ULTRASOUND PRINCIPLES AND INTERACTION WITH TISSUES

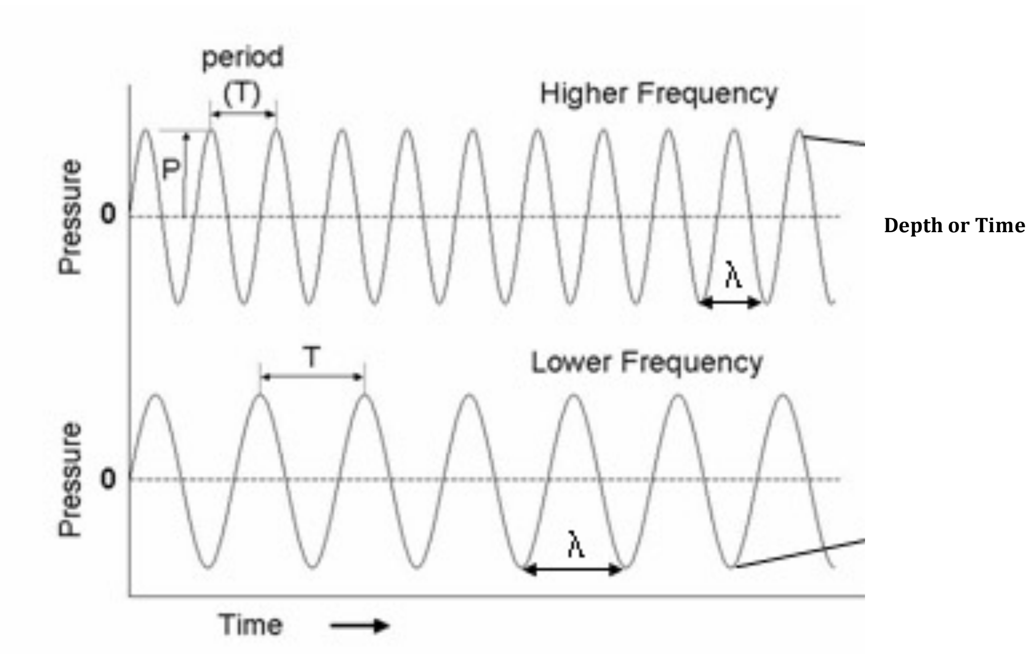
ULTRASOUND WAVES AND PROPAGATION

Ultrasound is high frequency sound waves where diagnostic imaging uses 2-15MHz, about 1000x higher then normal hearing frequencies of 20Hz to 20kHz.

- **the higher the frequency the better the resolution of an image but the consequence is reduced depth penetration of imaging**

Ultrasound waves are created by oscillations in pressure at the the probe face contact with the body. This creates compression (increased pressure) and rarefaction (reduced pressure). These resulting oscillating changes in pressure constitute the ultrasound wave.

- particle movement is in the same direction as the energy resulting in a longitudinal wave.

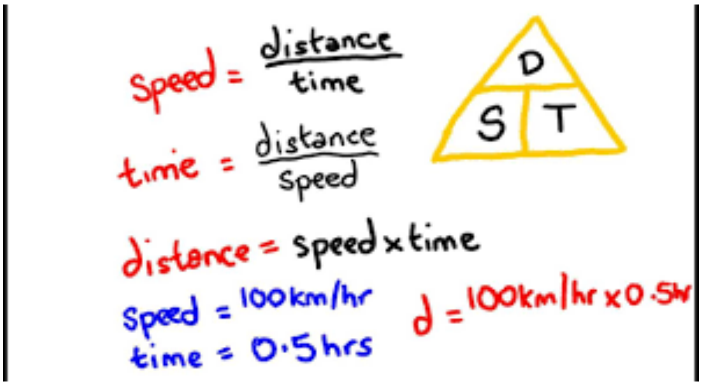


Source: USRA

- Amplitude (A) is maximum variation in pressure from baseline
- Period (T) is time for one cycle and is related to frequency (cycles per second) in Hertz

$$f = {}^{1}/_{T}$$

Variation in pressure over time or in depth produces the same wave pattern. Linking the temporal variation of the wave with spatial variation is the propagation speed of the ultrasound wave through tissue (1540m/sec in soft tissue)
Wavelength (**λ**) is the physical distance of one cycle (peak-peak distance)



$s = {}^{d}/_{t}$

Source: Tecmath

If :
c = s (speed of propagation)
λ = d (distance in one cycle)

We know:

$f = {}^{1}/_{t}$

Therefore substituting into speed/distance/time equation

$c = \lambda \times f$

$\lambda = {}^{c}/_{f}$

- **inverse relationship between λ and *f* means the higher the frequency the shorter the wavelength (at *f* of 15MHz in soft tissue λ= 0.10mm) hence the better the resolution of an image.**

DIAGNOSTIC ULTRASOUND TISSUE INTERACTION

Interaction of diagnostic ultasound waves with tissue creates our ability to create useful imaging. The major interactions with tissue are:

- attenuation
- reflection
- scattering
- refraction

ATTENUATION

The reduction of wave energy/intensity (I) as it travels through tissue is the attenuation

- measured in dB unit based on logarithms, used to express ratio of two quantities $^{I1}/_{I2}$ (also used as units for gain, and dynamic range)

$$\text{attenuation} = (10 \times \log {}^{I1}/_{I2})\ \text{dB}$$

$^{I1}/_{I2}$	dB
1	0
2	3
10	10
100	20
1000	30
0.1	-10
0.01	-20

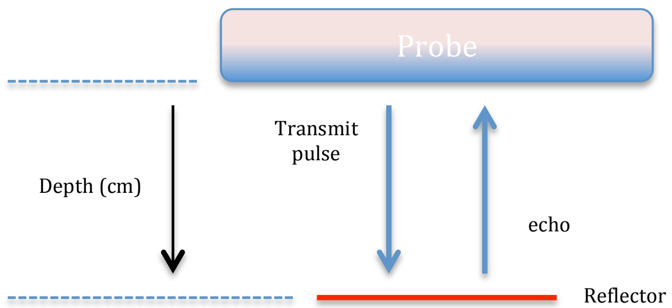
Causes of attenuation:
- friction producing heating
- reflection, scattering, and any divergnce of the beam

Attenuation is dependent on:
- α= attenuation coefficient for the tissue (dB/cm/MHz)
- *f* of the wave
- L (the distance/length travelled by the wave)

$$\text{attenuation (dB)} = \alpha \times L \times f$$

Attenuation occurs for the transmit pulse and the received echo and therefore the roundpath attenuation for a certain depth occurs over twice this distance.

$$\text{roundpath attenuation (dB)} = \alpha \times (2\times \text{depth}) \times f$$



For a 2MHz frequency at 10cm depth with typical soft tissue α= 0.5 dB/cm/MHz:

Roundpath attenuation = 20dB or a 100 x reduced intensity

For a 4MHz frequency this would 40dB attenuation 10000 x reduced intensity

Attenuation limits maximum depth of imaging for a machine:

- maximum penetration depth in a particular tissue type at certain *f* will be constant for that machine
- **and depth of penetration is inversely related to frequency**

REFLECTION

Interaction between relatively large smooth surface ie between differing tissue interfaces:

- the **differentiation between tissue types on ultrasound is dependent on the acoustic impedance *Z*** *(Rayls)*= ρ (density) x c (propagation speed in the tissue)

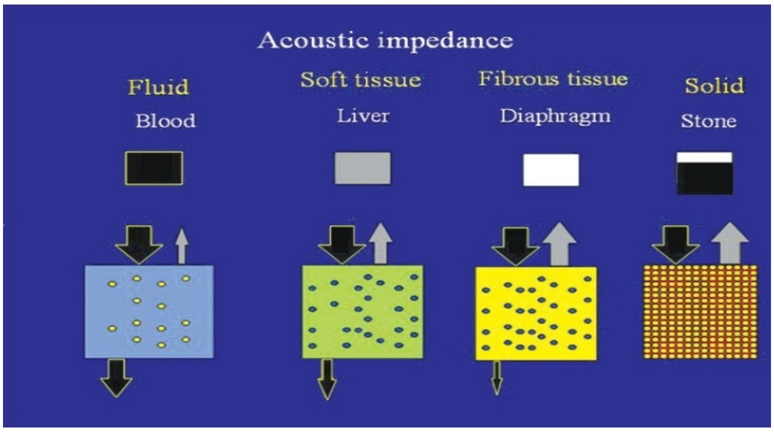
If *Z1 (tissue 1) = Z2 (tissue2)* then reflection is virtually 0, and if there is marked difference in acoustic impedance then reflecton is close to 1 hence:

- **tissues with a similar acoustic impedance will look similar on ultrasound despite being totally different tissue types**

the interface **R** (reflection coefficient) = (reflected intensity)/(incident intensity)

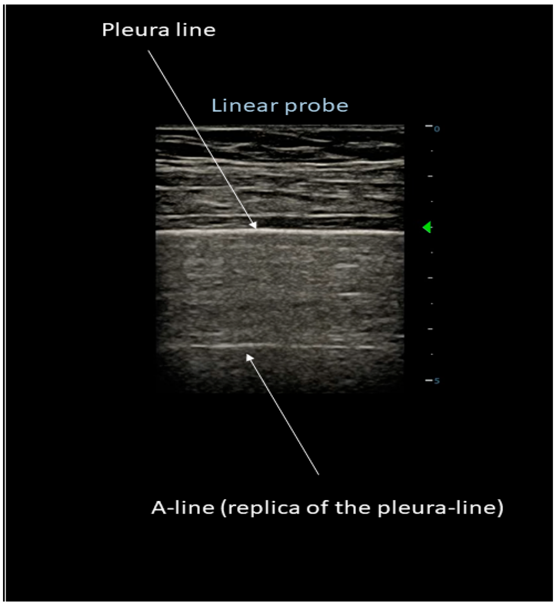
$$\mathbf{R} = (Z2-Z1)^2/(Z2+Z1)^2$$

- the R will be the same no matter which way the waves are passing through the interface
- R = 0.01 = 1% reflection at the interface in either direction and 99% will be transmitted



R=(reflected intensity)/(incident intensity)

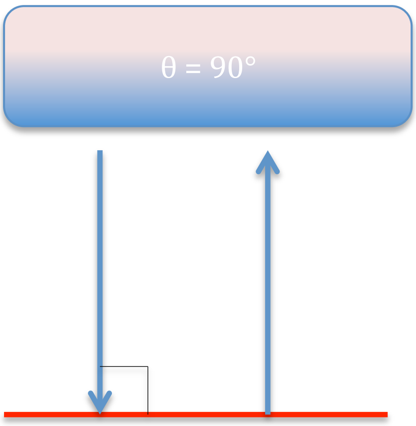
Source: Abu-Zidan- Journal of Emergencies, Shock, and Trauma (2011)

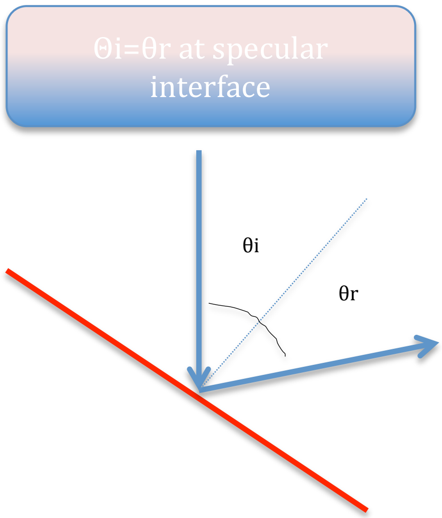


R ≈ 1.0 at soft tissue air interface of the normal lung produces intense pleural line

(reverberation artifact A-line replica of pleural line at 2x depth)

Incident angle of ultrasound wave at the interface will affect the reflection of echoes and transmission



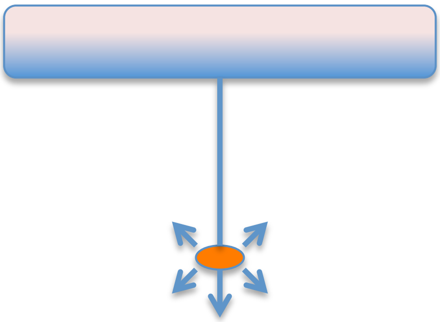


- non perpendiculr imaging of a smooth interface will result in the angle of reflection (θr) being equal to the incident angle (θi) [At a true specular or mirror like interface]
- this means reflected echoes may not be detected by the probe face depending on the angle of interrogation

SCATTERING

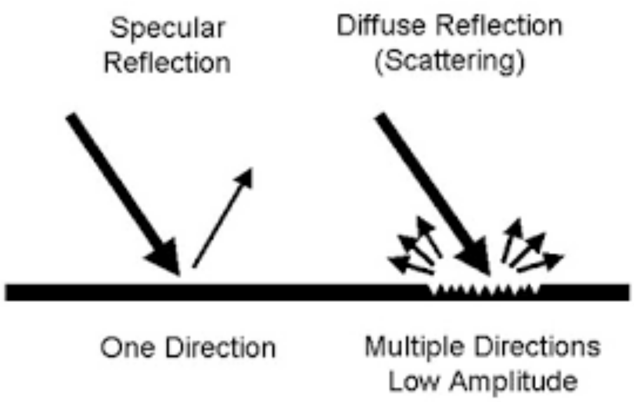
Interaction of ultrasound waves with small reflectors ie. capillaries , RBC, and bile ducts.

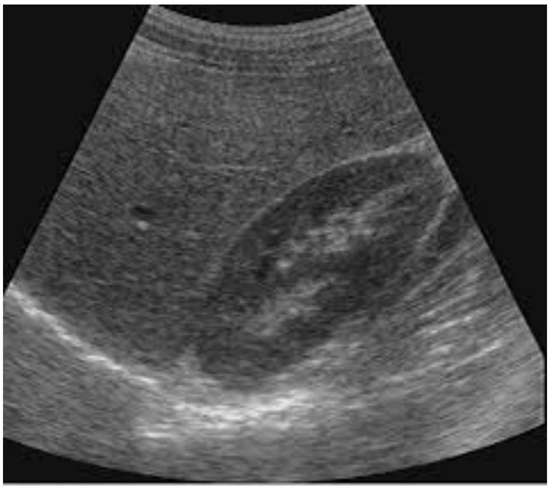
- scattering is multi directional and low energy
- produces the low level to mid grey on the display, which makes up most of the displayed image.



Scatterers will produces the speckle and the echotexture seen in an image

- this is the sum of multiple scatterers
- they have an additive random effect causeing variation in amplitude of received echoes by the probe

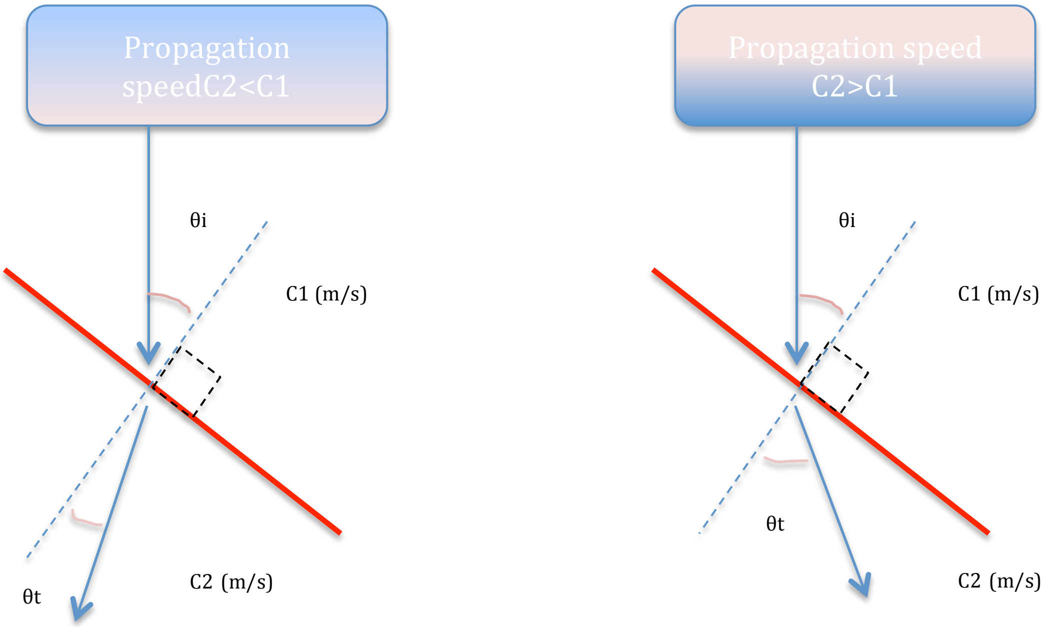




Speckle effect produced by scattering resulting in echotexture of Liver and Kidney

REFRACTION

Bending of light or sound waves as it passes from one medium to another with different propagation speeds (c)



Angle of incidence (θi) and transmission (θt) measured relative to line drawn perpendicular to the interface

- if propagation speed (c2) is less in the second tissue then the θt will be less then the θi (closer to perpendicular)

- if propagation speed (c2) is more in the second tissue then the θt will be larger then the θi (away from the perpendicular)

This refraction can be determined by using Snell's Law:

$$\sin\theta i / c1 = \sin\theta t / c2$$

- when the θi increases the bending of the wave increases

- when the θi is perpendicular to the interface then the θt is 0^{o} and no deflection of the wave occurs regardless of propagation speeds

When c2>c1 a critical incident angle for θi exists:

- when critical θi is meet then the θt=90^{o} and transmitted waves run along the tissue plane interface

- **when θi is greater then the critical angle then complete reflection occurs at the interface**

KEY POINTS

ULTRASOUND WAVES AND PROPAGATION

- **inverse relationship between λ and *f* means the higher the frequency the shorter the wavelength, hence the better the resolution of an image.**

TISSUE INTERACTIONS

ATTENUATION:

- Attenuation occurs for the transmit pulse and the received echo and therefore the roundpath attenuation for a certain depth occurs over twice this distance.

- **Attenuation limits maximum depth of imaging for a machine:**

- maximum penetration depth in a particular tissue type at certain *f* will be constant for that machine
- **and depth of penetration is inversely related to frequency**

REFLECTION

- the **differentiation between tissue types on ultrasound is dependent on the differing tissue acoustic impedance *Z*** *(Rayls)*

- if $Z1 \approx Z2$ then the reflection coefficent R will be close to 0 and the tissues will appear very similar on the ultrasound image
- if there is a large differential in tissue Z then $R \approx 1.0$ and near comlpete reflection occurs

SCATTERING

- **scatterers will produces the speckle and the echotexture seen in an image – the majority of the grey scale image**

REFRACTION

- if c2>c1 then the θt will be greater then the θi
- if c2<c1 then the θt will be less then the θi

- **When c2>c1 a critical incident angle θi exists:**

- when critical θi is meet then the $\theta t=90^{o}$ and transmitted waves run along the tissue plane interface

- **when θi is greater then the critical angle then complete reflection occurs at the interface**

REFERENCES

The Physics and technology of Diagnostic Ultrasound: A Practitioner's Guide. By Dr Robert Gill.

Artifacts in Diagnostic Medical Ultrasound: Volume 1 Grayscale Artifacts. By Martin Necas