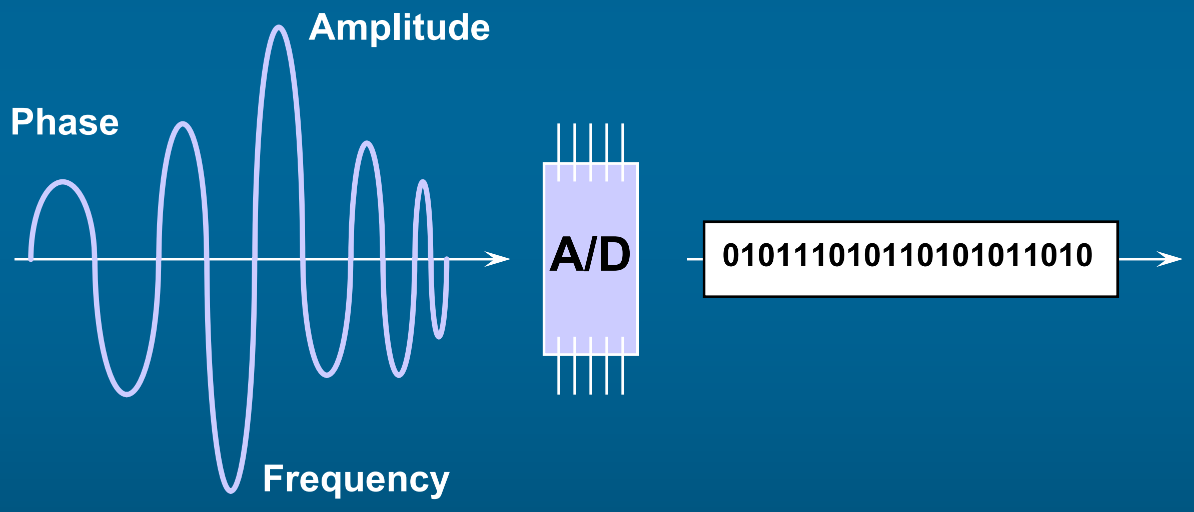
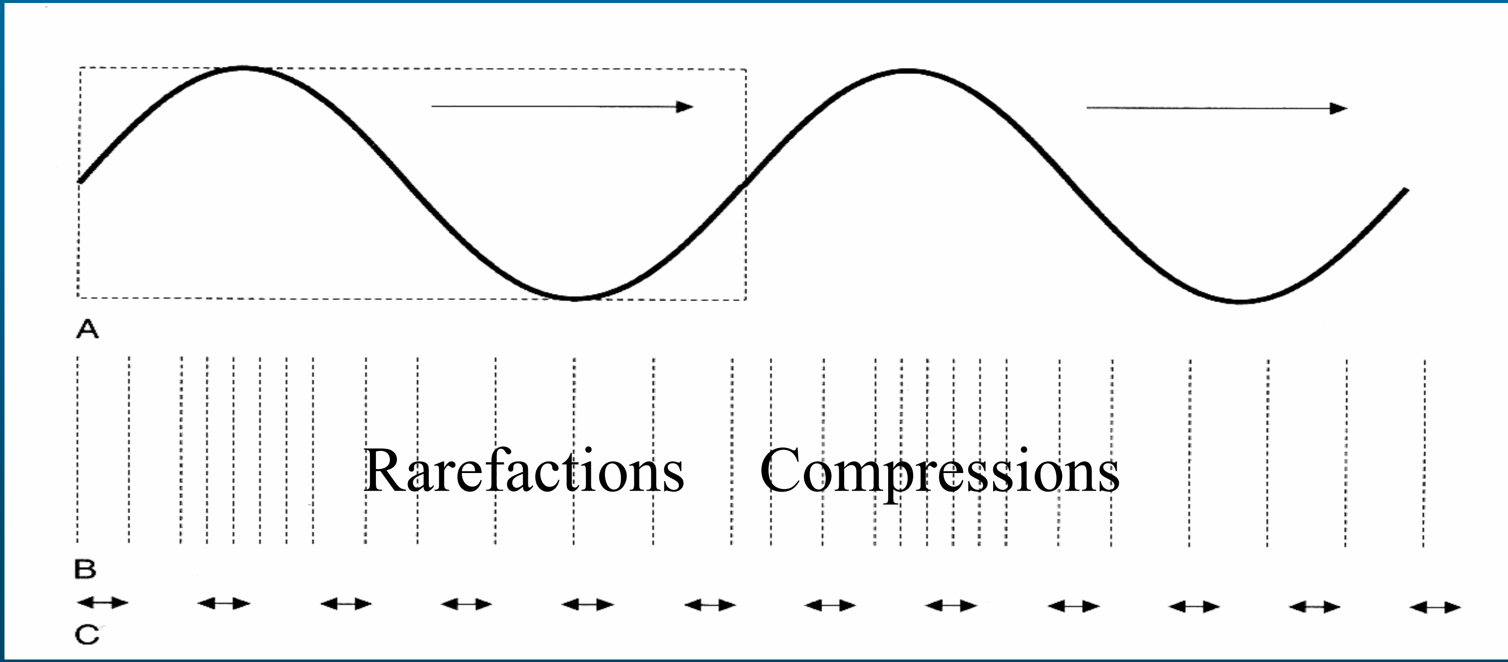
Basic Ultrasound Physics



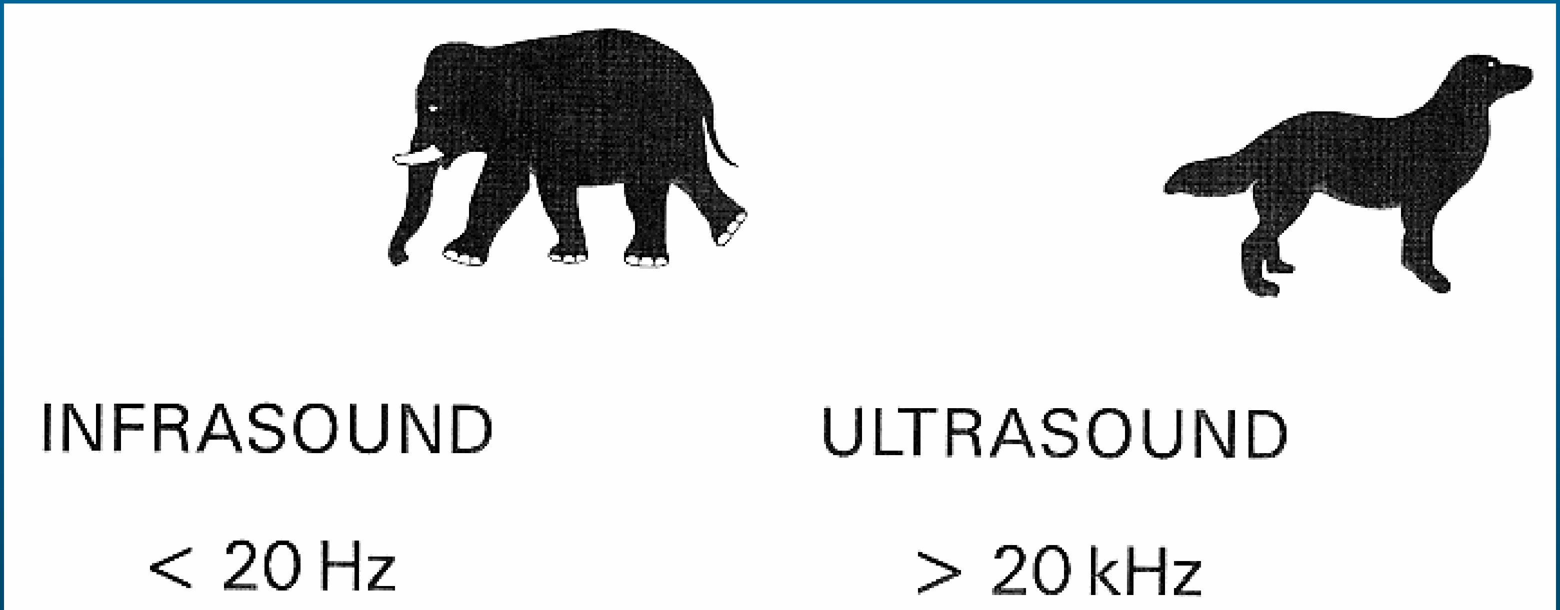
Waves

- There are two types of waves:
  - Transverse waves: these waves are perpendicular to the direction of energy transfer, e.g., violin string.
  - Longitudinal waves: these waves are parallel to the direction of energy transfer, e.g., a pulse from a piston in a cylinder, sound waves.



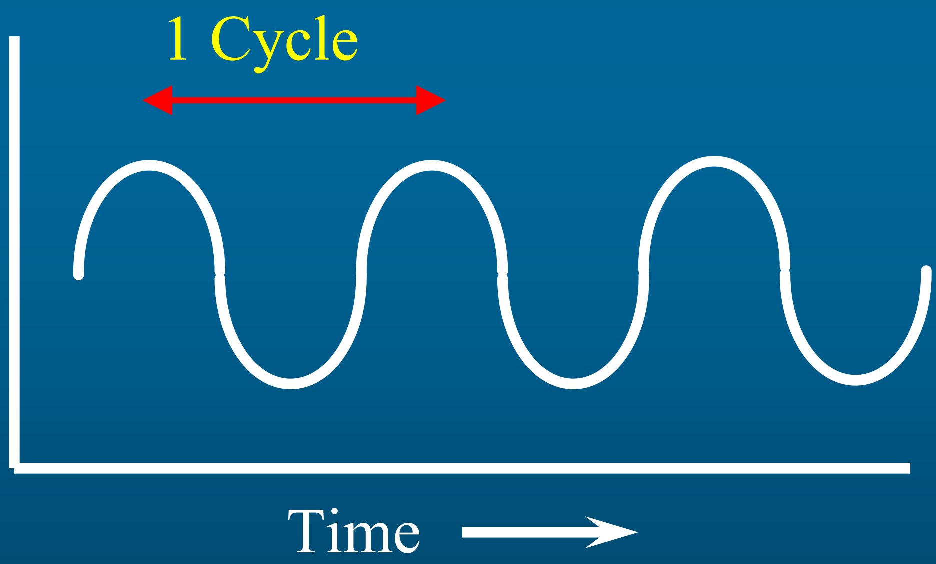
What is Ultrasound?

- Ultrasound is a wave with a frequency exceeding the upper limit of human hearing
  - greater than 20,000 Hz (hertz)



Waves

- We can measure longitudinal waves in two ways:
  - Distance: the wave length
  - Frequency: how many times per second the compression peak occurs at a point in space.



Waves

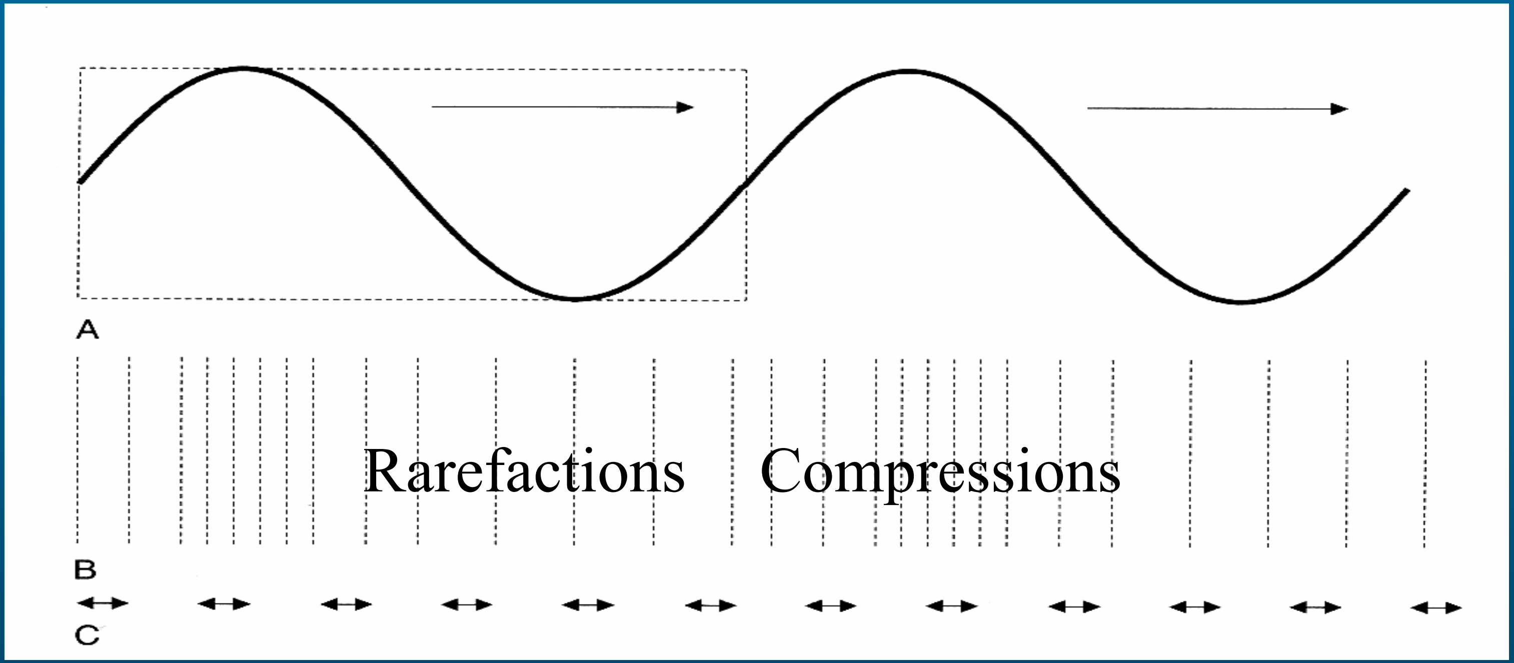
- Frequency (f) and wavelength (λ) are related by the speed of sound in the medium:

$$v = f\,\lambda$$

- Generally speaking, V is related to the compressibility of the medium, slower in gasses, faster in liquids, and fastest in solids.

What is Sound?

- Sound is a mechanical wave that travels in a straight line
- Requires a medium through which to travel



What is Sound?

- Sound has:
  - Energy: or work, in Joules (1 J = 1 kgm2/s2)
  - Power: is rate of energy, in Watts (1 W = 1 J/s)
  - Intensity: is pressure, force per unit area, in Pascals (1 P = 1 N/m2)
- Sound intensity/energy/power changes over many orders of magnitude.
- We use logarithmic measures, called decibels (dB). A dB is a dimensionless measure. It is a ratio.
- We pick some standard to measure, call it S0, and measure signal strength (intensity) w.r.t. S0.

$$X\ (\text{dB}) = 10 \log_{10} (S/S_0)$$

What is Sound?

- For example:
  - S0=1:
    - S=10, X=10 dB
    - S=2, X=3 dB
    - S=0.5, X=-3 dB
    - S=0.1, X=-10 dB

What is Sound?

- Speed of sound in biological media:

TABLE 19-3 Approximate Velocities of Ultrasound in Selected Materials

Nonbiologic Material	*Velocity (m/sec)*	*Biologic Material*	*Velocity (m/sec)*
Acetone	1174	Fat	1475
Air	331	Brain	1560
Aluminum (rolled)	6420	Liver	1570
Brass	4700	Kidney	1560
Ethanol	1207	Spleen	1570
Glass (Pyrex)	5640	Blood	1570
Acrylic plastic	2680	Muscle	1580
Mercury	1450	Lens of eye	1620
Nylon (6-6)	2620	Skull bone	3360
Polyethylene	1950	Soft tissue (mean value)	1540
Water (distilled), 25°C	1498		
Water (distilled), 50°C	1540		

Velocity (propagation speed)

- The speed with which a sound wave travels through a medium
- Units of measure are distance/time
  - cm/sec
- The speed of sound is determined by the **density** and **stiffness** of the media in which it travels
  - slowest in air/gasses
  - fastest in solids
- Average speed of ultrasound in the body is **1540 m/sec**

What is Sound?

- Energy loss is called attenuation. There are many mechanisms that cause that. The main ones we care about are:
  - Absorption: conversion to heat
  - Reflection: organized change in direction of the wave (specular: mirror like)
  - Scatter: disorganized change in direction

- Attenuation is denoted by α, a coefficient that describes how energy is dissipated.

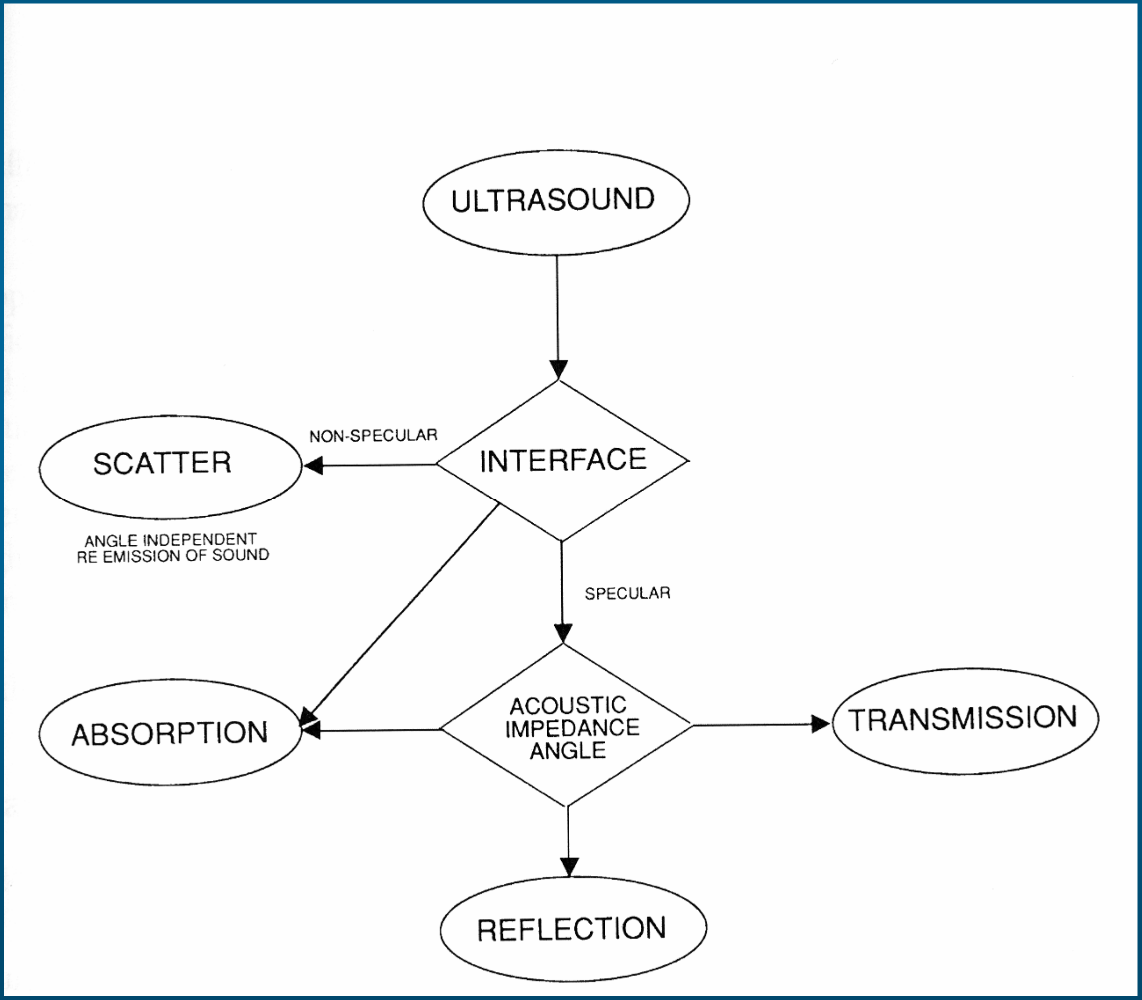
What is Sound?

- For biological tissues, α is poorly estimated.

TABLE 19-4 Attenuation Coefficients α for 1-MHz Ultrasound

Material	*α (dB/cm)*	*Material*	*α (dB/cm)*
Blood	0.18	Lung	40
Fat	0.6	Liver	0.9
Muscle (across fibers)	3.3	Brain	0.85
Muscle (along fibers)	1.2	Kidney	1.0
Aqueous and vitreous humor of eye	0.1	Spinal cord	1.0
		Water	0.0022
Lens of eye	2.0	Caster oil	0.95
Skull bone	20	Lucite	2.0

Interactions of Ultrasound with Tissue



Interactions of Ultrasound with Tissue

- Reflection
- Scattering
- Transmission
- Attenuation

Interactions of Ultrasound with Tissue

- Reflection
- Scattering
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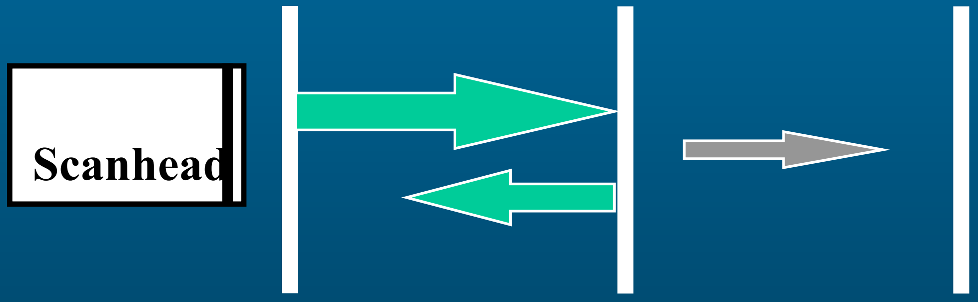
Reflection

- Reflection occurs at a boundary/interface between two adjacent tissues
- The difference in *acoustic impedance* (z) between the two tissues causes reflection of the sound wave

z = density x velocity



$z = 1.1 \times 10^6$ $z = 1.7 \times 10^6$

Reflection

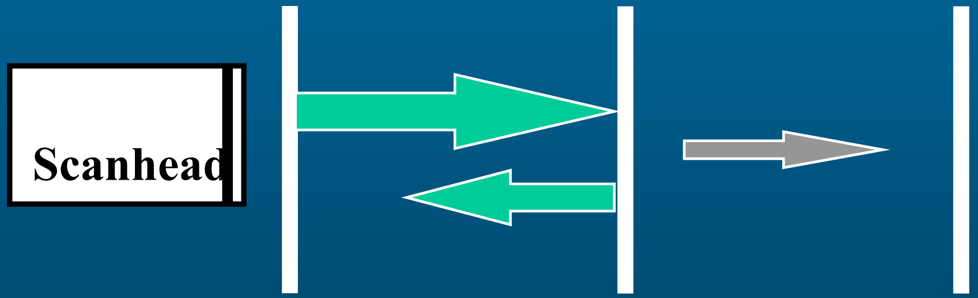
Approximate Acoustic Impedances of Selected Materials

Material	*Acoustic Impedance* $(kg\text{-}m^{-2}\text{-}sec^{-1}) \times 10^{-4}$
Air at standard temperature and pressure	0.0004
Water	1.50
Polyethylene	1.85
Plexiglas	3.20
Aluminum	18.0
Mercury	19.5
Brass	38.0
Fat	1.38
Aqueous and vitreous humor of eye	1.50
Brain	1.55
Blood	1.61
Kidney	1.62
Human soft tissue, mean value	1.63
Spleen	1.64
Liver	1.65
Muscle	1.70
Lens of eye	1.85
Skull bone	6.10

Reflection

- The greater the difference in acoustic impedance between two adjacent tissues, the greater the reflection
- If there is no difference in acoustic impedance, there is no reflection

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

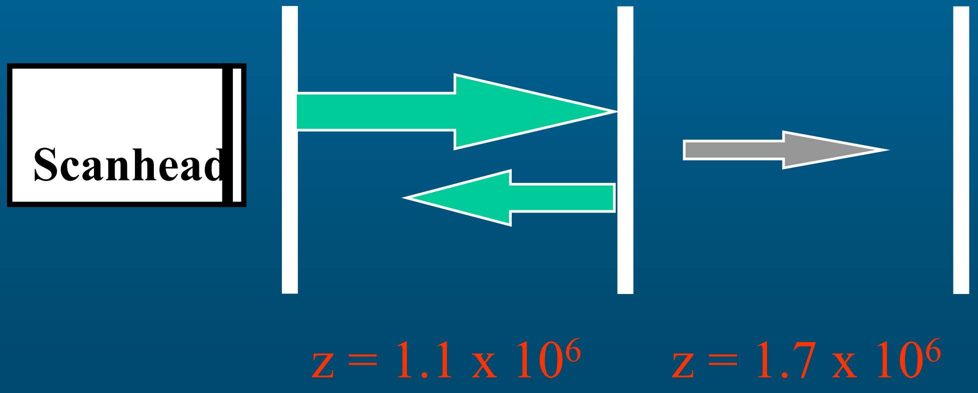


$z = 1.1 \times 10^6$ $z = 1.7 \times 10^6$

Reflection

- The greater the difference in acoustic impedence between two adjacent tissues, the greater the reflection
- If there is no difference in acoustic impedence, there is no reflection

$$\alpha_T = 1 - \alpha_R = \frac{4Z_1Z_2}{(Z_2 + Z_1)^2}$$



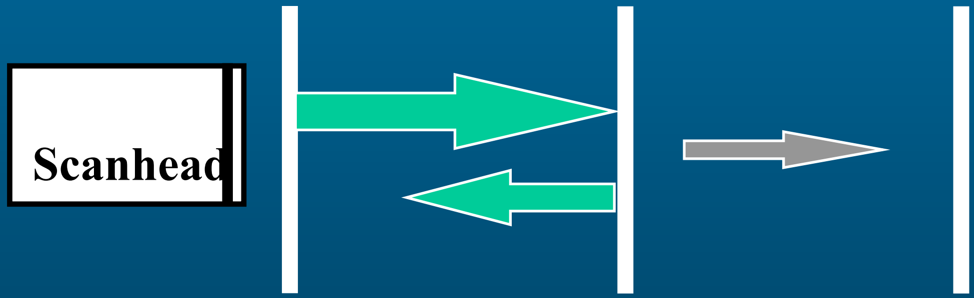
Reflection

- Example 1:

At a "liver-air" interface, Z_1 = 1.65 and Z_2=0.0004 (both multiplied by 10^{-4} with units kg/(m^2sec).

$$\alpha_R = \frac{(1.65 - 0.0004)^2}{(1.65 + 0.0004)^2} = 0.9995$$

$$\alpha_T = \frac{4(1.65)(0.0004)}{(1.65 + 0.0004)^2} = 0.0005$$



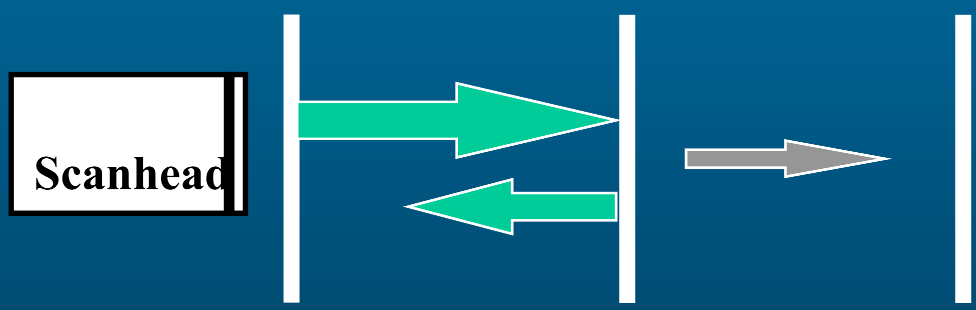
Reflection

- Example 2:

At a “muscle-liver” interface, Z_1 = 1.70 and Z_2=1.65 (both multiplied by 10^{-4} with units kg/(m^2sec).

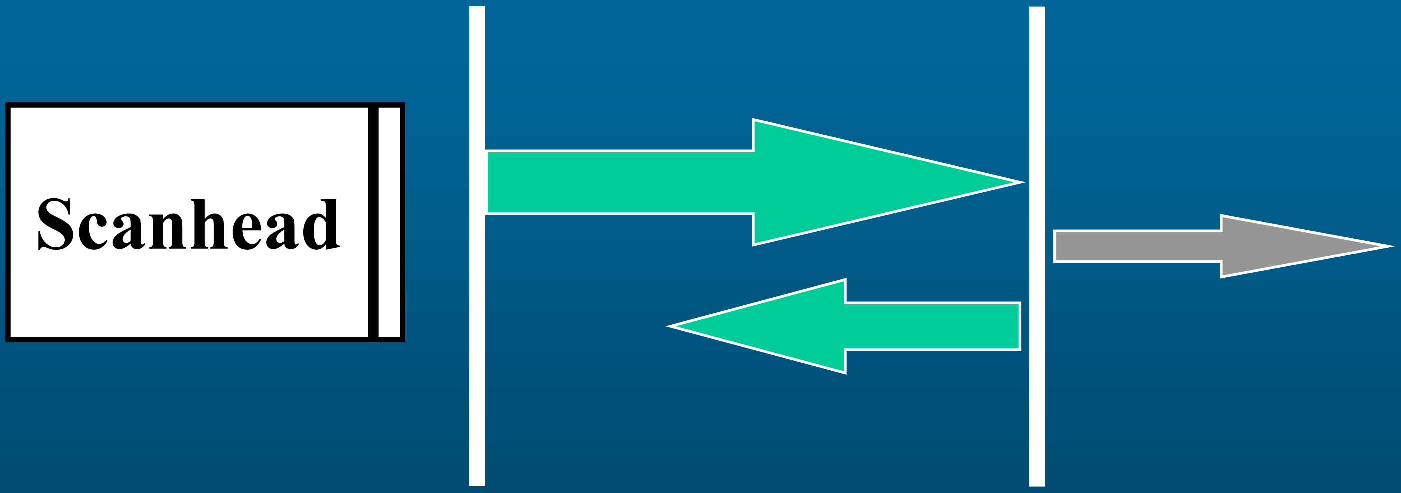
$$\alpha_R = \frac{(1.70 - 1.65)^2}{(1.70 + 1.65)^2} = 0.015$$

$$\alpha_T = \frac{4(1.70)(1.65)}{(1.70 + 1.65)^2} = 0.985$$



Reflection

– Reflection from a smooth tissue interface (specular) causes the sound wave to return to the scanhead
– The ultrasound image is formed from reflected echoes

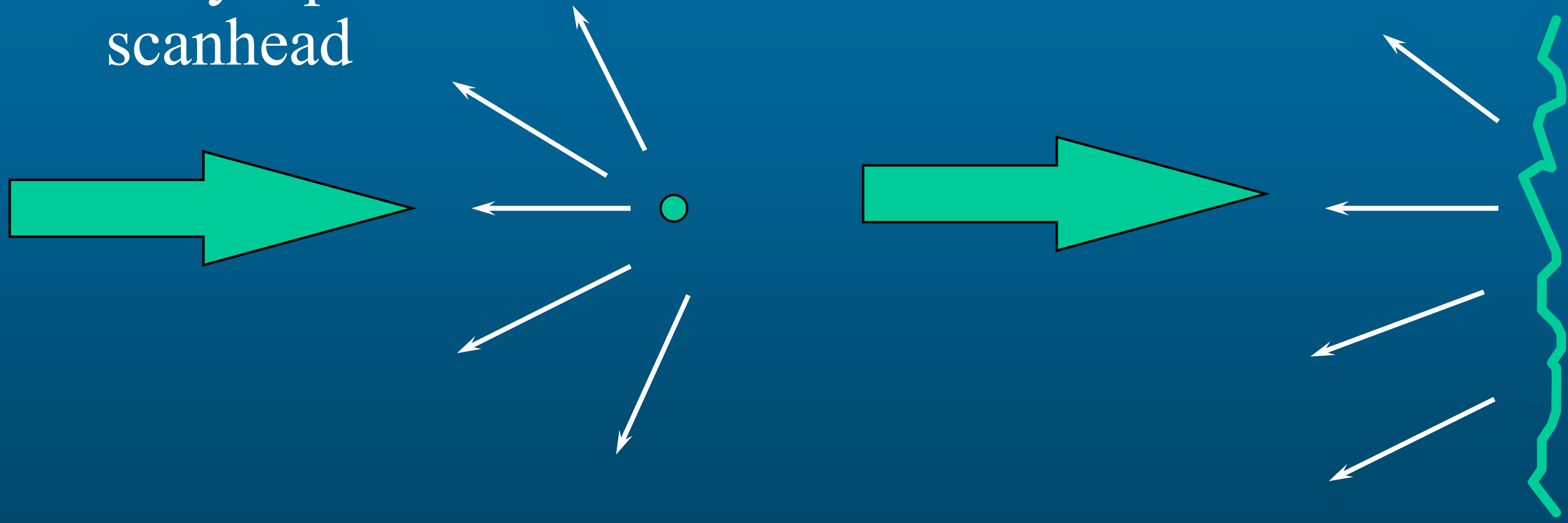


Interactions of Ultrasound with Tissue

- Reflection
- Scattering
- Transmission
- Attenuation

Scattering

- Redirection of the sound-wave in several directions
- Caused by interaction with a very small reflector or a very rough interface
- Only a portion of the sound-wave returns to the scanhead



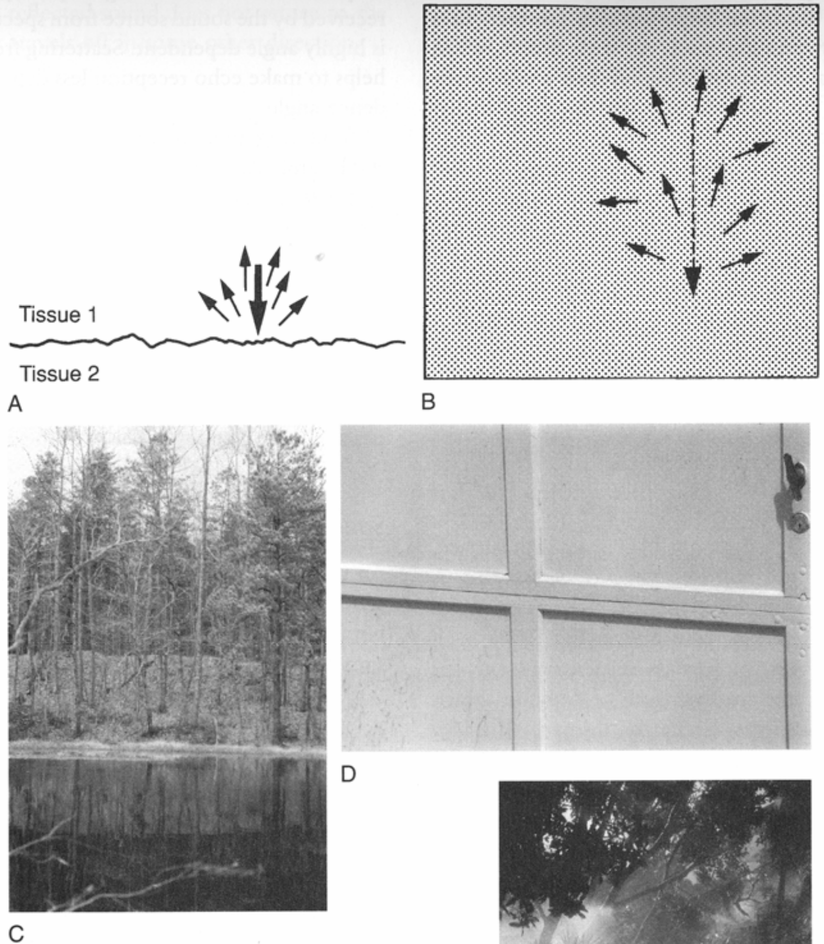


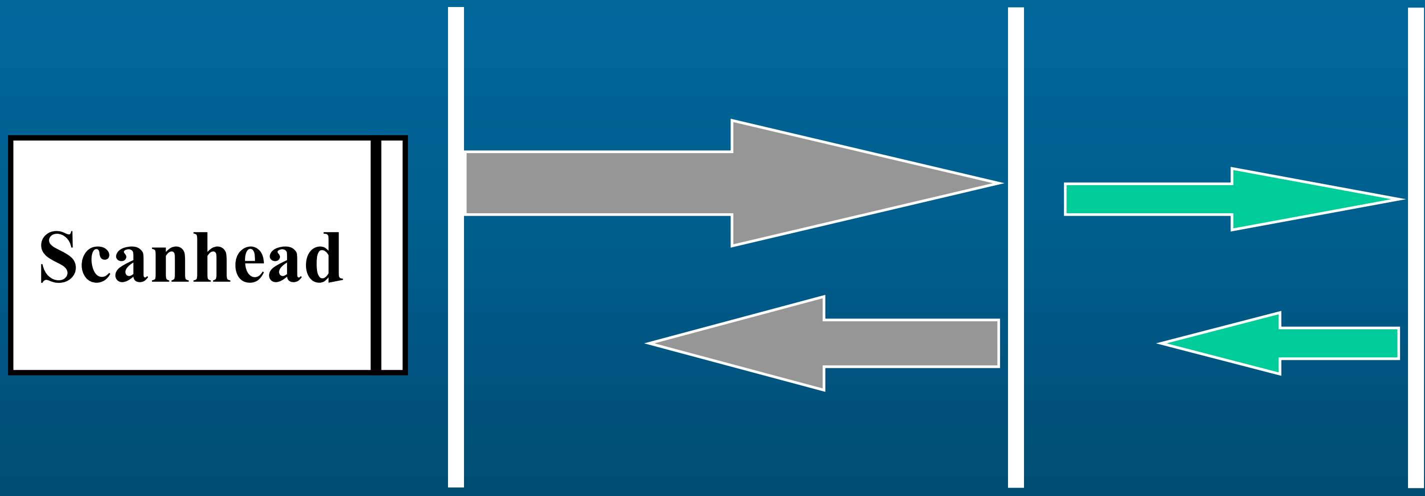
FIGURE 2.26 A sound pulse may be scattered by a rough boundary between tissues (*A*) or within tissues due to their heterogeneous character (*B*). The differences between a specular surface (smooth pond) (*C*), a scattering surface (garage door) (*D*), and a scattering medium (fog) (*E*) are illustrated.

Interactions of Ultrasound with Tissue

- Reflection
- Scattering
- Transmission
- Attenuation

Transmission

- Not all of the sound-wave is reflected, therefore some of the wave continues deeper into the body
- These waves will reflect from deeper tissue structures

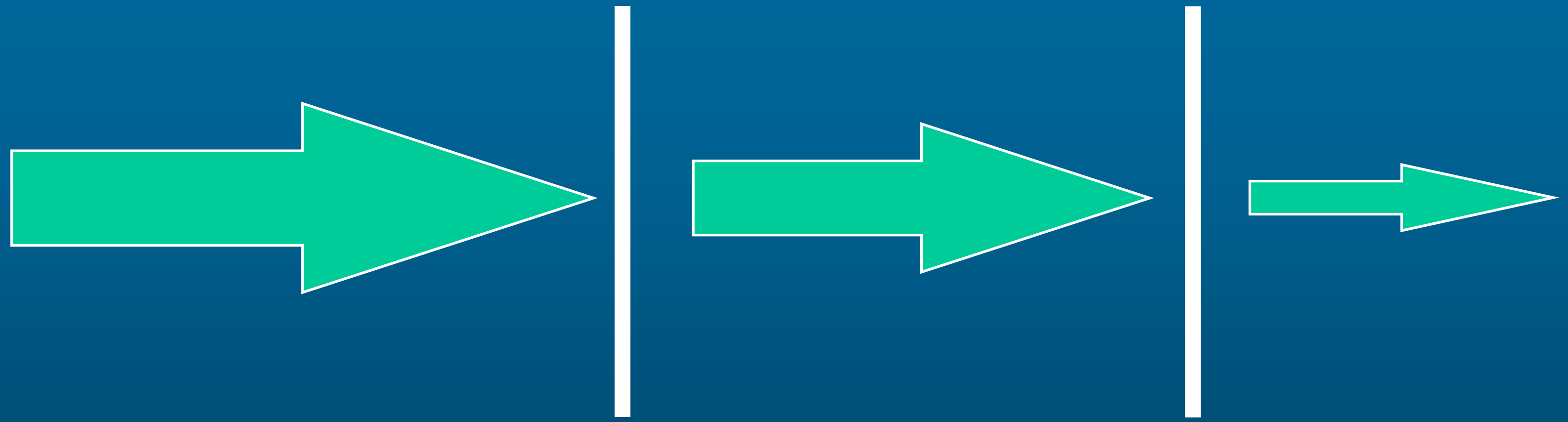


Interactions of Ultrasound with Tissue

- Reflection
- Scattering
- Transmission
- Attenuation

Attenuation

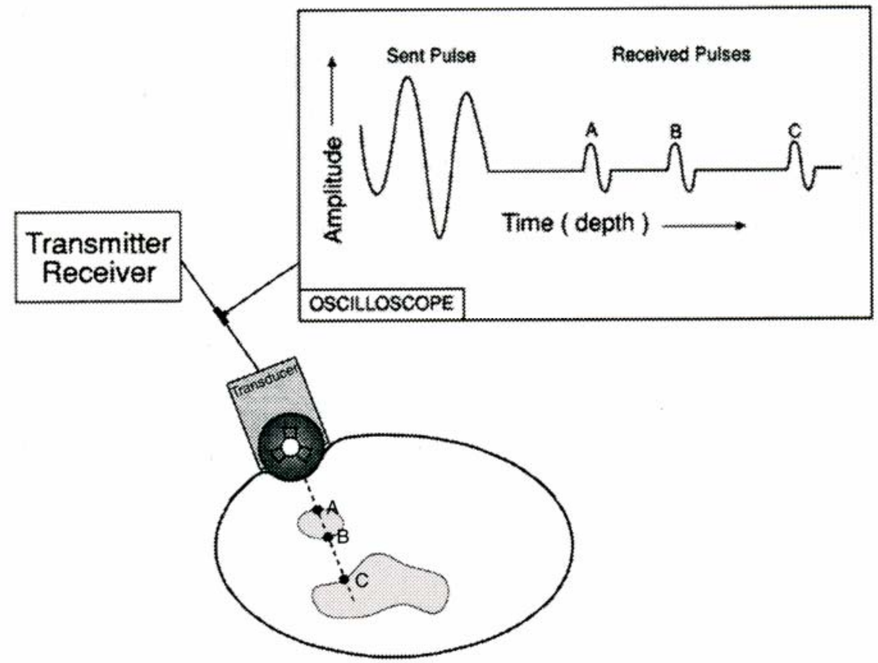
- The deeper the wave travels in the body, the weaker it becomes
- The amplitude/strength of the wave decreases with increasing depth



Ultrasound Image Formation: Pulsed Ultrasound

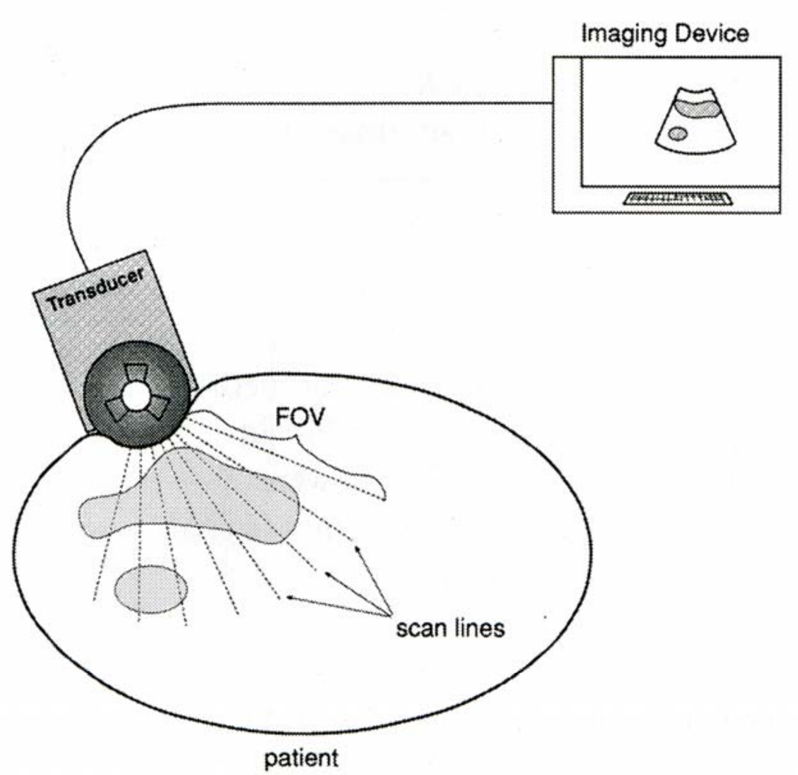
- Pulse-Echo Method
  - Ultrasound scanhead produces “pulses” of ultrasound waves
  - These waves travel within the body and interact with various organs
  - The reflected waves return to the scanhead and are processed by the ultrasound machine
  - An image which represents these reflections is formed on the monitor

Pulsed Ultrasound



MARGIN FIGURE 21-1
A-mode (amplitude mode) of ultrasound display. An oscilloscope display records the amplitude of echoes as a function of time or depth. Points A, B, and C in the patient appear as peaks-A, B, and C in the A-mode display.

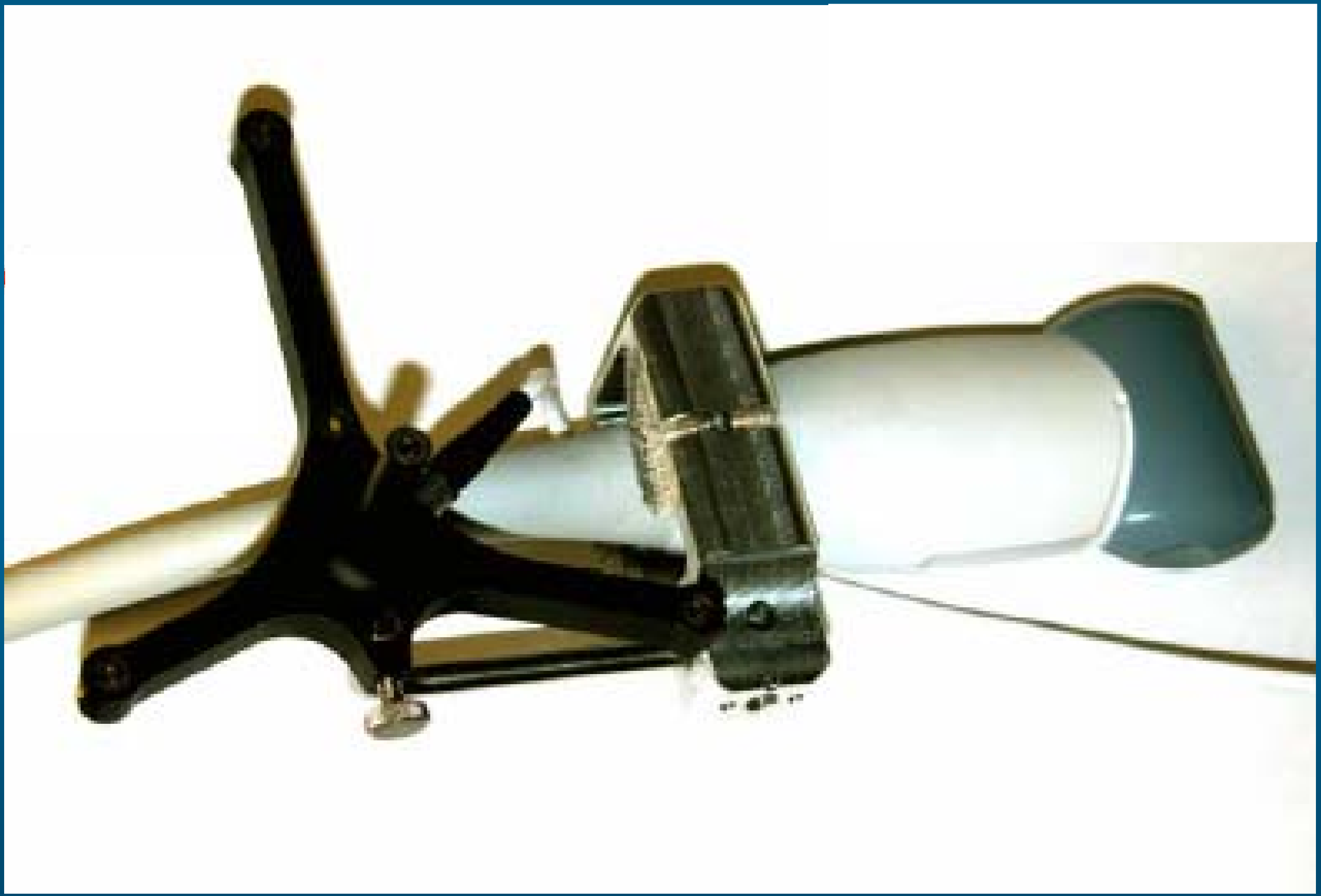
Pulsed Ultrasound



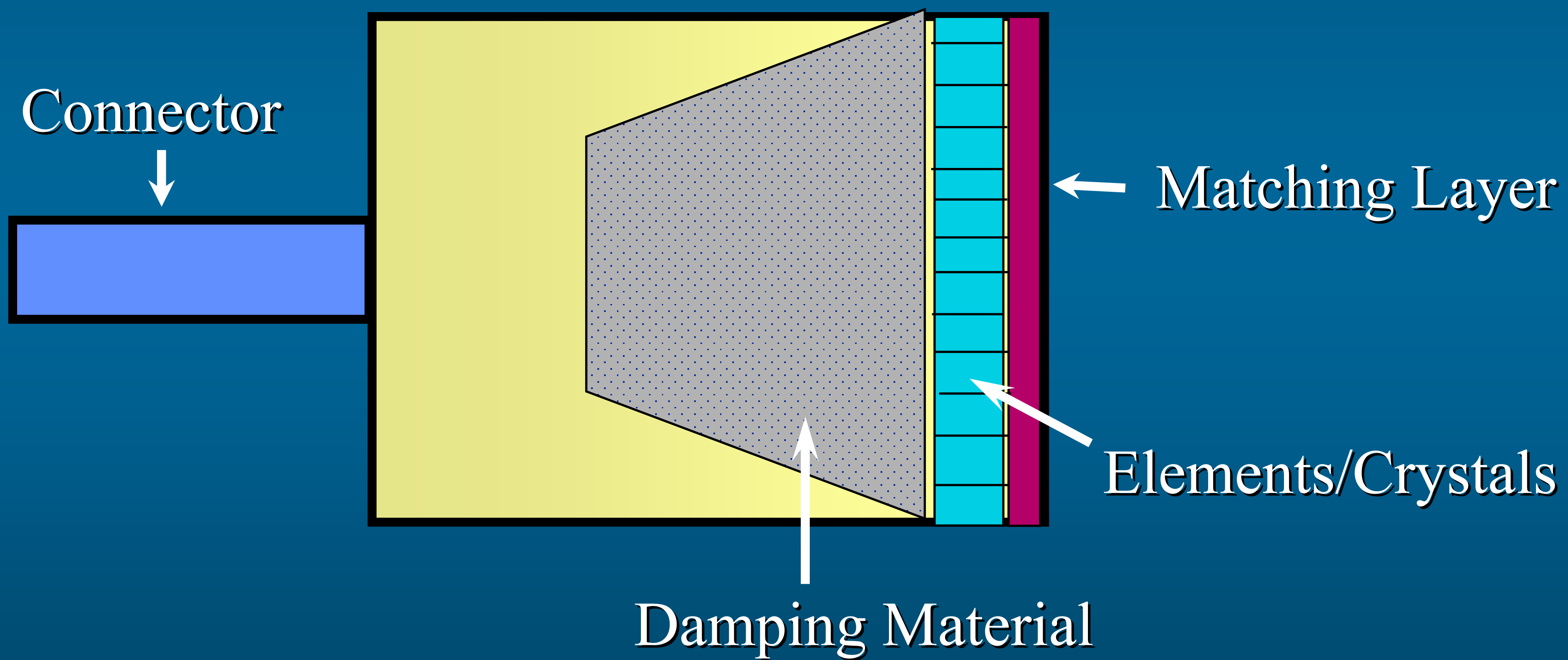
MARGIN FIGURE 21-4
A B-mode image consists of scan lines. The length of the scan lines determines the depth within the patient that is imaged [the field of view (FOV)].

Scanhead Construction

Scanhead Construction



Scanhead Construction



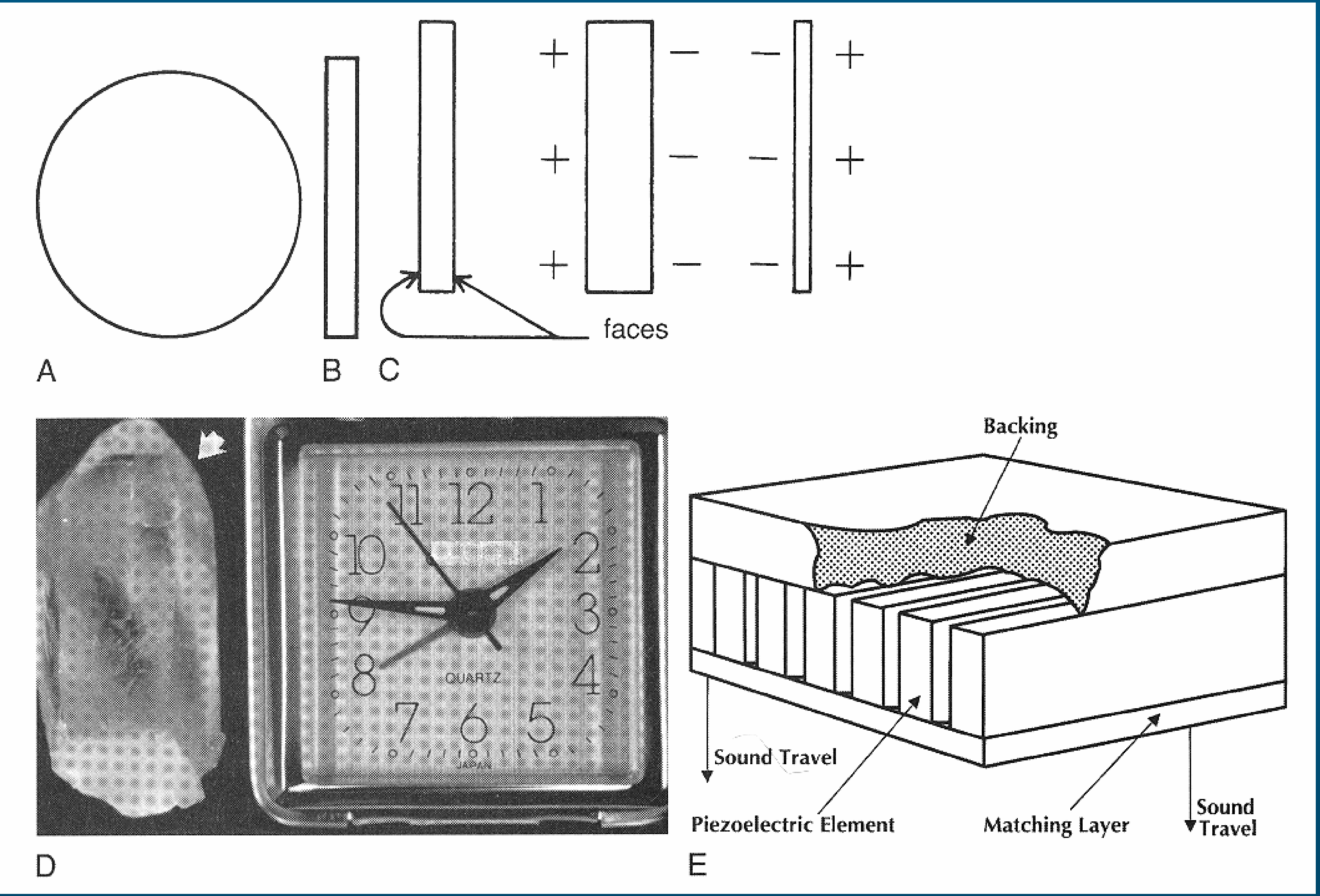
Scanhead Construction

- Matching Layer
  - has acoustic impedance between that of tissue and the piezoelectric elements
  - reduces the reflection of ultrasound at the scanhead surface
- Piezoelectric Elements
  - produce a voltage when deformed by an applied pressure
  - quartz, ceramics, man-made material
- Damping Material
  - reduces “ringing” of the element
  - helps to produce very short pulses

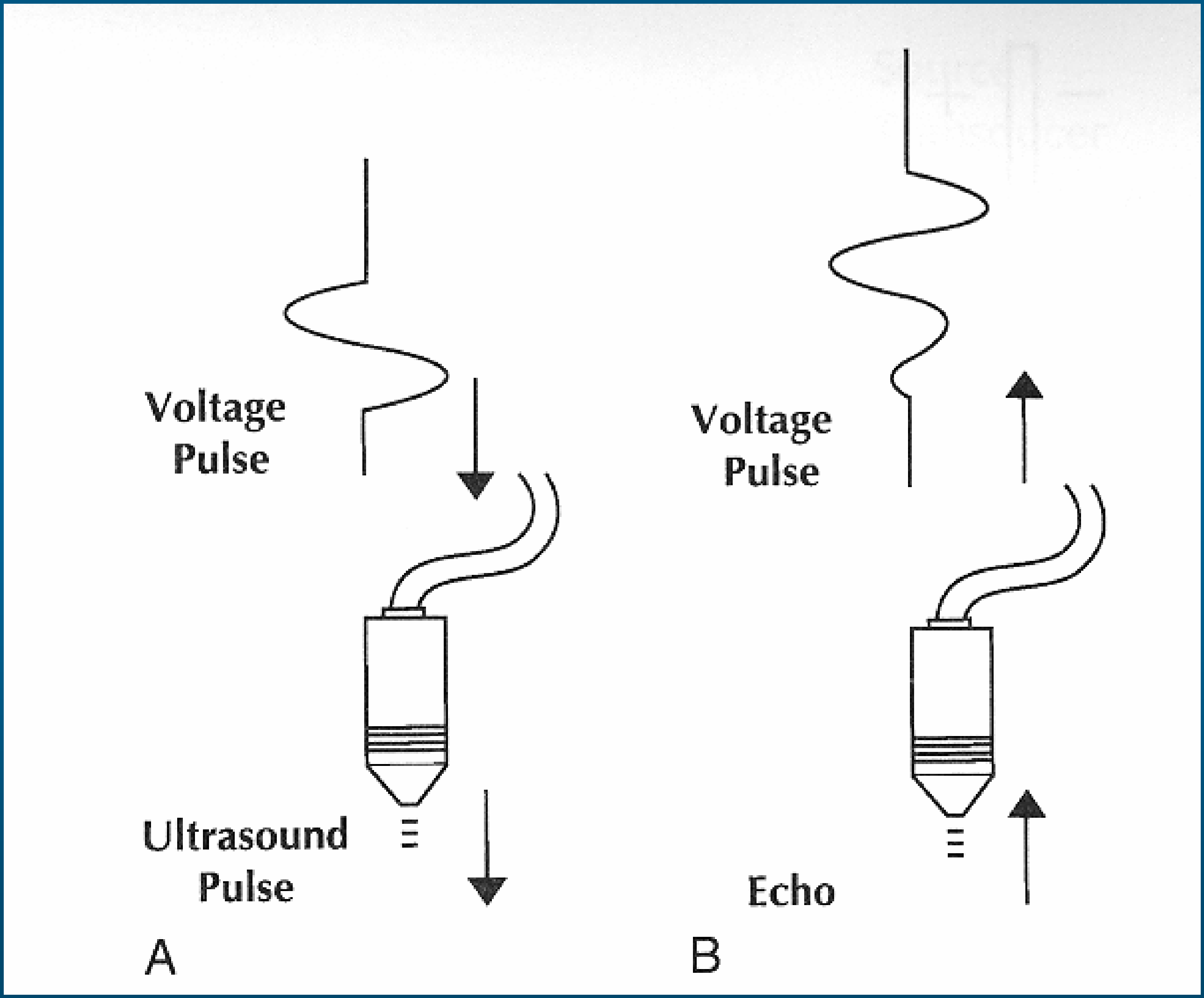
Piezoelectric Elements/Crystals

- Some crystals change shape (in at least one direction) with applied voltage. This is reversible: a change in dimension produces a change in voltage.
- The piezoelectric element/crystal produces the ultrasound pulses
  - Electrical pulses applied to the crystal cause it to expand and contract
  - This produces the transmitted ultrasound pulses

Piezoelectric Elements/Crystals



Piezoelectric Elements/Crystals



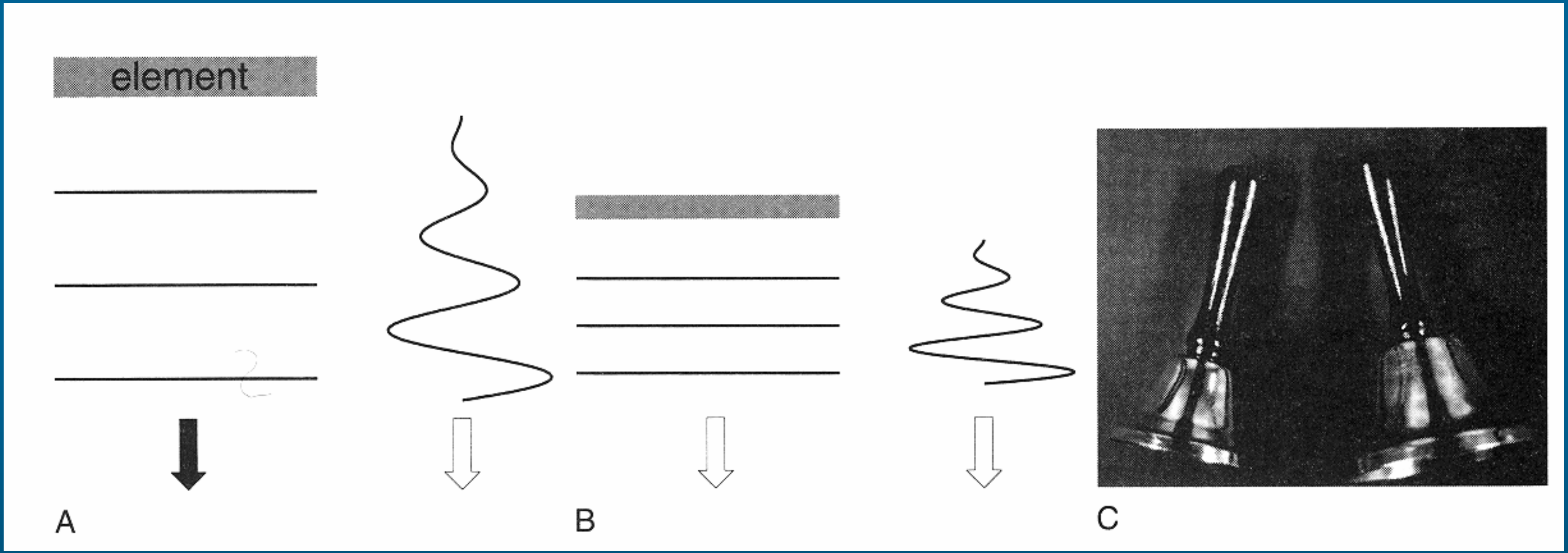
Piezoelectric Crystals and Frequency

- The **frequency** of the scanhead is determined by the **thickness** of the crystals
- Thinner elements produce HIGHER frequencies
- Thicker elements produce LOWER frequencies

Low Frequency
3 MHz

High Frequency
10 MHz

Piezoelectric Crystals and Frequency

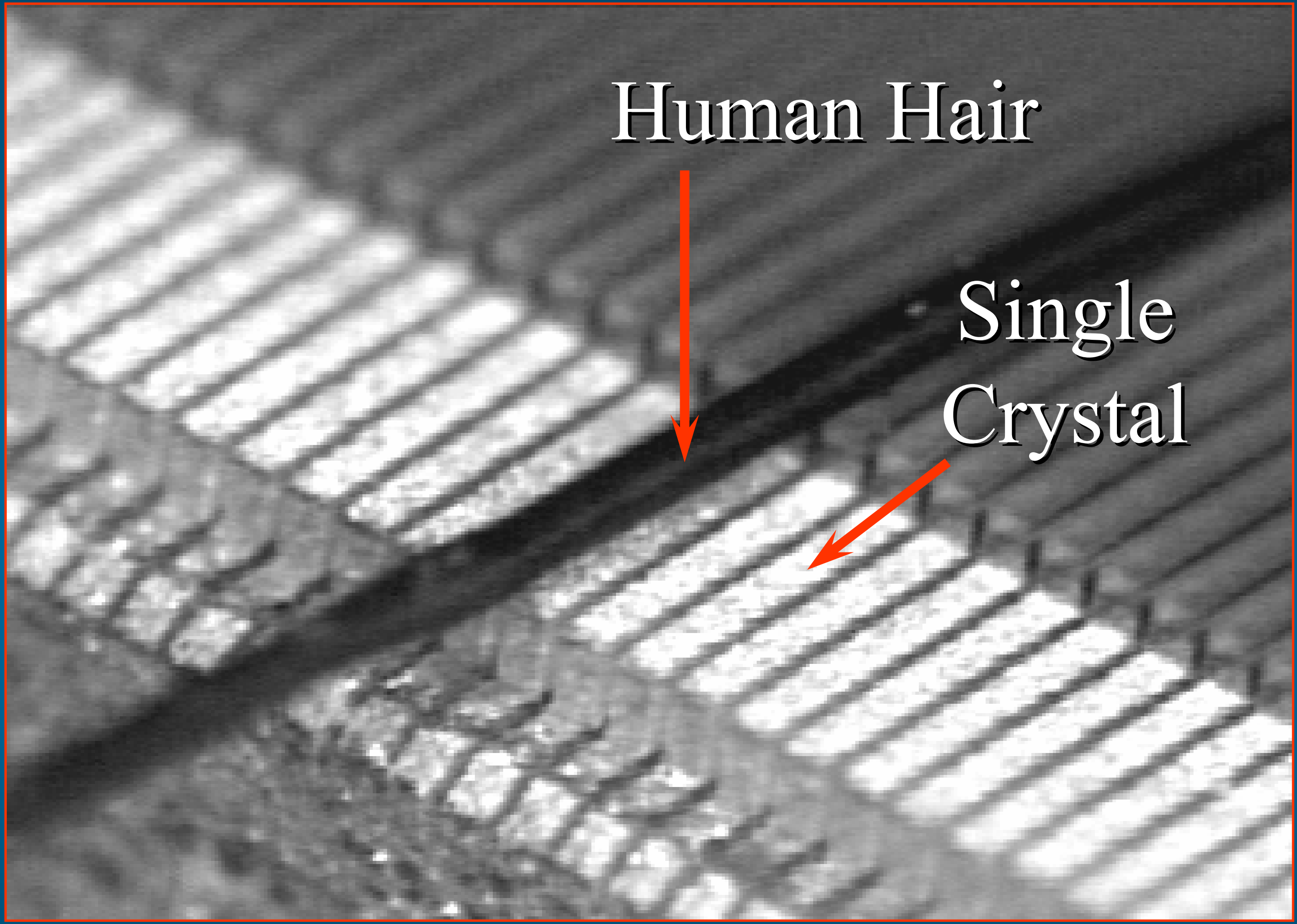


Piezoelectric Crystals and Frequency

TABLE 3.1 Transducer Element Thickness* for Various Operating Frequencies

Frequency (MHz)	Thickness (mm)
2.0	1.0
3.5	0.6
5.0	0.4
7.5	0.3
10.0	0.2

* Assuming an element propagation speed of 4 mm/μs.



Microscopic view of scanhead

Frequency vs. Resolution

- The frequency also affects the **quality** of the image
  - the higher the frequency, the shorter the wavelength
  - the shorter the wavelength, the better the axial resolution
- Therefore, **higher** frequency scanheads produce better image resolution

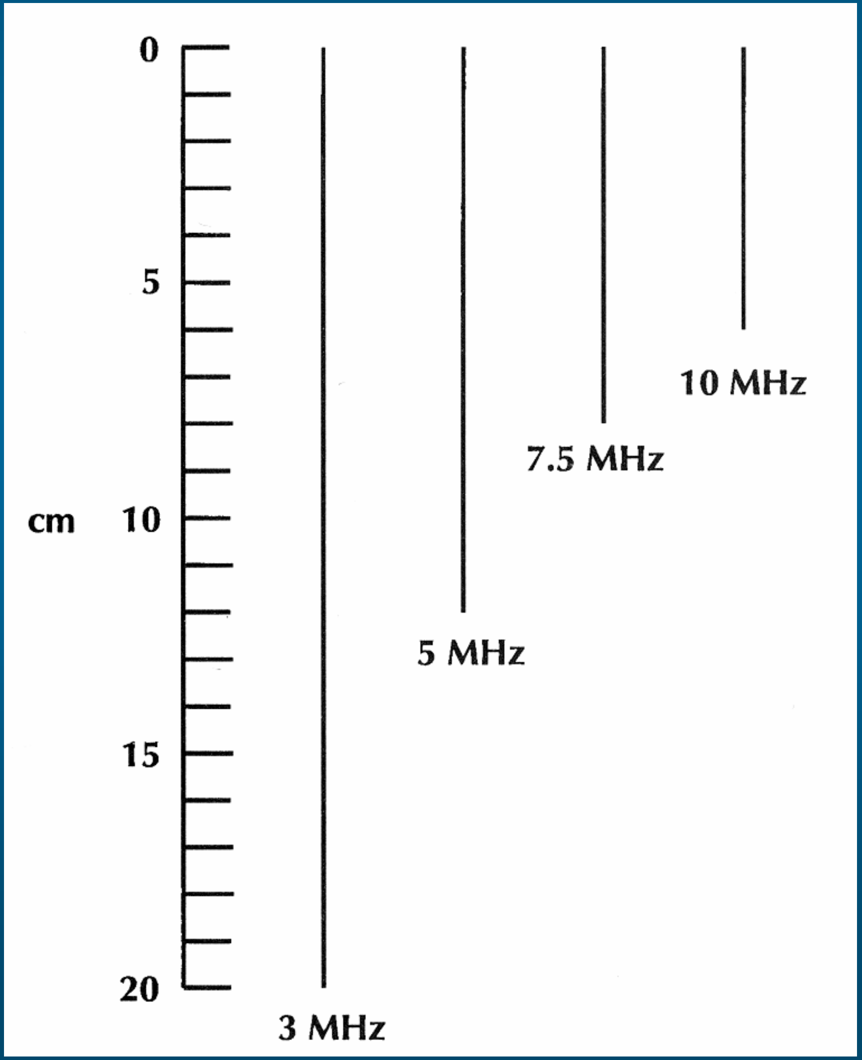
Frequency vs. Depth of Penetration

However-

- The HIGHER the frequency, the LESS it can penetrate into the body
- The LOWER the frequency, the DEEPER the penetration

This is the challenge of ultrasound imaging!!

Frequency vs. Depth of Penetration

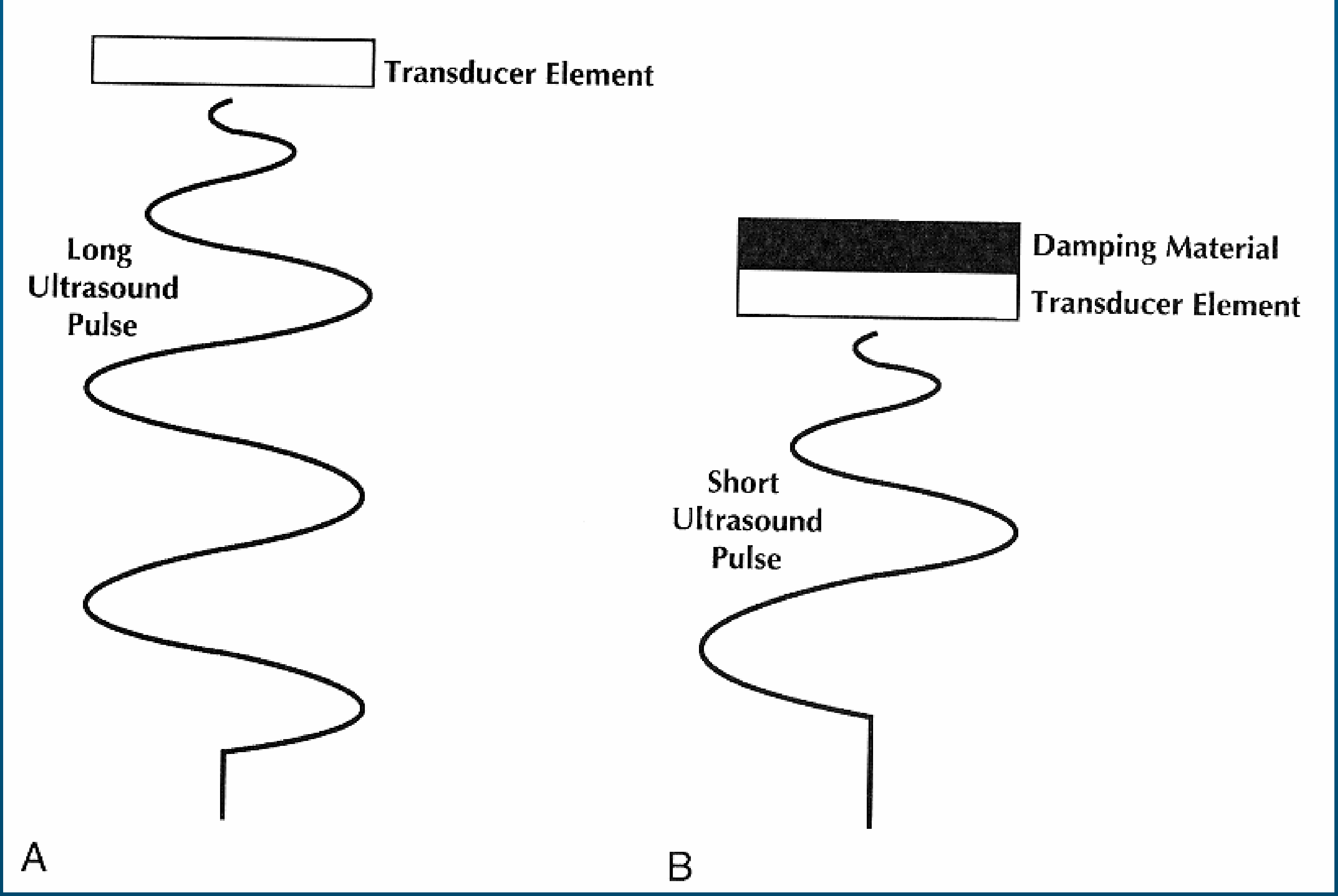


Therefore-

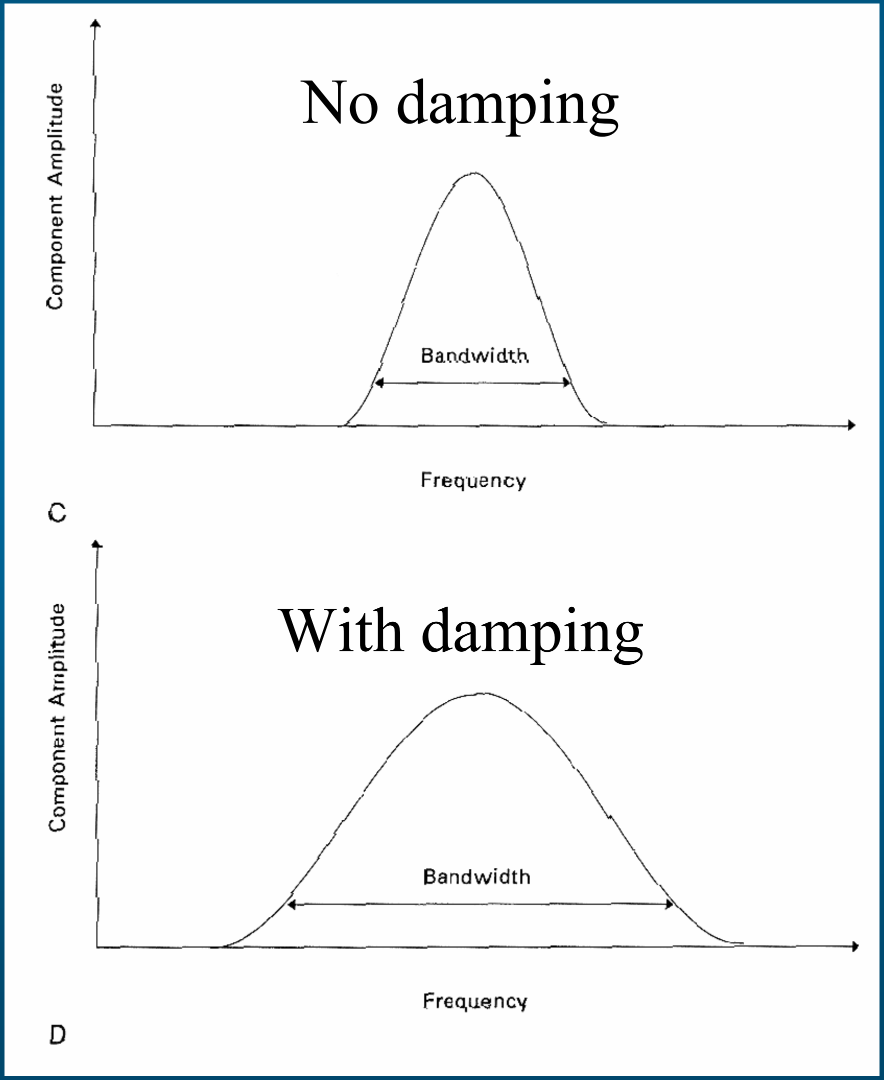
High frequency scanheads have the best resolution, but the least amount of penetration (e.g. L10-5)

Lower frequency scanheads provide more penetration, but poorer resolution (e.g.C4-2)

Damping

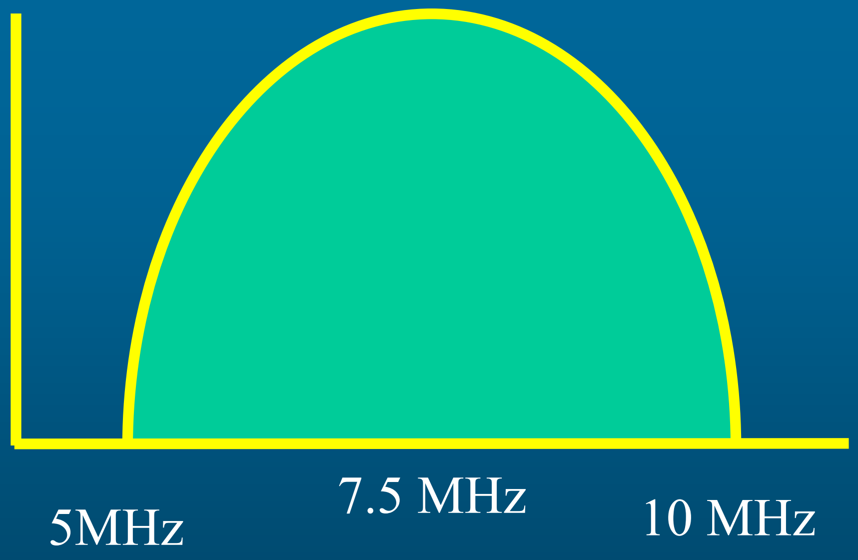

Transducer Element
Long
Ultrasound
Pulse
A
Damping Material
Transducer Element
Short
Ultrasound
Pulse
B

Damping


No damping
Component Amplitude
Bandwidth
Frequency
C
With damping
Component Amplitude
Bandwidth
Frequency
D

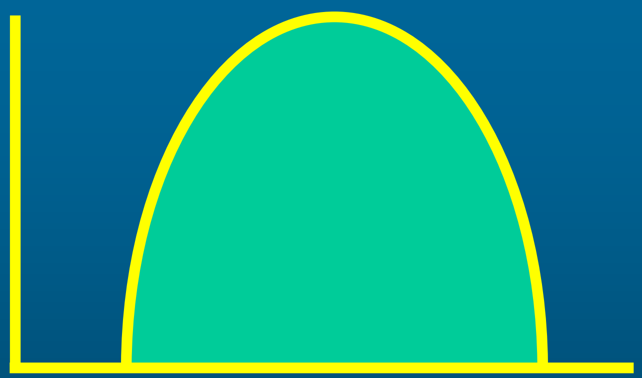
Bandwidth

- Bandwidth is the range of frequencies emitted by the scanhead
- Each crystal emits a spectrum of frequencies



Bandwidth

- A **broadband** scanhead is one which uses the entire frequency bandwidth to form the image
- A **narrowband** scanhead uses only a portion of the frequency range to form the image

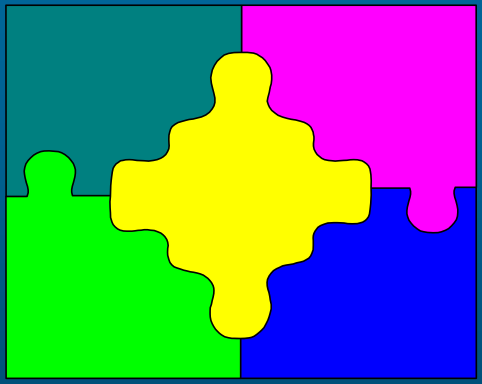


The Returning Echo

- Reflected echoes return to the scanhead where the piezoelectric elements convert the ultrasound wave back into an electrical signal
- The electrical signal is then processed by the ultrasound system

Goal of an Ultrasound System

- **The ultimate goal of any ultrasound system is to make like tissues look alike and unlike tissues look different**

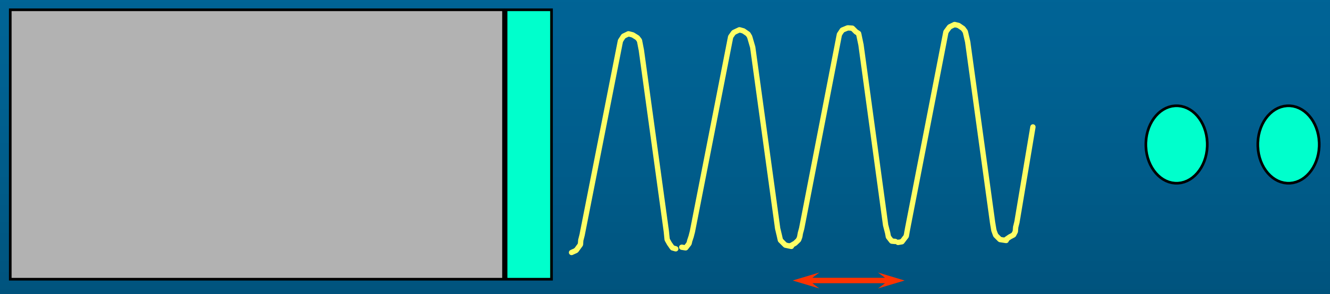


Accomplishing this goal depends upon...

- **Resolving capability of the system**
  - axial/lateral resolution
  - spatial resolution
  - contrast resolution
  - temporal resolution
- **Beamformation**
  - send and receive
- **Processing Power**
  - ability to capture, preserve and display the information

Types of Resolution

- Axial Resolution
  - specifies how close together two objects can be **along the axis** of the beam, yet still be detected as two separate objects
  - wavelength affects axial resolution



Types of Resolution

- Axial Resolution

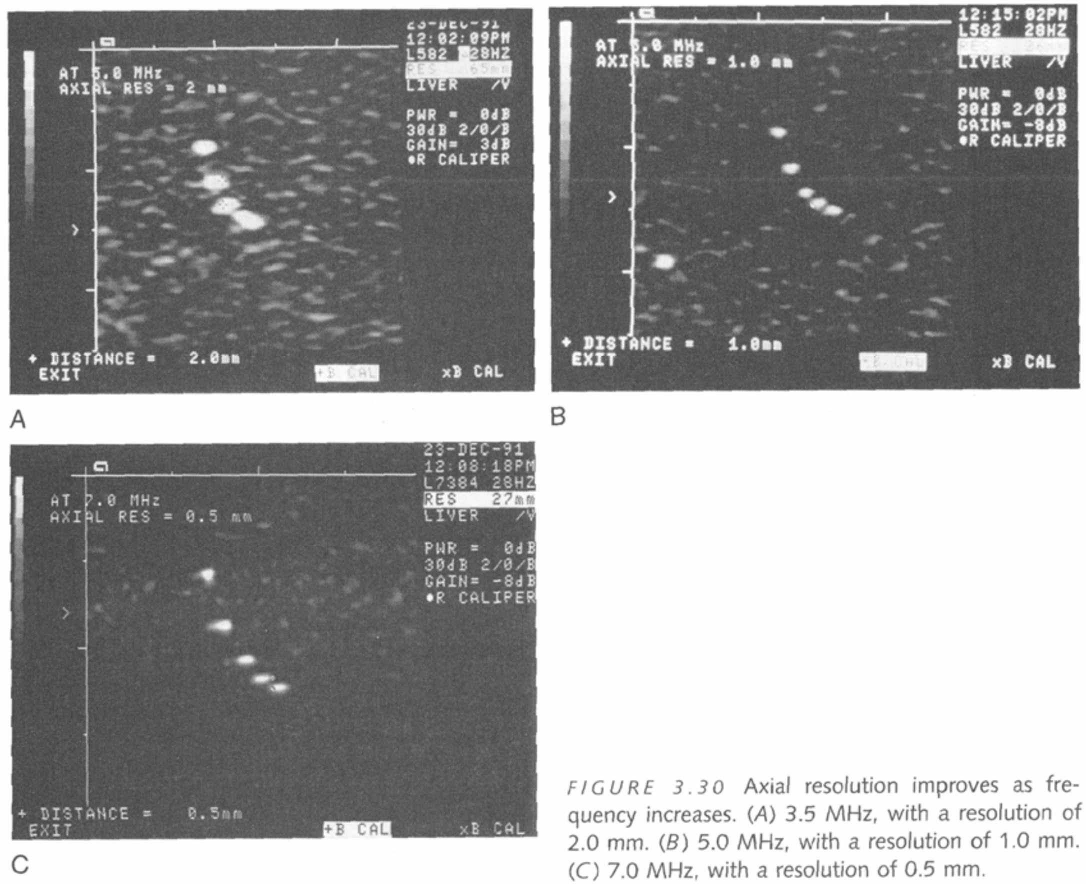
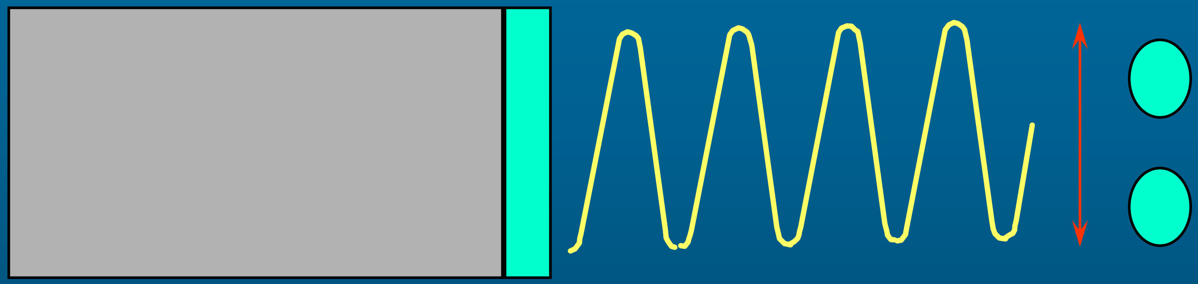


FIGURE 3.30 Axial resolution improves as frequency increases. (*A*) 3.5 MHz, with a resolution of 2.0 mm. (*B*) 5.0 MHz, with a resolution of 1.0 mm. (*C*) 7.0 MHz, with a resolution of 0.5 mm.

Types of Resolution

- Lateral Resolution
  - the ability to resolve two adjacent objects that are **perpendicular** to the beam axis as separate objects
  - Beam width affects lateral resolution

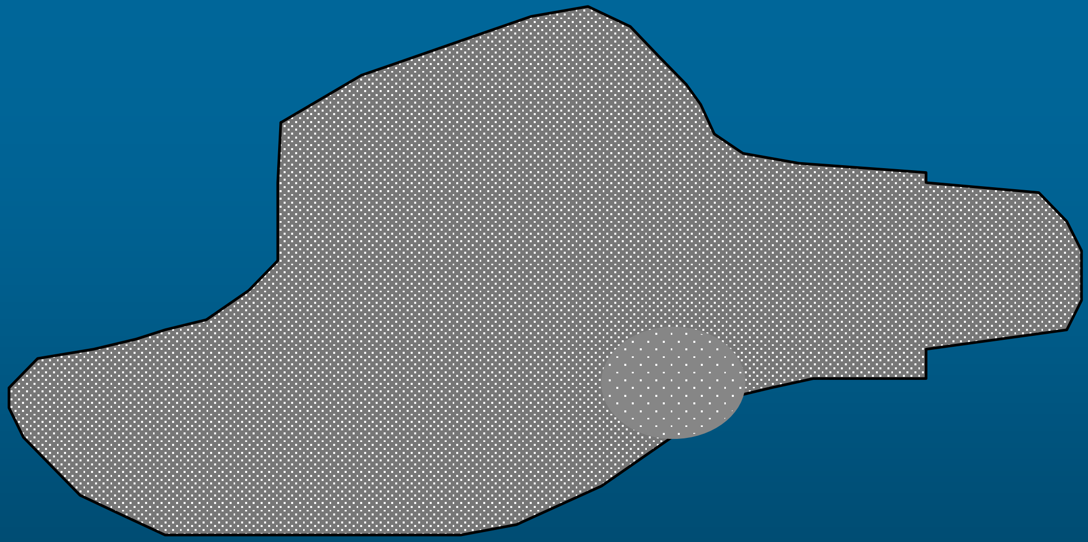


Types of Resolution

- Spatial Resolution
  - also called *Detail Resolution*
  - the combination of AXIAL and LATERAL resolution
  - some companies may use this term

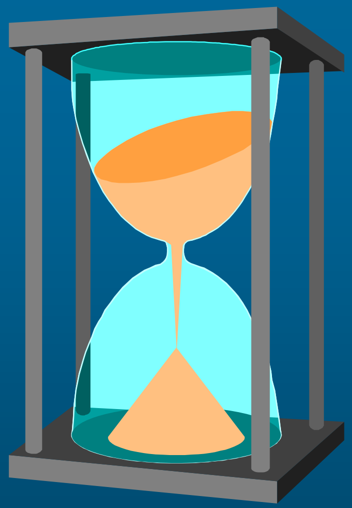
Types of Resolution

- Contrast Resolution
  – the ability to resolve two adjacent objects of different intensity/reflective properties as separate objects

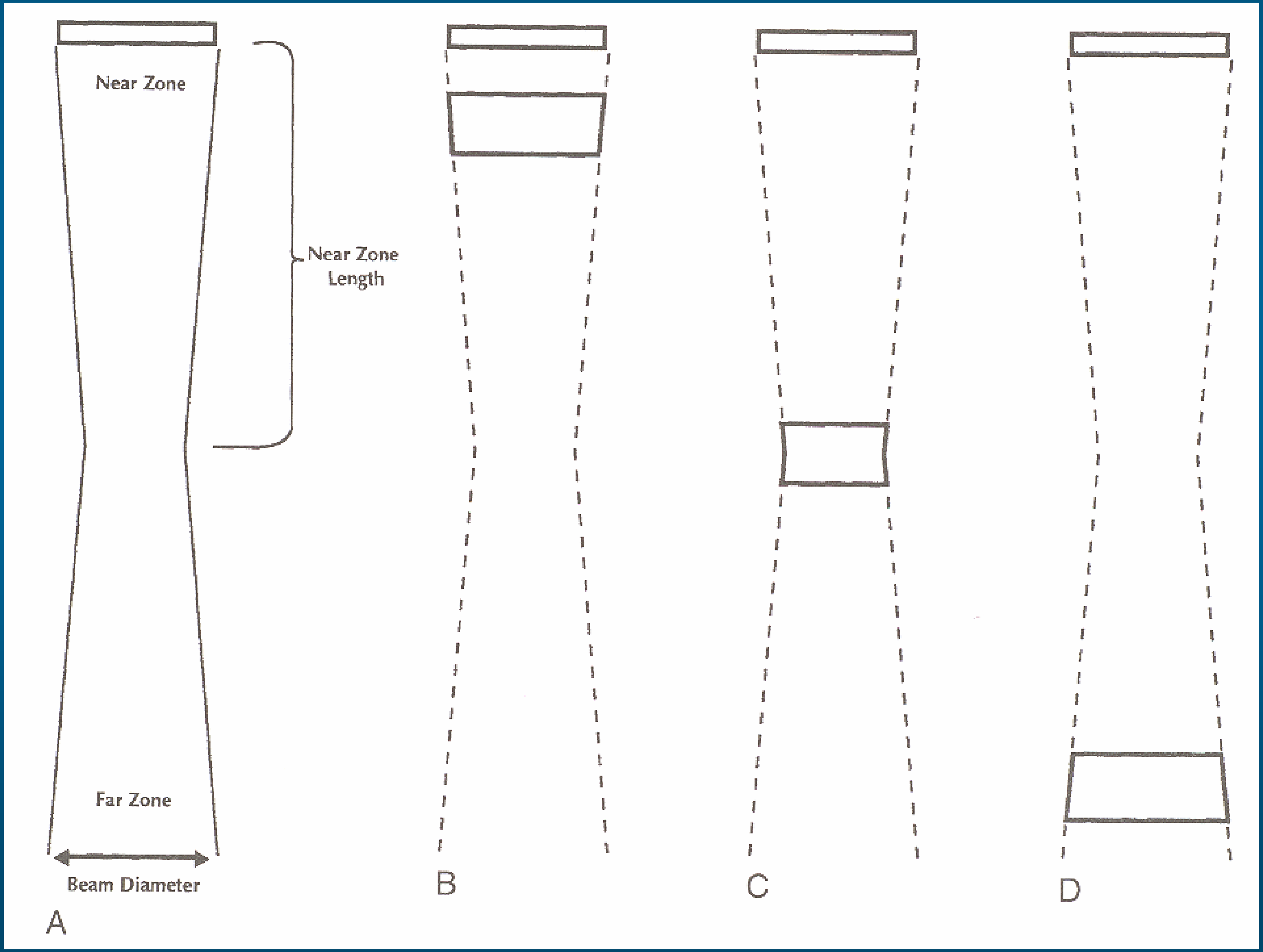


Types of Resolution

- Temporal Resolution
  - the ability to distinguish very rapid events in sequence
  - also known as frame rate



Near and Far Zones



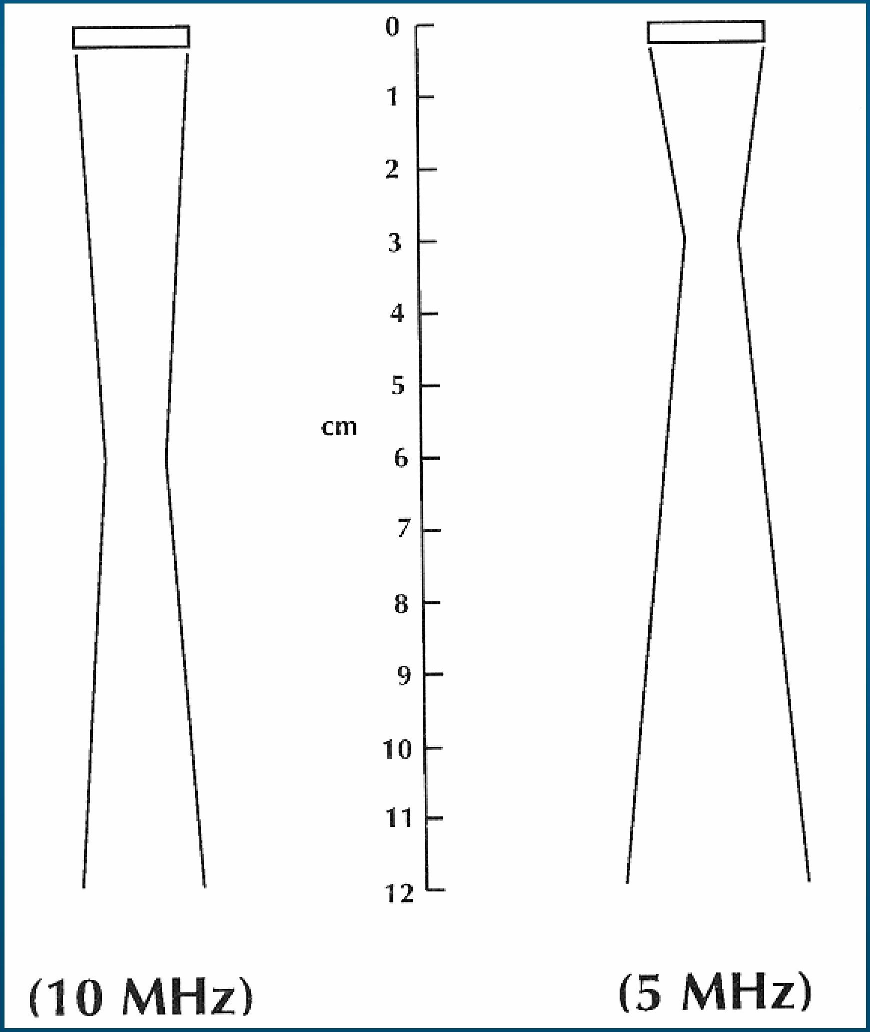
Near and Far Zones

- Near Zone: is also called Fresnel Zone…

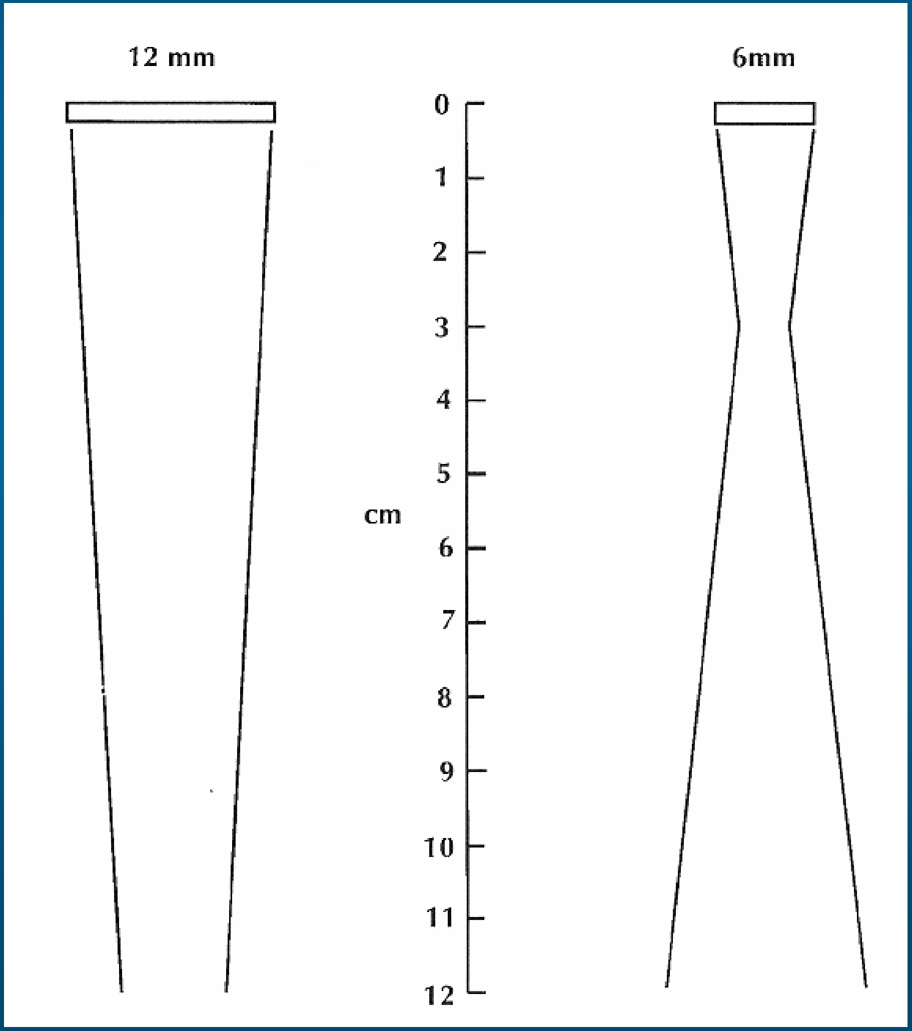
Length of Fresnel Zone = (Radius of the transducer)^2/wavelength

- Far Zone: is also called Fraunhofer Zone…

Near and Far Zones

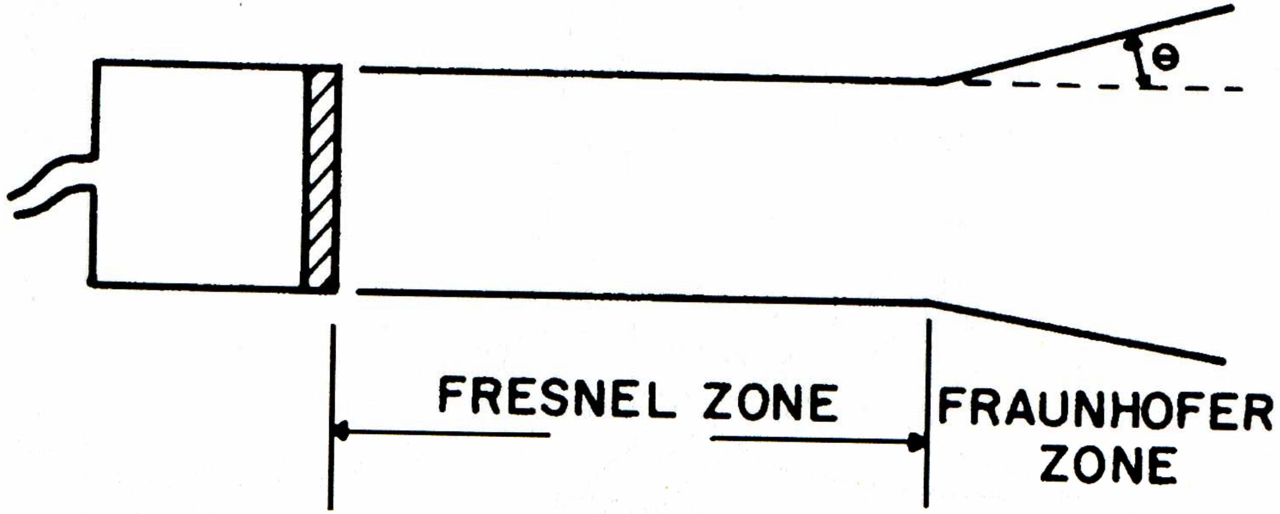


Near and Far Zones



Near and Far Zones

Sin (θ) = 0.6 (wavelength)/(Radius of the transducer)

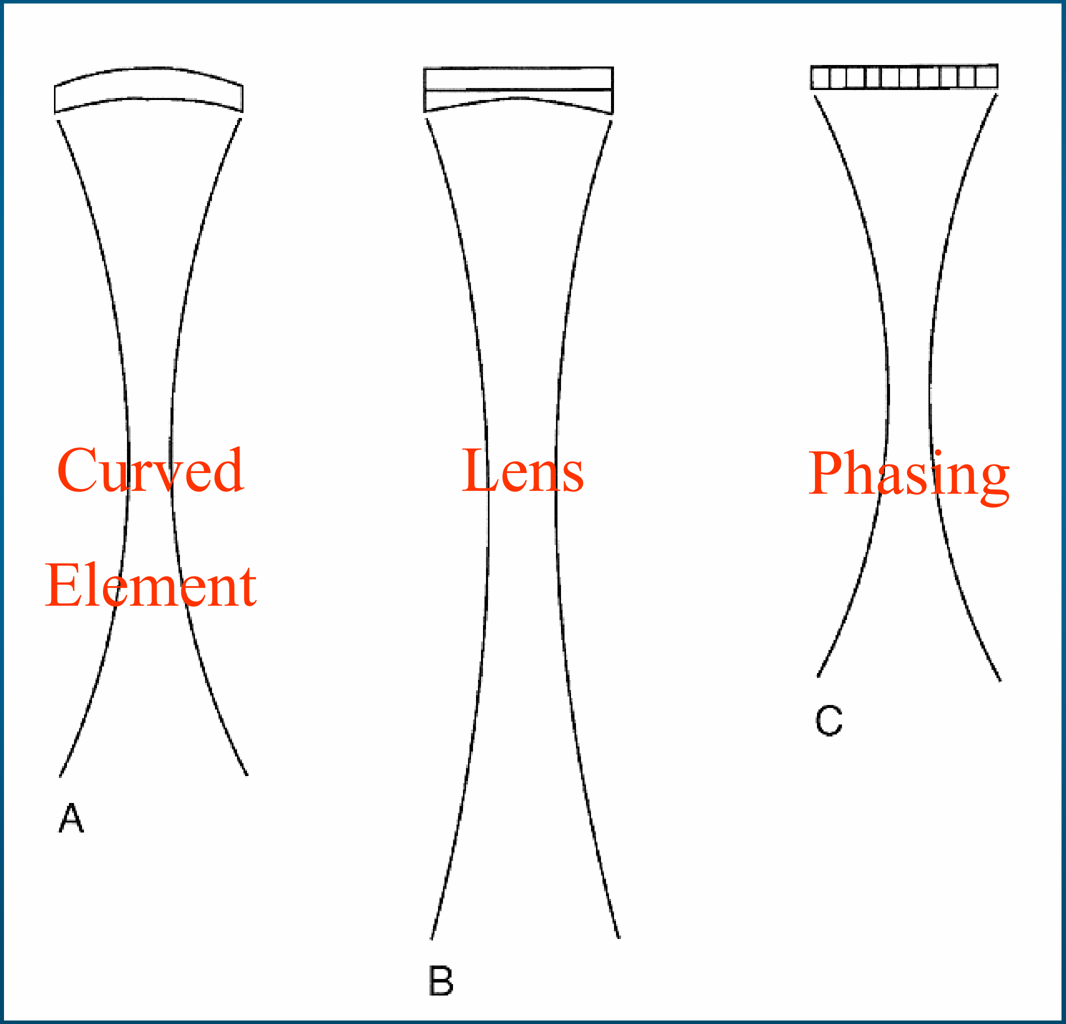


MARGIN FIGURE 20-4
Divergence of the ultrasound beam in the Fraunhofer region.. Angle θ is the Fraunhofer divergence angle.

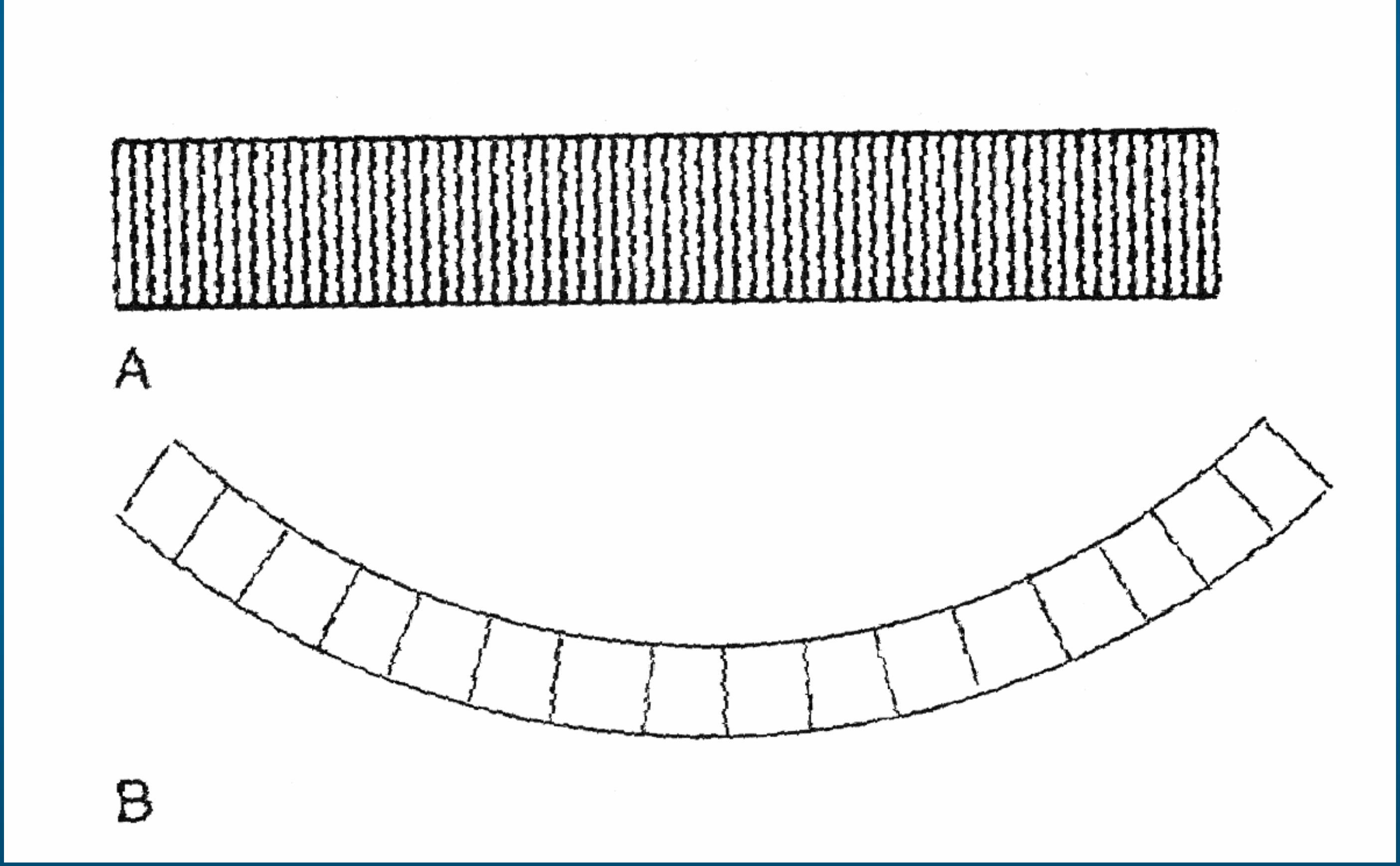
Near and Far Zones

- Rules for Transducer Design:
  - The near-field length increases with increasing frequency
  - Beam divergence in the far field decreases with increasing frequency
- For a given transducer frequency:
  - The near-field length increases with increasing transducer diameter.
  - Beam divergence in the far field decreases with increasing transducer diameter.

Focusing



Linear/Cuved Arrays



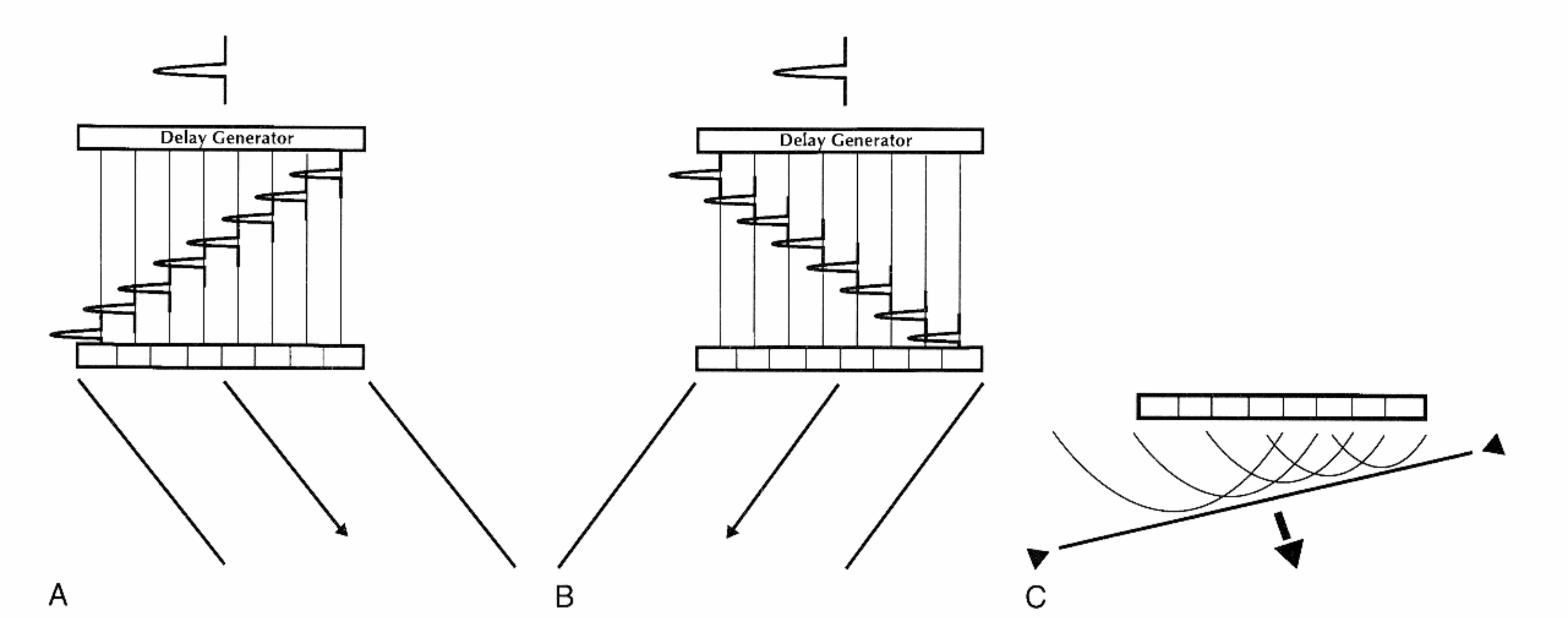
Linear Phased Arrays

Fact #1: If an echo comes from a point source, it propagates as a spherical wave. Cross-section hit different time.

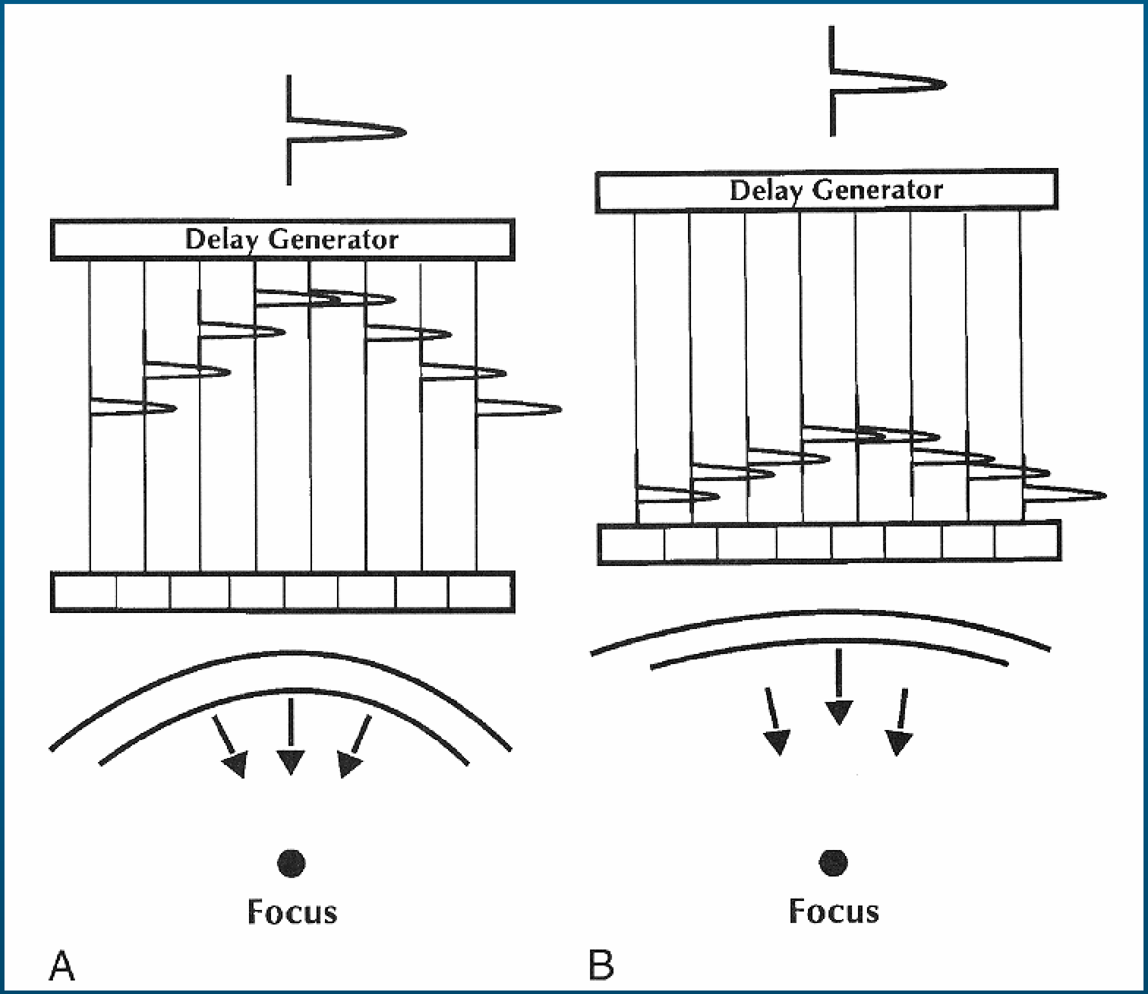
Fact #2: By introducing a delay in firing & receiving signals, a plane wave can be “steered”.

Linear Phased Arrays

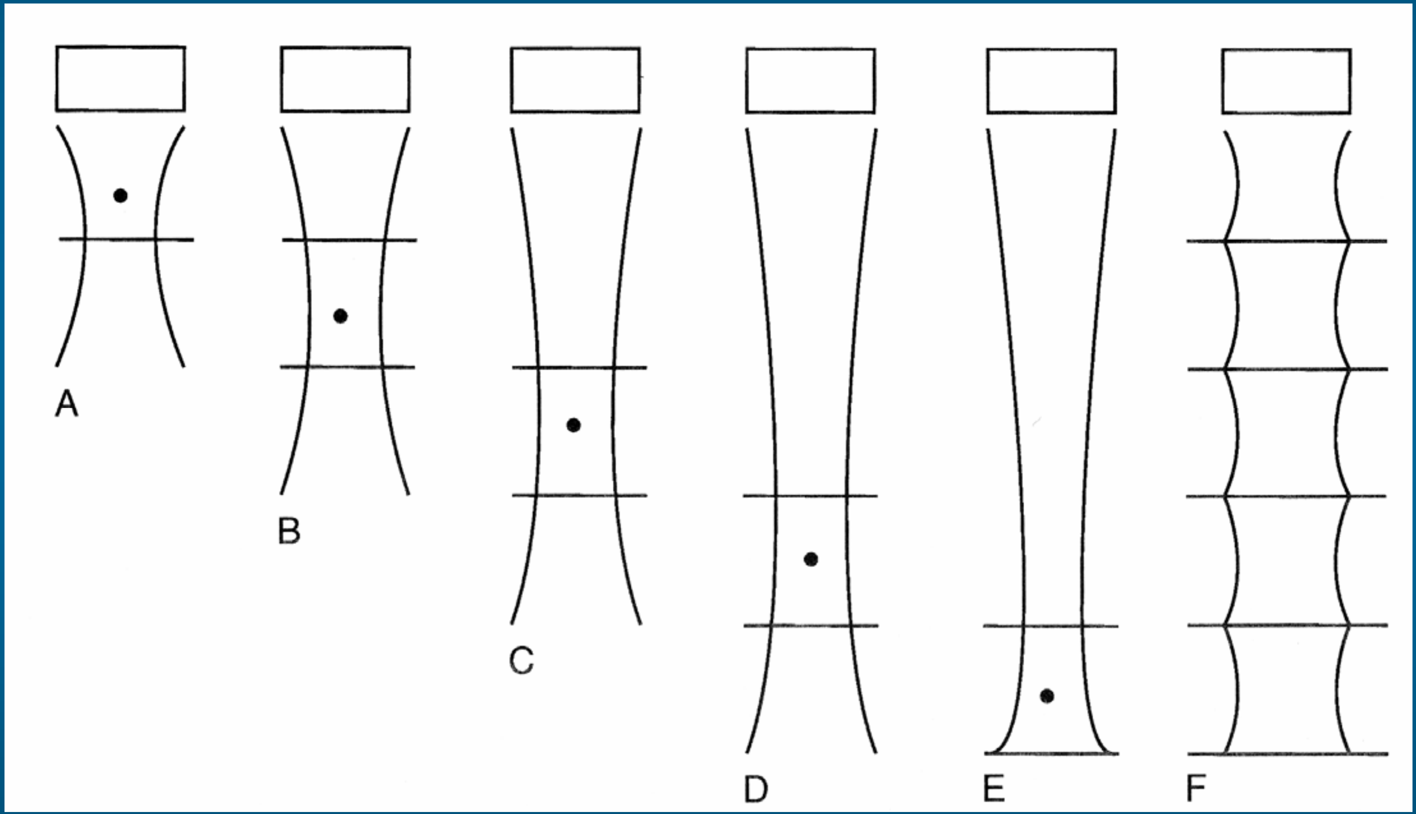
By introducing a delay in firing & receiving signals, a plane wave can be “steered”.



Electronic Focusing

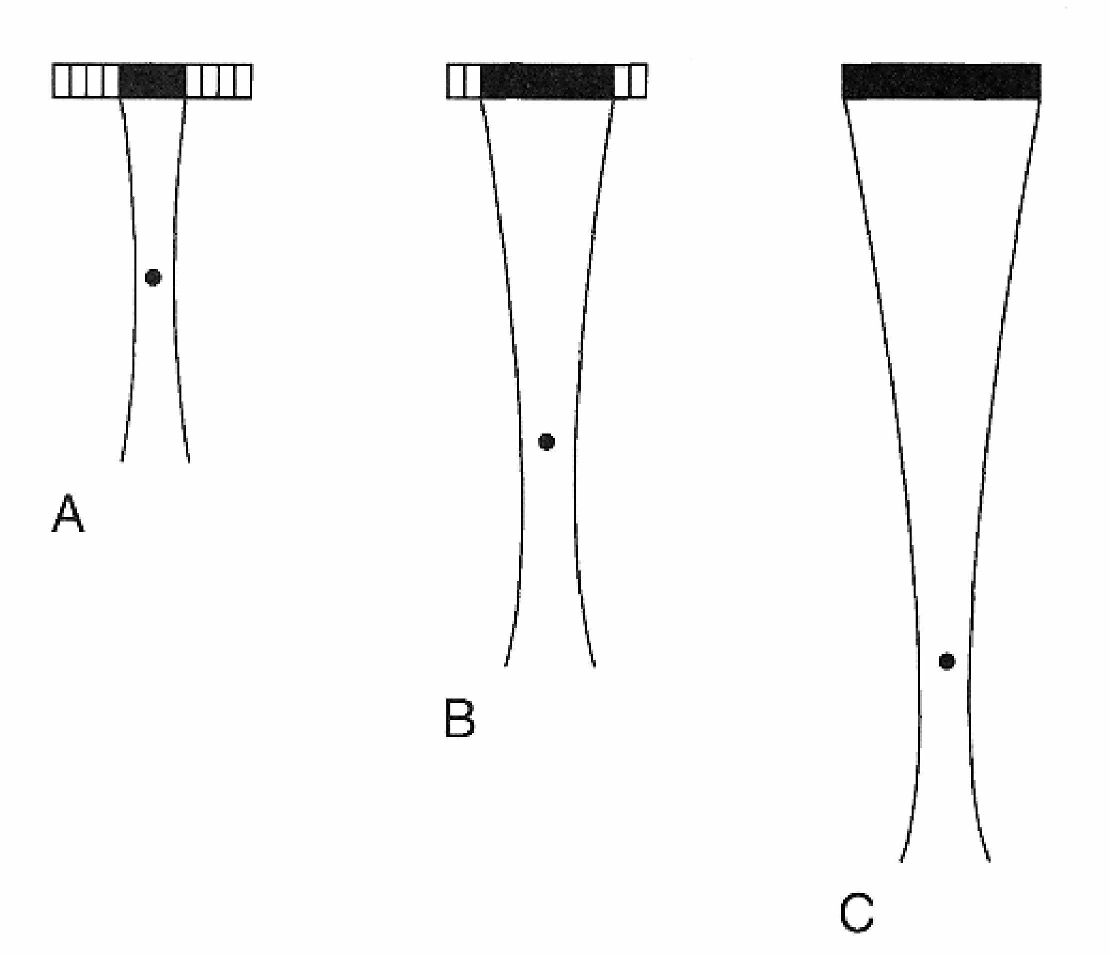


Multiple Focusing

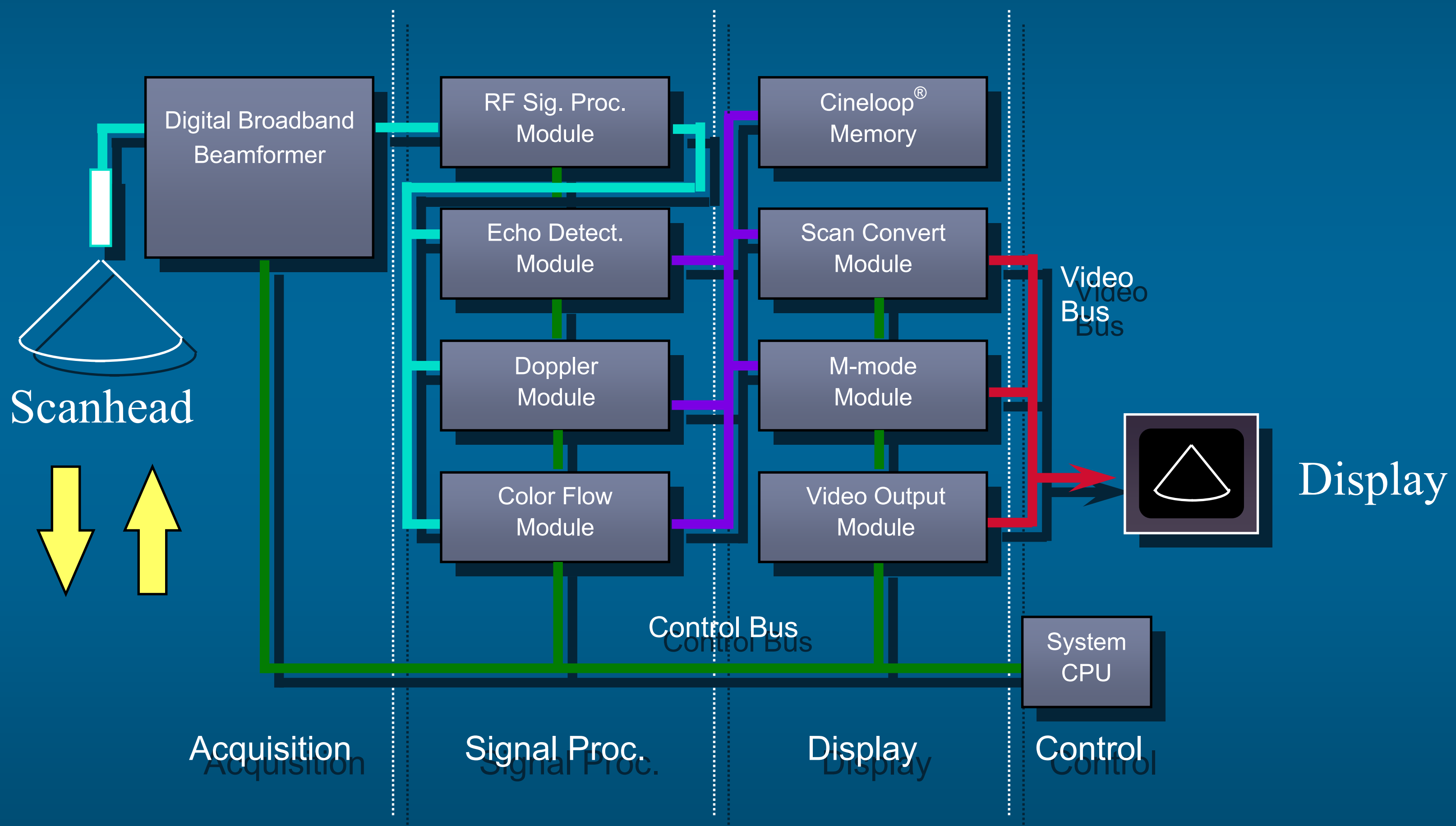


Frame rate is reduced

Variable Aperture

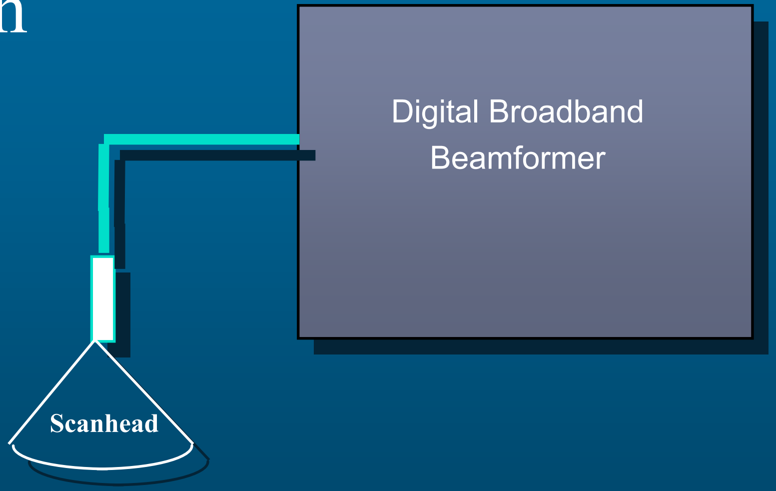


Components of an Ultrasound System



Components of an Ultrasound System

- The BEAMFORMER is the ultrasound “engine”
- It coordinates and processes all the signals to and from the scanhead elements
- It is the main component responsible for image formation



Components of an Ultrasound System

As the US passes through tissue, it attenuates and loses strength. There are many unpredictable parameters that affect this attenuation, such as the patient, tissues, coupling, and the pathology. The simplest way is to use Time-Gain Compensation (TGC). This is also called depth-gain compensation (DGC). Assuming that US propagates at 1540 m/s, machines allow the operator to compensate (amplify) the signal by varying a weight (gain).

Components of an Ultrasound System

How is this done?

Simple machines have 3 circular dials (knobs):

- Initial gain
- Final gain
- Slope

Additional controls may be used to set the time which the gains switch.

How is the image formed on the monitor?

- The **strength** or **amplitude** of each reflected wave is represented by a dot
- The **position** of the dot represents the depth from which the returning echo was received
- The **brightness** of the dot represents the strength of the returning echo
- These dots are combined to form a complete image

Image Display
Position of Reflected Echoes

- Display screen divided into a matrix of PIXELS (picture elements)

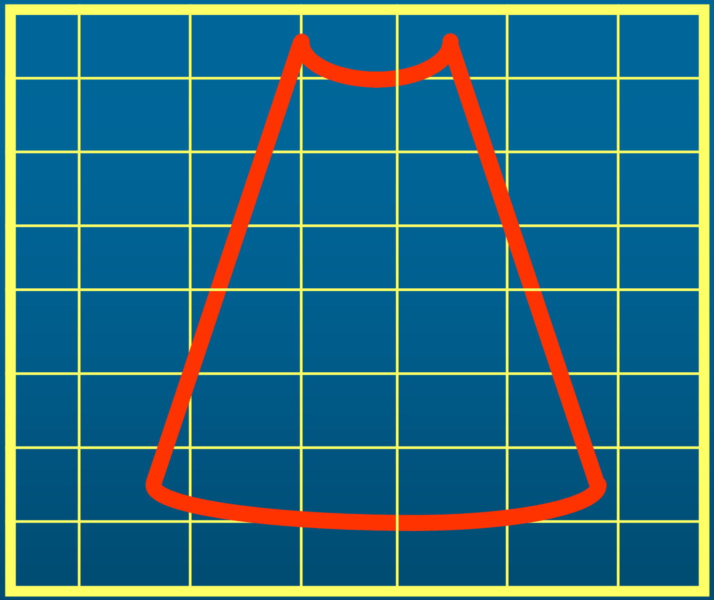


Image Display
Position of Reflected Echoes

- How does the system know the depth of the reflection?
- TIMING
  - The system calculates how long it takes for the echo to return to the scanhead
  - The velocity in tissue is assumed constant at 1540m/sec

$$\text{Velocity} = \frac{\text{Distance x Time}}{2}$$

Strength of Reflected Echoes

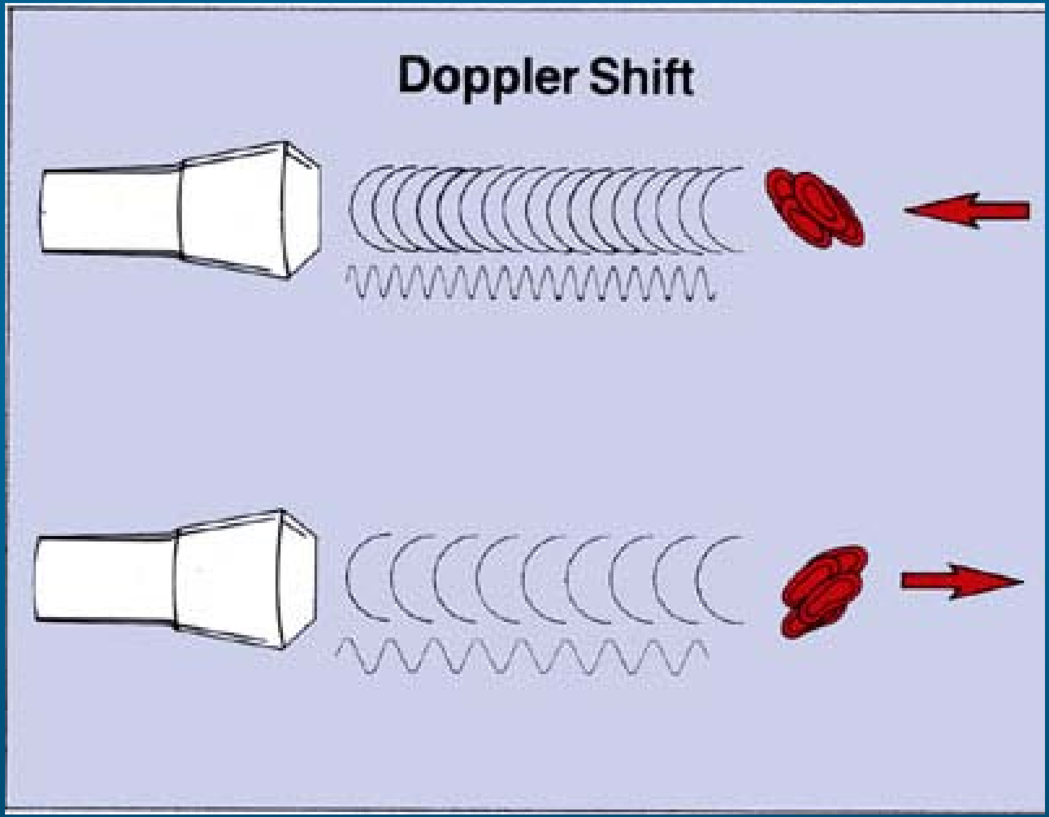
- Strong Reflections = White dots
  - Diaphragm, gallstones, bone
- Weaker Reflections = Grey dots
  - Most solid organs, thick fluid
- No Reflections = Black dots
  - Fluid within a cyst, urine, blood

16 WEEK FETAL FACE

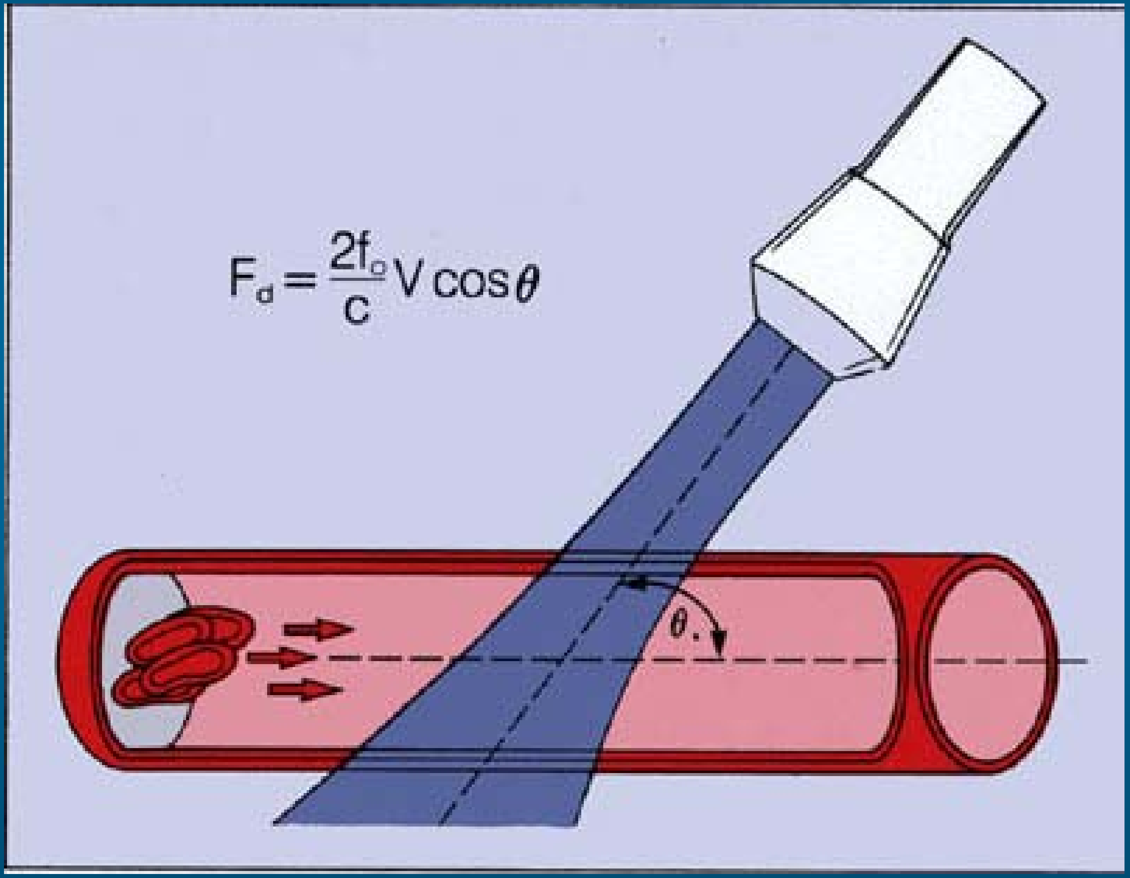
Other modes used with 2D Imaging

- DOPPLER is used to **hear** and **measure** blood flow
- COLOR or CPA (Color Power Angio) is added to **visualize** blood flow

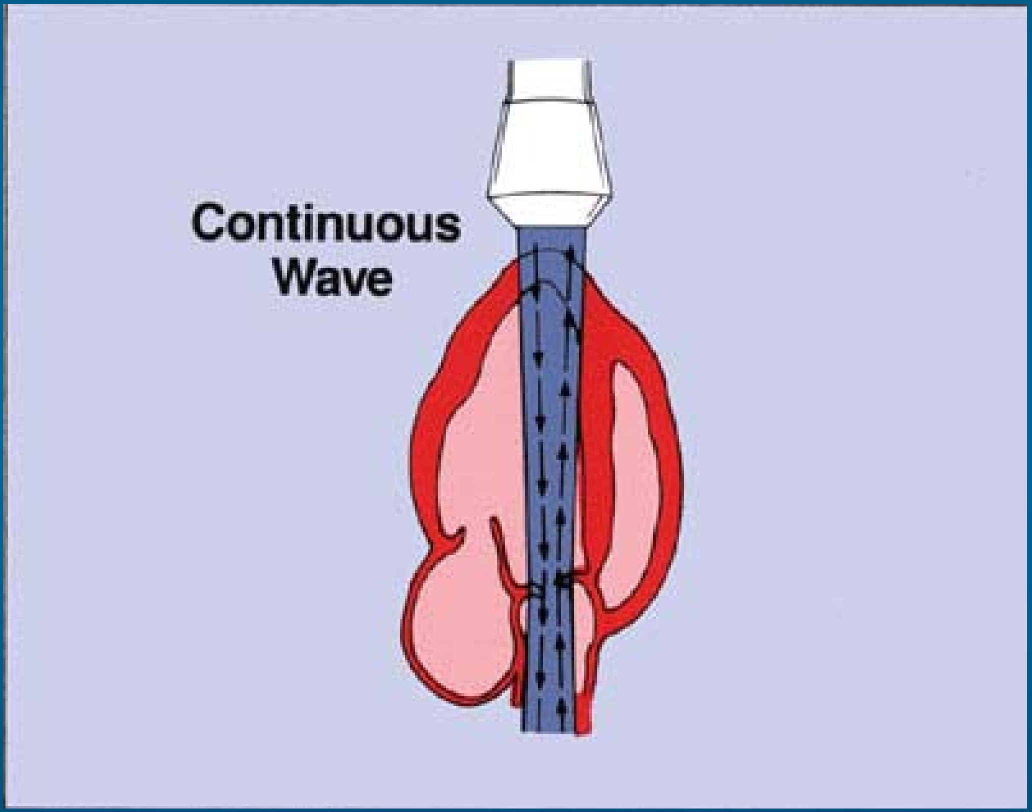
Doppler



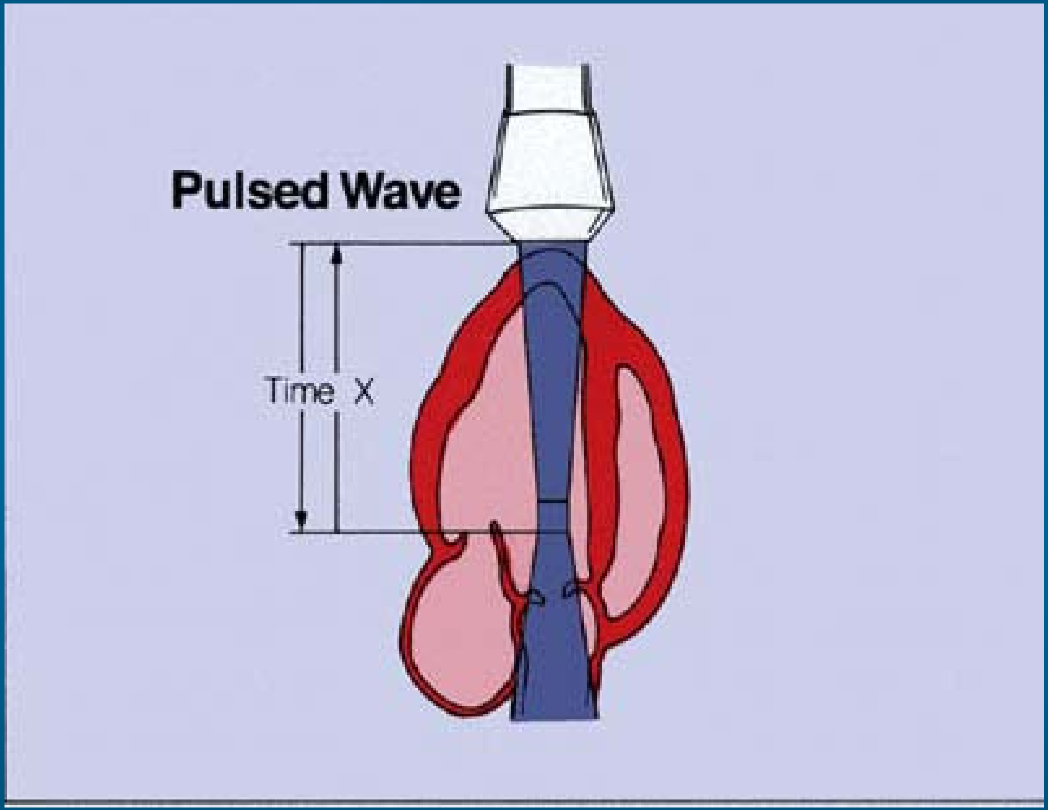
Doppler



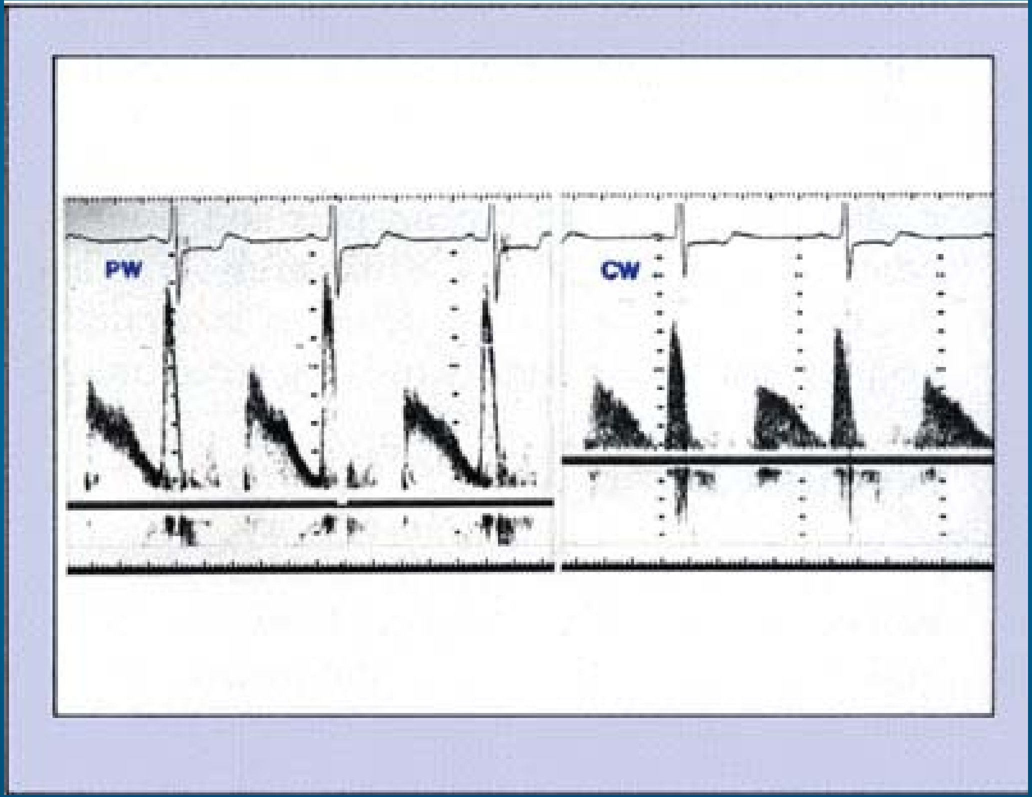
Doppler



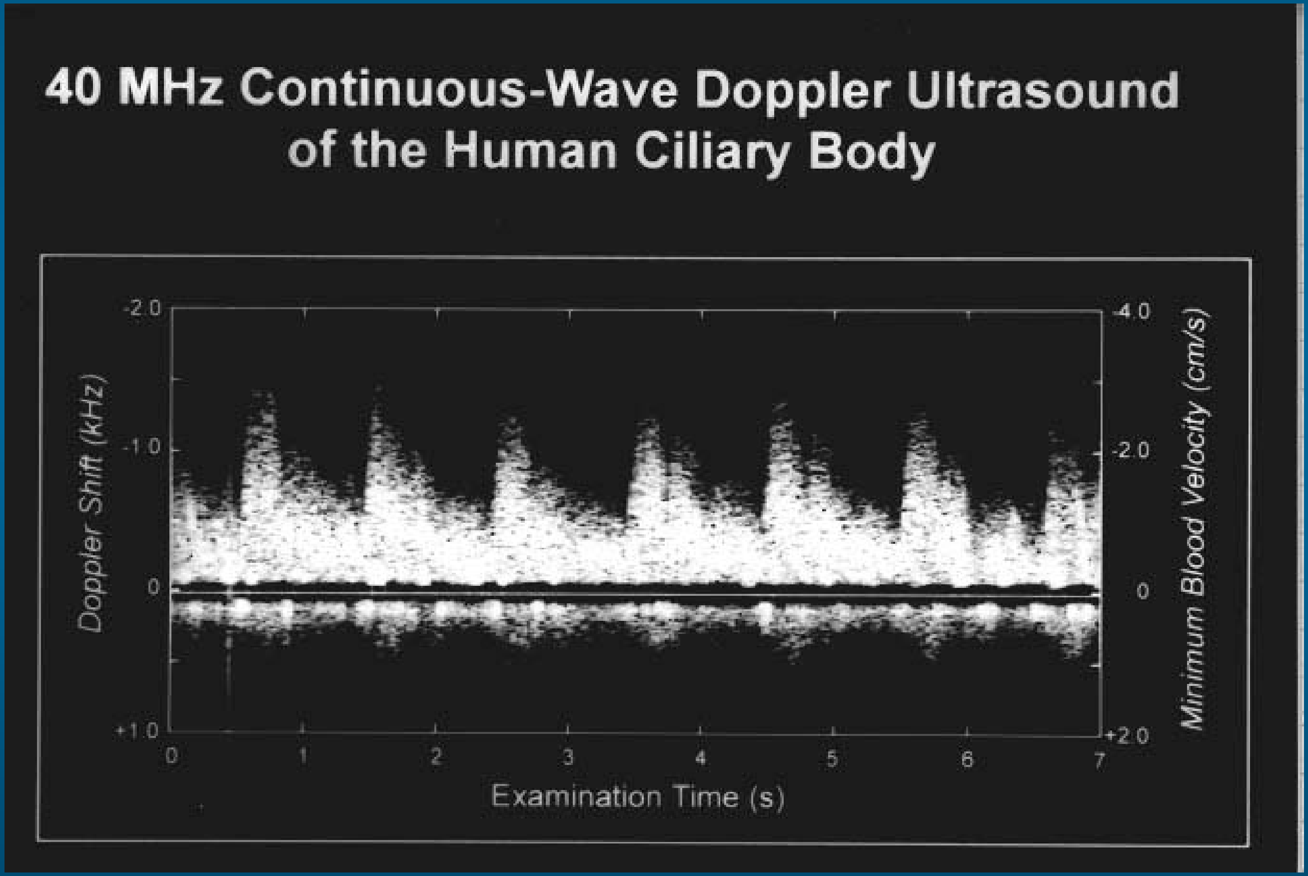
Doppler



Doppler



Doppler


40 MHz Continuous-Wave Doppler Ultrasound
of the Human Ciliary Body
Doppler Shift (kHz)
-2.0
-1.0
0
+1.0
Minimum Blood Velocity (cm/s)
-4.0
-2.0
0
+2.0
0
1
2
3
4
5
6
7
Examination Time (s)

Color Doppler