جامعة الانبار
كلية العلوم التطبيقية – هيت
قسم الفيزياء الحياتية

الاجهزة الطبية

Ultrasound I

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Introduction

Ultrasound is a non-ionizing method which uses sound waves of frequencies (2 to 10 MHz) exceeding the range of human hearing for imaging

Medical diagnostic ultrasound uses ultrasound energy and the acoustic properties of the body to produce an image from stationary and moving tissues

Ultrasound is used in pulse-echo format, whereby pulses of ultrasound produced over a very brief duration travel through various tissues and are reflected at tissue boundaries back to the source

Introduction

Returning echoes carry the ultrasound information that is used to create the sonogram or measure blood velocities with Doppler frequency techniques

Along a given beam path, the depth of an echo-producing structure is determined from the time between the pulse-emission and the echo return, and the amplitude of the echo is encoded as a gray-scale value

In addition to 2D imaging, ultrasound provides anatomic distance and volume measurements, motion studies, blood velocity measurements, and 3D imaging

1. Characteristics of Sound Frequency

Frequency (f) is the number of times the wave oscillates through a cycle each second (sec) (Hertz: Hz or cycles/sec)

- Infra sound < 15 Hz
- Audible sound ~ 15 Hz - 20 kHz
- Ultrasound > 20 kHz; for medical usage typically 2-10 MHz with specialized ultrasound applications up to 50 MHz

period (τ) - the time duration of one wave cycle: $\tau = 1/f$

1. Characteristics of Sound Speed

The speed or velocity of sound is the distance travelled by the wave per unit time and is equal to the wavelength divided by the period (1/f)

speed = wavelength / period

speed = wavelength x frequency

$c = \lambda f$

$c\ [m/sec] = \lambda\ [m] * f\ [1/sec]$

Speed of sound is dependent on the propagation medium and varies widely in different materials

1. Characteristics of Sound Speed

TABLE 16-1. DENSITY AND SPEED OF SOUND IN TISSUES AND MATERIALS FOR MEDICAL ULTRASOUND

Material	Density (kg/m^3)	c (m/s)	c (mm/μs)
Air ←	1.2	3[illegible] ←	0.33
Lung	300	6[illegible]	0.60
Fat ←	924	1,4[illegible] ←	1.45
Water	1,000	1,4[illegible]	1.48
Soft tissue ←	1,050	1,5[illegible] ←	1.54
Kidney	1,041	1,5[illegible]	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

PZT, lead-zirconate-titanate.

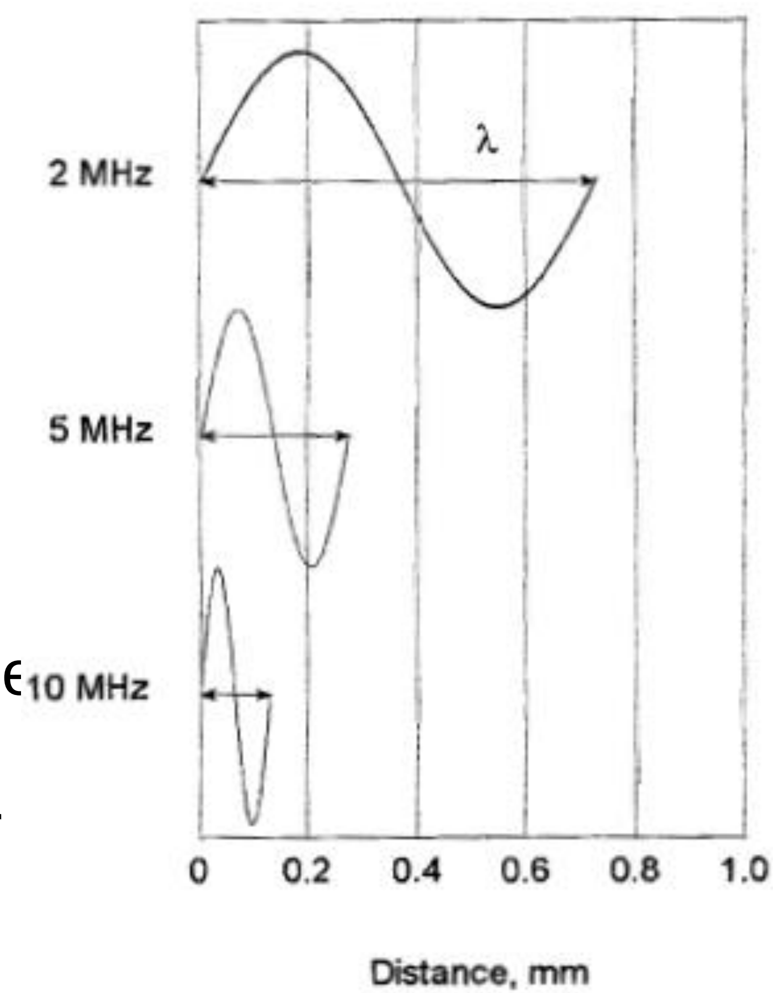
A highly compressible medium such as air, has a low speed of sound, while a less compressible medium such as bone has a higher speed of sound

The difference in the speed of sound at tissue boundaries is a fundamental cause of contrast in an ultrasound image

1. Characteristics of Sound
Wavelength, Frequency and Speed

The ultrasound frequency is unaffected by changes in sound speed as the acoustic beam propagates through various media.

Thus, the ultrasound wavelength is dependent on the medium ($c = \lambda f$)
A change in speed at an interface between two media causes a change in wavelength
Higher frequency sound has shorter wavelength

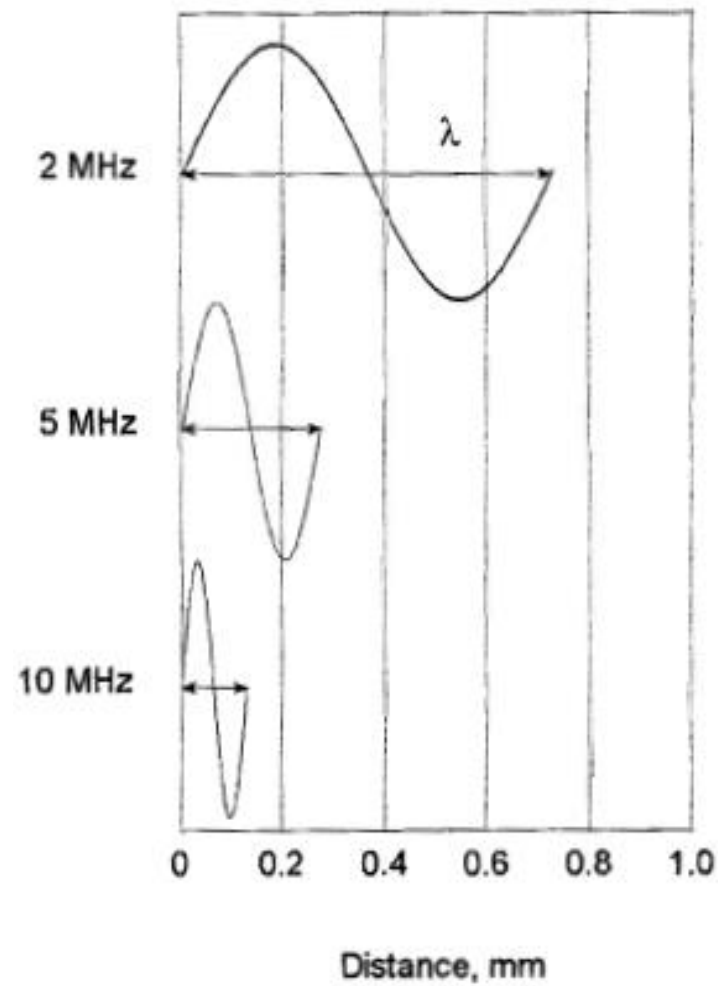


1. Characteristics of Sound Wavelength, Frequency and Speed

Ultrasound wavelength determines the spatial resolution achievable along the direction of the beam

A high-frequency ultrasound beam (small wavelength) provides superior resolution and image detail than a low-frequency beam

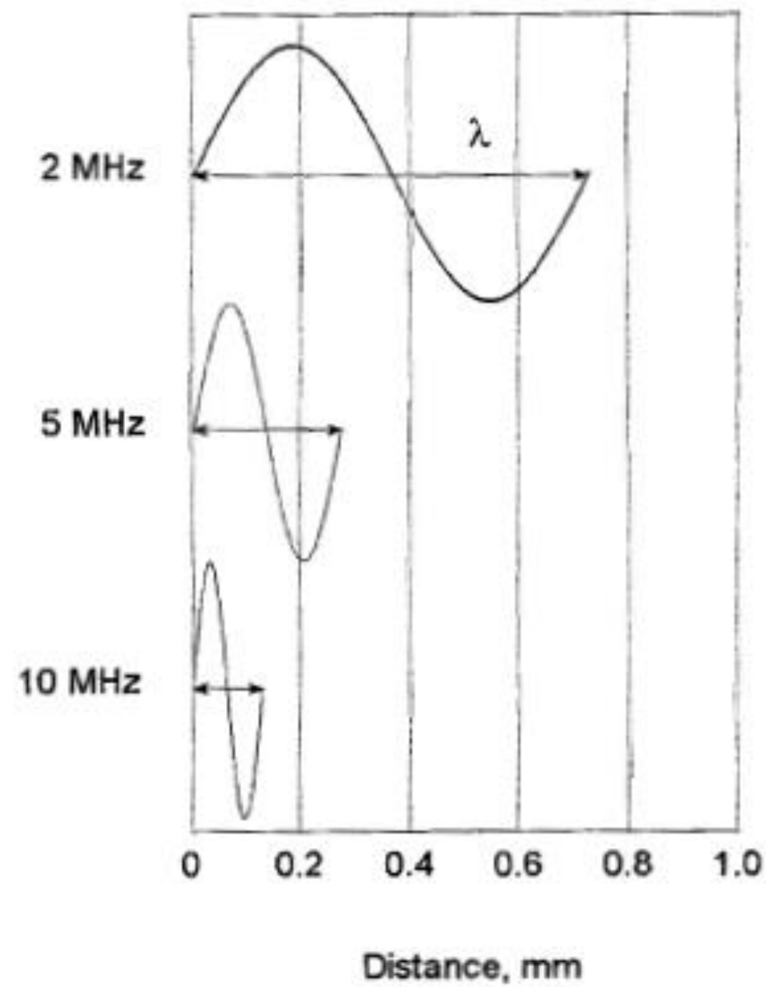
However, the depth of beam penetration is reduced at high frequency and increased at low frequencies



1. Characteristics of Sound Wavelength, Frequency and Speed

For thick body parts (abdomen), a lower frequency ultrasound wave is used (3.5 to 5 MHz) to image structures at significant depth

For small body parts or organs (thyroid, breast), a higher frequency is employed (7.5 to 10 MHz)



D63. The wavelength of a 2 MHz ultrasound beam is _________ mm.
A. 0.02
B. 0.55
C. 0.77
D. 2.0
E. 5.0

D63. The wavelength of a 2 MHz ultrasound beam is _________ mm.
A. 0.02
B. 0.55
C. 0.77 (Answer)
D. 2.0
E. 5.0

C Wavelength $\lambda = c / f$
The average velocity in tissue is 1540 m/sec. Frequency = 2×10^6 /sec
= 1540 m/sec / 2×10^6 /sec = 770×10^{-6} m = 0.77 mm

1. Characteristics of Sound Pressure, Intensity and the dB scale

The amplitude of a wave is the size of the wave displacement
Larger amplitudes of vibration produce denser compression bands and, hence, higher intensities of sound.

Intensity of ultrasound

- is the amount of power (energy per unit time) per unit area
  proportional to the square of the pressure amplitude, $I \propto P^2$
  units of milliwatts/cm^2 or mW/cm^2
- is measured in decibels (dB) as a relative intensity
  - (Losses) $dB = 10 \log_{10} (I_2/I_1)$ or $dB = 20 \log_{10} (P_2/P_1)$
  - I_1 and I_2 are intensity values
  - P_1 and P_2 are pressure or amplitude variations

1. Characteristics of Sound Pressure, Intensity and the dB scale

TABLE 16-2. DECIBEL VALUES, INTENSITY RATIO, AND PRESSURE AMPLITUDE RATIOS

Decibels (dB)	Intensity Ratio		Pressure Amplitude Ratio	
	I_2/I_1	Log (I_2/I_1)	P_2/P_1	Log (P_2/P_1)
0	1	0	1	0
3	2	0.3	1.414	0.15
6	4	0.6	2	0.3
12	16	1.2	4	0.6
20	100	2	10	1
40	10,000	4	100	2
60	1,000,000	6	1000	3
–3	0.5	–0.3	0.707	–0.15
–6	0.25	–0.6	0.5	–0.3
–20	0.01	–2	0.1	–1
–40	0.0001	–4	0.01	–2

1. Characteristics of Sound Pressure, Intensity and the dB scale

Example: Calculate the remaining intensity of a 100-mW ultrasound pulse that loses 30 dB while traveling through tissue.

Relative Intensity (dB)

$$= 10 \log \frac{I_2}{I_1}$$

$$-30 \text{ dB} = 10 \log \frac{I_2}{100 \text{ mW}}$$

$$-3 = \log \frac{I_2}{100 \text{ mW}}$$

$$10^{-3} = \frac{I_2}{100 \text{ mW}}$$

$$I_2 = 0.001 \text{x} 100 \text{ mW} = 0.1 \text{mW}$$

1. Characteristics of Sound – Key Points

Propagation of sound - Key Points

- **Speed of sound is dependent on the medium**
- **Ultrasound frequency is independent of the medium, and does not change**
- **Wavelength changes with the changes of speed**

c [m/sec] = λ [m] * f [1/sec]

For most calculations, the average speed of sound in soft tissue=1540 m/sec,
In air = 330 m/sec
and in fatty tissue = 1450 m/sec

2. Interactions of Ultrasound with Matter

Ultrasound interactions are determined by the acoustic properties of matter

As ultrasound energy propagates through a medium, interactions that occur include

- reflection
- refraction
- scattering
- Absorption (attenuation)

2. Interactions of Ultrasound with Matter
Acoustic Impedance

Acoustic Impedance, Z

is equal to density of the material times speed of sound in the material in which ultrasound travels, $Z = \rho c$

ρ = density (kg/m^3) and c = speed of sound (m/sec)

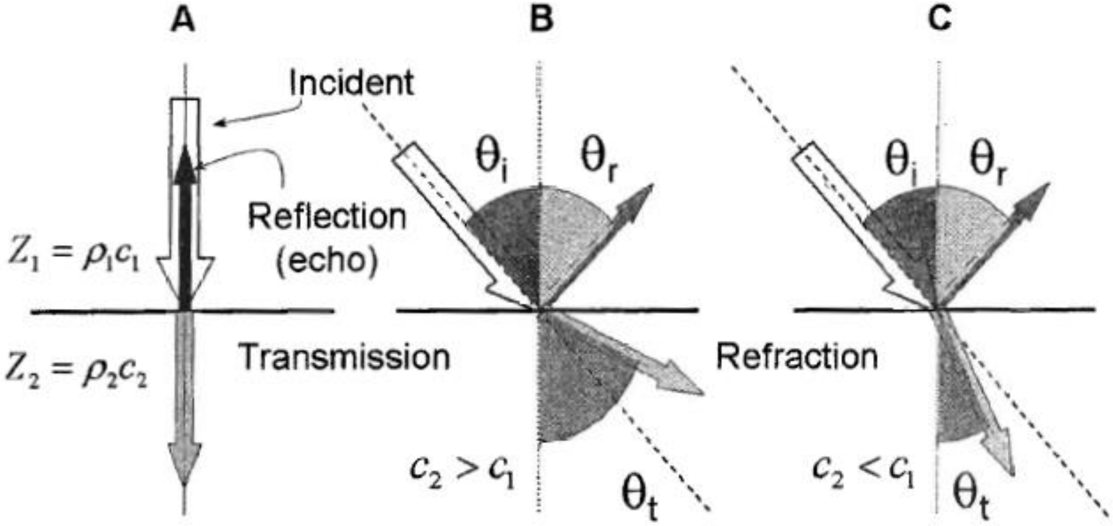
measured in rayl (kg/m^2sec)

Air and lung media have low values of Z, whereas bone and metal have high values

Large differences in Z (air-filled lung and soft tissue) cause reflection, small differences allow transmission of sound energy

The differences between acoustic impedance values at an interface determines the amount of energy reflected at the interface

2. Interactions of Ultrasound with Matter
Reflection



A portion of the ultrasound beam is reflected at tissue interface

- The sound reflected back toward the source is called an echo and is used to generate the ultrasound image
- The percentage of ultrasound intensity reflected depends in part on the angle of incidence of the beam
- As the angle of incidence increases, reflected sound is less likely to reach the transducer

2. Interactions of Ultrasound with Matter Reflection

Sound reflection occurs at tissue boundaries with differences in acoustic impedance

- The intensity reflection coefficient, $R = I_r/I_i = ((Z_2 - Z_1)/(Z_2 + Z_1))^2$
- The subscripts 1 and 2 represent tissues proximal and distal to the boundary.
- Equation only applies to normal incidence
- The transmission coefficient = T = 1 – R
- $T = (4Z_1Z_2)/(Z_1+Z_2)^2$

TABLE 16-4. PRESSURE AND REFLECTION COEFFICIENTS FOR VARIOUS INTERFACES

Tissue Interface	Pressure Reflection	Intensity Reflection
Liver–kidney	–0.006	0.00003
Liver–fat	–0.10	0.011
Fat–muscle	0.12	0.015
Muscle–bone	0.64	0.41
Muscle–lung	–0.81	0.65
Muscle–air	–0.99	0.99

Diagnostic Question

D54. Approximately what fraction of an ultrasound beam is reflected from an interface between two media with Z values of 1.65 and 1.55?

A. 1/2

B. 1/10

C. 1/100

D. 1/500

E. 1/1024

$$R = ((Z_2 - Z_1)/(Z_2 + Z_1))^2$$
$$= (1.65-1.55)^2 / (1.65 + 1.55)^2 = 1/1024$$

Diagnostic Question

D58. Ultrasound moves with the highest velocity in:

	medium	Z
A.	Fat	1.38×10^6
B.	Blood	1.61×10^6
C.	Muscle	$1{:}70 \times 10^6$
D.	Bone	7.80×10^6

2. Interactions of Ultrasound with Matter
Tissue reflections

- Air/tissue interfaces reflect virtually all of the incident ultrasound beam Gel is applied to displace the air and minimize large reflections
- Bone/tissue interfaces also reflect substantial fractions of the incident intensity
- Imaging through air or bone is generally not possible
  - The lack of transmissions beyond these interfaces results in an area void of echoes called shadowing
- In imaging the abdomen, the strongest echoes are likely to arise from gas bubbles
- Organs such as kidney, pancreas, spleen and liver are comprised of sub-regions that contain many scattering sites, which results in a speckled texture on images
- Organs with fluids such as bladder, cysts, and blood vessels have almost no echoes (appear black)

2. Interactions of Ultrasound with Matter Refraction

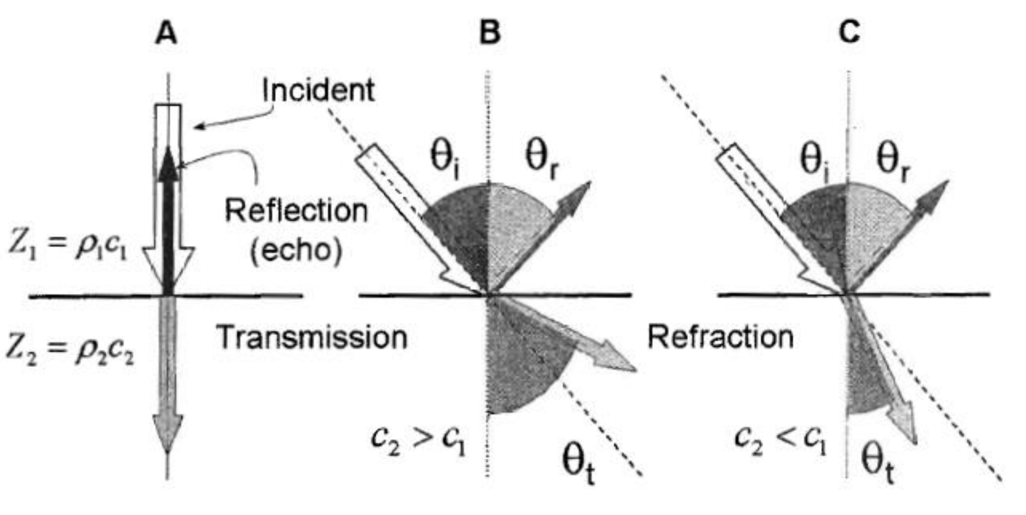
Refraction is the change in direction of an ultrasound beam when passing from one medium to another with a different acoustic velocity, Wavelength changes causing a change in propagation direction ($c = \lambda f$)

$\sin(\theta_t) = \sin(\theta_i) * (c_2/c_1)$, Snell's law;

for small $\theta \leq 15^o$: $\theta_t = \theta_i * (c_2/c_1)$

When $c_2 > c_1$, $\theta_t > \theta_i$, When $c_1 > c_2$, $\theta_t < \theta_i$

Ultrasound machines assume straight line propagation



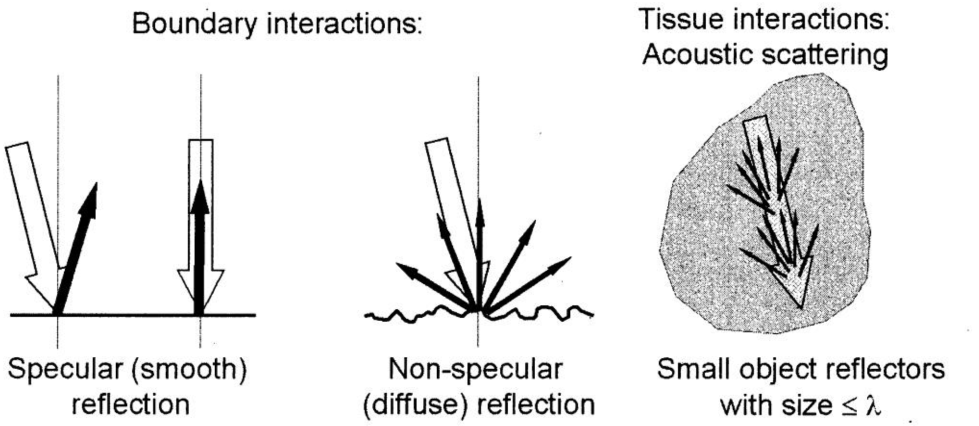
2. Interactions of Ultrasound with Matter Scatter

Acoustic scattering arises from objects within:

- tissue that are about the size of the wavelength of the incident beam or smaller,
- represent a rough or nonspecular reflector surface

As frequency increases, the non-specular (diffuse scatter) interactions increase, resulting in an increased attenuation and loss of echo intensity

Scatter gives rise to the characteristic speckle patterns of various organs, and is important in contributing to the grayscale range in the image



2. Interactions of Ultrasound with Matter Attenuation

Ultrasound attenuation, the loss of energy with distance travelled, is caused chiefly by scattering and tissue absorption of the incident beam (dB)

The intensity loss per unit distance (dB/cm) is the attenuation coefficient

- Rule of thumb: attenuation in soft tissue is approx. **1 dB/cm/MHz**

- The attenuation coefficient is directly proportional to and increases with frequency

Attenuation is medium dependent

2. Interactions of Ultrasound with Matter – Key Points

Acoustic Impedance, Z

is equal to density of the material times speed of sound in the material in which ultrasound travels,

$$Z = \rho c$$

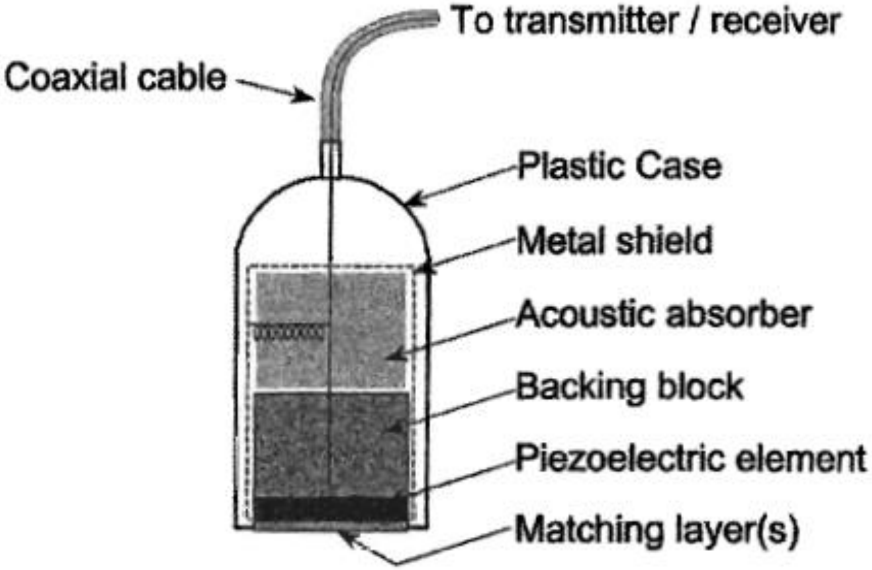
ρ = density (kg/m^3) and c = speed of sound (m/sec)

As ultrasound energy propagates through a medium, interactions that occur include

- reflection
- refraction
- scattering
- Absorption (attenuation)

3. Transducers

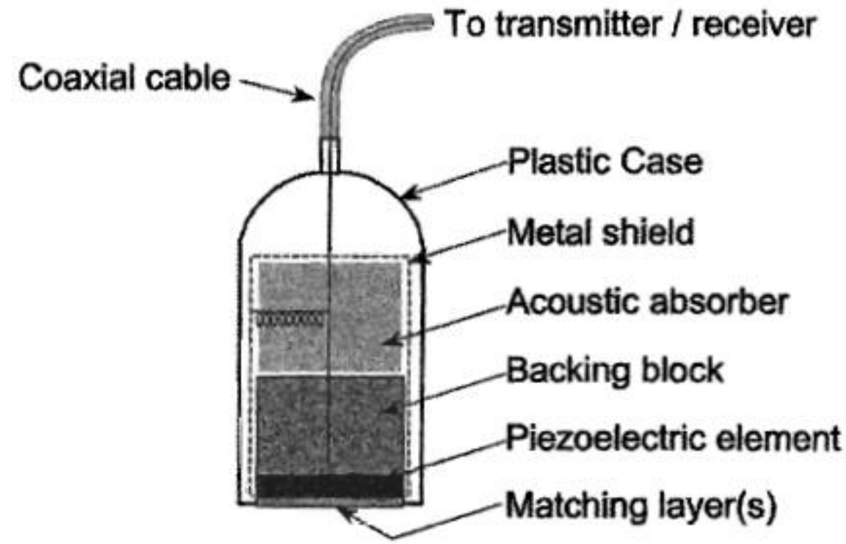
- A transducer is a device that can convert one form of energy into another
- Piezoelectric transducers convert electrical energy int ultrasonic energy and vice versa
- Piezoelectric means pressure electricity



3. Transducers

High-frequency voltage oscillations are produced by a pulse generator and are sent to the ultrasound transducer by a transmitter

The electrical energy causes the piezoelectric crystal to momemtarily change shape (expand and contract depending on current direction)



3. Transducers

1. This change in shape of the crystal increases and decreases the pressure in front of the transducer, thus producing ultrasound waves

2. When the crystal is subjected to pressure changes by the returning ultrasound echoes, the pressure changes are converted back into electrical energy signals

3. Return voltage signals are transferred from the receiver to a computer to create an ultrasound image

4. Transducer crystals do not conduct electricity but are coated with a thin layer of silver which acts as an electrode

3. Transducers

The piezoelectric effect of a transducer is destroyed if heated above its temperature limit

Transducers are made of a synthetic ceramic (peizoceramic) such as lead-zirconate-titanate (PZT) or plastic polyvinylidence difluoride (PVDF) or a composite

A transducer may be used in either pulsed or continuous-wave mode

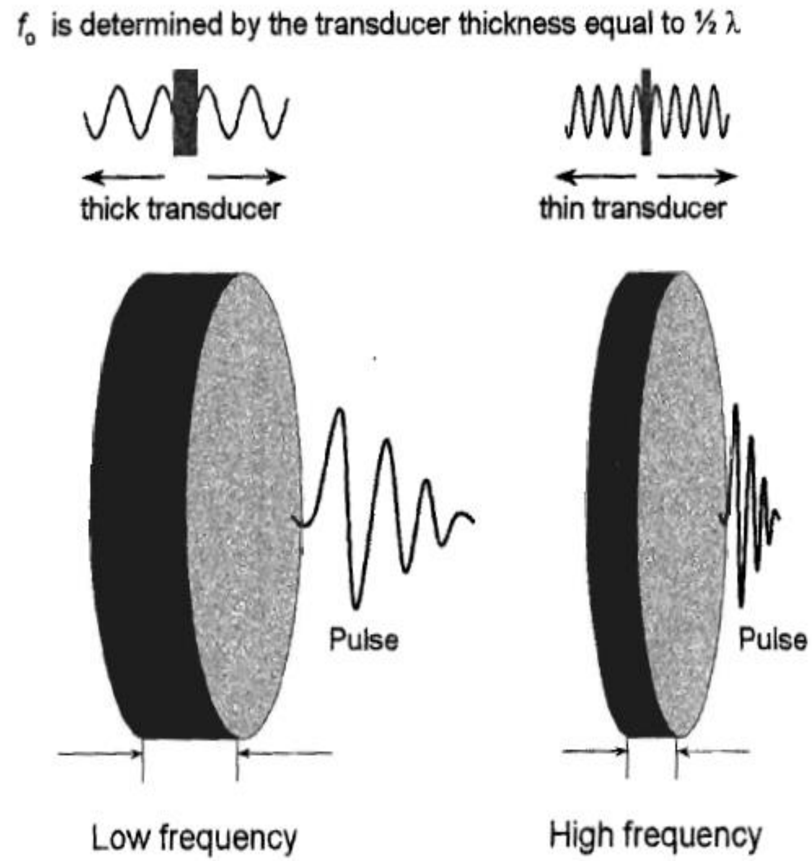
A transducer can be used both as a transmitter and receiver of ultrasonic waves

3. Transducers

The thickness of a piezoelectric crystal determines the resonant frequency of the transducer

The operating resonant frequency is determined by the thickness of the crystal equal to ½ wavelength ($t=\lambda/2$) of emitted sound in the crystal compound

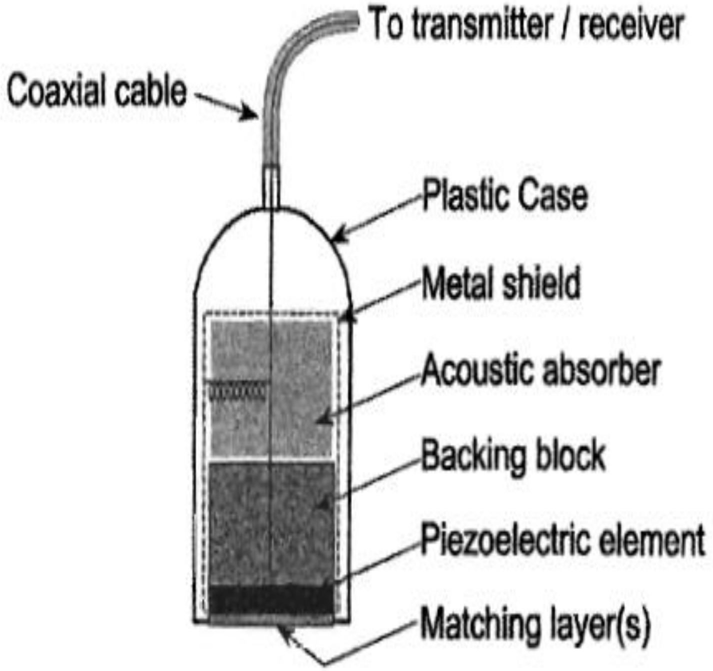
Resonance transducers transmit and receive preferentially at a single "center frequency"



3. Transducers Damping Block

The damping block absorbs the backward directed ultrasound energy and attenuates stray ultrasound signals from the housing

It also dampers (ring-down) the transducer vibration to create an ultrasound pulse with a short spatial pulse length, which is necessary to preserve detail along the beam axis (axial resolution)



3. Transducers Q factor

The Q factor is related to the frequency response of the crystal

- **The Q factor determines the purity of the sound and length of time the sound persists, or ring down time**
- **Q = operating frequency (MHz) / bandwidth (width of the frequency distribution)**
- **$Q = f_0/BW$**
- **High-Q transducers produce a relatively pure frequency spectrum**
- **Low-Q transducers produce a wider range of frequencies**