Ultrasound
Bushberg – Chapter 16
RSNA & AAPM Physics Curriculum: Module 15

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a copy of this lecture may be found at:
http://courses.washington.edu/radxphys/PhysicsCourse.html

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Sources of information on Fluoroscopy

- Bushberg Chatper 16
- AAPM/RSNA web modules
  - Basic US Imaging and Display
  - Image Quality – Artifacts – Doppler
  - US – Concepts and Transducers
- AAPM/RSNA Physics Tutorials
  - Topics in US: Doppler US Techniques: Concepts of Blood Flow Detection and Flow Dynamics
    Radiographics 2003; 23: 1315-1327
  - Topics in US: B-mode US: Basic Concepts and New Technology
    Radiographics 2003; 23: 1019-1033
- AAPM/RSNA Physics Curriculum – Module 15 Outline

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Lecture Objectives

- Lecture 1
  - Characteristics of sound waves
    - Sound propagation; wavelength, frequency, amplitude, etc; pressure, intensity, dB scale
  - Interactions of ultrasound with material
    - Impedance, reflection, refraction, scattering, attenuation
  - Introduction to image acquisition
    - U/S components, pulse-echo imaging operation
- Lecture 2
  - Transducers
  - Image properties and qualities
    - Near vs. far field; Fresnel zone;
    - Spatial resolution (axial, lateral, and elevational), distance measurements, contrast
  - More on image acquisition
    - image formation (transmit power, gain, TGC, frame rate, etc)
- Lecture 3 – June 24th
  - Clinical ultrasound lecture – Dr. Tasneem Lalani
    - Doppler, harmonic imaging, 3D, etc; discussion on artifacts and diagnosis

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Characteristics of Sound

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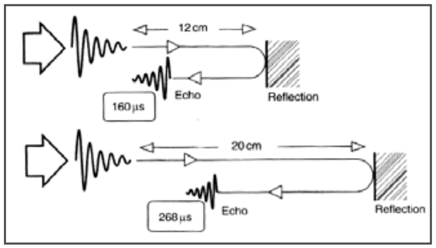
Ultrasound: Characteristics of Sound

The basics – how ultrasound images are formed?

- Mechanical energy is transmitted into tissue producing vibrations
- Energy propagates through the tissue
- _Time_ between pulse emission and echo return determines _depth_
- _Amplitude_ of the echo determines _grey scale_
- “call and response” pulse-echo imaging

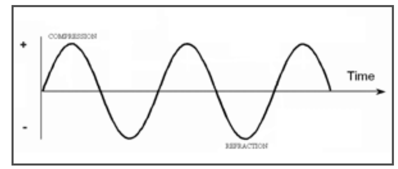


c.f. Dowsett, et al. The Physics of Diagnostic Imaging, 2nd ed., p. 512.

Ultrasound: Characteristics of Sound

Propagation of Sound

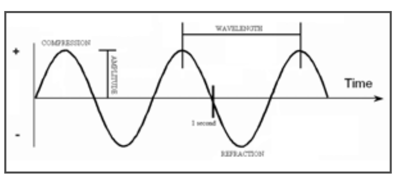
- Sound is mechanical energy
- Particles in the medium transfer the mechanical energy (small back and forth displacement); vibrational motion produces
  - Compression (high pressure = high amplitude signal)
  - Refraction (low pressure = low amplitude signal)



Ultrasound: Characteristics of Sound

Wavelength, frequency and speed

- Wavelength (λ) [mm or µm] – distance between compression and refraction (distance b/w two repeated points on a sine wave)
- Frequency (f) [cycles per second = Hertz (Hz)] – number of times the wave oscillates through a cycle each second
  - _Infrasound_ – sound w/ f < 15 Hz
  - _Audible_ – 15 Hz < f < 20 kHz
  - _Ultrasound_ – f > 20 kHz (*generally, medical ultrasound is 2-10 MHz*)
- Period (1/f) [seconds] – time duration of one wave cycle



Ultrasound: Characteristics of Sound

Wavelength, frequency and speed

- Wavelength (λ) [mm or µm]
- Frequency (f) [Hz]
- Period (1/f) [sec]
- Speed (velocity) of sound [m/sec] –
  - Distance traveled per unit time

$$c\,[\text{m/sec}] = \frac{\lambda[m]}{period[\sec]} = \frac{\lambda[m]}{1/f[Hz]}$$

$$c\,[\text{m/sec}] = \lambda[m] \cdot f[Hz]$$

  - Speed of sound depends on the bulk modulus (B) and density (ρ) of the medium it is propagating
    - Bulk modulus (B) measures the stiffness (resistance to being compressed)
      - In compressible mediums (air), speed of sound is slow
      - In less compressible mediums (bone), speed of sound is fast
    - In less density (ρ) mediums, the higher speed of sound fast

$$c\,[\text{m/sec}] = \sqrt{\frac{B\,[\text{kg per m-sec}^2]}{\rho\,[\text{kg per m}^3]}}$$

Ultrasound: Characteristics of Sound

$c = \lambda \cdot f$ $\quad c = \sqrt{\frac{B}{\rho}}$

Bushberg. Table 16-1. Density and speed of sound in tissues and materials for medical ultrasound.

Material	Density (kg/m³)	c (m/s)	c (mm/µs)
Air	1.2	330	0.33
Lung	300	600	0.60
Fat	924	1,450	1.45
Water	1,000	1,480	1.48
Soft Tissue	1,050	1,540	1.54
Kidney	1,041	1,565	1.57
Blood	1,058	1,560	1.56
Liver	1,061	1,555	1.55
Muscle	1,068	1,600	1.60
Skull Bone	1,912	4,080	4.08
PZT	7,500	4,000	4.00

- ***Review Question:***
  Using a 2 MHz beam, what is the wavelength in soft tissue?

$$\lambda = \frac{c}{f} = \frac{1540\ \text{m/s}}{2\ \text{MHz}} = \frac{1540\ \text{m/s}}{2 \times 10^6\ /\text{s}}$$
$$\lambda = 0.00077\text{m} = 0.77\text{mm}$$

- What if a 10 MHz beam is used?

$$\lambda = \frac{c}{f} = \frac{1540\ \text{m/s}}{10 \times 10^6\ /\text{s}}$$
$$\lambda = 0.154\text{mm}$$

- *Important Concept: a higher frequency beam has a shorter wavelength*

Ultrasound: Characteristics of Sound

$c = \lambda \cdot f$ $\quad c = \sqrt{\frac{B}{\rho}}$

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Skull Bone	1,912	4,080	4.08
PZT	7,500	4,000	4.00

- ***Review Question:***
  A 5 MHz beam travels from soft tissue into fat. Calculate the wavelength in each medium and percent wavelength change.

In soft tissue:
$$\lambda = \frac{c}{f} = \frac{1540\ \text{m/s}}{5\ \text{MHz}} = 0.31\ \text{mm}$$

In fat:
$$\lambda = \frac{c}{f} = \frac{1450\ \text{m/s}}{5\ \text{MHz}} = 0.29\ \text{mm}$$

A decrease in wavelength of 5.8% is due to the different speeds of sound in each tissue.

Ultrasound: Characteristics of Sound

Wavelength, frequency and speed

Note – the change in (Δ) c affects the wavelength at tissue interfaces, *but the U/S frequency is NOT affected as it propagates through different media.*

The wavelength and frequency determine resolution and attenuation.

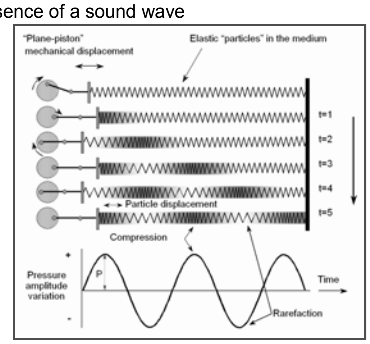
- High frequency (small wavelength) → improved spatial resolution, however, depth of penetration is reduced
- Low frequency (long wavelength) → increased depth of penetration, but resolution is degraded
- *More on penetration and resolution (and image quality) later…*

Constructive and destructive interference – mostly dependent on phase

Ultrasound: Characteristics of Sound

Pressure, intensity, and dB Scale

- Recall: mechanical energy causes particle displacements, which alter local pressure in propagation medium
- Pressure amplitude – peak max or min value from the average pressure in the absence of a sound wave



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 471.

Ultrasound: Characteristics of Sound

Pressure, intensity, and dB Scale

Note: Newton (N) is a unit of force $N = \frac{kg \cdot m}{s^2}$

- Pressure (P) [pascal (Pa)]
  - 1 Pa = 1 Newton (N) per m^2
  - Atmosphere: P = 14.7 lbs per in^2 = 100,000 Pa = 100 kPa = 0.1 MPa
  - Diagnostic U/S pressure on the order of about 1 MPa
- Intensity (I) [milliwatts per cm^2] – power (energy per unit time) per unit area

$$I \propto P^2$$

  - Absolute intensity level depends on method of U/S production (pulsed or continuous)
- Relative intensity and power are described in units terms decibel (dB)
  - In diagnostic U/S, the intensity of the incident pulse can be up to 1 million times more than the echo pulse
  - The log function "compresses" the large ratios and "expands" the small ratios into a more manageable range.

Ultrasound: Characteristics of Sound

Pressure, intensity, and dB Scale

- Relative intensity and power are described in units terms decibel (dB)

$$\text{Relative Intensity (dB)} = 10\log\left(\frac{I_2}{I_1}\right)$$

$$\text{Relative Power (dB)} = 20\log\left(\frac{P_2}{P_1}\right)$$

- A change in 10 dB → an order magnitude (10x) change in intensity
- A change in 20 dB → two orders magnitude (100x) change in intensity

Review Question: Find the "half-value" thickness for ultrasound.

The half-value thickness indicates the intensity is decreased by 50%.

$$\text{dB} = 10\log\left(\frac{I_2}{I_1}\right) = 10\log(0.5) = -3\,\text{dB}$$

Ultrasound: Characteristics of Sound

Pressure, intensity, and dB Scale

- ***Review Question***: Calculate the remaining intensity of a 100-mW U/S pulse that loses 30 dB while traveling through tissue.

$$-30\text{dB} = 10\log\left(\frac{I_2}{100mW}\right)$$

$$-3 = \log\left(\frac{I_2}{100mW}\right)$$

$$10^{-3} = \left(\frac{I_2}{100mW}\right)$$

$$I_2 = \left(10^{-3}\right)\left(100mW\right) = 0.1mW$$

Ultrasound Interactions with Matter

Interactions of Ultrasound with Matter

Interactions are dependent on acoustic properties of matter.

- Acoustic Impedance
- Interactions
  - Reflection – occurs at tissue boundaries (acoustic impedance of adjacent materials)
  - Refraction – change in direction of transmitted energy
  - Scattering – occurs by reflection or refraction; energy diffuses in many direction (affects texture and grey scale of acoustic image)
  - Absorption – acoustic energy is converted into heat (sounds energy is lost)
  - Attenuation – loss of intensity from absorption and scattering

Interactions of Ultrasound with Matter

Acoustic Impedance (Z)

- Similar to the stiffness and flexibility of spring
- Dependent on medium density and speed of sound
- SI Units is 1 kg per m² per second = 1 rayl

$$Z = \rho \cdot c$$
$$Z[\text{rayls}] = \rho[\text{kg per m}^3] \cdot c[\text{m per sec}]$$

Bushberg. Table 16-3. Acoustic impedance (Z) for selected tissues

Tissue	Z (rayls)
Air	0.0004×10^6
Lung	0.18×10^6
Fat	1.34×10^6
Water	1.48×10^6
Kidney	1.63×10^6
Blood	1.65×10^6
Liver	1.65×10^6
Muscle	1.71×10^6
Skull bone	7.8×10^6

Interactions of Ultrasound with Matter

Acoustic Impedance (Z)

$$Z = \rho \cdot c$$

- For the energy transfer between two adjacent mediums:
  - A large difference in the impedance results in a large reflection of energy
  - A minor difference in the impedance allows continued propagation of energy (little reflection at the interface)
  - Example: soft tissue to air-filled lung – large ΔZ, beam almost entirely reflected
  - …whereas if $Z_1 \sim Z_2$, then only minor reflections occur
- *Important concept: acoustic impedance gives rise to difference in transmission and reflection of U/S energy (basis for pulse echo imaging)*

c.f. Scherzinger & Stamm. AAPM/RSNA Web Modules. Ultrasound Concepts and Transducers. Section III: Impedance.

Interactions of Ultrasound with Matter

Reflection – result of acoustic impedance

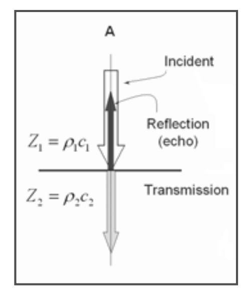
- Reflection coefficient – describes fraction of sound intensity incident on a interface that is reflected
- Note: reflection depends on angle of incidence…
- FOR PERPENDICULAR INCIDENCE:
  - *Intensity reflection coefficient*
    Recall: Intensity is proportional to P²

$$R_I = \frac{I_r}{I_i} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

  - *Pressure reflection amplitude coefficient*

$$R_P = \frac{P_r}{P_i} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

$$I \propto P^2$$



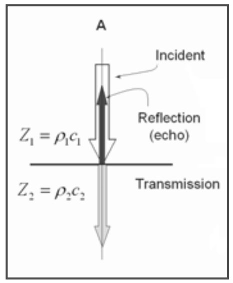
c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 478.

Interactions of Ultrasound with Matter

Reflection

- Intensity transmission – (T_I) fraction of incident intensity transmitted across the boundary
  - *Conservation of energy –* $T_I = 1 - R_I$

$$R_I = \frac{I_r}{I_i} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$



Interactions of Ultrasound with Matter

Review Question: *What percentage of the U/S beam is transmitted from fat to muscle?*

$$R_{I(fat\rightarrow muscle)} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 = \left(\frac{1.71-1.34}{1.71+1.34}\right)^2 = 0.015$$

$$T_{I(fat\rightarrow muscle)} = 1 - R_{I(fat\rightarrow muscle)} = 0.985$$

98.5% of the ultrasound is transmitted across the interface

Review Question: *What percentage is transmitted from muscle to lung?*

$$R_{I(muscle\rightarrow lung)} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 = \left(\frac{0.18-1.71}{0.18+1.71}\right)^2 = 0.655$$

$$T_{I(muscle\rightarrow lung)} = 1 - R_{I(muscle\rightarrow lung)} = 0.345$$

$$R_I = \frac{I_r}{I_i} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

Bushberg. Table 16-3. Acoustic impedance (Z) for selected tissues

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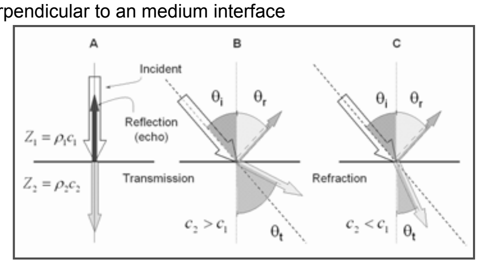
Interactions of Ultrasound with Matter

Refraction

- As with light, sound is *refracted* if the incident sound is not perpendicular to an medium interface



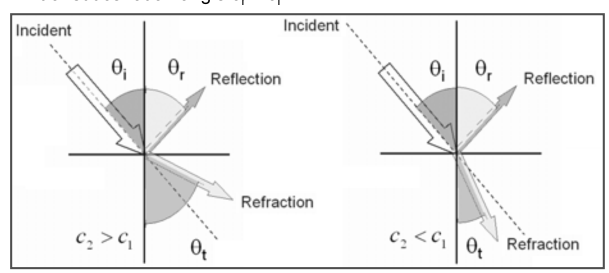
- Remember, U/S frequency does not change at the boundary
- Speed of the sound (both transmitted and reflected) changes
- Angles (measured relative to normal incidence at the boundary) of transmission and reflection are determined by the change in the speed of sound

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 478.

Interactions of Ultrasound with Matter

Refraction

- The refraction angle increases with the speed difference and the incident angle according to Snell's Law $\frac{\sin\theta_t}{\sin\theta_i} = \frac{c_2}{c_1}$
  - When $c_2 > c_1$, then $\theta_t > \theta_i$
  - When $c_2 < c_1$, then $\theta_t < \theta_i$
- The reflected fraction of the incident beam is directed away from the transducer at an angle $\theta_r = \theta_i$

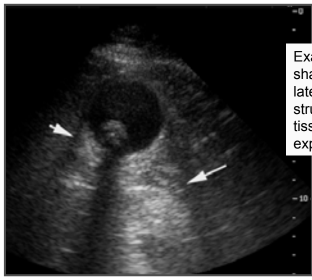


c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 478.

Interactions of Ultrasound with Matter

Refraction

- No refraction if…
  - Angle of incident is normal
  - Speed of sound is the same in both mediums
- Straight line propagation is assumed in ultrasound
  - Refraction ‘artifacts’ cause shadows and enhancements because the sound waves are bent from their expected paths



Example: Refraction causes the shadows (arrows) seen at the lateral edges of fluid-filled structures as sound passes from tissue to fluid and is bent from its expected path.

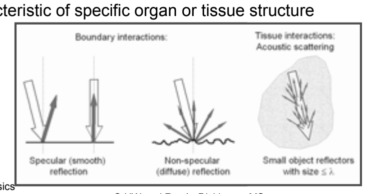
c.f. Scherzinger & Stamm. AAPM/RSNA Web Modules. Ultrasound Concepts and Transducers. Section IV: Refraction. Fig. 13

Interactions of Ultrasound with Matter

Scattering

- Specular reflectors – smooth boundary between media; uniform medium
- Diffuse reflectors – irregular surfaces or media
  - Reflects fewer echoes directly back to the transducer
  - Can cause diminished strength (amplitude) in echoes because of destructive interference

- Two cases for scattering:
  - At the boundary – smaller wavelengths cause the boundary to become ‘rough’ and the reflections become diffuse
  - Or small object reflectors in tissue – diffuse scattering patterns are characteristic of specific organ or tissue structure



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 480.

Interactions of Ultrasound with Matter

Scattering

Small object reflectors characteristic of an organ

The arrows represent sound scattered from “reflectors” in the normal liver. These waves interfere, causing notable echotexture patterns for many normal and pathologic tissues.

c.f. Scherzinger & Stamm. AAPM/RSNA Web Modules. Ultrasound Concepts and Transducers. Section II.A. Fig. 4.

Interactions of Ultrasound with Matter

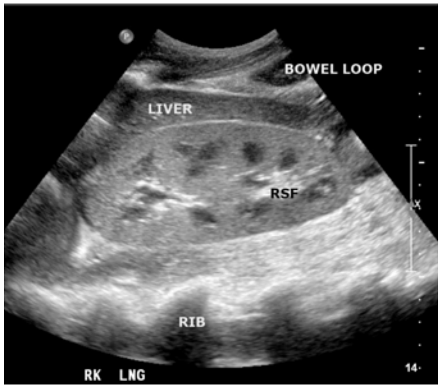
Scattering

- Scatter from diffuse reflectors affects the signal amplitude
- Scatter depends on:
  - Number of scatters (small objects) per unit volume
  - Acoustic impedance difference
  - Size of the scatters
  - Ultrasonic frequency (because frequency is relate to wavelength)

- *Hyperechoic* – high scatter amplitude relative to avg background signal
- *Hypoechoic* – lower scatter amplitude relative to avg background signal

Interactions of Ultrasound with Matter

Scattering



Note the differing U/S appearance of anatomic structures

Bright or Hyperechoic Structures
- Renal sinus fat

Dark or Hypoechoic Structures
- Renal pyramids
- Fluid filled bowel loop

Uniform, mid-level echogenicity
- Liver
- Renal cortex

Notable reflective surfaces
- Anterior surface of kidney
- Anterior surface of liver

c.f. Scherzinger & Stamm. AAPM/RSNA Web Modules. Ultrasound Concepts and Transducers. Section II.B. Fig. 3.

Interactions of Ultrasound with Matter

Attenuation – results from scatter and absorption (heat)

- Attenuation is the loss of acoustic energy (signal amplitude)
- Absorbed acoustic energy
  - Attenuation coefficient, μ [dB per cm], is relative intensity lost per centimeter of travel
  - U/S attenuation is approximately proportional to frequency
  - RULE OF THUMB: for soft tissue, the beam intensity attenuates by 0.5 dB per cm per MHz
  - Since the dB scale is logarithmic, the signal intensity is attenuated exponentially with distance
- Ultrasound half value thickness (HVT) – thickness to attenuate incident intensity by 50%
  - Indicates a 3 dB reduction in relative intensity (or 6 dB drop in pressure amplitude)
  - Increasing frequency → decreasing HVT

Interactions of Ultrasound with Matter

Review Question: Calculate the approximate intensity HVT in soft tissue for 2 MHz and 10 MHz ultrasound beams.

Recall: attenuation coefficient ~ 0.5 dB per cm per MHz

Recall: a 50% reduction in intensity corresponds to 3dB

$$HVT_{f[MHz]}[cm] = \frac{3dB}{\left(\frac{0.5\,dB/cm}{MHz}\right)\cdot f[MHz]} = \frac{6[\text{cm per MHz}]}{f[MHz]}$$

$$HVT_{2MHz}[cm] = \frac{6[\text{cm per MHz}]}{2MHz} = 3cm$$

$$HVT_{10MHz}[cm] = \frac{6[\text{cm per MHz}]}{10MHz} = 0.6cm$$

Recall: as frequency increases, HVT decreases.

Interactions of Ultrasound with Matter

Review Question: For the previous question, determine the # of HVTs the incident beam and the echo travel at 6-cm depth.

$$HVT_{2MHz}[cm] = 3cm$$

$$HVT_{10MHz}[cm] = 0.6cm$$

Note: A 6-cm depth requires a travel distance of 12-cm (round trip).

$$\frac{12cm}{3\,\text{cm per HVT}_{2\text{MHz}}} = 4\,\text{HVT}_{2\text{MHz}}$$

$$\frac{12cm}{0.6\,\text{cm per HVT}_{10\text{MHz}}} = 20\,\text{HVT}_{10\text{MHz}}$$

Recall: as frequency increases, HVT decreases and attenuation increases.

Interactions of Ultrasound with Matter

Review Question: Calculate the approximate intensity loss for a 5-MHz U/S wave traveling round trip to a depth of 4 cm in liver and reflected from an encapsulated air pocket (assume 100% reflection).

Using 0.5 dB per cm for a 5-MHz beam, the attenuation coefficient is?

2.5 dB/cm.

Total distance traveled is?

8 cm.

Total intensity lost is?

20 dB. (8 cm * 2.5 dB/cm = 20 dB)

Recall: $$\text{Relative Intensity} = 20\text{ dB} = 10\log\left(\frac{I_{incident}}{I_{echo}}\right)$$

$$10^2 = \frac{I_{incident}}{I_{echo}}$$

$$I_{echo} = 0.01(I_{incident})$$

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Interactions of Ultrasound with Matter

Review Question: In the previous example, the echo intensity is one-hundredth of the intensity of the initial U/S wave intensity.

$$I_{echo} = 0.01(I_{incident})$$

What if the boundary did not have 100% reflection??

Say only 1% of the incident intensity was reflected (a typcial value).

$$\frac{I_{incident}}{I_{echo}} = \frac{I_{incident}}{1\%(0.01 \cdot I_{incident})} = \frac{1}{0.0001} = 10{,}000$$

$$\text{Relative Intensity} = 10\log(10{,}000) = 40dB$$

The point of this exercise is to show that the dynamic range of the U/S transducer is very large…

However, when penetration to deeper structures is important, lower frequency transducers must be used because of the strong dependence of attenuation with frequency

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Ultrasound Image Acquisition

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Ultrasound Image Data Acquisition

Parts of an U/S System – Hardware components

- Beam former – generation of electronic delays for individual transducer elements in an array to achieve transmit/receive focusing and beam steering
- Pulser (transmitter) – electrical voltage for exciting piezoelectric (PZT) elements; controls output transmit power by an applied voltage
  - Increased transmit amplitude increases the SNR but increases power deposition to the patient – power indicated by thermal index (TI) or mechanical index (MI) depending on the vendor
- Transmit/receive switch – synchronized electronically with pulser
  - Transmit – high voltage used for creating pulses is ~150 V
  - Receive – system of amplifiers for return echo induced voltages in PZT (return echoes create ~1V to ~2μV signals)
- Scan converter/image memory
- Display

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Ultrasound Image Data Acquisition

Pulse Echo Operation

- U/S beam intermittently transmitted by the pulser, with a majority of time occupied by listening for echoes
  - "call and response" pulse-echo imaging
  - Transmitted pulse is generally 2-3 cycles long (usually 1-2 μsec pulses)
- Time delay b/w transmit and receive is directly related to the depth of the interface; U/S assumes the speed of sound in soft tissue (1540 m/sec or 0.154 cm/μsec)

$$Time[\mu \sec] = \frac{2D[cm]}{c[cm/\mu \sec]} = \frac{2D[cm]}{0.154\,cm/\mu \sec} = 13\mu \sec \cdot D[cm]$$

$$\text{Distance}\,[cm] = 0.077 \cdot Time(\mu \sec)$$

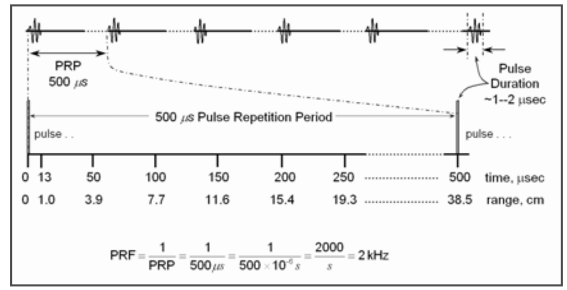
- A one pulse echo sequence produces one amplitude-modulated (A-line) of image data
- Many repetitions are required to construct an image from individual A-lines

Ultrasound Image Data Acquisition

$$\text{Time} = \frac{2D}{c}$$

Pulse Echo Operation

- Transmit the signal
  - Pulse repetition frequency (PRF) – # of times the transducer is pulsed per second (typically, 2 to 4 kHz)
- Listen for echoes
  - Pulse repetition period (PRP) – time between pulses; the inverse of the PRF



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 503.

Ultrasound Image Data Acquisition

Pulse Echo Operation

- Increasing the frequency of the pulses (PRF) results in less listening time
  - If a new pulse is emitted before the most distance echo from the previous pulse returns to the transducer, the echo will be "mapped" as a prompt echo (indicating a signal for a return echo close to the transducer)
- Maximum range – determined by how long the receiver "listens" for echoes

$$\text{Max Range}\,[cm] = \frac{c[cm/\sec] \cdot PRP[\sec]}{2}$$

$$\text{Max Range}\,[cm] = \frac{154{,}000\,cm/\sec \cdot PRP[\sec]}{2}$$

$$\text{Max Range}\,[cm] = 77{,}000\,cm/\sec \cdot PRP[\sec] = \frac{77{,}000\,cm/\sec}{PRF[Hz]}$$

Ultrasound Image Data Acquisition

Pulse Echo Operation

Review Question: For a beam with a 2kHz pulse repetition frequency, what is the corresponding PRP and max range?

$$PRP[\sec] = \frac{1}{PRF[Hz]} = \frac{1}{2kHz} = 0.0005\sec = 500\mu\sec$$

$$\text{Max Range}\,[cm] = \frac{154{,}000\,cm/\sec \cdot 0.0005\sec}{2} = 38.5\,cm$$

Ultrasound Image Data Acquisition

Pulse Echo Operation

- *Caution!!!* Do not confused PRF with the frequency of the transducer!!
  - Transducer frequency is MHz – pulse repetition frequency (PRF) is kHz
  - Transducer period is μsec – pulse repetition period (PRP) is msec
- Previously, we talked about high frequency transducers, which have better resolution, but poor depth penetration. Because the limited depth of penetration, more pulses can be emitted (higher PRF) because the echoes do not have as far to travel.
- Conversely, low frequency transducers (used for penetration), need longer PRP (to listen for distance echoes), therefore low PRF.

Ultrasound Image Data Acquisition

Modes of Operation

- A-mode: amplitude
  - Single pulse echo
  - Clinical Application – ophthalmology
- B-mode: brightness
  - Brightness is proportional to the signal amplitude
  - Used in M-mode and 2D grey-scale imaging
  - Generates a 2D image; covers a plane of interest rather than on single line of transmit/receive
- M-mode: motion
  - Fixed transducer position and beam direction – measure of motion patterns for anatomy along a single line
  - Recent developments in Doppler U/S replaced the need for M-mode