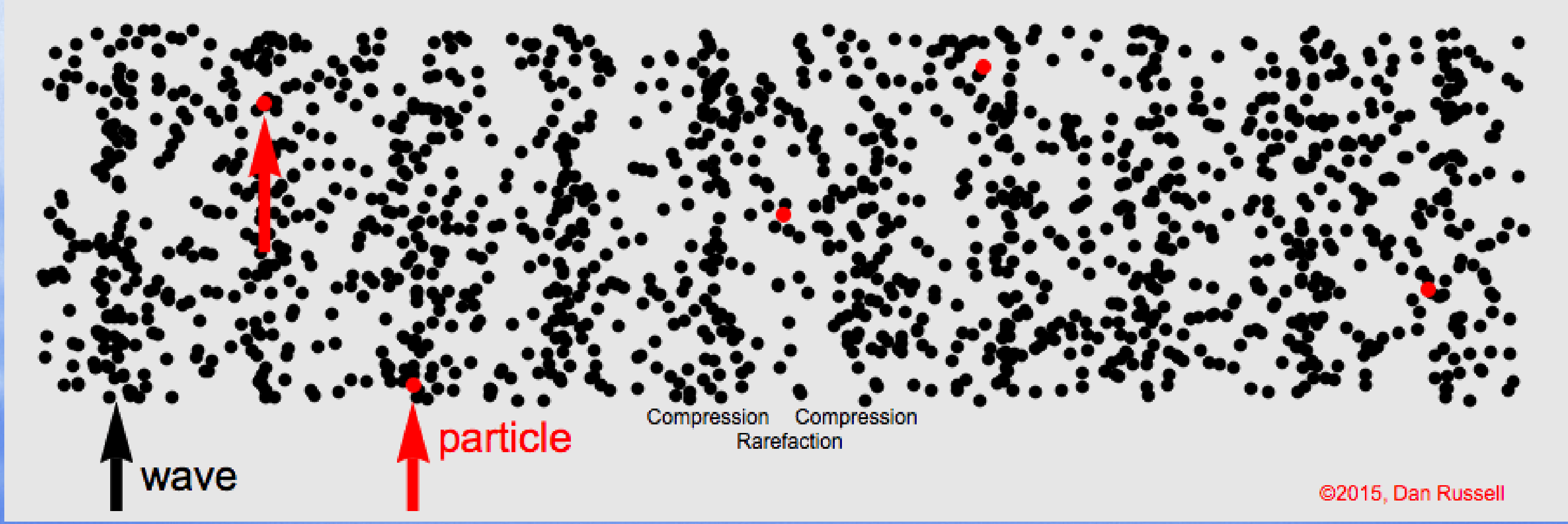
Ultrasound Physics

Jacqui George, Principal Vascular Scientist
University Hospitals Plymouth

Physics of Sound Waves

- Mechanical energy transmitted as a pressure wave
- Characterised by wavelength λ, frequency f and amplitude.
- Wave equation $c = f\lambda$

  (c=speed of sound or acoustic velocity)



https://www.acs.psu.edu/drussell/demos/waves/wavemotion.html

Acoustic Properties of Tissue

- Acoustic properties are speed of sound (c) and acoustic impedance (Z)

- Speed of sound depends on density (ρ) and compressibility (K)

$$c=1/\sqrt{(K\rho)}$$

- Speed of sound varies with tissue type (1540m/s in soft tissue) but is NOT frequency dependent

Acoustic properties of tissues

- Acoustic impedance defined as density x speed of sound

$$Z=\rho c$$

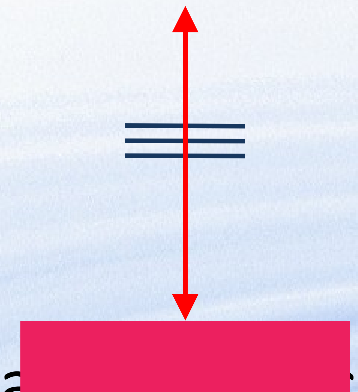
- Analogous to momentum

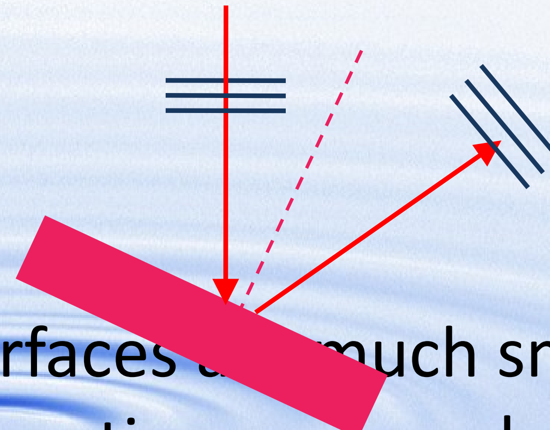
- Difference in acoustic impedance determines amount of
sound energy reflected at an interface.

Reflection coefficient $R=(Z_1-Z_2)^2/(Z_1+Z_2)^2$

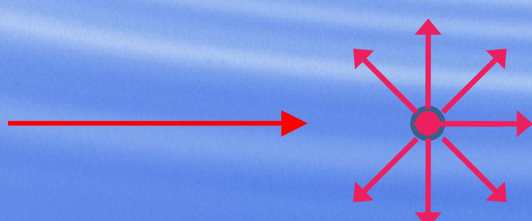
Interaction with tissues

- Reflection -Angle of incidence =angle of reflection.





- Scattering occurs when interfaces are much smaller than a wavelength (ie blood cells or tissue parenchyma) and is strongly frequency dependent.

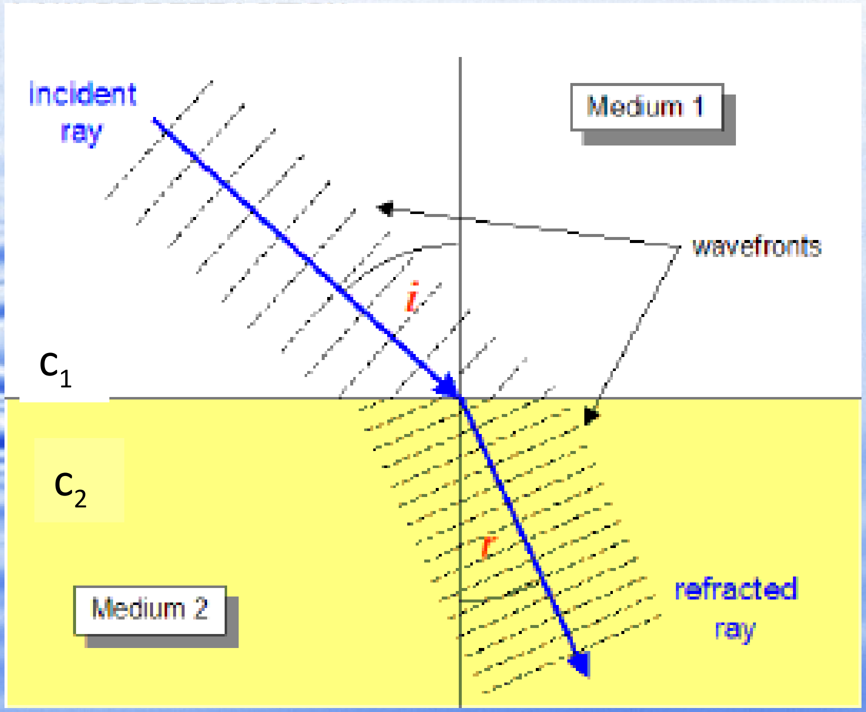


Interaction with tissues

- Refraction occurs to transmitted wave when there is a change in the speed of sound

Snell's law:

$c_1/c_2 = \sin\theta_i/\sin\theta_r$



Attenuation

- Ultrasound beam loses energy as it travels by absorption, reflection, scattering and beam divergence.
- Intensity is amount of energy in ultrasound beam

Ratio	1/2	1/10	1/100	1/1000
dB	-3	-10	-20	-30

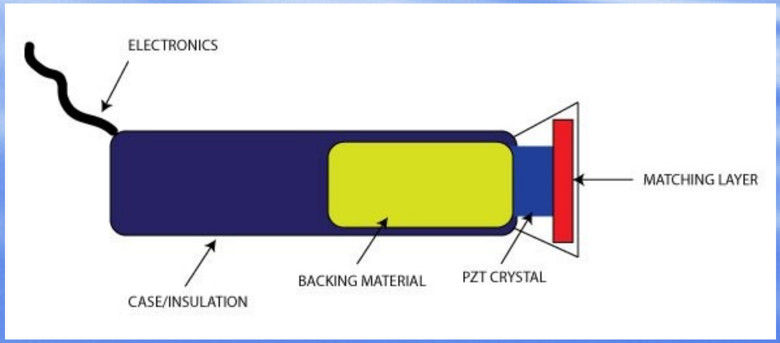
- Change in intensity expressed in decibels

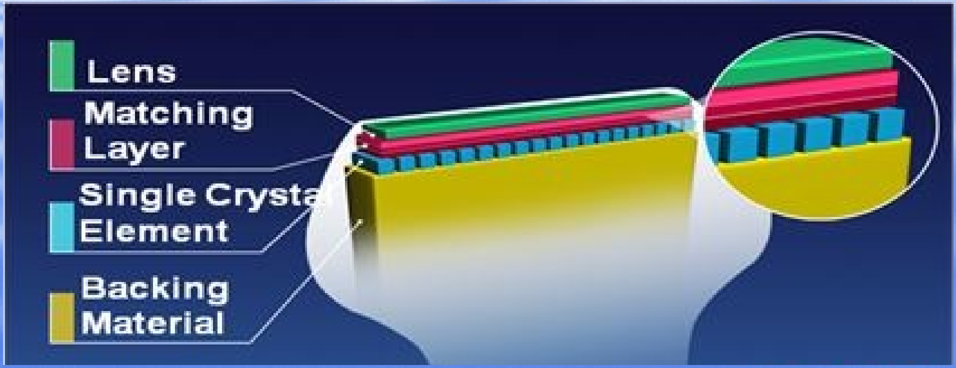
$$\text{Level dB} = 10 \log I/I_{ref}$$

- Attenuation coefficient gives rate that energy is lost

Production of ultrasound

- Piezoelectric crystal ie PZT (Lead zirconate titanate)
- Thickness of crystal determines resonance frequency, crystal thickness is half a wavelength
- Matching layer in front of crystal improves energy transfer
- Backing material reduces pulse length
- Arrays of transducer elements are used for imaging



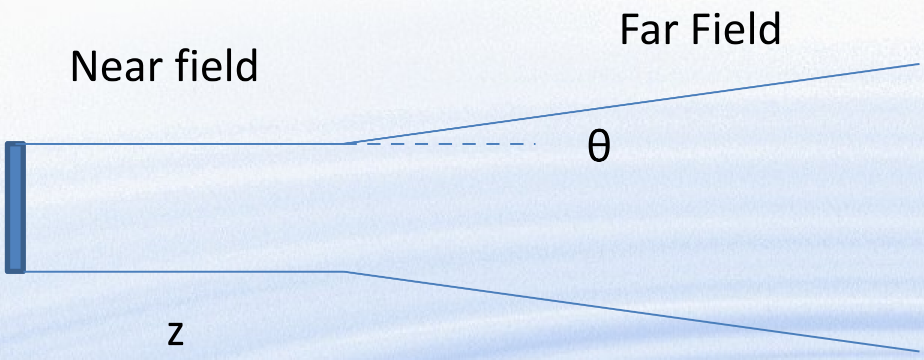


Continuous wave and pulsed ultrasound

- If transducer element has a continuous sinusoidal voltage applied across it, it creates CW ultrasound
- For most applications a voltage spike is applied to produce a short pulse of ultrasound
- Imaging requires very short pulses, pulsed Doppler uses longer pulses.
- A pulse of ultrasound is made up of a range of frequencies called the bandwidth, centred around the transmit frequency.
- The shorter the pulse the wider the bandwidth.
- Mechanical coefficient (Q-value)=centre frequency/bandwidth.
- Axial resolution = pulse length/2, improves with frequency

Beam shape

Lateral resolution depends on beam width so ideally beam should be very narrow



Near field length (z) = fa^2/c

Far field divergence $\sin\theta = 0.6c/fa$

a=radius of transducer
f=transmit frequency

Small diameter –short NFL, wide divergence in far field

High frequency –long near field, less divergent

Focusing is used to narrow beam in region of interest to improve lateral resolution

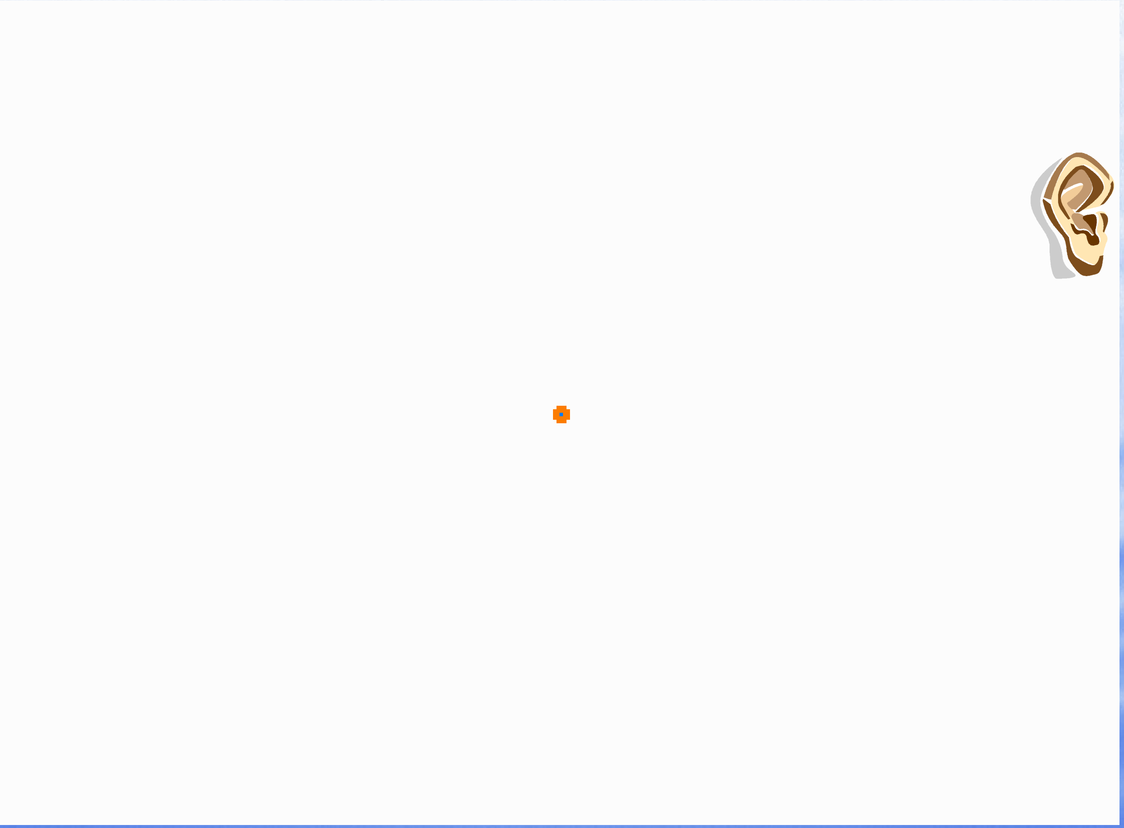
Ultrasound Image formation

- Pulse echo technique - $t=2d/c$

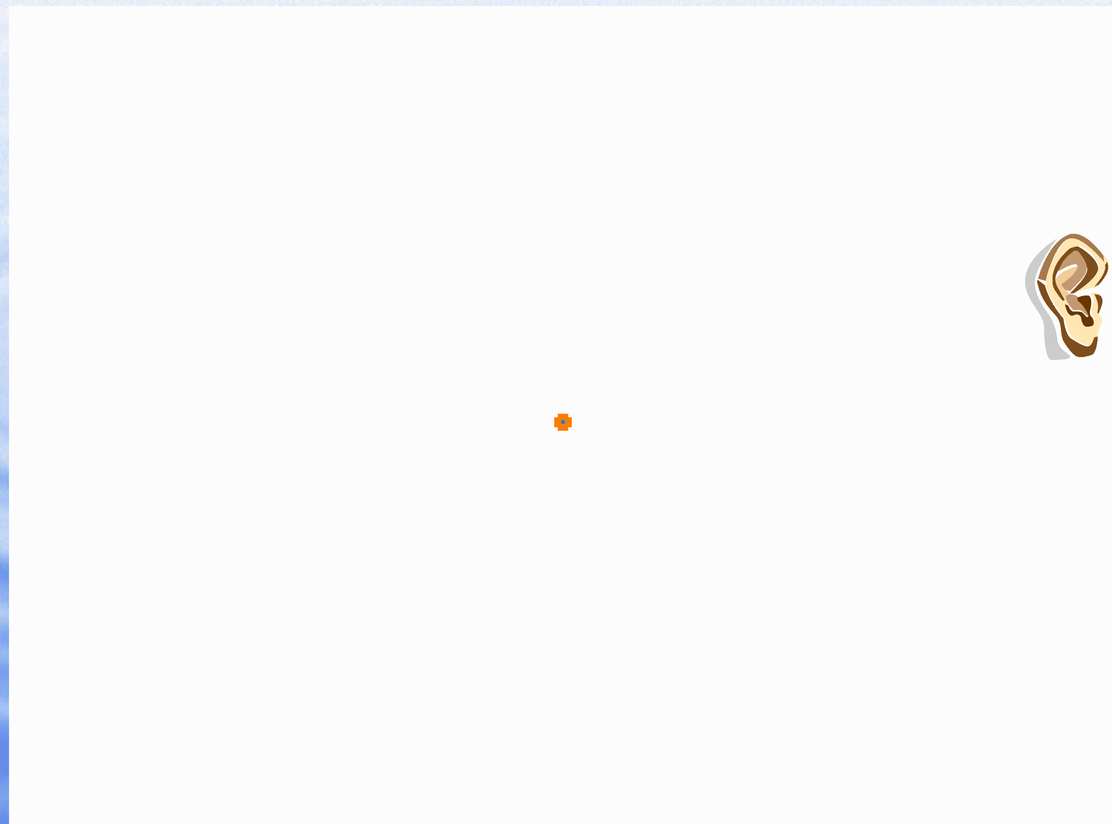
  1cm(round trip) takes 13μs
- Echo amplitude is displayed as grayscale shade.
- Time gain compensation (TGC) applied
- Beam is swept –electronic arrays achieve this by firing elements in groups with delays to achieve focusing.
- Pulse repetition frequency is number of pulses per second – limited by depth.

Doppler ultrasound

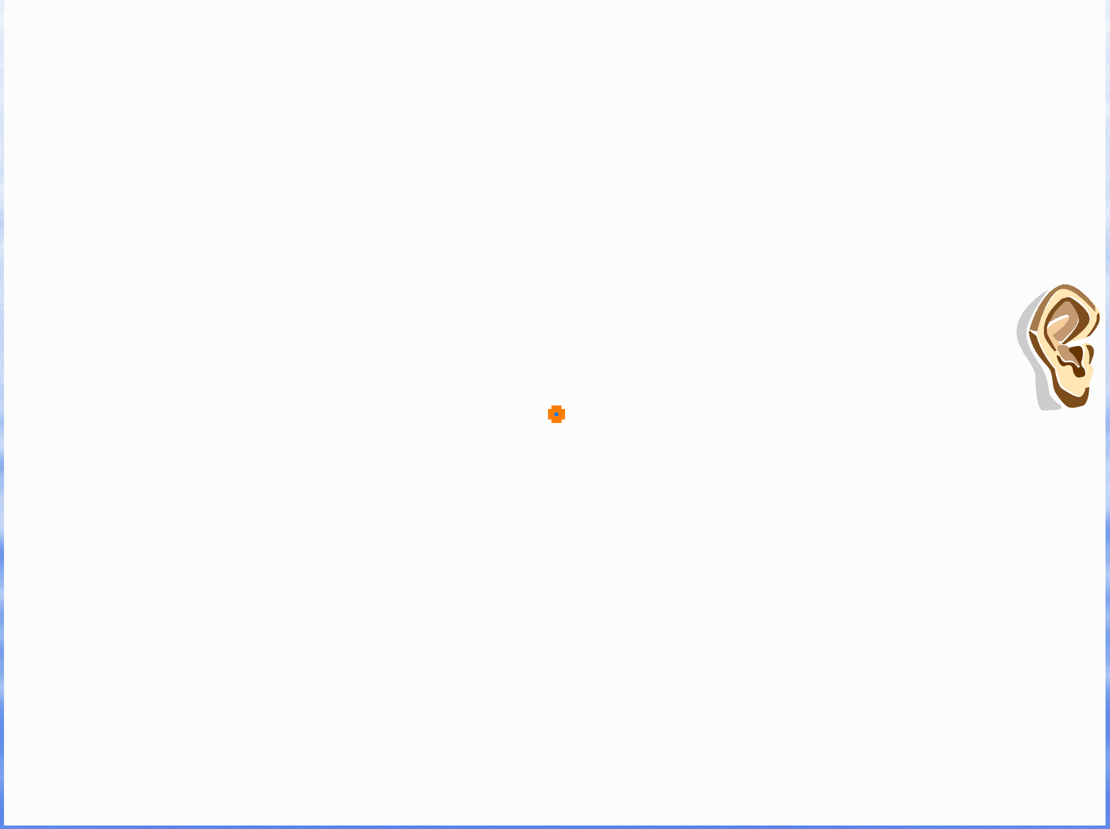
Stationary Source



Source moving towards receiver



Source moving away from receiver

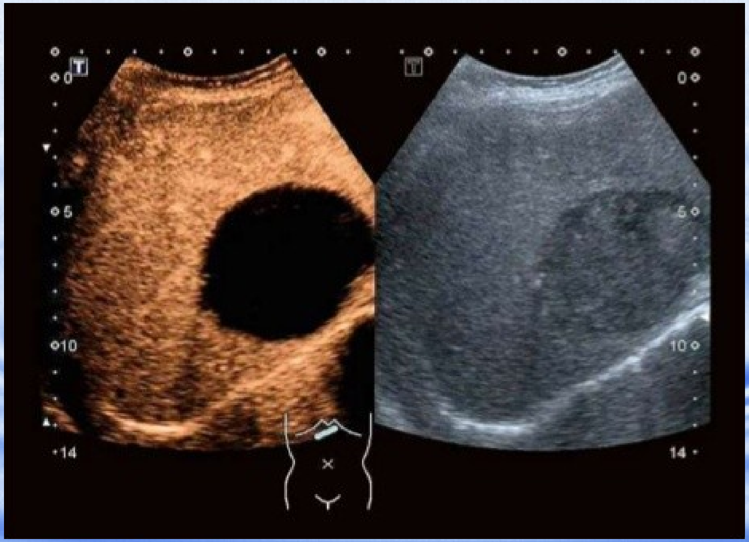


Doppler

- Doppler shift frequency $f_d = 2f_o v \cos\theta/c$
- Pulsed Doppler uses sampling technique so is subject to sampling theorum.
- Maximum frequency detectable f_{max} = PRF/2 (Nyquist limit)
- Aliasing occurs when Nyquist limit is not met.
- Spectral trace/sonogram displays range of Doppler frequencies obtained vs time.
- Colour Imaging estimates mean velocity by comparing successive echo trains by autocorrelation technique.
- Power Doppler displays amplitude of Doppler signal instead of mean velocity

Contrast and Harmonic Imaging

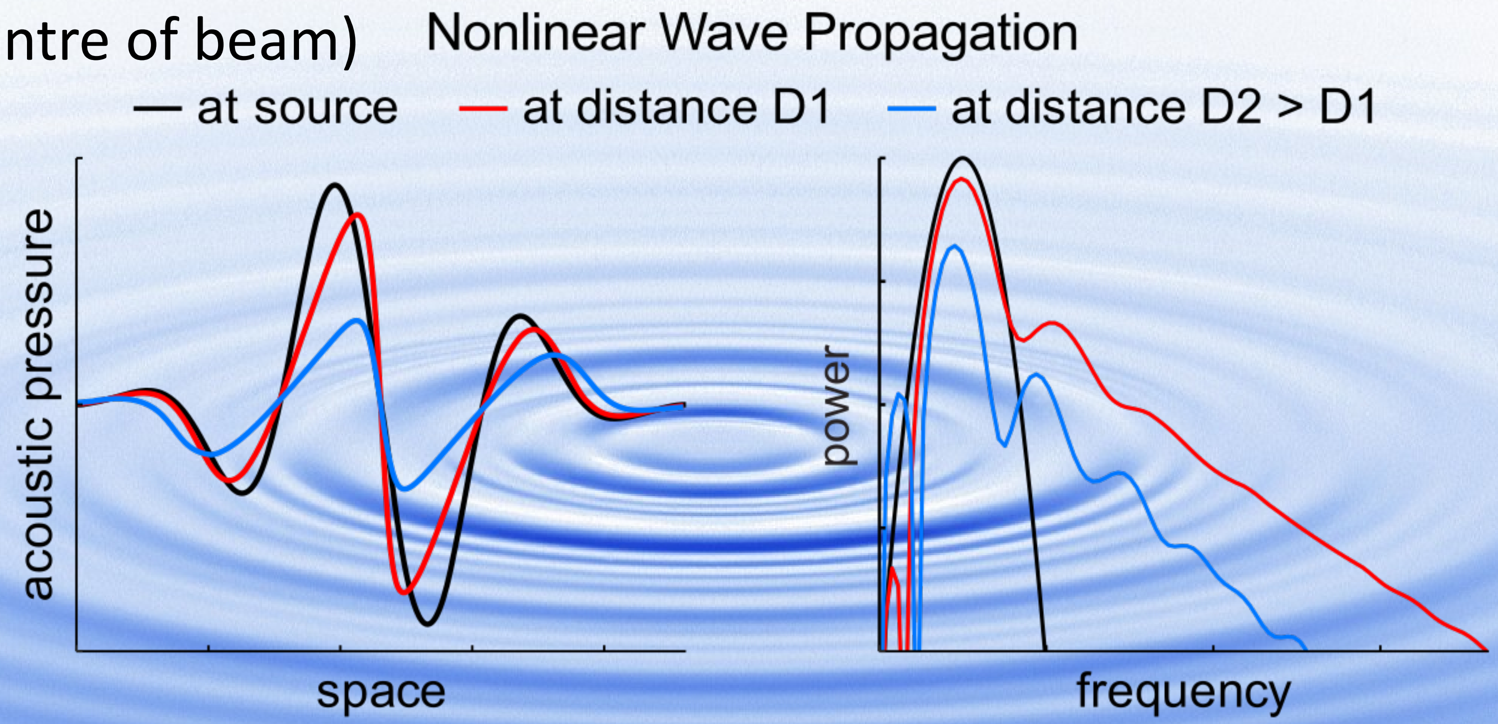
- Contrast –encapsulated gas bubbles (<6 microns) –increase reflectivity of blood pool
- Resonate in ultrasound field, producing strong echoes.



- At higher powers non linear effects produce harmonics – multiples of fundamental frequency.

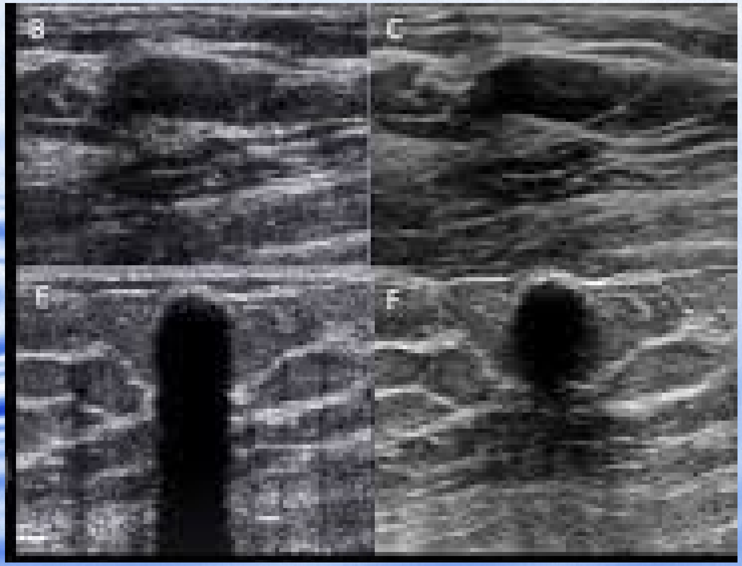
Tissue Harmonic Imaging

- Tissue Harmonics depends on non linear propagation of ultrasound, only occurs if sound wave is intense enough (ie centre of beam)



Question 4E

E Spatial compounding reduces artefacts by averaging frames obtained from different angles. (True)

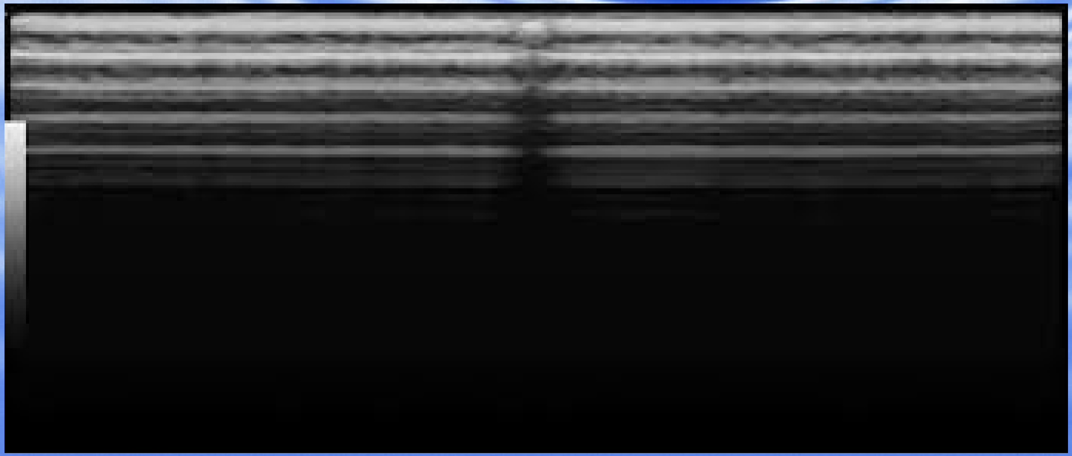


Safety

- Main Acoustic output parameters are:
  - Acoustic Power (mW),
  - Peak rarefaction pressure p- (Mpa),
  - Spatial peak temporal average intensity Ispta (mW/cm^2)
- Bioeffects may occur due to heating or mechanical effects (cavitation, radiation force).
- Thermal index (TI) –ratio of acoustic power emitted to the power required to heat tissue by 1 degree
- Mechanical index estimates potential for transient cavitation $MI=p-/\sqrt{f}$

Ultrasound Quality Assurance

- Level 1 QA -Operator tests
  - Visual inspection of equipment –ie transducer or cable damage, functioning of brakes and switches
  - Element dropout
  - Uniform reverberation pattern

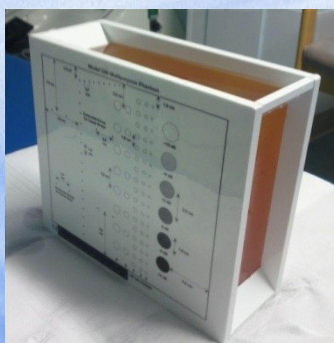


Ultrasound Quality Assurance

Level 2 QA –requires specialist equipment
Acceptance testing followed by periodic testing (annually)

Measurement of Imaging parameters

- Resolution –axial, lateral and contrast
- Caliper accuracy
- Doppler function




Ultrasound Quality Assurance

Measurement of Acoustic Power output

- Calorimeter –absorbs energy and records temperature change
- Radiation force balance –measures force exerted on an absorber placed in the ultrasound field.