



Physics of diagnostic ultrasound

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History

■ Discovery

High frequency (“ultrasound”)

■ Lazzaro Spallanzini, 1794

Bats navigation

■ Francis Galton 1876

Galton whistle (above audible
frequency)

■ Pierre and Jacques Curie 1880

piezoelectric effect



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- Paul Langevin

piezoelectric materials and SONAR

- Sokolov 1928

detect hidden flaws in materials

- Medical uses of ultrasound 1930

therapeutic applications such as cancer treatments

- First use of diagnostic ultrasound
 - Dr. Karl Dussik, 1942
 - Locate brain tumors
 - Two devices
 - Emitter and receiver

General method

- Place small transducer against the skin
 - Emits high frequency sound waves
 - Detects bounce back waves
- Different tissues reflect different waves
- Reconstruction software
 - Viewing structure on a screen

Comparison between ultrasound and x-ray

	Diagnostic Ultrasound	X-rays (radiology)
wave type	longitudinal mechanical waves	electromagnetic waves
transmission requirements	elastic medium	No medium
generation	stressing the medium	accelerating electric charges
velocity	depends on the medium through which it propagates	It is relatively constant: 299,792.456.2 m/s
similar waves	seismic, acoustic	radio, light

Various Uses

- View soft tissue
 - Heart
 - Pelvis and reproductive organs
 - Kidneys, liver, pancreas, gall bladder
 - Eye
 - Thyroid
 - Blood vessels
 - Fetus

Ultrasound

The most wonderful thing about ultrasound is that it is sound. Just sound that is above the range of human hearing. It even travels at exactly the same speed as sound in any medium.

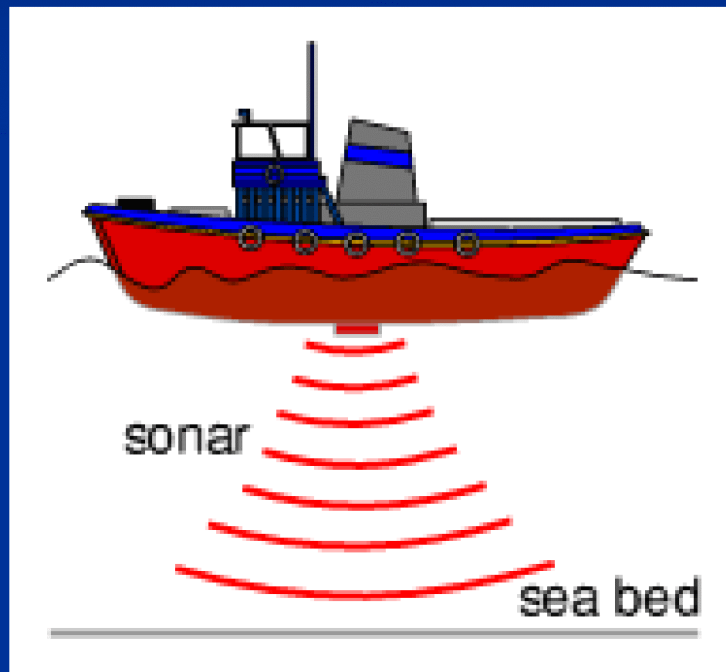
Humans can hear sound within the frequency range of about 20 to 20,000 Hz, so any sound above 20 kHz is ultrasound. Easy isn't it?!

Ultrasound in Hospitals

- Most of you will be familiar with the idea that unborn babies can be photographed - *if rather unclearly* - by using ultrasound. This is safe compared to X-rays, which may damage the child.
- Apart from giving parents the first photograph for the album, it allows doctors to check for certain birth defects, checking its size - and even if there is more than one!



Ultrasound and SONAR



Let us take a look at a typical question about SONAR and depth at sea:

A ship sends a pulse of ultrasound and receives an echo 0.3 seconds later. If the speed of sound in water is 1500 m/s calculate its depth.

speed = distance / time

... distance = speed × time

distance = 1500 × 0.3 = 450 m

BUT this is the total distance travelled by the sound - so the depth is half of this.

Depth = 450 / 2 = 225 m

Be careful - when dealing with reflected sound (echoes) exam questions often try to trick you into using the total distance, not the one you want.

Waves

We all have some idea of what a wave is. Most of us have seen waves on the sea:



Waves transfer energy from one place to another. They do this by *vibrating something* up and down, or back and forth.

In almost all waves, the direction of wave motion is at 90° to the oscillation. For others, the oscillations are in the *same direction* as the wave

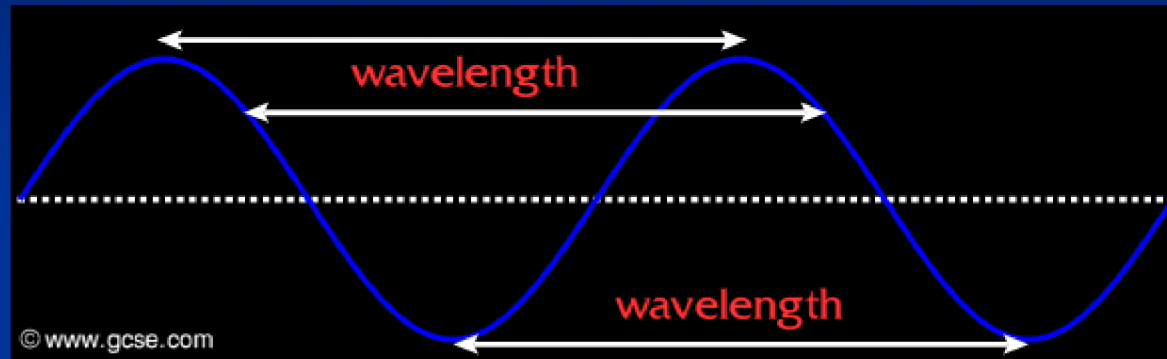
Sound Waves

- Sound waves are mechanical
- Require a medium for transmission
- Pulses are transmitted through liquids (the human body) as longitudinal waves resulting from the displacement of molecules within the transmitting medium.

Frequency

- In physics, we normally expect frequency to be how many times something happens per second.
- For a wave, frequency means: how many waves per second.
- Frequency has the unit of "per second", but we use a special unit for this: hertz (Hz).
- Historical note: hertz is named after the German physicist, Heinrich Hertz (d. 1967)

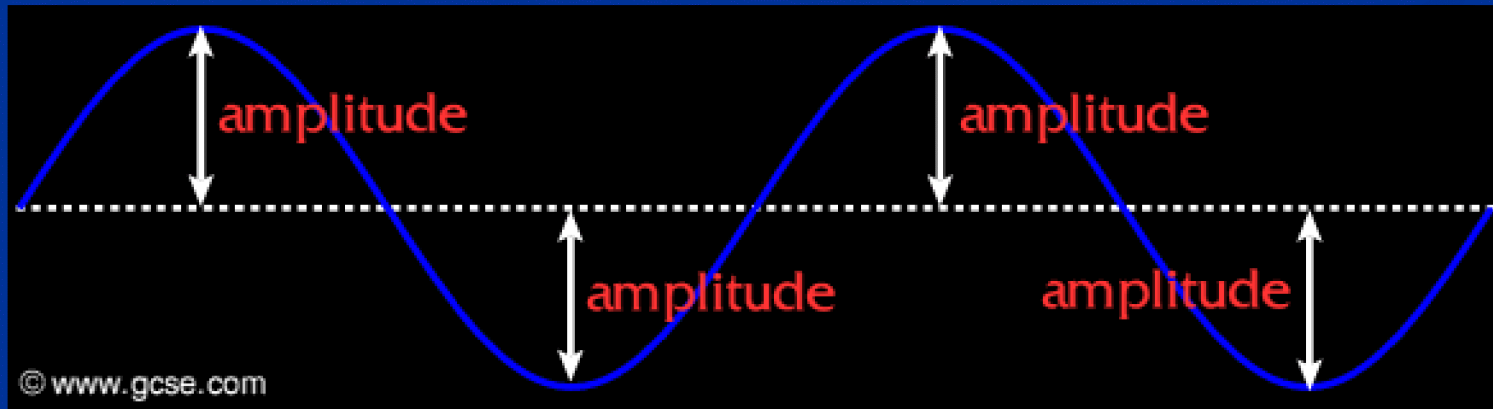
Wavelength



Notice that the correctly drawn wavelength starts and finishes at parts of the wave that are doing the same thing.

Amplitude

- We call the amount of movement from equilibrium displacement. Amplitude is just the *maximum displacement* of a wave:



Speed, Frequency & Wavelength

- Isobel sets up a ripple tank to produce 2 waves each second (i.e. frequency = 2 Hz). She times the waves 2 s to travel the 100 cm distance to the other side of the tank. She measures the distance between the waves as 25 cm: this is the wavelength.
- A frequency of 2 Hz means one wave is produced every 0.5 s (this is known as the time period of the waves and is $1 \div \text{frequency}$).
- In 0.5 s, waves move 25 cm, so we can find the speed by:

$$\text{speed} = \frac{\text{distance}}{\text{time}} = \frac{\text{wavelength}}{\text{time period}} = \frac{25 \text{ cm}}{0.5 \text{ s}} = 50 \text{ cm/s}$$

Speed, Frequency & Wavelength

We can check the speed found using the length of the tank and the time taken:

$$\text{speed} = \frac{\text{distance}}{\text{time}} = \frac{100 \text{ cm}}{2 \text{ s}} = 50 \text{ cm/s}$$

So the relationship between speed, frequency and wavelength is:

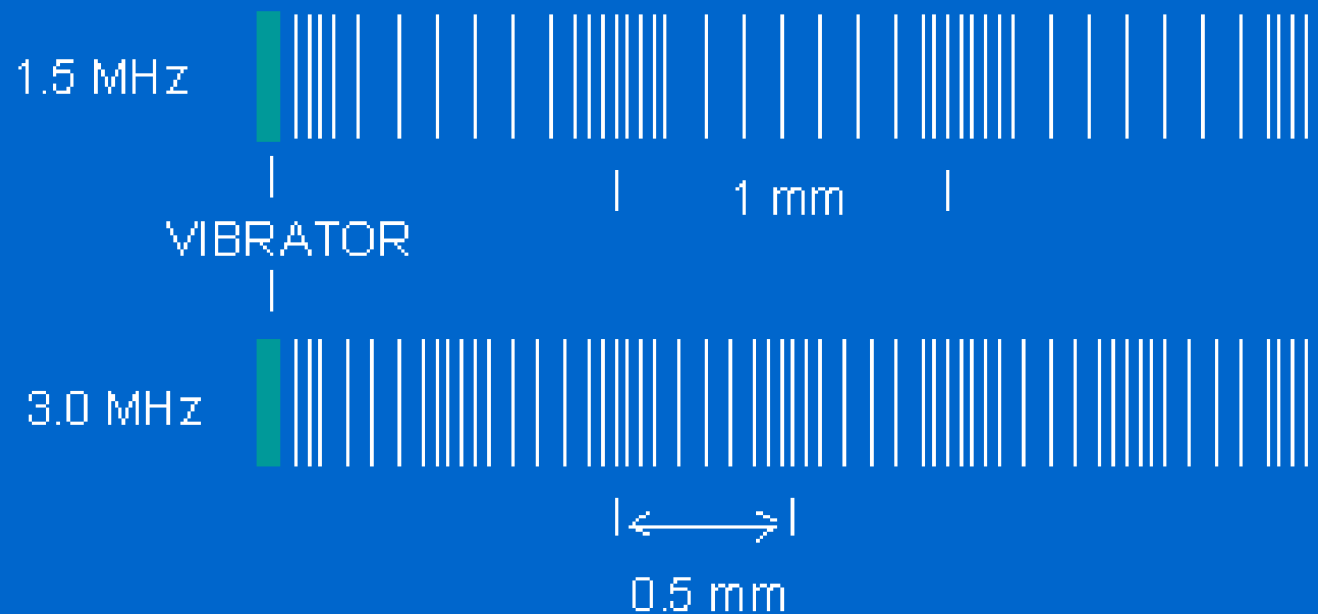
$$\text{wave speed} = \text{frequency} \times \text{wavelength}$$

$$v = f \times \lambda$$

Frequency

- By Definition is greater than 20 kHz
- Medical ultrasound is performed in the range of 1 - 20 MHz
- Radiology imaging range is 1 - 10 MHz
- Audio range is 20 - 20,000 Hz

The wavelength of sound decreases
as its frequency (MHz) increases



Velocity of Ultrasound Waves

- Velocity of ultrasound waves in tissue is independent of the wave frequency, depending primarily on the physical makeup of the material through which the sound is being transmitted.

Velocity of Ultrasound Waves

- velocity of sound is inversely proportional to compressibility
- directly proportional to density
- velocity in tissue is 1540 m/sec
 - travels 1 cm in 13 μ secs

Formation of Ultrasound Waves

- Medical ultrasound waves are generated by electrically vibrating a transducer
 - Like a piston in water
- The wavelength of the ultrasound wave is the distance between two bands of compression or rarefaction

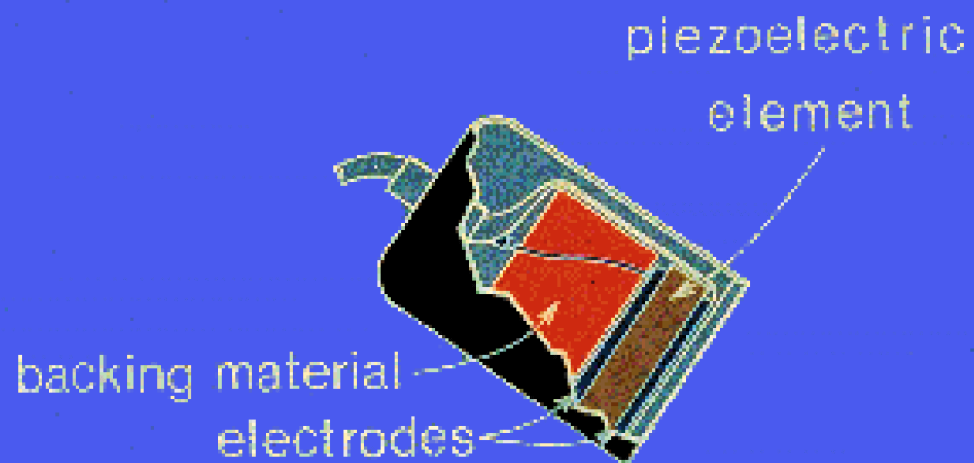
Approximate Velocities of Ultrasound in Selected Material

<u>Material</u>	<u>Velocity (m/sec)</u>
Fat	1,475
Brain	1,560
Liver	1,570
Kidney	1,560
Spleen	1,570
Blood	1,570
Muscle	1,580
Lens of eye	1,620
Skull Bone	3,360
Soft tissue (mean Value)	1,540
Air	331

The Transducer

- A transducer converts one form of energy into another.
- Ultrasound transducers convert electric energy into ultrasonic energy and, upon return of the reflected sound, ultrasonic energy into electric signals.

The Transducer



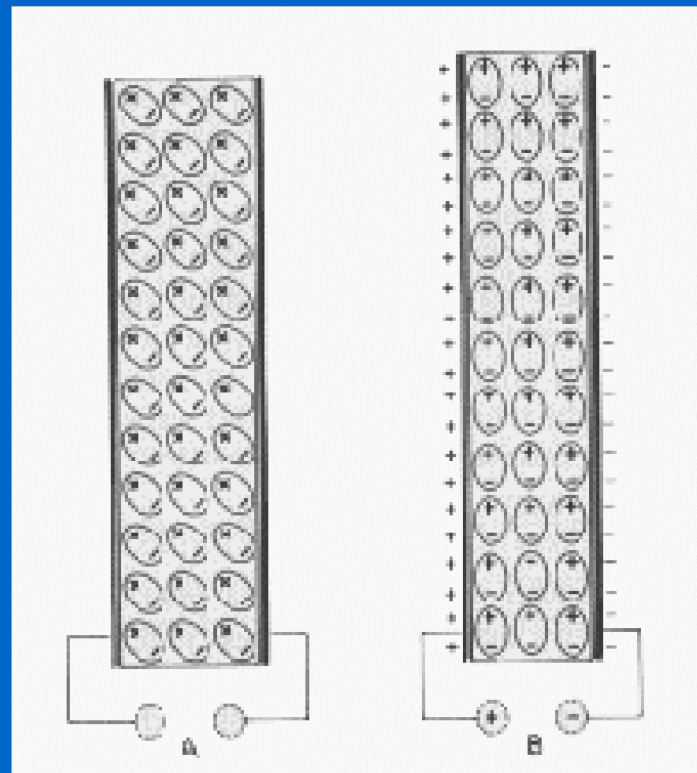
Major Components

- The crystal is the “active” portion of the transducer.
- The backing block is used to dampen the crystal oscillations in order to form finite pulses and establish the pulse length.
- Located between the crystal and patient may also be a focusing lens and generally a quarter wavelength impedance matching layer.

Piezoelectric Crystals

- Materials that change in physical dimension when an electric field is applied.
- Most common material is lead zirconate titanate (PZT).
- Quartz is a naturally occurring piezoelectric crystal studied by the Curies and used in therapeutic ultrasound transducers.

Piezoelectric Crystals



An electric field
realigns the dipoles
in a piezoelectric
crystal

Curie Temperature

- The crystals are polarized at high temperatures.
- Re-heating the crystals above the curie temperature can destroy the crystal polarization, i.e., autoclaving
- Typical curie temperatures range from 325 - 375 °C.

Resonant Frequency

- The thickness of the crystal determines the resonant frequency.
- Transducers are generally designed to operate at the frequency corresponding to the wavelength of twice the crystal thickness.

Characteristics of an Ultrasonic Beam

- Shape of the Beam
- Fresnel Zone
- Fraunhofer Zone
- Dispersion Angle
- Transducer Operating Frequency

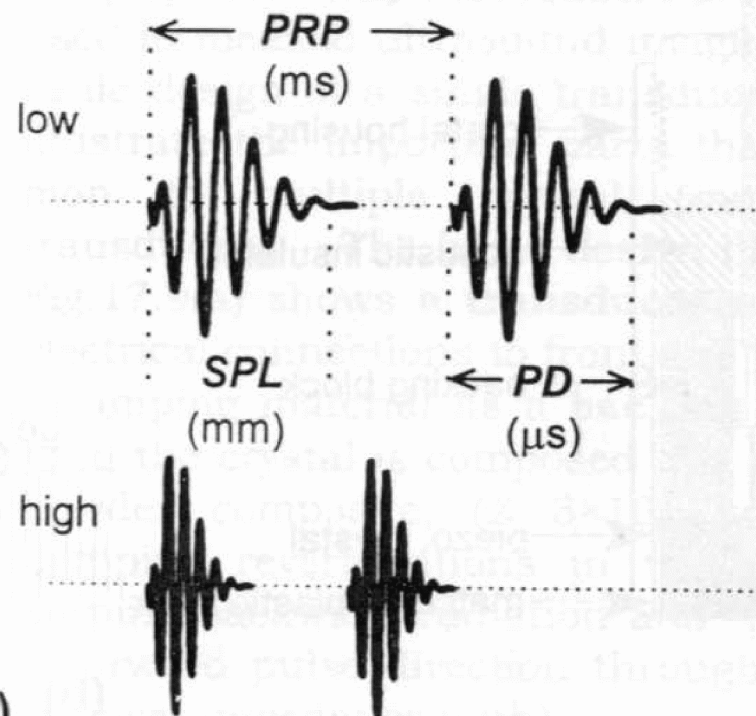
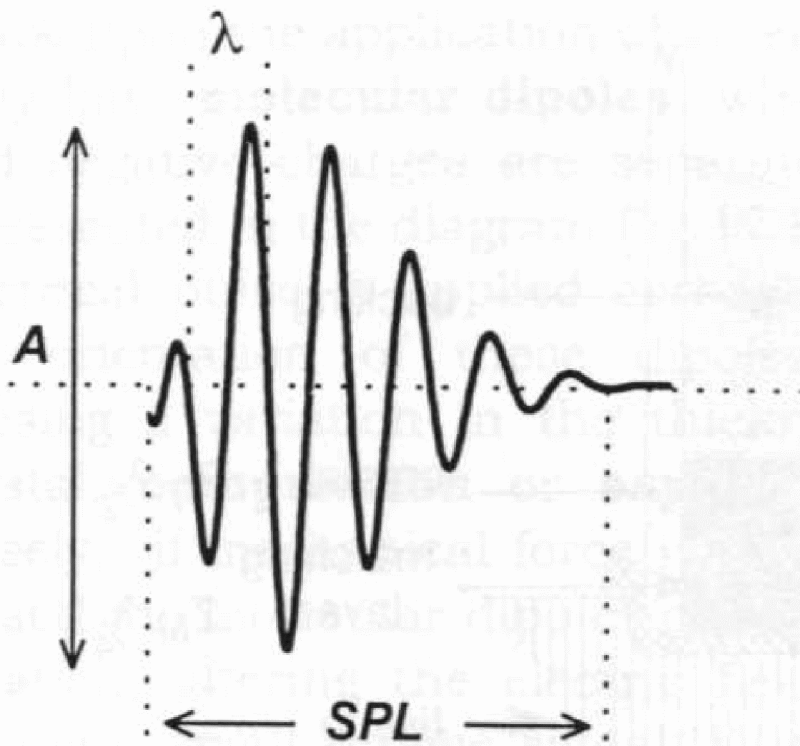


Figure 17.10 (a) Ultrasound pulse shape showing 3 cycles having wavelength λ and amplitude A and spatial pulse length SPL . (b) increasing frequency shortens SPL .

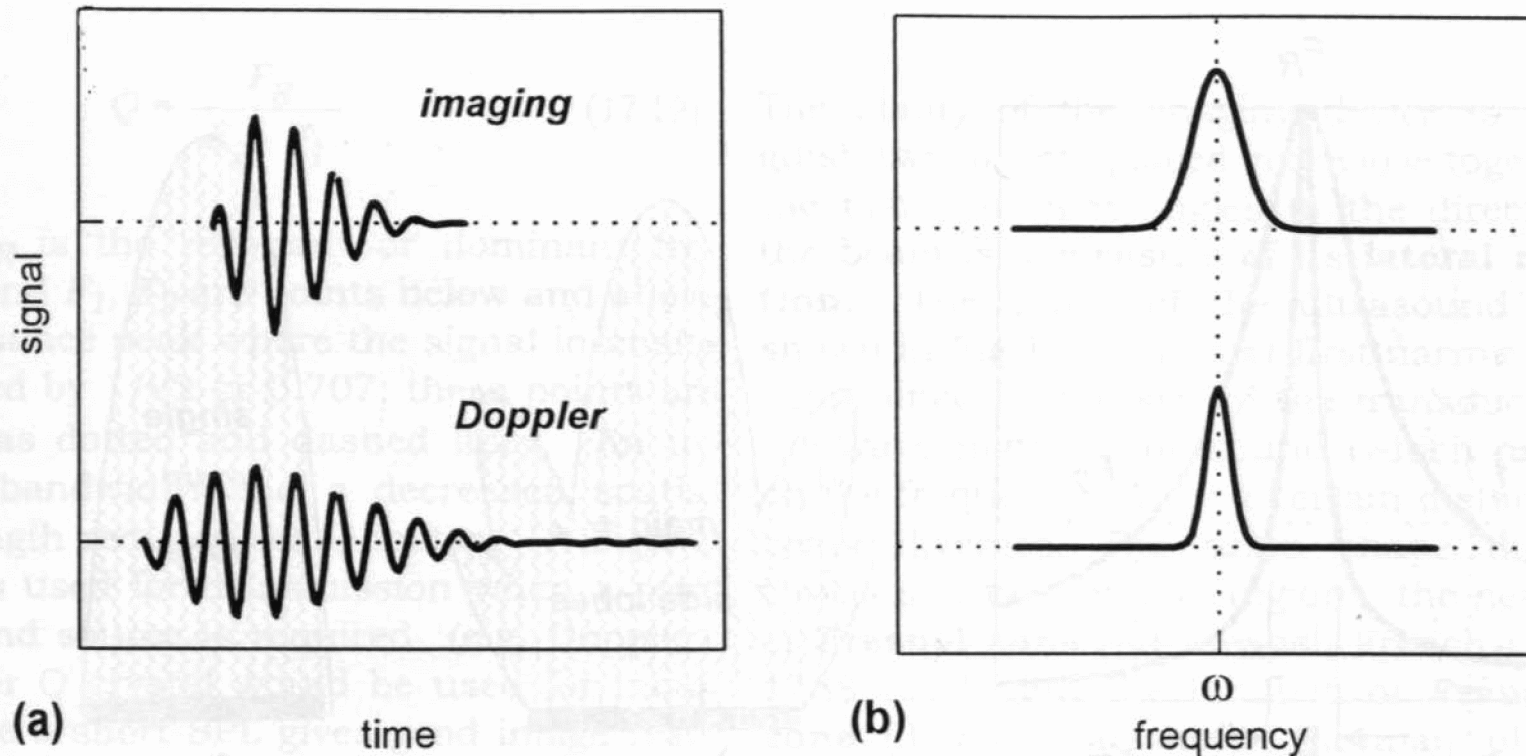


Figure 17.11 (a) Two signals showing the difference between a broad bandwidth short SPL pulse used for imaging and a narrow bandwidth long SPL pulse used for Doppler flow measurements. (b) Fourier analysis reveals the frequency component.

Table 17.6 Frequency, SPL and PD for 3λ

<i>Frequency</i> (MHz)	<i>SPL</i> (mm)	<i>PD</i> (μ s)
2.5	1.8	1.2
5.0	0.9	0.6
7.5	0.6	0.4
10.0	0.45	0.3

Shape of the Beam

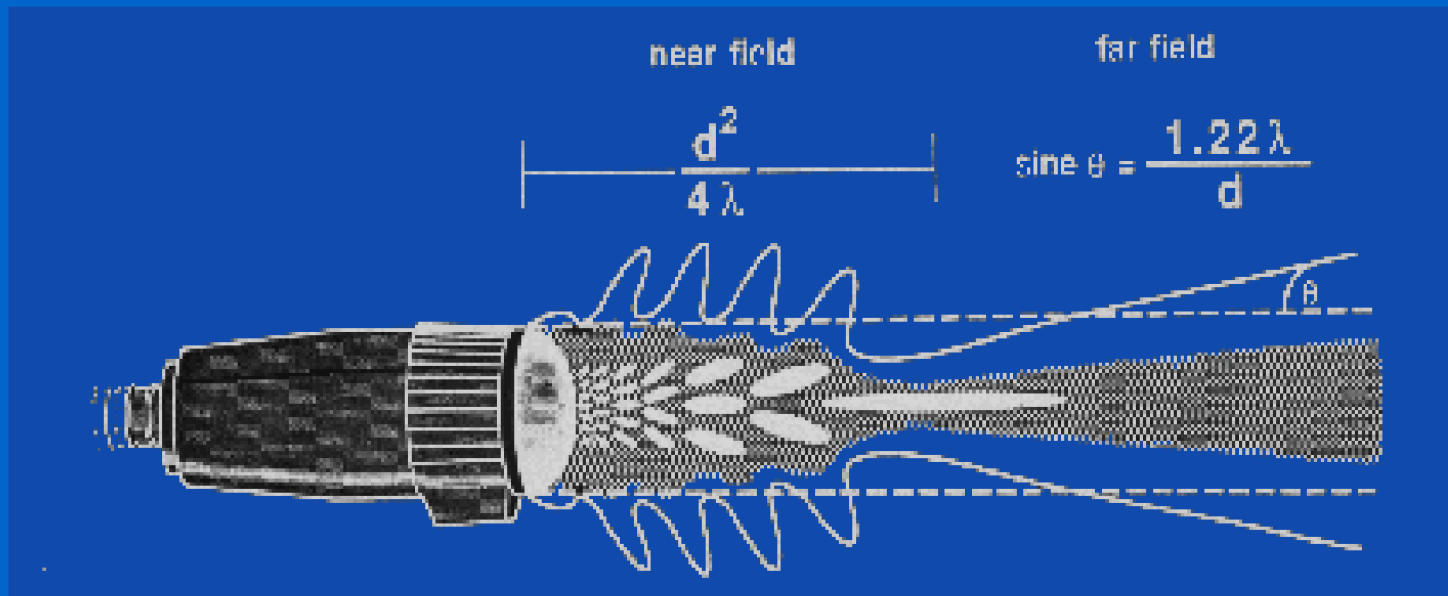


Figure 29-7, Radiologic Science for Technologists, Stewart C. Bushong

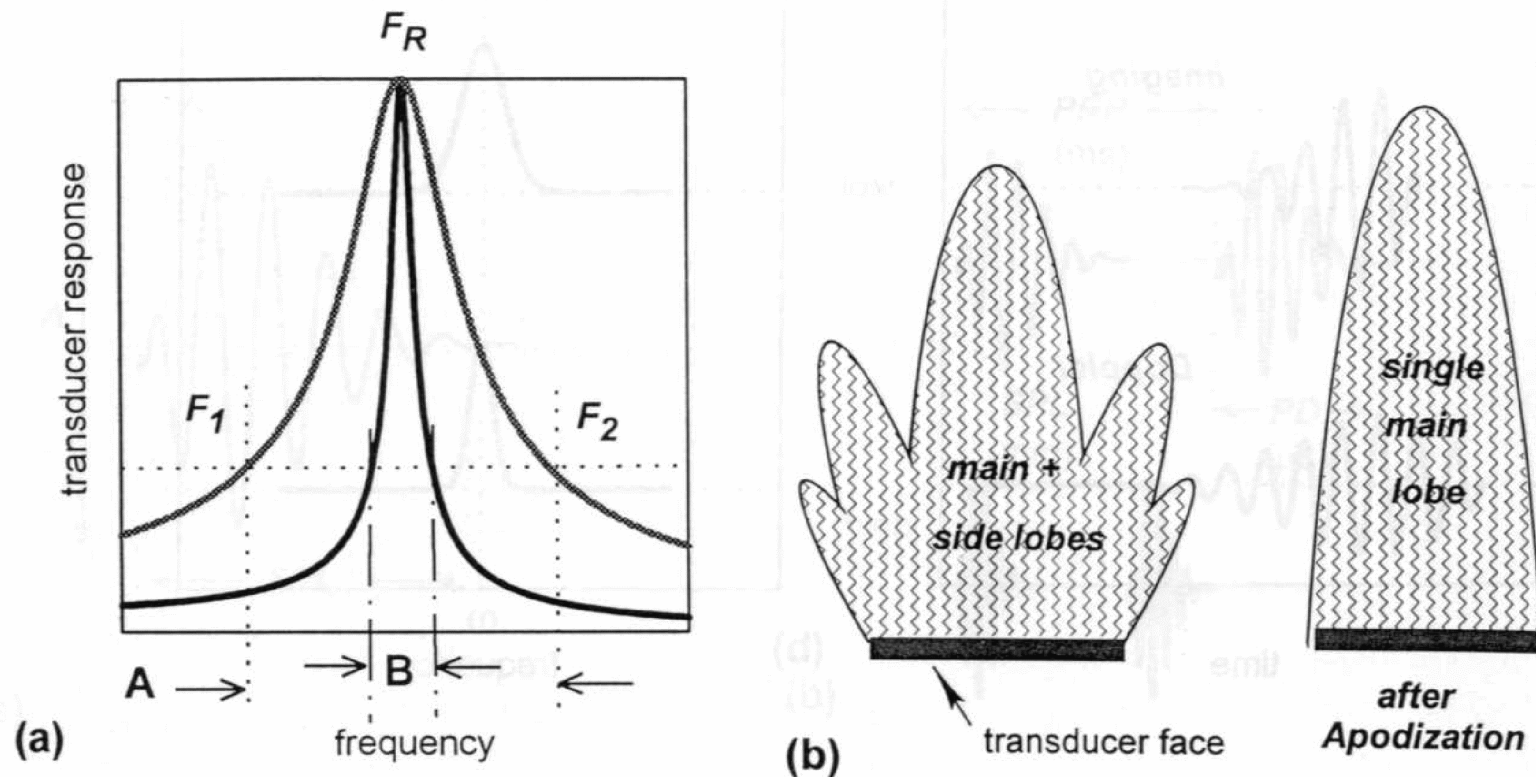


Figure 17.12 (a) Two signals having a low(A) and high (B) Q factor. The horizontal line represents a 0.707 reference point (not to scale). (b) The ultrasound beam projecting from the transducer face showing side-lobes which can decrease main lobe power unless removed by apodization.

Fresnel Zone

- Near Field
- Has “side lobes” which can give a low intensity, misplaced image of an object.
- The length of the Fresnel zone is determined by the diameter of the transducer and the ultrasound wavelength for unfocused transducers.
- Best lateral resolution.

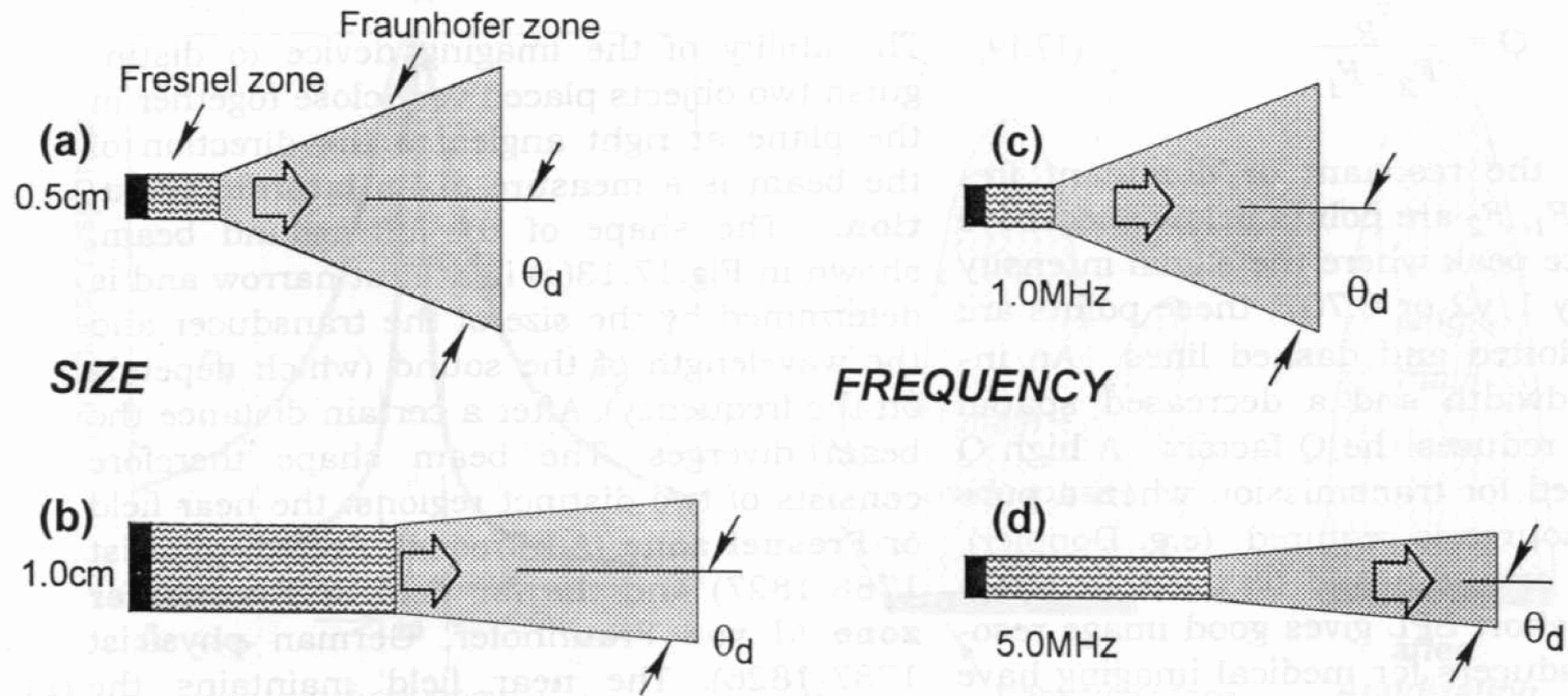


Figure 17.13 The variation of Fresnel and Fraunhofer zones for a single element transducer having sizes (a) 0.5 and (b) 1.0cm. The beam profile for the 0.5cm transducer is then shown at (c) 1MHz and (d) 5MHz.

Table 17.7 Transducer resolution

<i>Frequency</i>	<i>Image depth</i>	<i>Axial res.</i>	<i>Lateral res.</i>
2.0	30	0.7	3.0
3.5	17	0.4	1.7
5.0	12	0.3	1.2
7.5	8	0.2	0.8
10.0	6	0.15	0.6

Fraunhofer Zone

- Far Field.
- Angle of dispersion depends on the diameter of the transducer and the wavelength of the ultrasound.

Note:

- As the transducer diameter is increased, the near field is lengthened and the far field divergence is decreased.
- Lateral resolution is decreased with increased transducer diameter.
- As transducer operating frequency is increased, the near field is lengthened and the far field divergence is decreased.

Near-field lengths and far-field divergence of commercially available transducers

Transducer diameter (mm)	Frequency (M Hz)	Near-field length (cm)	Far-field divergence
8	10	10.4	1°21'
8	5	5.2	4°25'
12	2.5	1.1	1°48'
12	5.0	11.7	1°48'
15	1.0	9.1	2°52'
20	1.0	6.5	5°23'

Radiologic Science for Technologist, Bushong, p. 505, Table 29-1

Transducer Operating Frequency

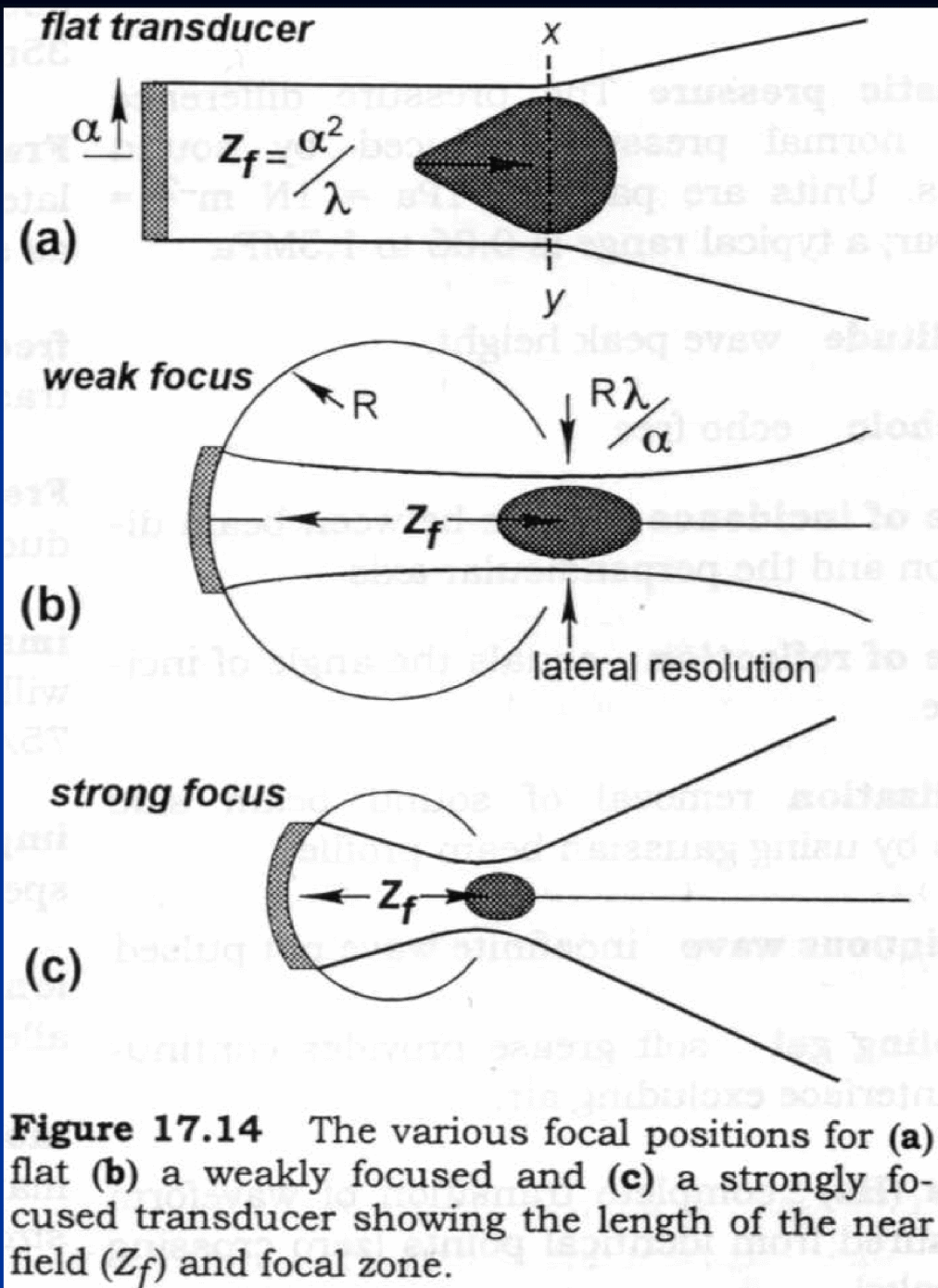
- High frequency ultrasound beams have two primary advantages over lower frequency ultrasound beams.
 - Depth or axial resolution is better.
 - Fresnel zone (near field) is longer.
- Primary disadvantage
 - tissue absorption increases with increased frequency

Selecting a Transducer

- A larger transducer are preferable for deep-lying structures.
- A small-diameter high-frequency transducer should be used for shallow structures and irregular surfaces of interest.
- A medium-frequency medium-diameter transducer could image abdominal studies.
- A low-frequency large-diameter transducer for larger patients or harder to penetrate areas.

Selecting a Transducer

- Depth of structure is primary consideration.
- The objective is to enhance lateral resolution by scanning the area of interest with a narrow beam.



Interactions Between Ultrasound and Matter

- Reflection
- Refraction
- Scattering
- Absorption

Specular Reflection

- Sound directed at right angles to a smooth interface larger than the width of the beam will be partially reflected toward the source.
- Angle of reflection = Angle of incidence
- Fraction reflected = $R = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$

Scattering

Non-Specular Reflections

- A beam that strikes a surface or object smaller than the beam cross-section or an irregular surface.

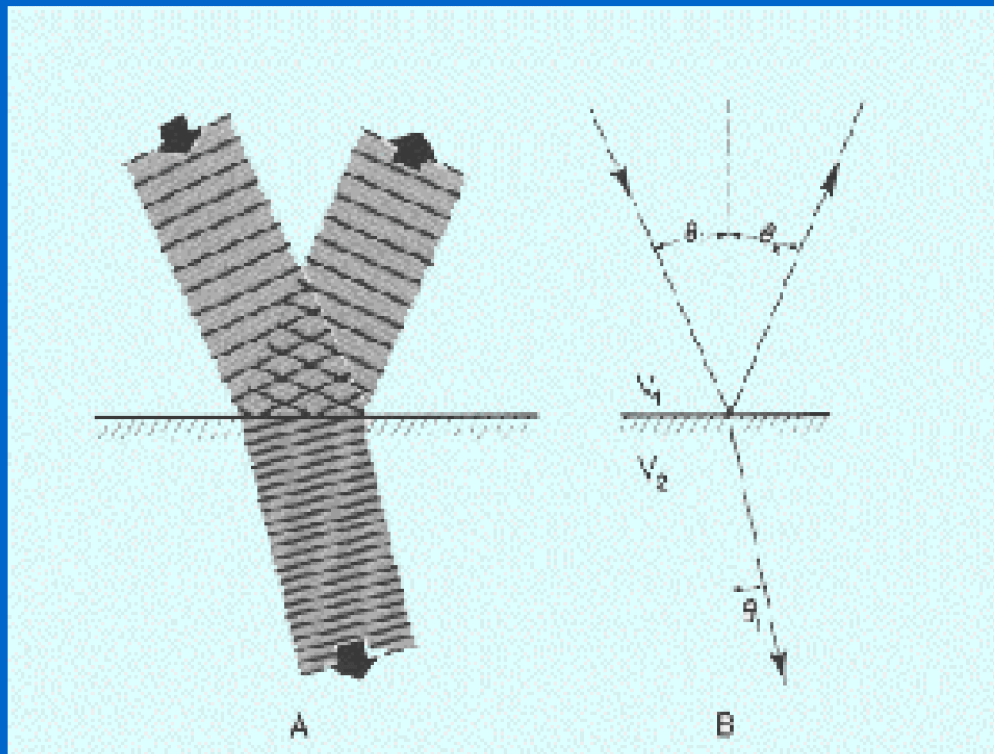
Refraction

- When sound passes from one medium to another is **frequency remains constant** but its wavelength changes to accommodate the new velocity in the second medium.
- When the beam strikes the second medium at an angle, the change in wavelength necessitates a change in direction.

Refraction

- The bending of waves as they pass from one medium to another.
- Snell's Law gives the angle of refraction.
- Critical Angle is the incident angle at which refraction causes no ultrasound to enter a medium.

Refraction



Snell's Law

$$\frac{\sin \theta_i}{\sin \theta_t} = \frac{v_1}{v_2}$$

- θ_i = incidence angle
- θ_t = transmitted angle
- v_1 = velocity of sound for incident medium
- v_2 = velocity of sound for transmitting medium

Absorption and Attenuation

- Absorption is the frictional losses resulting from the conversion of ultrasound energy into heat.
- Attenuation refers to total propagation loss, including absorption, scattering, and reflection.
- For soft tissue attenuation is approximately equal to 1 dB/MHz-cm.

Absorption and Attenuation

- Attenuation through tissue layers is additive in units of dB.
- Attenuation increases linearly with increased frequency.
- Remember - the ultrasound beam must travel to and from the reflecting interface, so the path length is 2 times the interface depth.

Imaging Principles

- Lateral or Horizontal Resolution
- Depth or Axial Resolution
- Focused Transducers
- Spatial Pulse Length
- Pulse Rate
- Maximum Scan Thickness
- Frame Rate

Lateral or Horizontal Resolution

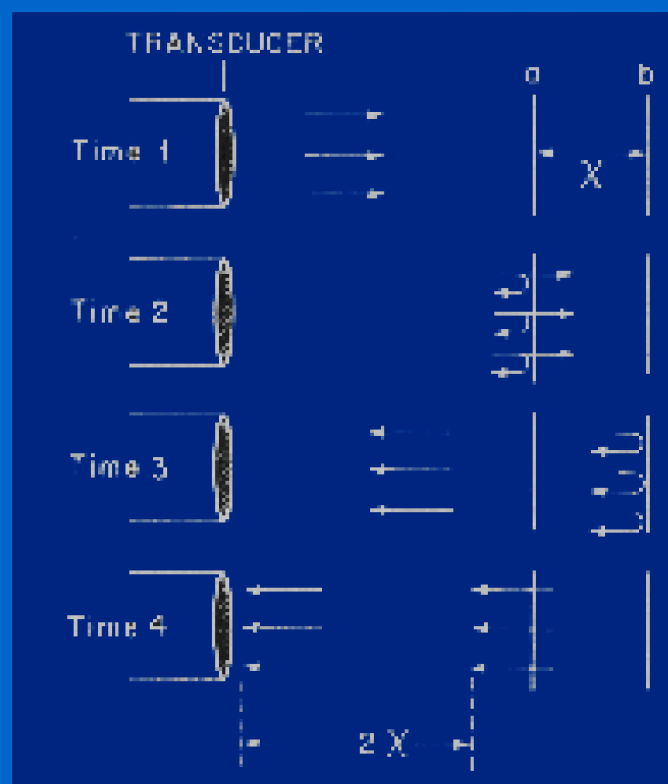
- Lateral resolution is the ability to separate two adjacent objects.
- The beam must be narrower than the space separating the objects.
- Very small diameter transducers have short Fresnel zones and can not generally be used except for ophthalmology work.

Depth or Axial Resolution

- Depth or Axial resolution is the ability of the beam to separate two objects lying in tandem along the axis of the beam.
- Two objects will be resolved if the spatial pulse length is less than twice the separation.
- Axial resolution is constant with depth.

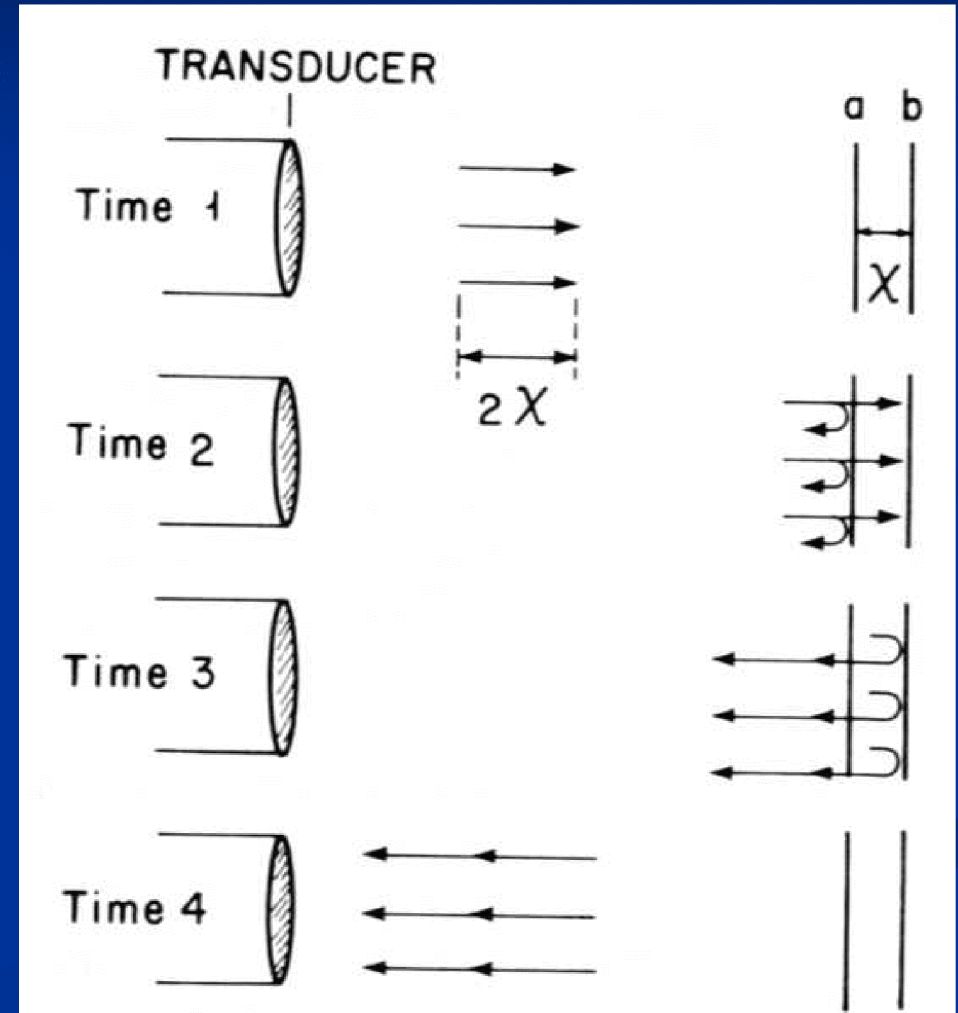
Depth (Axial) Resolution

This figure shows a time sequence of an ultrasonic pulse resolving two surfaces, a and b, separated by x distance.



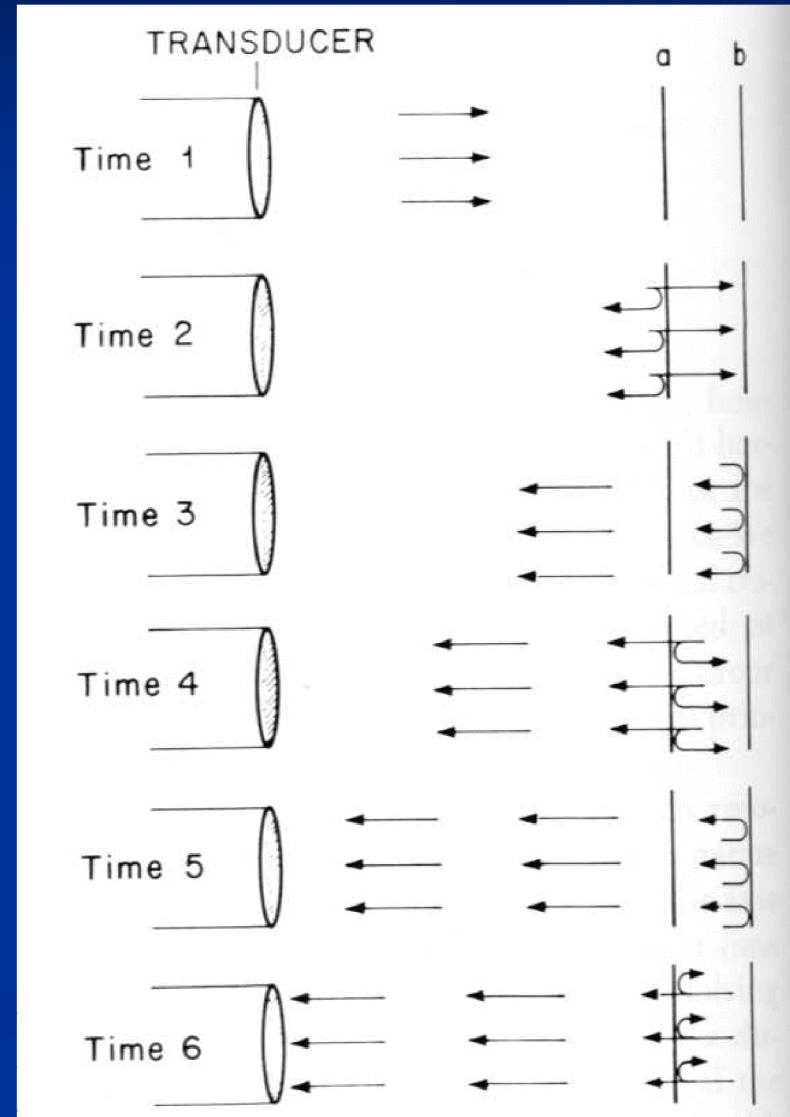
Unsatisfactory Depth Resolution

- This figure shows two objects separated by exactly half a spatial pulse length.
- The transducer only sees one pulse, so the two surfaces are not resolved.



Reverberation images

this figure shows how these spurious images are produced.

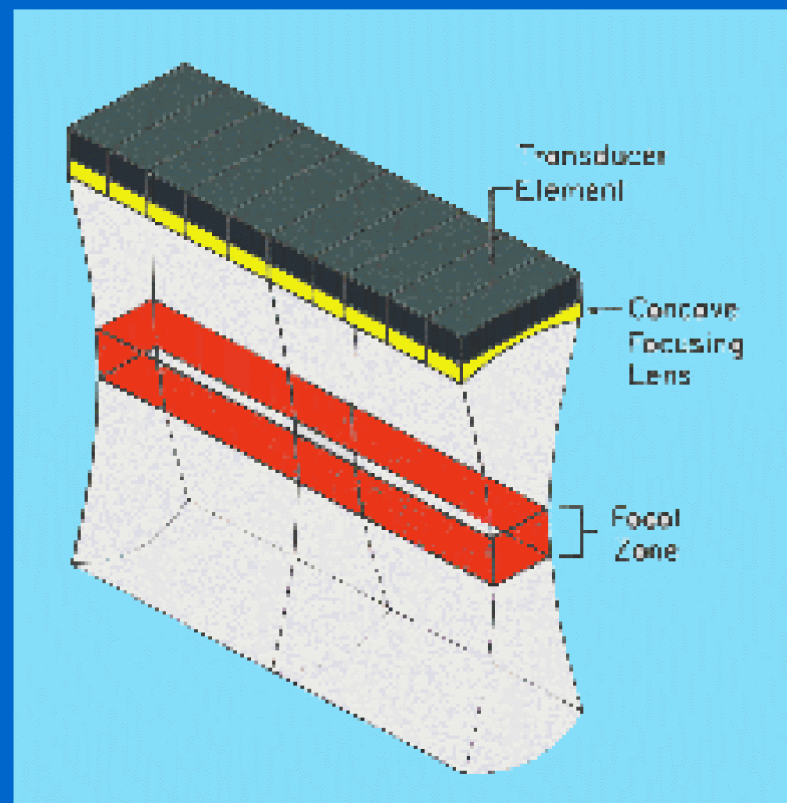


Focused Transducers

- Give improved lateral resolution at depth.
- Focusing types:
 - Curved crystals
 - Acoustic mirrors
 - Acoustic lenses
 - Electronic focusing (phased array)
- Focusing is either weak or strong depending on the beam diameter reduction

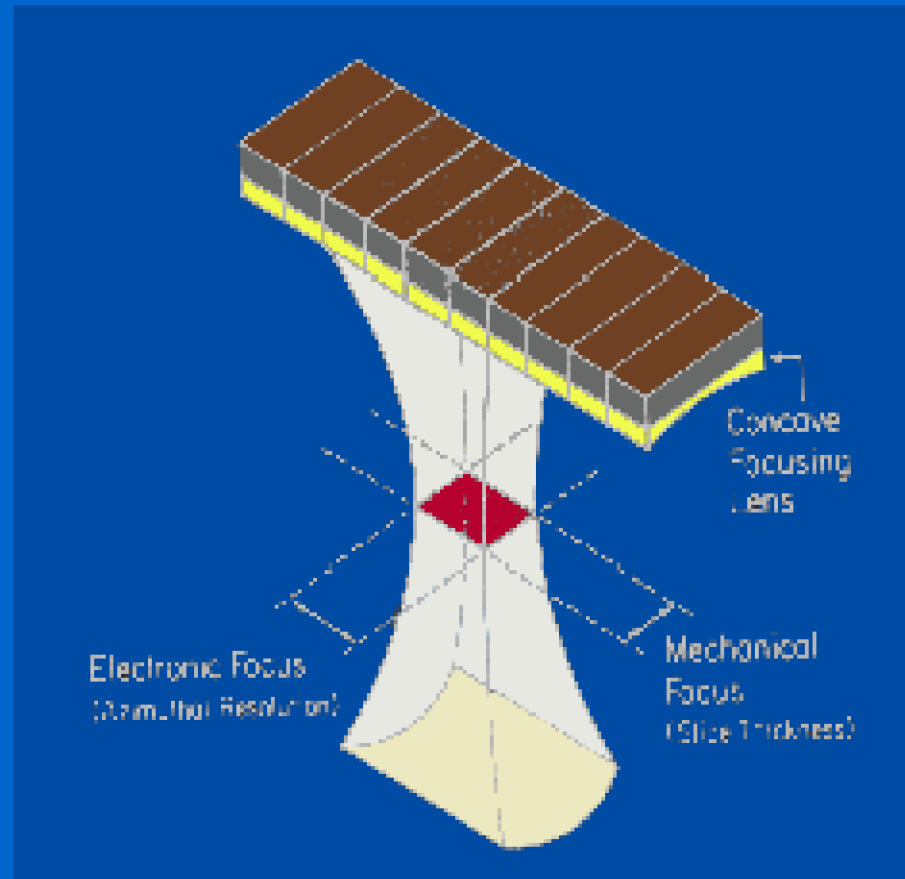
Focused Transducers

A concave lens used to focus a linear array



Focused Transducers

Resolution in the plane parallel to the image (azimuthal resolution) is accomplished electronically.

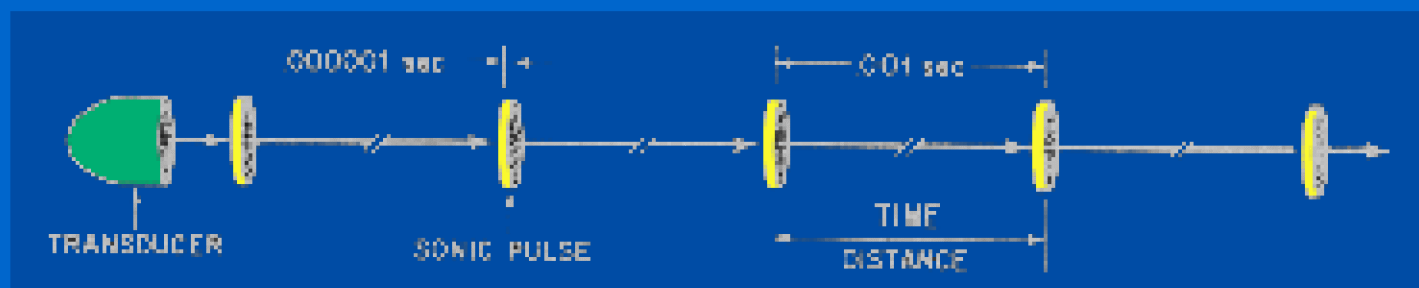


Spatial Pulse Length

- Axial resolution is determined by spatial pulse length.
- Dampening block limits the number of cycles of the crystal to between 2-6 cycles.
- Spatial Pulse Length = # cycles x wavelength

Pulse Rate

- Number of separate pulses that are produced each second.
- Remember - the transducer must act as a transmitter and a receiver.
- Common pulse rate for abdominal imaging is 1,000 pulses/second.
- Different and unrelated to frequency.



Maximum Thickness

- The maximum scan thickness is determined by the speed of the ultrasound beam and the pulse repetition period, PRP.
 - Speed of sound in soft tissue = 154,000 cm/sec
 - Distance traveled = $(154,000 \text{ cm/sec})^{-1}$
= 0.0000065 sec/cm
 - Maximum scan depth = PRP (μsec)/2 x (6.5 μsec)

Frame Rate

- Determined by the pulse repetition period and the number of scan lines.
 - Pulse Repetition Frequency = $1 / \text{PRP}$
 - Frame Time = $\text{PRP} \times N$ (number of scan lines)
 - Frame Rate = $1 / \text{Frame Time} = 1 / (\text{PRP} \times N)$
= $1 / [(13 \mu\text{sec}) \times (\text{maximum scan depth}) \times N]$

Frame Rate

- Increasing the pulse repetition period, maximum scan depth or number of scan lines will decrease the frame rate in direct proportion

Ultrasound Imaging Systems and Displays

- A- Mode
- TM- Mode
- B- Mode
- Real-time
- Doppler

A-Mode

- Amplitude mode employed for ophthalmology, echoencephalography, and for accurate depth measurements in B-mode scanning, as well as to determine solid versus cystic nature of masses.

TM-Mode

- Designed to show time/motion relationships of structures; used primarily in echocardiography.

B-Mode

- Essentially an A-mode display viewed from above.
- The B-mode produces a picture of a slice of tissue.

Mode Comparison

If the A-mode image contains moving interfaces and is converted to a B-mode display so that the vertical axis is time driven, M-mode display results.

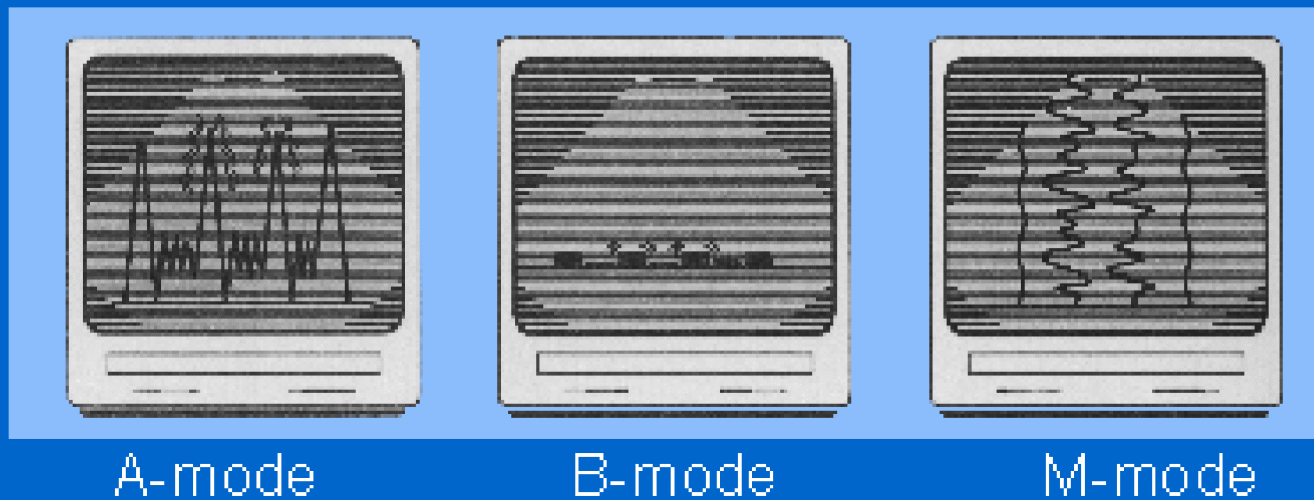


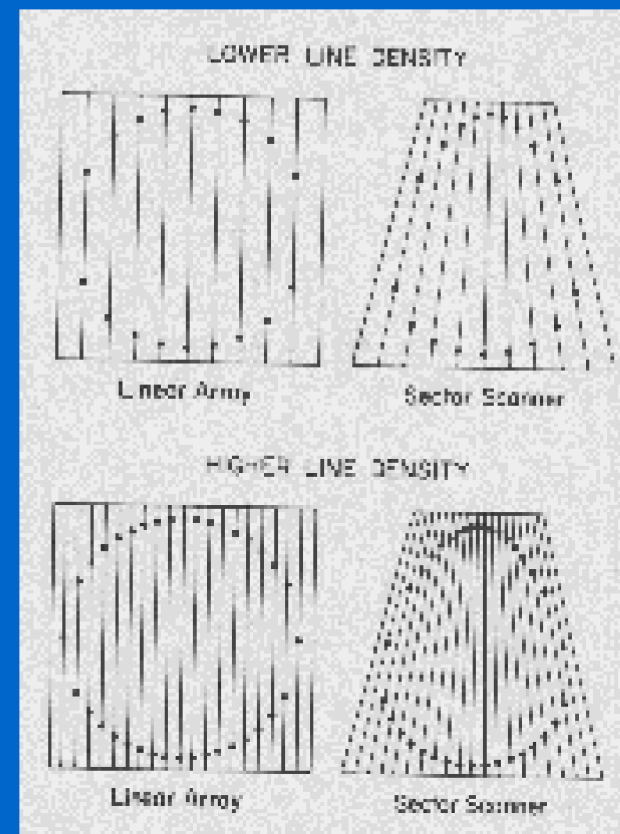
Figure 29-17, Radiologic Science for Technologists, Stewart C. Bushong

Real-Time

- Allows viewing of motion and performing of imaging studies faster than with B-mode scanning.
- Frame rates from 8 - 40 frames per second.
- uses linear array, phased array, annular or sector transducers.

Real-Time Imaging

Image resolution improves in both linear array and sector real time images as the number of lines per frame increases.

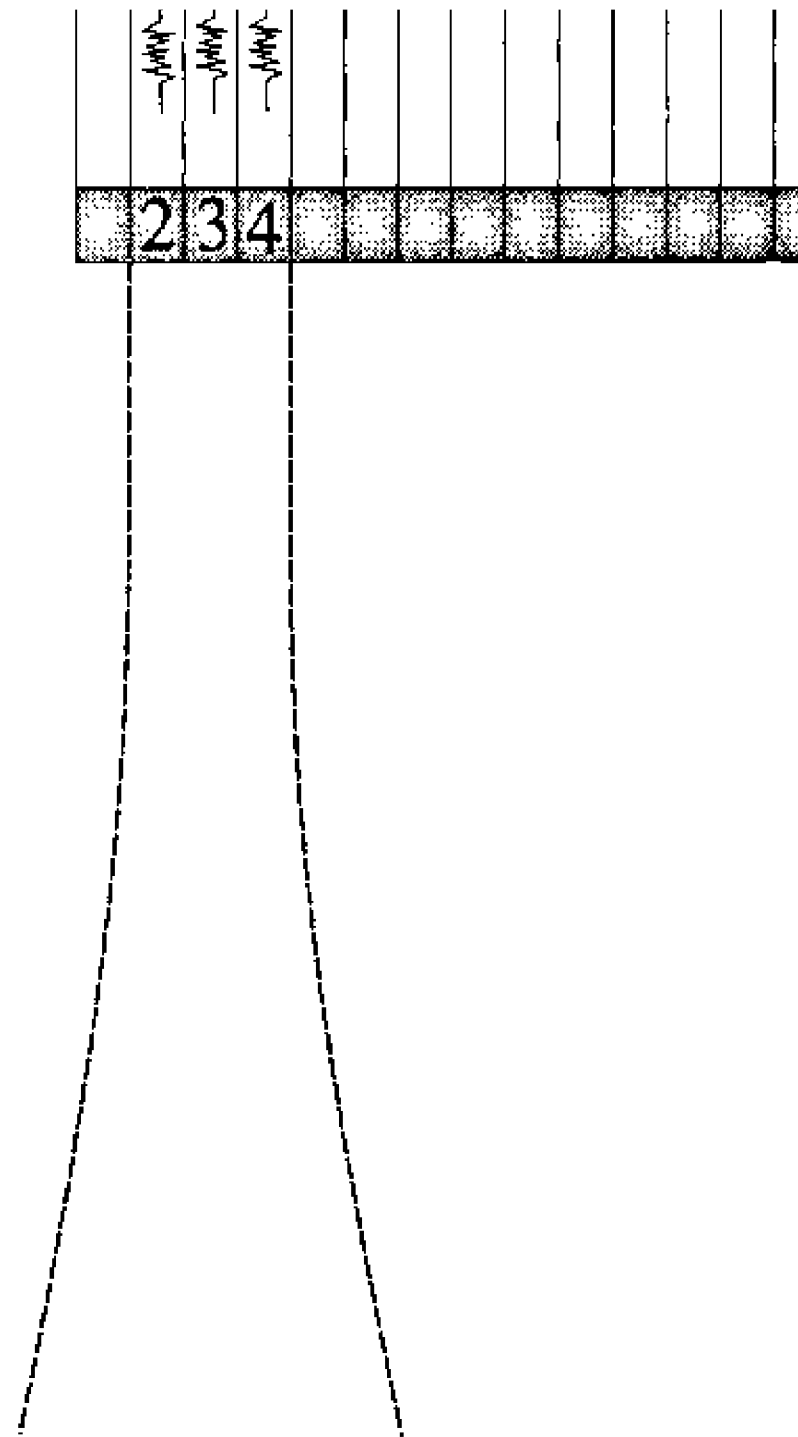
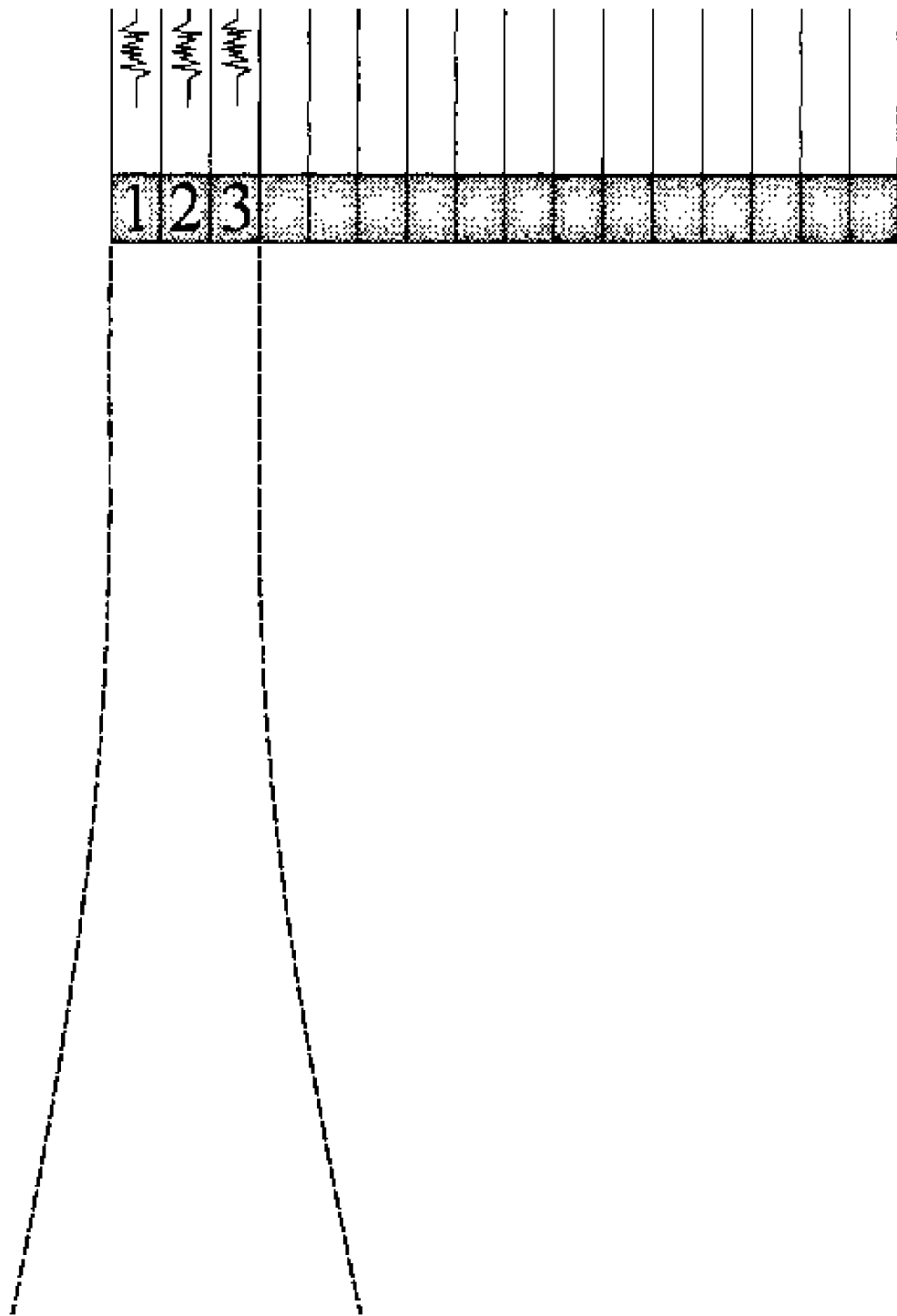


Sector Scanning

- Resolution becomes poorer at increasing depths.
- Good resolution is obtained in the region near the transducer because there are a large number of lines of sight per unit area.
- The resolution becomes poorer at greater depths, since the number of lines of sight per unit area decreases.

Linear Arrays

- The transducer is manipulated electronically to focus as well as to sweep (or steer) the ultrasound beam throughout the region of interest.
- Two types of electronic systems are available.
 - Sequential Linear Arrays
 - Segmental Linear Arrays



Sequential Linear Arrays

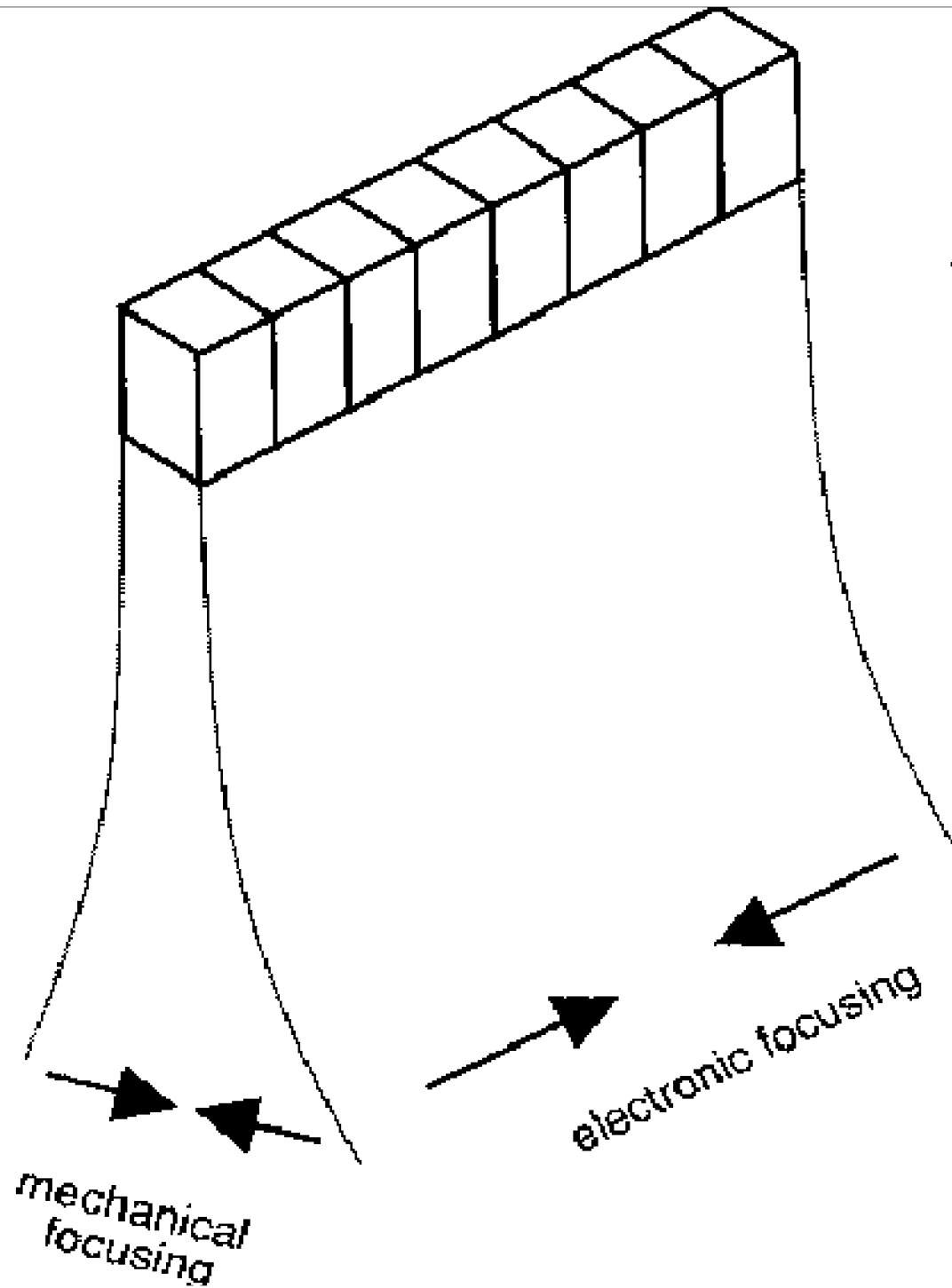
- Transducer consists of multiple crystals arranged in a straight row.
- Each crystal produces an ultrasound beam and then receives the returning echoes for data collection along one line of sight.
- The crystals are activated in a sequential fashion to form the individual lines of sight, a time delay for collection of the returning echoes are imposed before the next crystal is fired.

Segmental Linear Arrays

- A group (segment) of crystals in the linear array is stimulated.
- A deeper near field and a less divergent far field is produced as compared with a single crystal acting alone.
- However, fewer lines of sight for the same given area are created resulting in poorer lateral resolution.
- A stepdown segmental array produces good temporal resolution (high frame rate) and good spatial resolution (beam size and number of lines of sight).

Linear Array

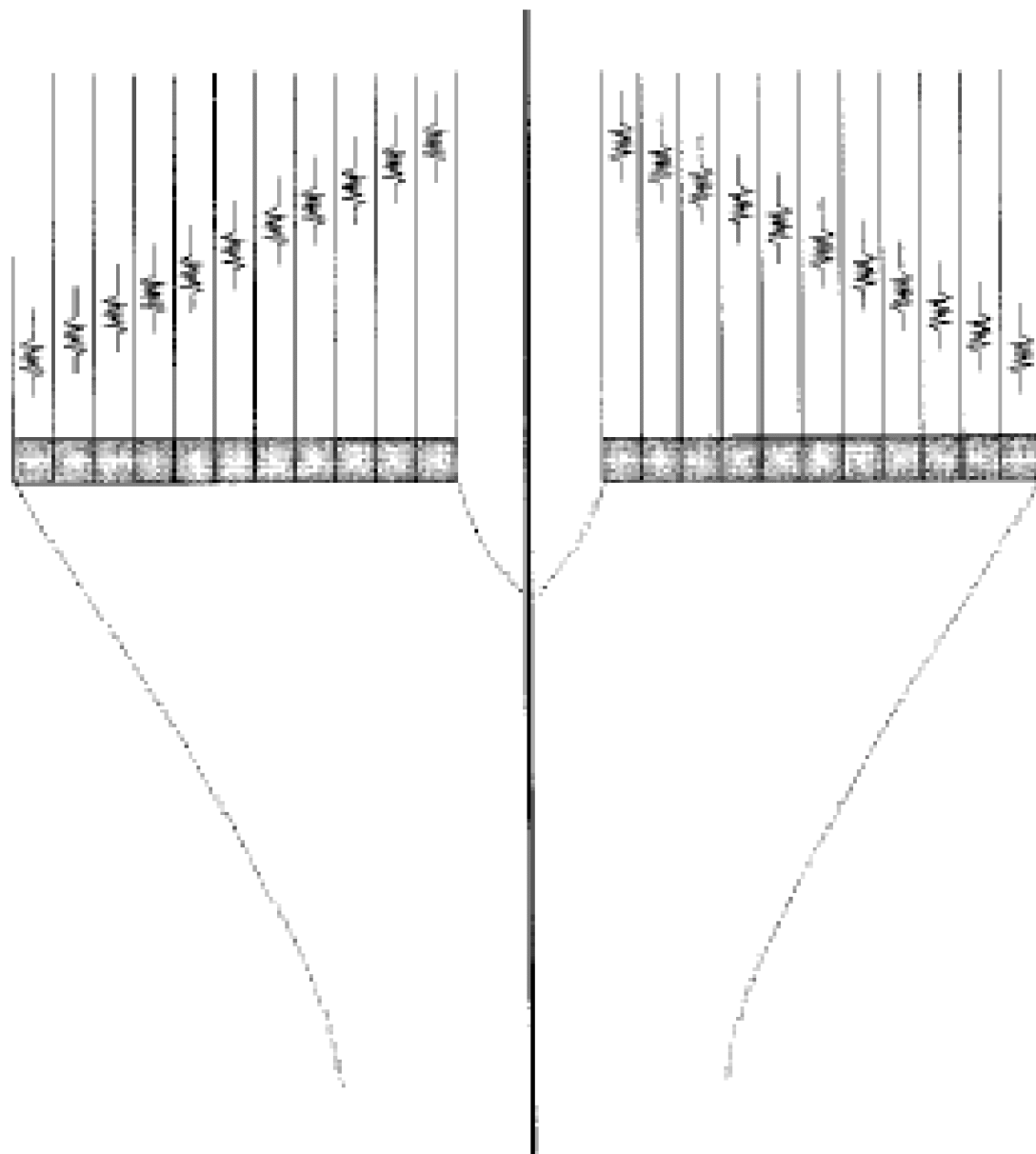
Acoustic Lens



electronic focusing

mechanical focusing

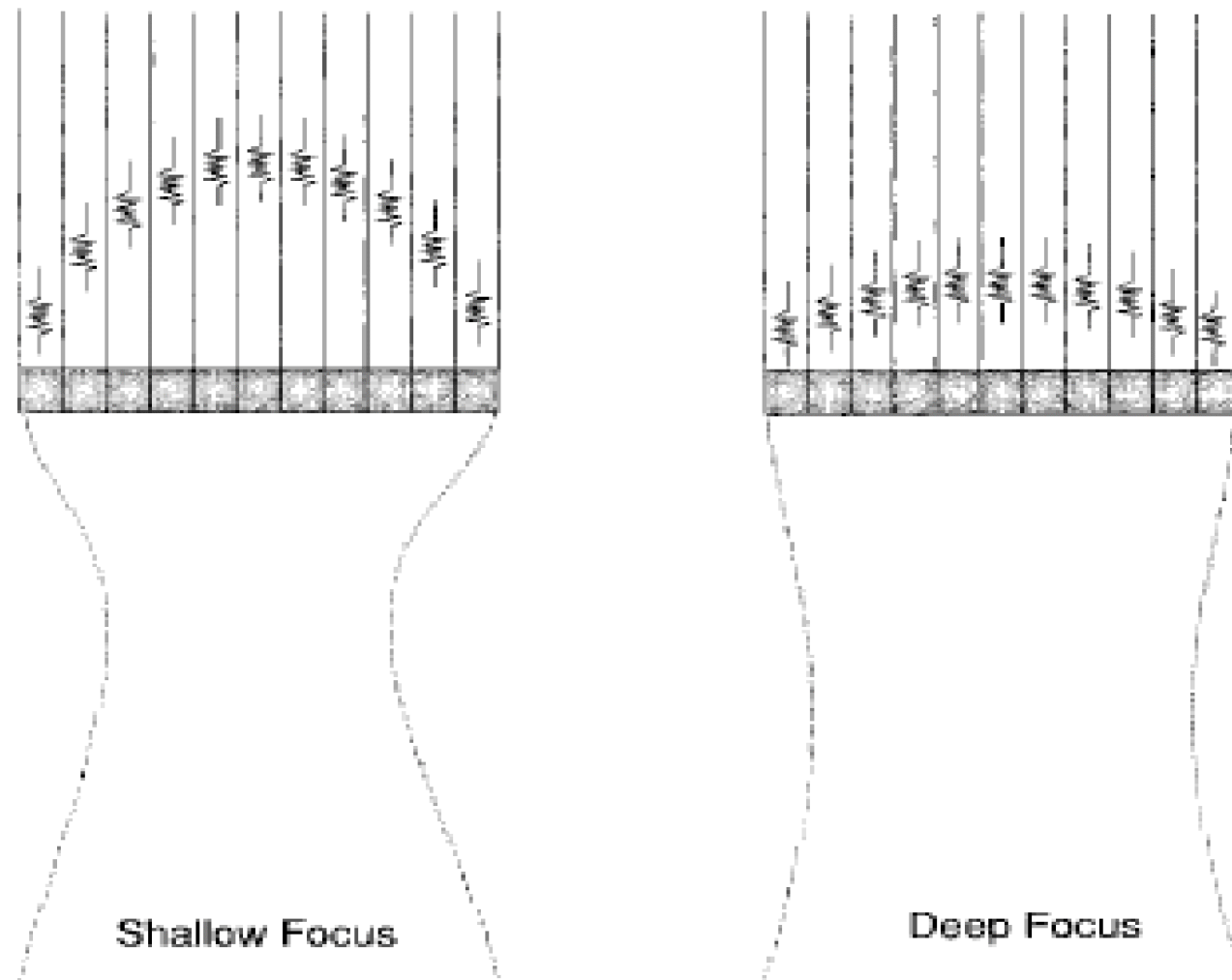
Sweep Right



Sweep Left

Dynamic Sweeping

(a)



Dynamic Focusing

(b)

FIGURE 20-6
Electronic scanning with a linear phased array.

The main distinction between the linear phased array and the linear switched array is that all of the elements of the phased array are used to produce each scan line while only a few of the elements of the switched array are used to produce each scan line.

Transducer Motions

Types of transducer motions used in ultrasound scanning.

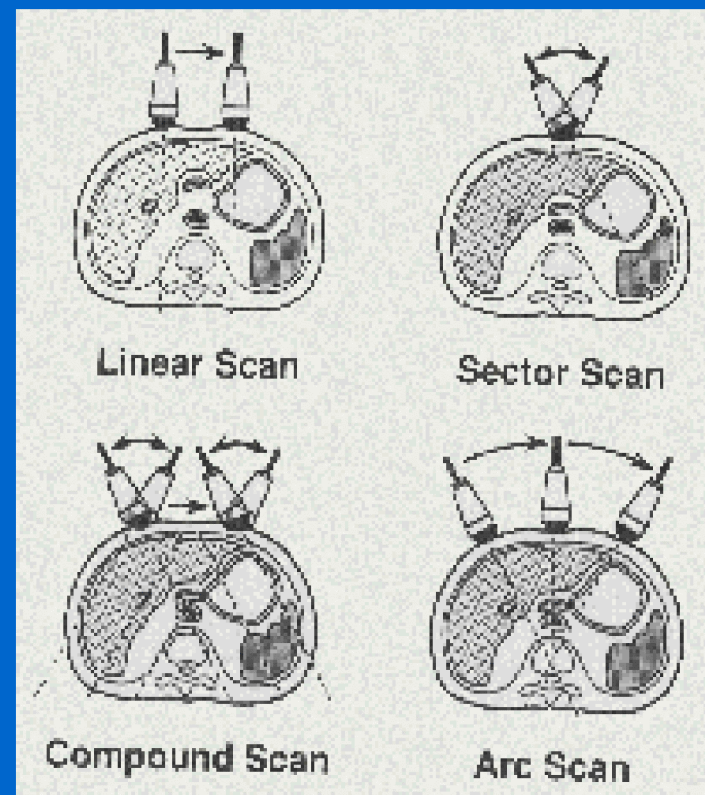
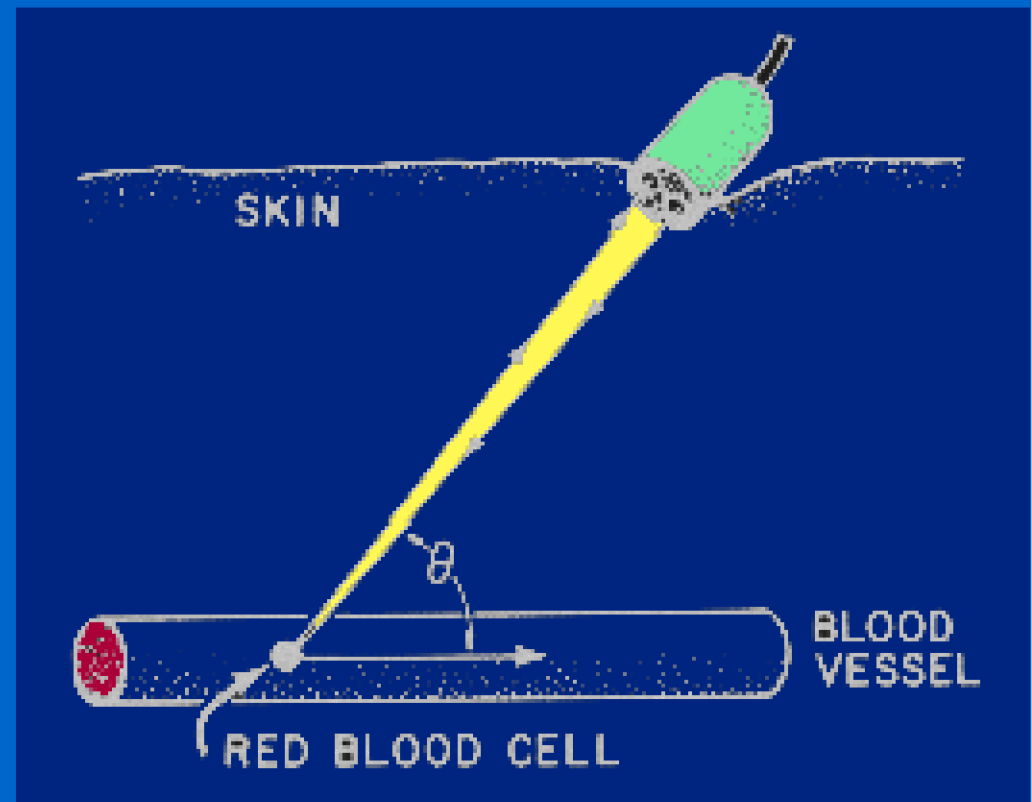


Figure 29-15, Radiologic Science for Technologists, Stewart C. Bushong

Doppler

- Used to quantitate blood flow.
- Measures a change in the detected frequency of an ultrasound beam reflected from a moving surface (primarily blood).



Doppler Transducers

- Continuous Wave Transducer- continuously emits a beam and must contain two crystals.
- Pulsed Wave Transducer - contains a single crystal which emits and detects the beam in the same manner as the imaging crystal.
 - has the advantage of depth discrimination.

Doppler Signal

- Scanning performed with 2-10 MHz transducers.
- Frequency shift will range from 0 to 10 kHz for velocities ranging from 0 to 100 cm/sec.
- The shift can be represented using an audio amplifier and speaker.
- Higher frequency transducers desirable.

Doppler Sound Shift

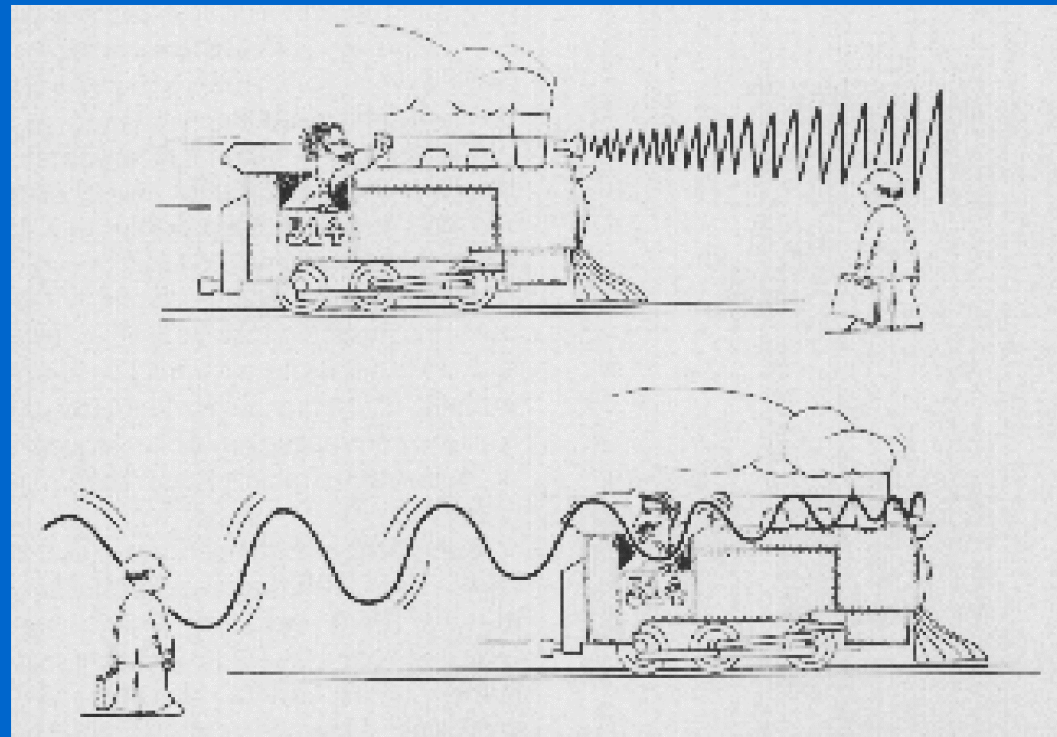


Figure 29-18, Radiologic Science for Technologists, Stewart C. Bushong

Color Flow Doppler

- Differentiate blood flow velocity using color.
- Generally, red is assigned to arteries and blue to veins.
- Two disadvantages:
 - Mean, rather than maximum, velocity computed
 - PRF limits the Doppler shift frequency that can be detected.

Color-Flow Imaging (Static Mode)

- A two-dimensional image of the flow is constructed by displaying the detected Doppler shifts as the transducer is moved across the scanning area.
- Each point in the image corresponds to a particular location of the transducer.
- Doppler signals are displayed as different colors depending on the magnitude of the frequency shift.
- May operate in either the CW or PW mode.

Duplex Scanners

- Duplex Doppler units combine real-time imaging with CW or PW Doppler detection.
- The real-time image depicts stationary reflectors (e.g., plaques inside the vessel and other anatomical structures) whereas the Doppler mode provides flow information for a selected region.
- Visualization of the physical size and shape of plaque is possible.

Time Gain Compensator (TGC) Control

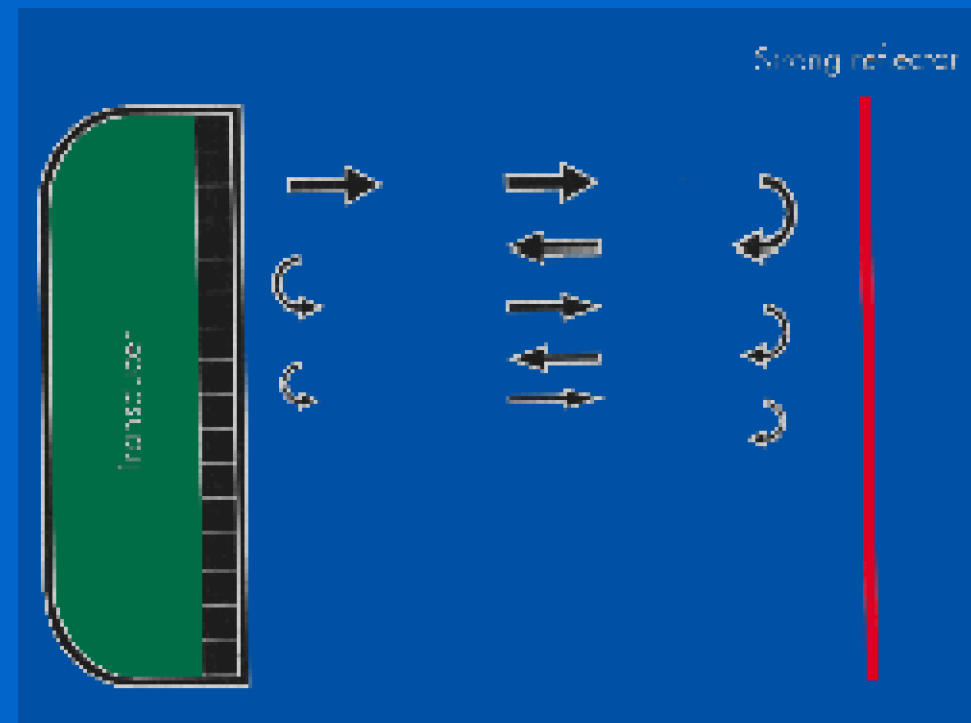
- Most important unit control.
- Amplifies signals returning from greater depths so that interfaces of equal fractional reflections produce the same amplitude signal.
- Shape of the TGC curve can be manipulated.

Imaging Artifacts

- Reverberation
- Refraction
- Multipath
- Range Ambiguity
- Mirror Image

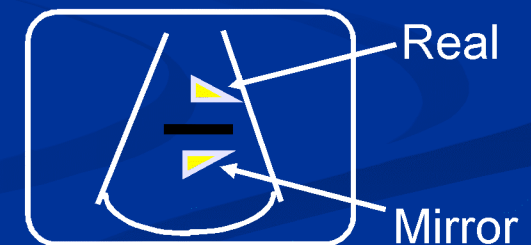
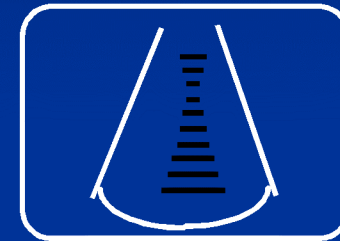
Reverberation

- Occurs when an acoustic signal encounters a highly reflective surface.
- Occur at regular intervals and decrease in intensity due to attenuation.



Artifacts

- **Reverberation** (multiple echo) artifact
 - “comet tail” effect is 1 example
 - can have dozens of multiple reflections between
 - transducer & reflector
 - 2 reflectors
- **Mirror Image**
 - common around diaphragm & pleura



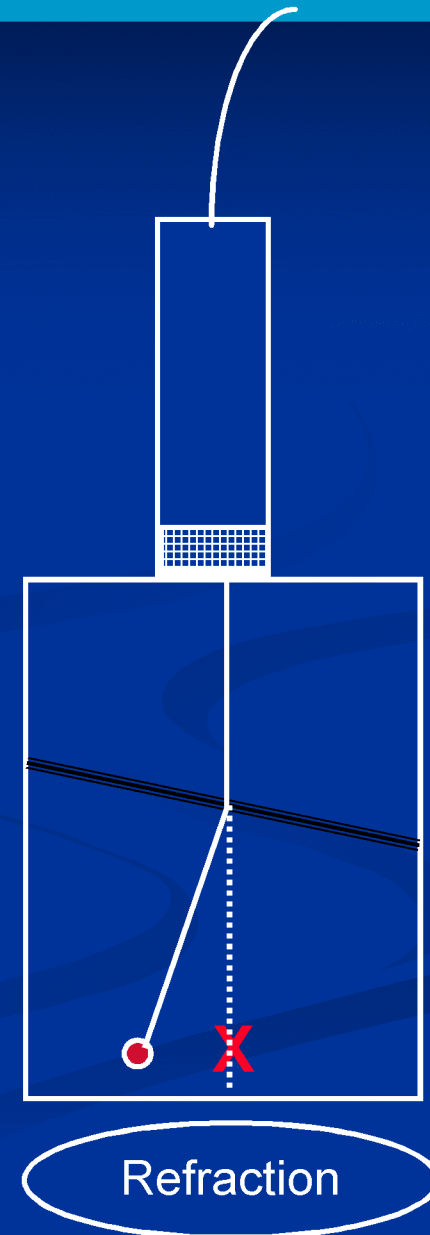
Refraction

- Occurs when ultrasound beam transverses interfaces and the wavelength changes due to change in speed of sound.

Refraction Artifact

- refraction alters beam direction
- direction of sound travel assumed to be direction sound transmitted

● Actual Object Position
X Position of Object on Image



Refraction Artifact

- refraction alters beam direction
- scanner places dot in wrong location along line of assumed beam direction
- can alter reflector shape



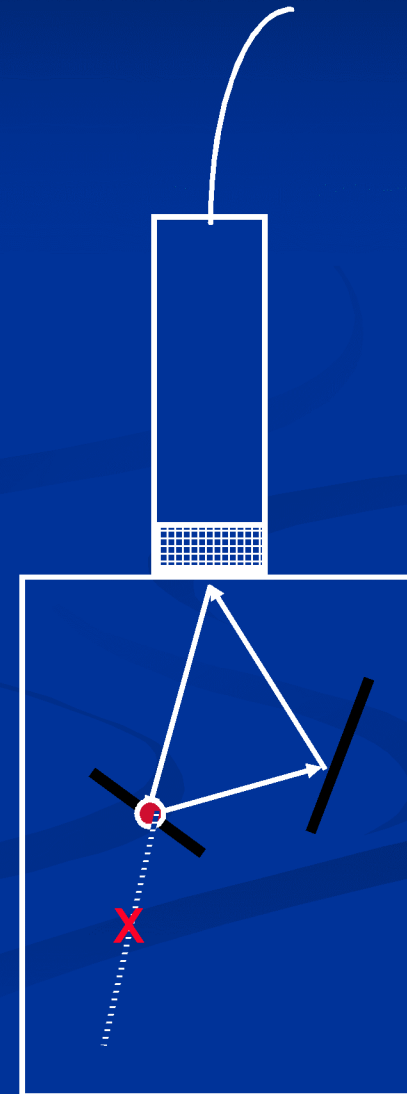
Multipath

- Occurs due to scattering of ultrasound beam.
- Common artifact is lesions within the upper portion of the liver appearing to be projected into the lung due to multiple path error.

Scanner Assumptions

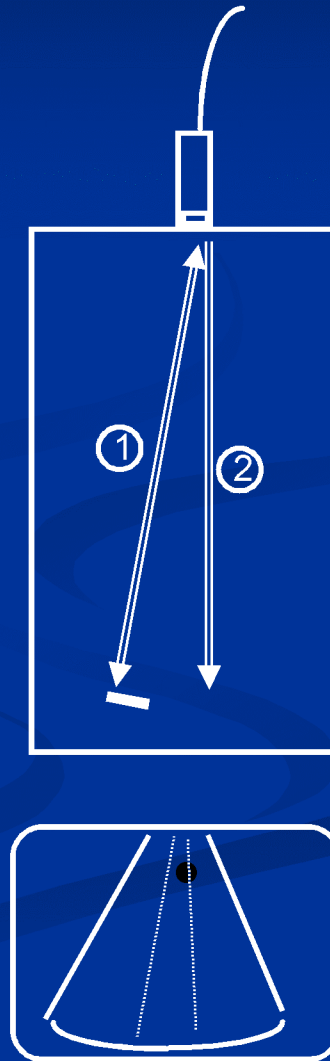
Multipath
Artifact

- Actual Object Position
- ✗ Position of Object on Image



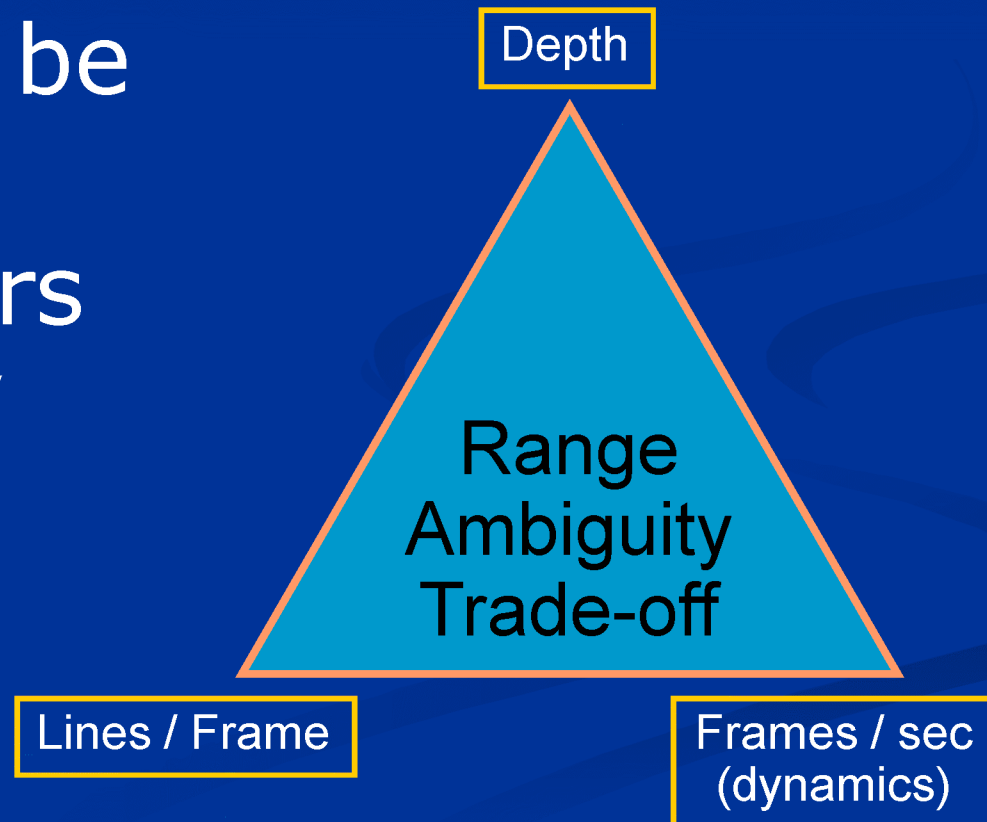
Range Ambiguity

- Reflection from 1st pulse reaches transducer after 2nd pulse emitted
 - scanner assumes this is reflection from 2nd pulse
 - places echo too close & in wrong direction



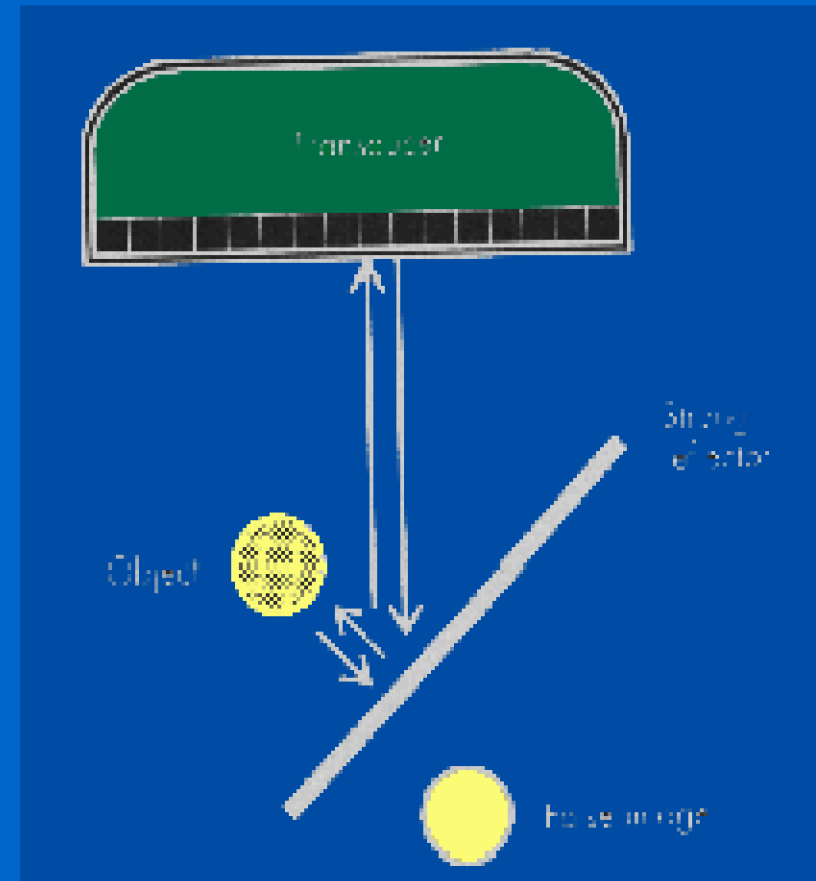
Range Ambiguity

- To improve any 1 of 3, at least 1 of other 2 must be reduced.
- many scanners automatically reduce frame rate as depth increases

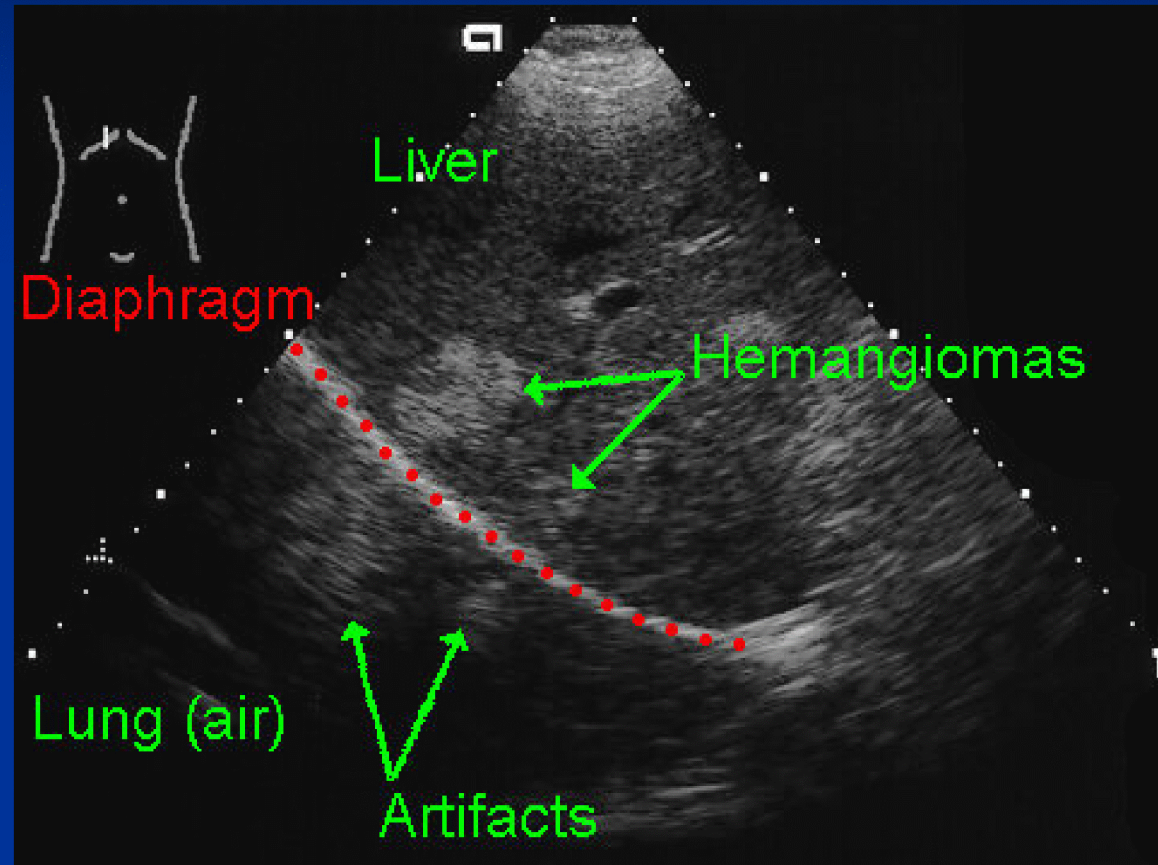
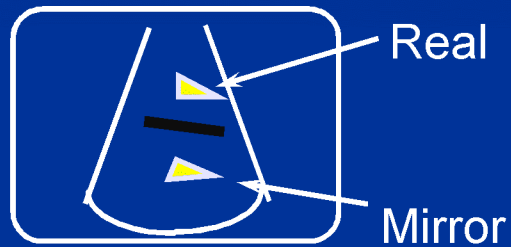


Mirror-Image

- Mirror-image artifacts are produced when an object is located in front of a highly reflective surface at which near-total reflection occurs.
- Examples of strong reflectors include the diaphragm, pleura, and bowel.



Multiple Reflection Scenario



Adverse Effects

- There are no known adverse effects at this time of medical ultrasound.
- It is recommended that ultrasound examinations be limited to those cases where there is an indication for their use, i.e., do not use as a generalized screening examination.

Biological Effects of Ultrasound

- An intensity level greatly above those used in diagnostic imaging can produce measurable effects, including:
 - Thermal Effects
 - Cavitation
 - Viscous Stresses

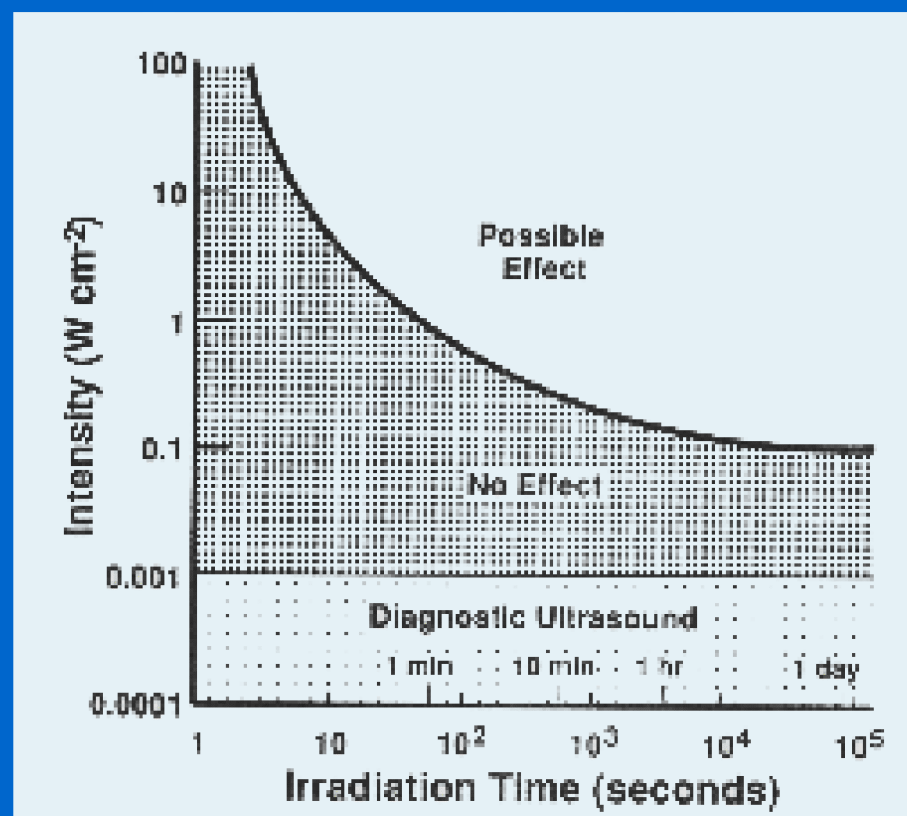


Figure 29-23, Radiologic Science for Technologists, Stewart C. Bushong

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