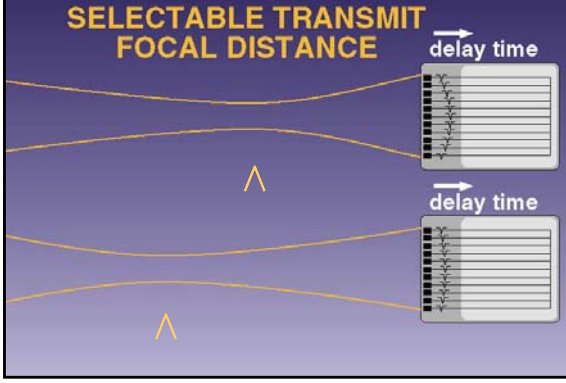
Transducer type chosen to fit the body part
- external
- intercavitary



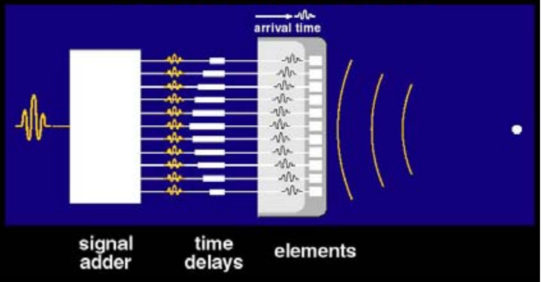
2nd-3rd trimester

4-6 weeks

SELECTABLE TRANSMIT FOCAL DISTANCE



ARRAY FOCUSING DURING RECEPTION



Focusing delays change in real time, "tracking" the reflector location.

Receive focusing off

Transmit focusing applied to a single depth

Dynamic receive focusing is disabled

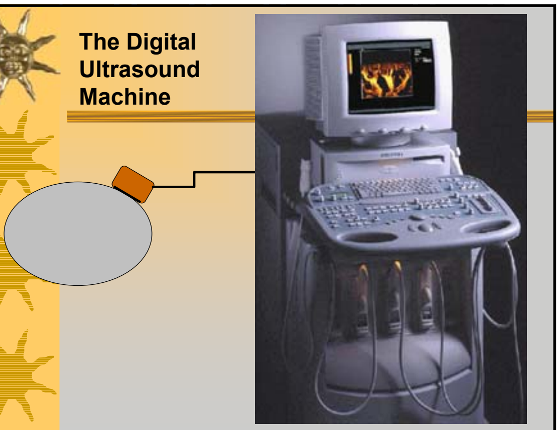
Point reflectors in a phantom
  1 column
  2 rows

Receive focusing on

Transmit focusing applied to a single depth

Receive focusing done in the "beam former"
- Uses time delays
- Changes dynamically

The Digital Ultrasound Machine



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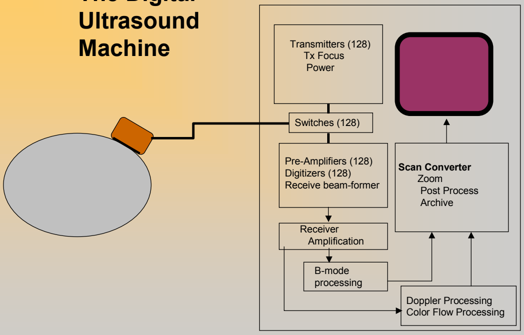


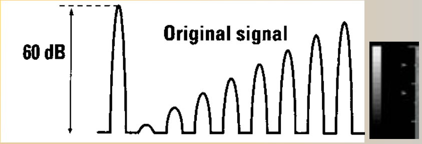
Dynamic Range (after TGC)

"local dynamic range"

Echo amplitude indicated by dot brightness.

- Modern imaging requires display of echo signals whose amplitudes vary by 60-90 decibels.
- 40 dB: 100/1 ratio of amplitudes
- 60 dB: 1,000/1 ratio
- 80 dB: 10,000/1 ratio

- 60-90 decibels is beyond the display capabilities of monitors. (Dynamic Range problem)



Monitor
Gray-Bar

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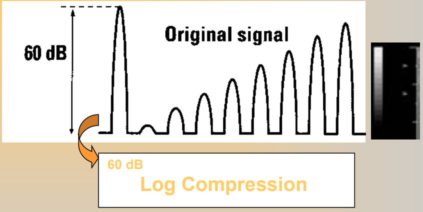

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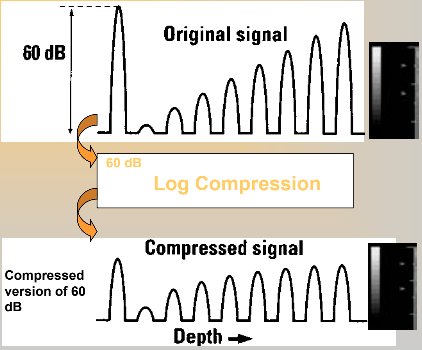
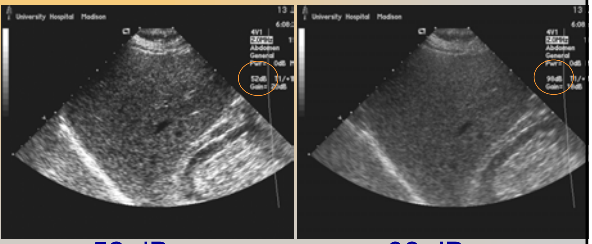


Monitor
Gray-Bar

Monitor
Gray-Bar

Dynamic Range Effects

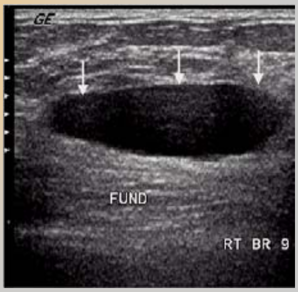


52 dB

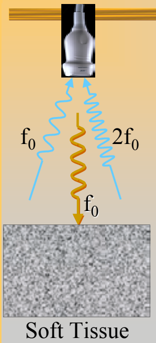
98 dB

Clinical Example: Breast mass (cyst?)

- Cyst on ultrasound:
  - Good “through transmission” (fluids have lower attenuation than tissues)
  - Echo free (just fluid; no reflectors)



Tissue Harmonic Generation



Transmitted Pulse

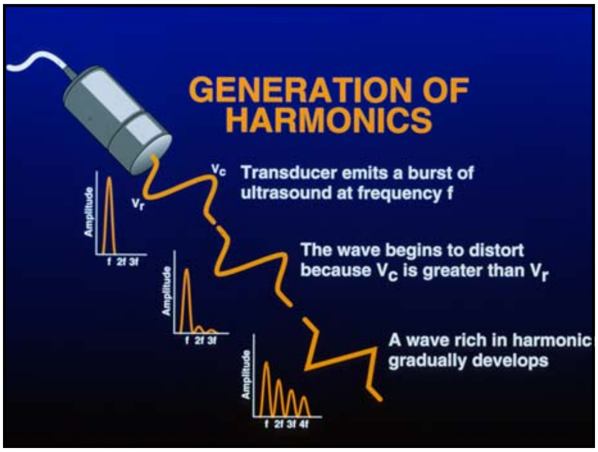
f_0 “Fundamental”

Reflected Echoes

f_0 “Fundamental”

2 f_0, 2nd Harmonic

Transmit Freq.	2nd Harmonic Freq.
2.25 MHz	4.5 MHz
3 MHz	6 MHz
5 MHz	10 MHz



GENERATION OF HARMONICS

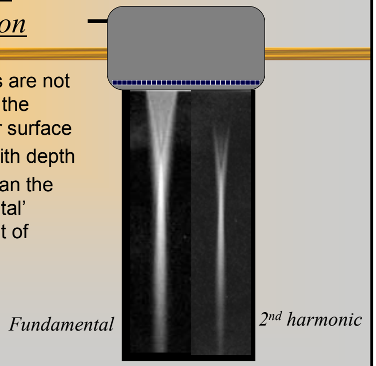
Transducer emits a burst of ultrasound at frequency f

The wave begins to distort because V_c is greater than V_r

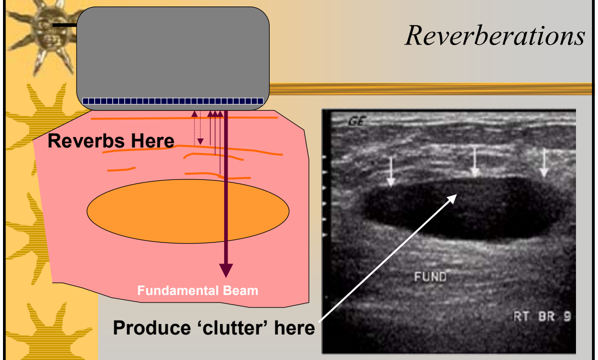
A wave rich in harmonic gradually develops

Harmonic Generation

- Harmonics are not present at the transducer surface
- Build up with depth
- Weaker than the ‘fundamental’ component of beam



Reverberations

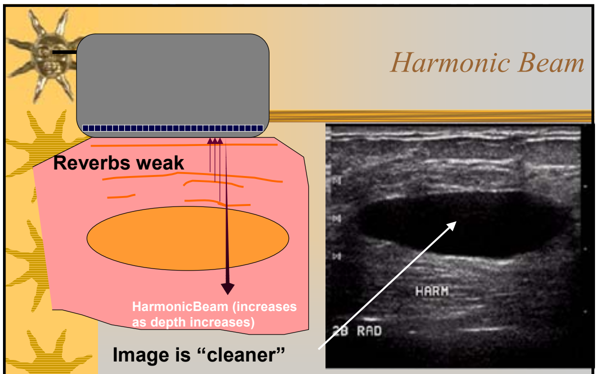


Harmonic Generation

- Harmonics are not present at the transducer surface
- Build up with depth
- Weaker than the ‘fundamental’ component of beam
- Can filter out fundamental frequency signals, only image with harmonic signals!

2nd harmonic

Harmonic Beam

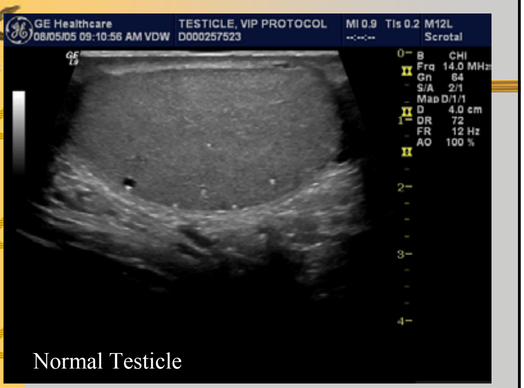


Reverbs weak

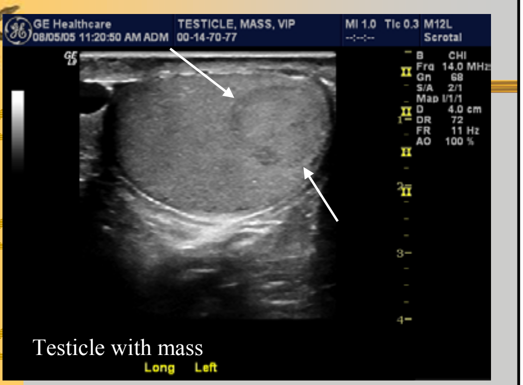
HarmonicBeam (increases as depth increases)

Image is “cleaner”

Gallstone

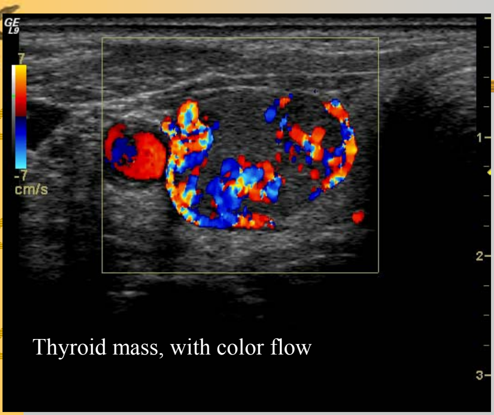


Normal Testicle



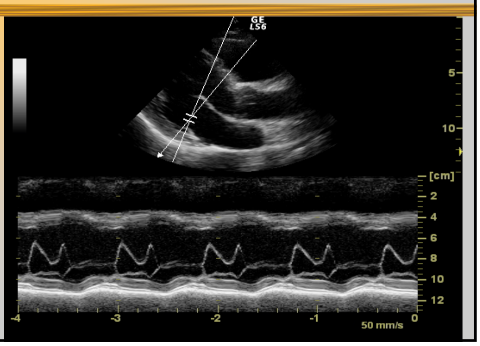
Testicle with mass

Thyroid mass

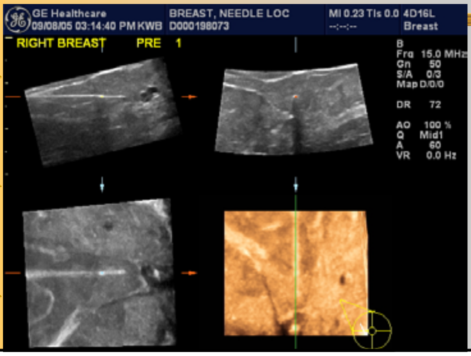


Thyroid mass, with color flow

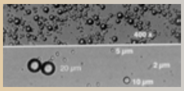
Cardiac



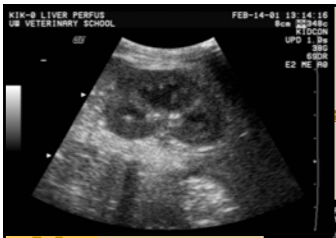
Biopsy, interventional



What's new? Contrast agents



Agent	**Mean Diameter**	**Shell/Gas Composition**
Optison	4 (microns)	Albumin/perfluorocarbon
Definity	2-6	Liposome/perfluorocarbon
Imagent	5	Surfactant membrane/perfluorohexane
Sonovue	2.5	Phospholipid/sulfer hexafluoride
Sonazoid	2-4?	Polymer/sulfer hexafluoride
AI-700	2-4?	Ploymer



Harmonic image, dog kidney

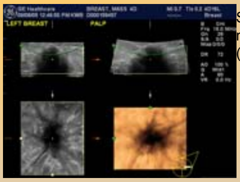
Harmonic image, dog kidney, 23 s after injection of "Definity"

What's new? 3-D

Resliced longitudinal view of a thyroid nodule (arrows) obtained from a 3D data set acquired in the transverse plane. With calibrated 3D scanning it is possible to acquire all needed thyroid data in the transverse plane and obtain longitudinal measurements from reconstructions in parasagittal planes.

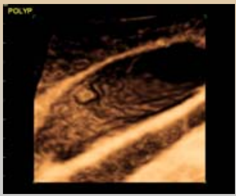
- Acquire volumetric data sets
- Skilled sonographer uses workstation to reformat image data for interpretation by sonographer and/or physician

Examples

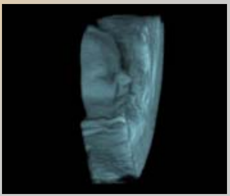


Spiculated mass (breast)

Umbilical cord



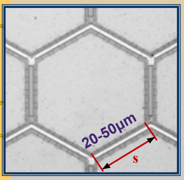
Gall bladder polyp

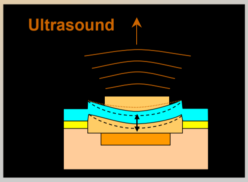


Fetal face

What's new? New Transducer Technology, CMUTS

- Operate like miniature drum heads
- Can integrate electronics directly on the sensor
- Excellent sensitivity; wide bandwidth; capacity for very dense elements
- Could significantly increase choices of 2-D, 3-D, and 4-D pulse-echo operation!





CMUT's (Capacitive micro-fabricated ultrasound transducers – www.sensant.com)

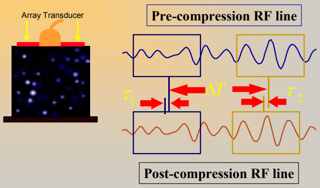
CMUT

PZT

Images of a mass in the breast

What's new? Parametric Imaging

Strain Imaging; Elasticity Imaging; Palpation imaging



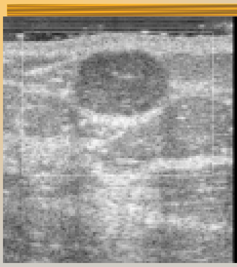
Pre-compression RF line

Post-compression RF line

(Gradient of the axial displacement)

$$Strain = \frac{\tau_2 - \tau_1}{\Delta T}$$

Strain Imaging with Ultrasound: breast

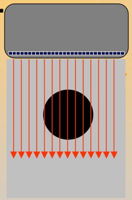


B-Mode Image

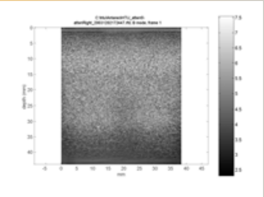
Tim Hall, University of Wisconsin

Elastogram

Compound Attenuation Image (Antares, 10 MHz)

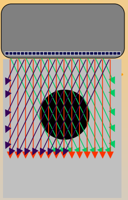


Cylinder A
1cm diameter
No BSC Contrast
0.7 dB/cm-MHz

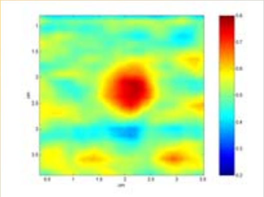


Shadow

High Frequency Compound Attenuation Image (Antares, 10 MHz)



Cylinder A
1cm diameter
No BSC Contrast
0.7 dB/cm-MHz



Measure energy lost/unit distance

Form attenuation images

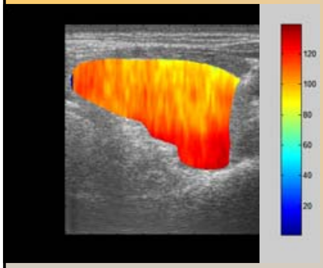
Parametric Imaging of Scatterer Size

- Acquire RF data from sample;
- Use a “reference phantom” to determine backscatter coefficient, BSC(ω) of sample (5 mm segments)
- Find scatterer size (correlation model) that yields closest fit of BSC(ω) frequency dependence.

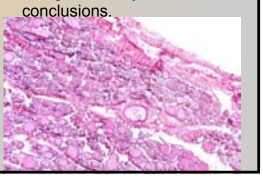
$$\hat{a} = \arg\min \frac{1}{n}\sum_{\omega_{\min}}^{\omega_{\max}}\left[\psi(\omega,\hat{a}) - \overline{\psi}(\hat{a})\right]^2$$

$$\psi(\omega,\hat{a}) = \log(BSC_s(\omega)) - \log(BSC_r(\omega,\hat{a}))$$

Scatterer size imaging



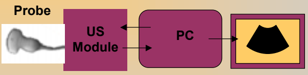
- Analyze frequency content of echo signals
- Fit to scattering models, where a free parameter is the size of the scatterer
- Normal thyroid:100-200 μm lobules
- Scatterer size image data appears to correlate, though too early to draw conclusions.



Compact Ultrasound

US Machine of the future

- Versatile, software controlled instruments



- In the future we can anticipate “smarter machines” with an acoustic “front end” linked to a versatile computer. (Transducer attached to a computer.) These will range from:
  - Sophisticated, high priced
  - Very basic, low cost

Summary

- Ultrasound imaging is a soft tissue imaging modality, requiring a soft tissue “window” to the organ of interest.
- Modern instruments continue to improve, through new transducer technology, incorporation of miniature digital devices, advanced signal and image processing, incorporation of contrast agents, volumetric acquisitions, image fusion, etc.
- Ultrasound plays a key role in all facets of medical imaging (liver, gall bladder, kidneys, prostate, breast, uterus, fetus, blood vessels, tumor detection, interventional, etc)