Physics of Ultrasound

Third lecture

Interaction of Ultrasound with Matter

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Third Stage

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1. *Introduction*

In order to use ultrasound for either diagnostic or therapeutic purposes, a beam of ultrasound must be directed into the tissues of the subject over a selected area of interest. The ultrasonic energy will then interact with the tissues along its path. The interaction processes are influenced by the characteristics of the ultrasound wave, as well as the physical properties of the tissues through which the beam passes.

2. *Acoustic impedance*

- Different materials respond differently to interrogation by ultrasound, depending on the extent to which their medium particles will resist change due to mechanical disturbance.
- This medium property is referred to as the characteristic acoustic impedance of a medium.
- It is a measure of the resistance of the particles of the medium to mechanical vibrations.
- This resistance increases in proportion to the density of the medium, and the velocity of ultrasound in the medium.
- Acoustic impedance, Z, may be defined as the product of medium density and ultrasound velocity in the medium.

$$Z = \text{density x velocity}$$

3. *Acoustic boundaries*

- Positions within tissue where the values of acoustic impedance change are very important in ultrasound interactions. These positions are called acoustic boundaries, or tissue interfaces.

- For example, urine in the bladder will have an acoustic impedance value which differs from that of the bladder wall; hence their common interface constitutes an acoustic boundary.
- The unique features of diagnostic ultrasound as an imaging modality are determined by the nature and distribution of the multitude of acoustic boundaries within the tissues of the body.
- In general, the extent to which an acoustic boundary affects a beam of ultrasound incident upon it will depend on the magnitude of the difference between the acoustic impedance values of the two structures on either side of the boundary.

4. *Reflection of ultrasound*

- The most important single interaction process for purposes of generating an ultrasound image is reflection.
- When a beam of ultrasound strikes an acoustic boundary, part of the beam energy is transmitted across the boundary, while some is redirected backwards, or reflected.
- Two types of reflection can occur, depending on the size of the boundary relative to that of the ultrasound beam, or on irregularities of shape on the surface of the reflector.
    - ✓ Specular reflections occur when the boundary is smooth and larger than the beam dimensions.
    - ✓ Non-specular reflections occur when the interface is smaller than the beam.

Specular reflections

- ☒ A specular reflector is an interface whose diameter is larger than one wavelength of the ultrasound beam.

☒ law of reflection of ultrasound:

Incident beam   NORMAL to interface   Reflected beam

NORMAL

Angle of incidence, i

Angle of reflection, r
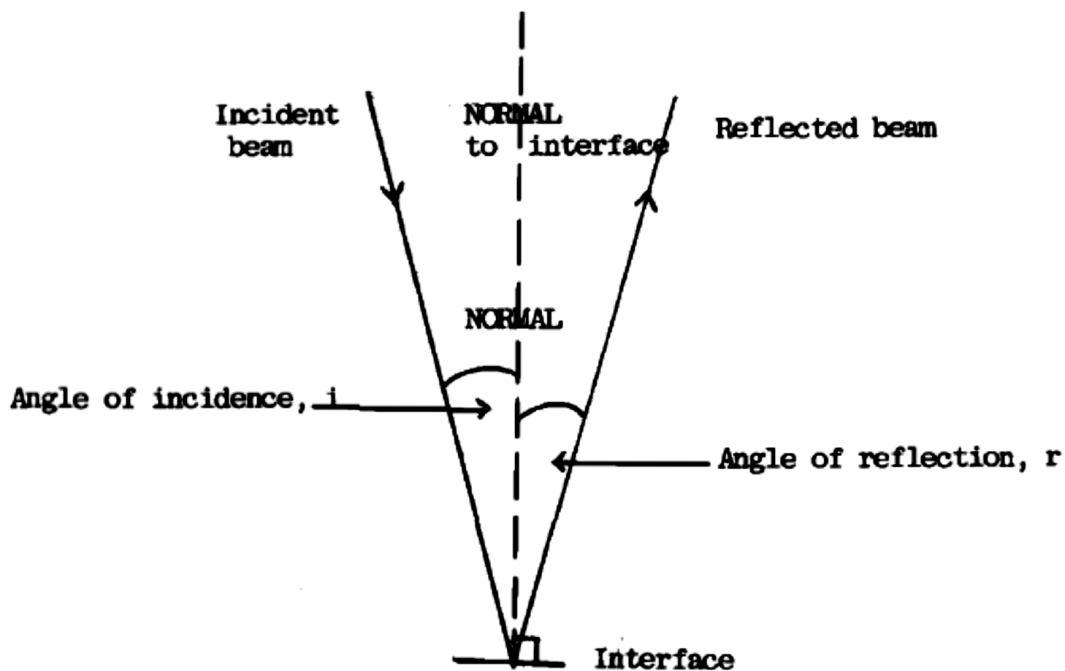
Interface

Specular reflection, angle of incidence = angle of reflection

✓ The angle, i, between the incident beam and the perpendicular direction to the interface is called the angle of incidence

✓ The line perpendicular to the interface is also called the normal to the reflecting surface.

✓ The reflected ultrasound will be on the opposite side of the normal in relation to the incident beam, and the angle it makes with the normal is called the angle of reflection, r.

✓ The reflected beam is referred to as the echo (by analogy with audible sound).

✓ The probability that an echo will go back to the transducer and be detected increases as the angles i and r decrease.

✓ Detection of an echo by the same transducer producing the incident beam requires that the angle of incidence be small, typically less than about 3°.

✓ The intensity of an echo due to specular reflection depends on the angle of incidence as well as the difference in acoustic impedance values of the two media forming the boundary.

✓ This difference in Z value is also called the acoustic mismatch

✓ The most useful specular reflection takes place when the ultrasound beam strikes a reflector at 90° to the surface of the boundary.

✓ This is referred to as normal incidence.

✓ The angles i and r are then equal to zero, and the echo goes straight back with a high probability of being picked up by the transducer.

✓ In this special case of specular reflection, the echo intensity in relation to the intensity of the ultrasound beam incident upon the boundary is given by the relation:

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

I_r = intensity of reflected echo.

I_i = intensity of incident beam at the boundary.

Z_1 = acoustic impedance of first medium

Z_2 = acoustic impedance of second medium.

✓ The ratio I_r/I_i is called the reflection coefficient. It represents the proportion of beam intensity that is reflected from the interface.

✓ The difference in Z-value at an interface which determines the reflection coefficient.

✓ A large change of Z value at an interface makes the reflection coefficient large and therefore gives rise to a large echo.

✓ Small changes of Z produce small echoes.

❖ Values of acoustic impedance for some materials

Material	Acoustic impedance (Rayl)
Muscle	1.70
Fat	1.38
Brain	1.58
Kidney	1.62
Liver	1.65
Blood	1.61
Soft tissue (average)	1.63
Water	1.48
Bone	7.80
Air (NTP)	0.0004

The following important observations can be made by examining the data in Table:

1. The values of Z for the soft tissues are quite similar to one another. We conclude that reflections at boundaries between soft tissues will give rise to generally small echoes.

2. The Z-value for air (and for other gaseous materials) is much lower than the soft tissue average. We conclude that reflection from a soft tissue/gas interface gives rise to a very large echo.

3. The Z-value for bone is several times higher than the soft tissue average. Therefore, a reflection from a soft tissue/bone interface produces a large echo.

**The percentages of ultrasonic energy reflected normally from different boundaries

Boundary	% reflection
Muscle/fat	1
Kidney/fat	0.6
Bone/muscle	41
Bone/fat	49
Soft tissue/air	99.9
Soft tissue/water	0.2

Implications for diagnostic ultrasound

1. Negative role of gas

✓ The near total reflection of ultrasound at boundaries between gas and other materials makes gas a barrier to the transmission of ultrasound

2. Need for coupling

✓ It is necessary to apply suitable gel or oil between the transducer surface and the patient's skin in order to exclude air.

3. Acoustically homogeneous media

✓ No echoes are seen within compartments in which the Z-value remains constant.

✓ The reflection coefficient is zero throughout such compartments and therefore there are no acoustic interfaces within.

✓ In clinical ultrasound, acoustic homogeneity is observed in liquid cavities as clear, echo-free zones.
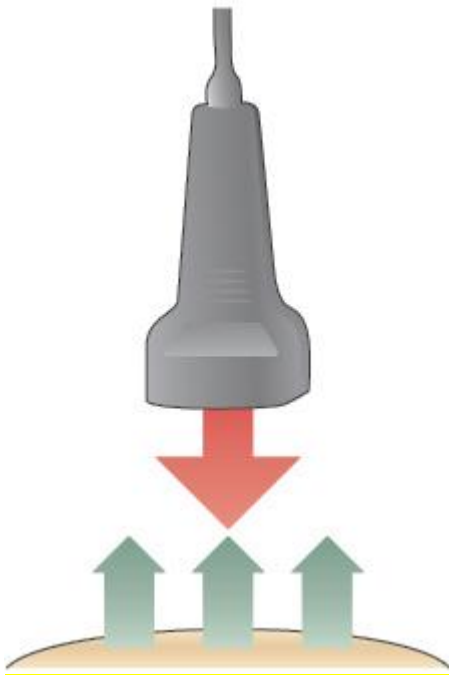
4. Transducer matching layer

✓ The front face of the transducer, between the piezoelectric crystal and the skin, has a matching layer made of a material of suitable Z and thickness which serves to reduce the acoustic mismatch between the crystal material and soft tissue.

- ✓ The Z-value of the matching layer is chosen to lie between that of the crystal and soft tissue.
- ✓ This reduces the reflection of ultrasound that would be experienced at the crystal/soft tissue interface in the absence of the matching layer, thus improving the transmission of ultrasound into the patient, and of the returning echo into the transducer.

Scattering of ultrasound (non-specular reflections)

+ When the reflecting interface is irregular in shape, and its dimensions are smaller than the diameter of the ultrasound beam, the incident beam is reflected in many different directions. This is known as non-specular reflection, or scattering.

+ The direction of scatter depends on the relative sizes of the scattering target and the ultrasound beam diameter

+ Energy incident upon the small target at quite large angles of incidence will have a chance of being detected at the transducer.

+ The dimensions of the interface should be about one wavelength of the ultrasound beam or less for scattering to occur.

+ It will be recalled that the wavelengths for typical diagnostic beams are 1 mm or less.

+ Within the organs, there are many structures which have dimensions of less than 1 mm, and so scattered ultrasound provides much useful information about the internal texture of organs.

+ Scattered echoes are much weaker than specular reflected echoes, but the high sensitivity of modern ultrasound equipment makes it possible to utilize information from scattered ultrasound for imaging

+ Scattering shows very strong frequency dependence, increasing rapidly as the frequency of ultrasound is increased.

Specular reflection

Diffuse reflection