

ULTRASOUND LECTURE SERIES

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Ultrasound: The Basics

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The Objectives

The program will enable the participants to be knowledgeable on the following aspects of diagnostic ultrasound technology:

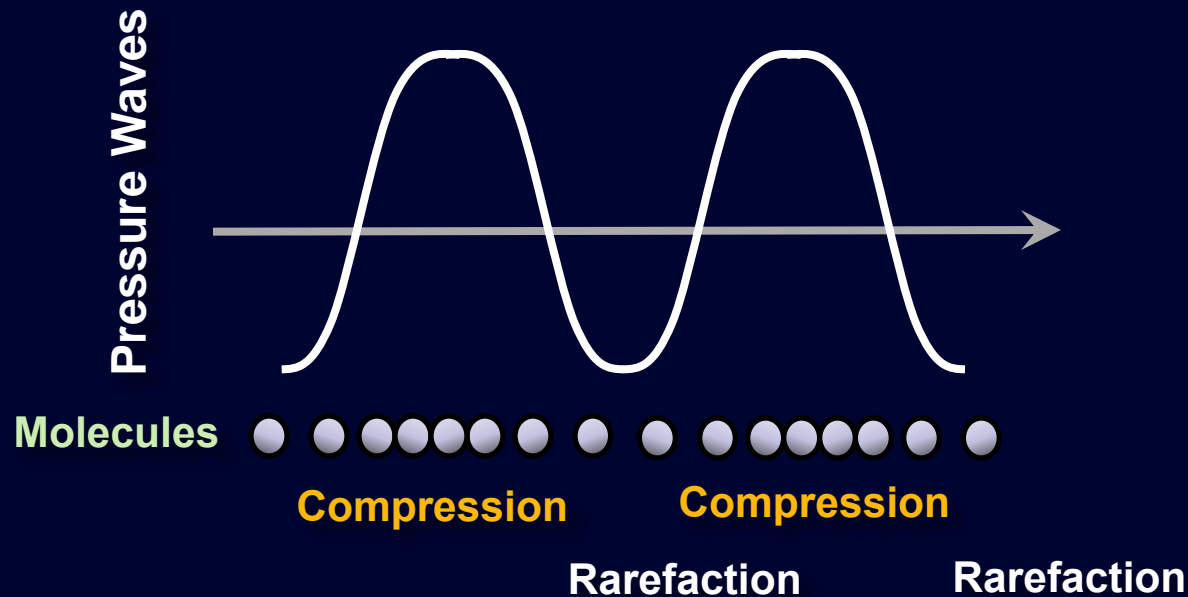
- Physics of sound and ultrasound**
- Modes of diagnostic ultrasound**
- Diagnostic ultrasound instrumentation**

For a more comprehensive and in-depth discussion of these topics, further reading is suggested at the end.

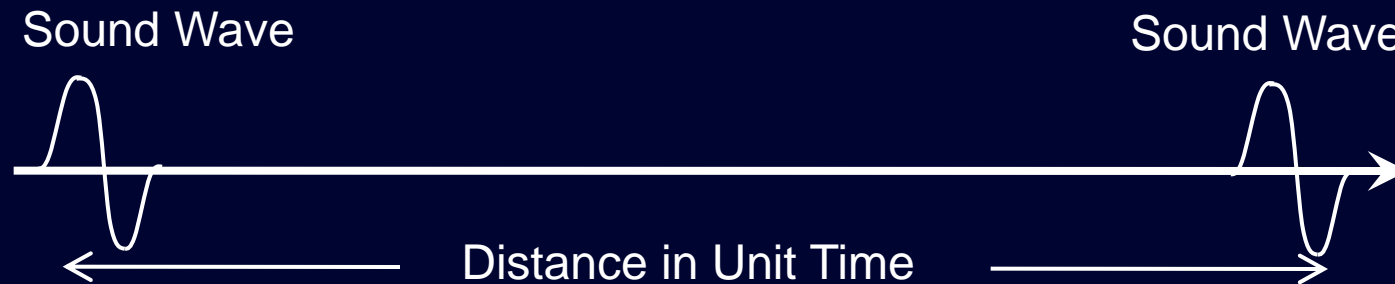
Ultrasound: The Basics
Physics of Ultrasound

Sound

- Sound is a form of mechanical energy that travels through solid or liquid media as pressure waves .
- Alternating molecular compression and rarefaction accompanies sound waves as they propagate along the medium.



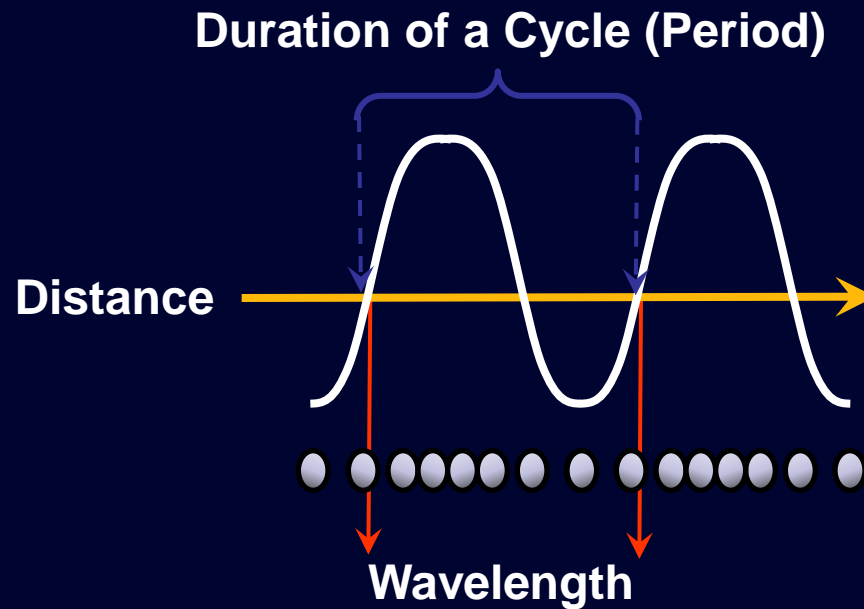
Propagation Speed of Sound



- The speed of sound wave moving through a tissue medium is its propagation speed.
- It is called velocity when the direction of motion is also known.
- The propagation speed of sound depends on the density and elasticity of the medium.
- The average propagation speed of ultrasound in soft tissues is approximately 1540 meters per second.
- The propagation speed value of ultrasound is used for depth localization of the echoes in the image.

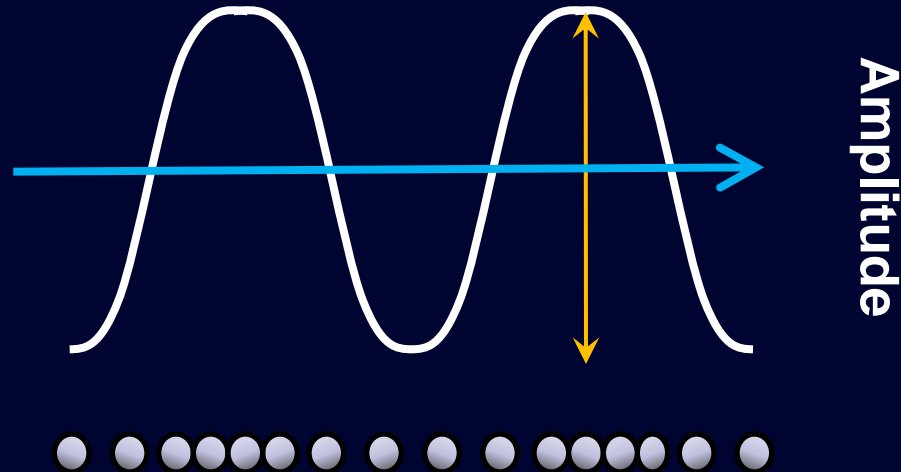
Sound Wave Characteristics

- Wavelength is the distance traveled by one cycle of compression and rarefaction.
- Period is the duration of one cycle and is measured in microseconds.



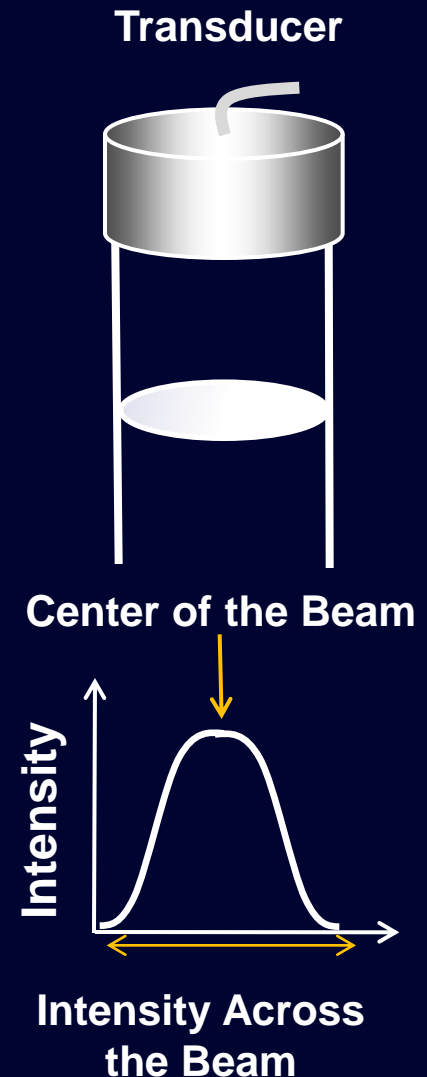
Amplitude

- Amplitude is the maximum variation in pressure generated in a medium by propagating ultrasound waves.
- Pressure amplitude is directly related to the amount of sound energy radiating from the sound source.

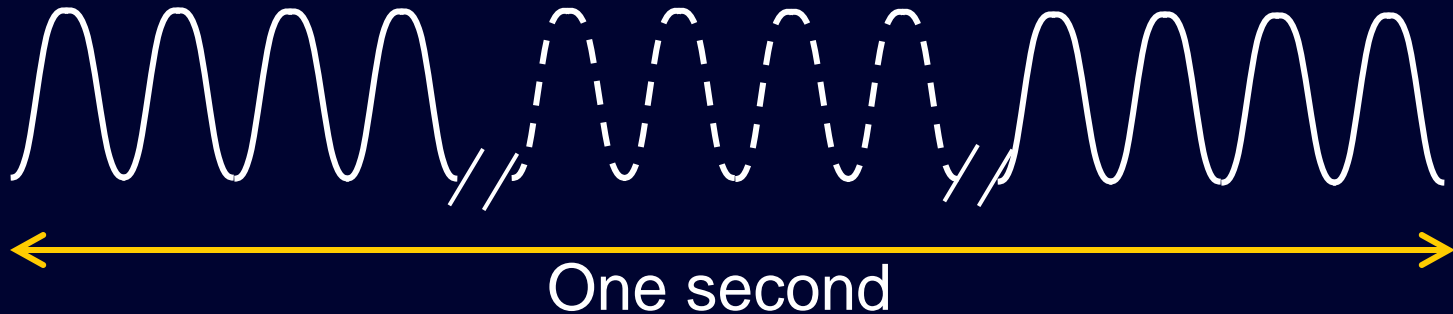


Power and Intensity

- Power is the rate of flow of ultrasonic energy through the cross-sectional area of the beam.
- Intensity of the wave is power divided by beam cross-sectional area.
- In diagnostic ultrasound, intensity is measured in milliwatts per square centimeter.
- Intensity is highest in the center of the beam and diminishes as it moves away from the transducer.
- Intensity varies with time in pulsed ultrasound with no power output in between pulses.
- Power and intensity are important biosafety considerations in diagnostic ultrasound.

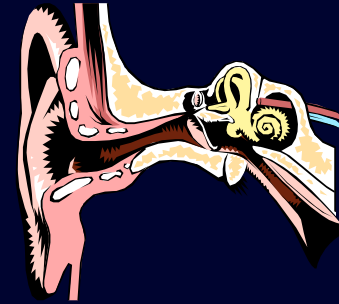


Sound Waves: Frequency



- Frequency is the number of cycles in a second.
- Frequency is inversely related to the period or the duration of a cycle.
- One cycle is a hertz (Hz).
- A kilohertz (KHz) is 1000 cycles per second.
- A megahertz (MHz) is 1 million cycles per second.

Frequency: Sound vs Ultrasound

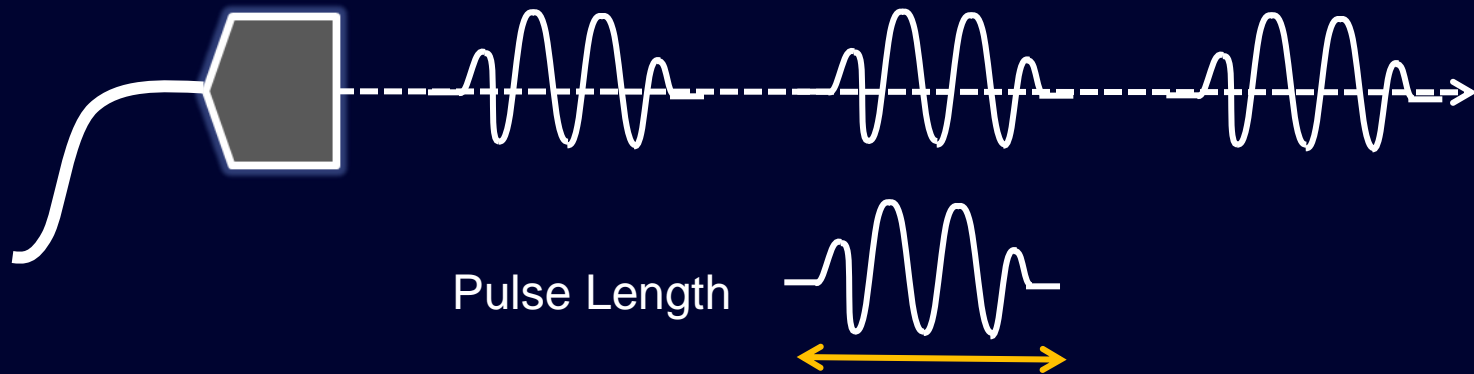


Audible sound frequency range is approximately 10 Hz to 20 KHz.

- Ultrasound is sound with a frequency >20 KHz and therefore inaudible to the human ear.
- Diagnostic ultrasound has a range of 1 to 15 MHz.
- In imaging, the higher the frequency, the better the resolution and the lower the penetration.

Pulsed Ultrasound

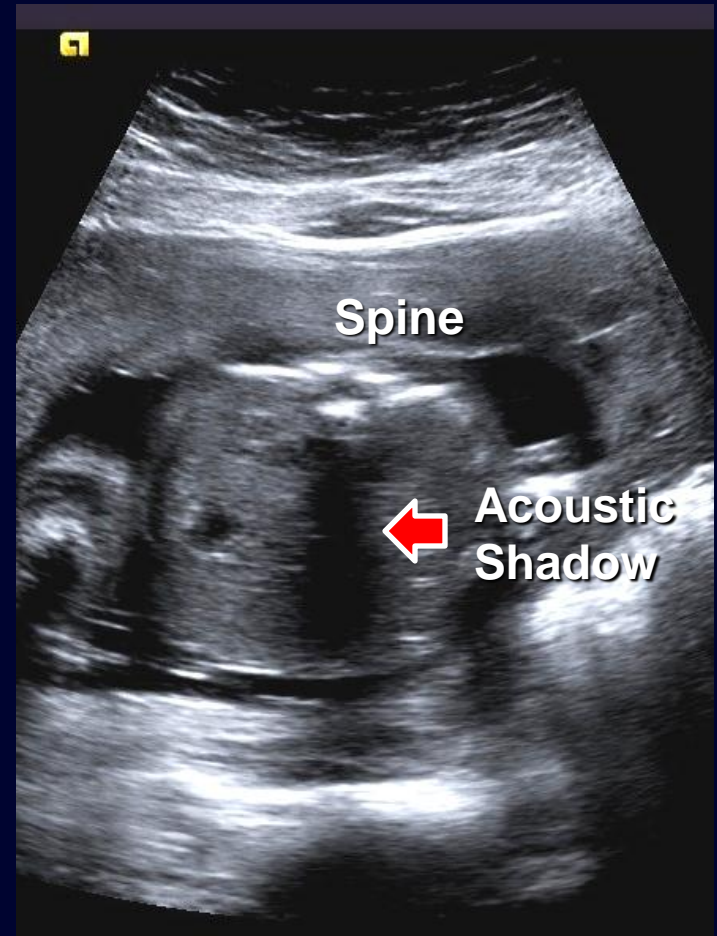
- Pulse echo imaging and pulsed Doppler systems transmit ultrasound waves in pulses.
- Echoes are received in between the transmitted pulses.
- The number of pulses transmitted per second is known as the pulse repetition frequency (PRF) and is measured in hertz.
- The length of one ultrasound pulse is the spatial pulse length. It is inversely related to the resolution.
- The pulse length ranges from 2 to 3 cycles in pulse echo imaging and 5 to 30 cycles in pulsed Doppler ultrasound.



Impedance

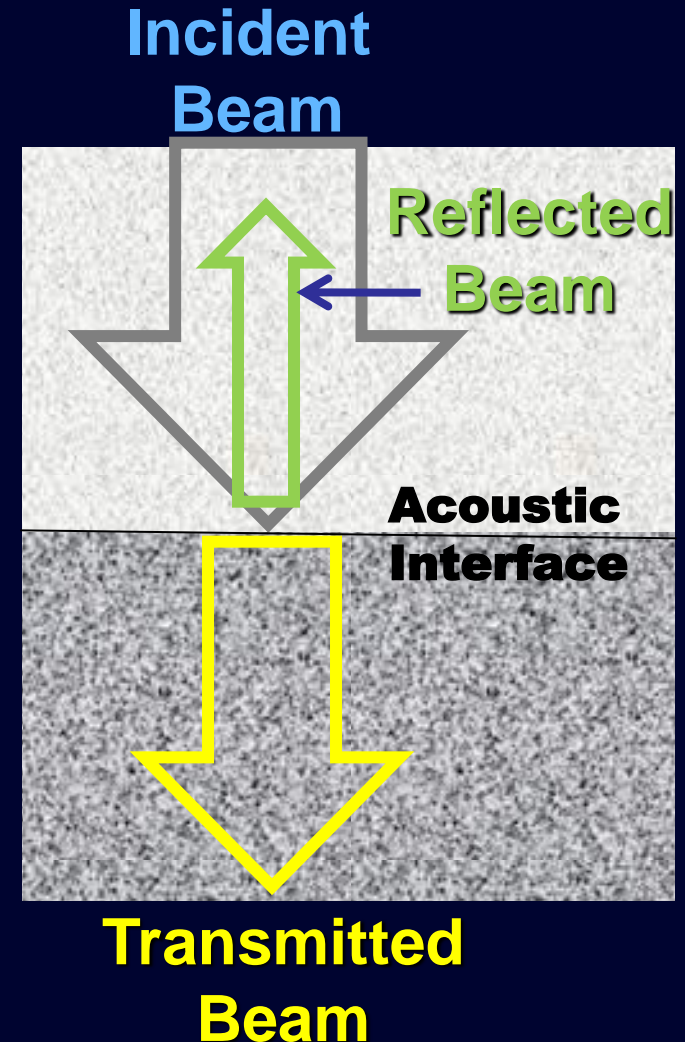
- Impedance is the resistance offered by a medium to ultrasound transmission.
- It is the product of density of the medium and the velocity of ultrasound.
- Bone has higher density and offers significantly higher acoustic impedance than soft tissues.
- Most soft tissues demonstrate similar acoustic impedance.

Acoustic shadow produced by the high acoustic impedance of the fetal spine blocking transmission.



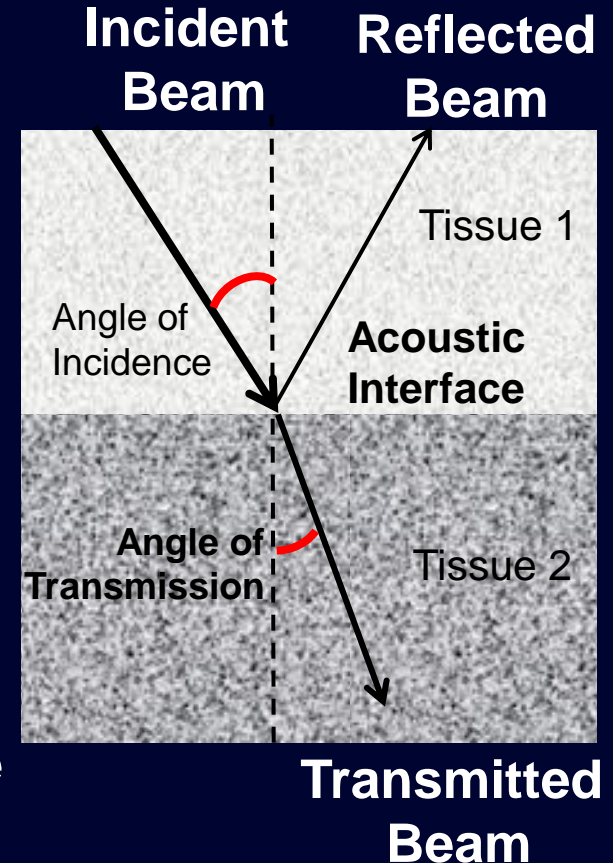
Ultrasound Reflection

- Propagating ultrasound is reflected at the interface of tissues with differing impedance.
- Acoustic interface is the boundary between adjacent tissues with differing impedance.
- A part of the incident beam will be reflected, and the rest will be transmitted.



Ultrasound Reflection

- Specular reflection occurs when the acoustic interface is smooth and significantly larger than the sound wavelength. Examples include fascia and vascular intima imaging.
- If the incident beam is perpendicular to the interface, the beam will be fully reflected to the transducer.
- If the angle of incidence is oblique, reflection will be oblique and at the same angle, and echoes will not return to the transducer.
- The transmitted beam will be refracted, and the angle of transmission will depend on the propagation speeds in the respective media. The higher the speed, the lesser the angle.



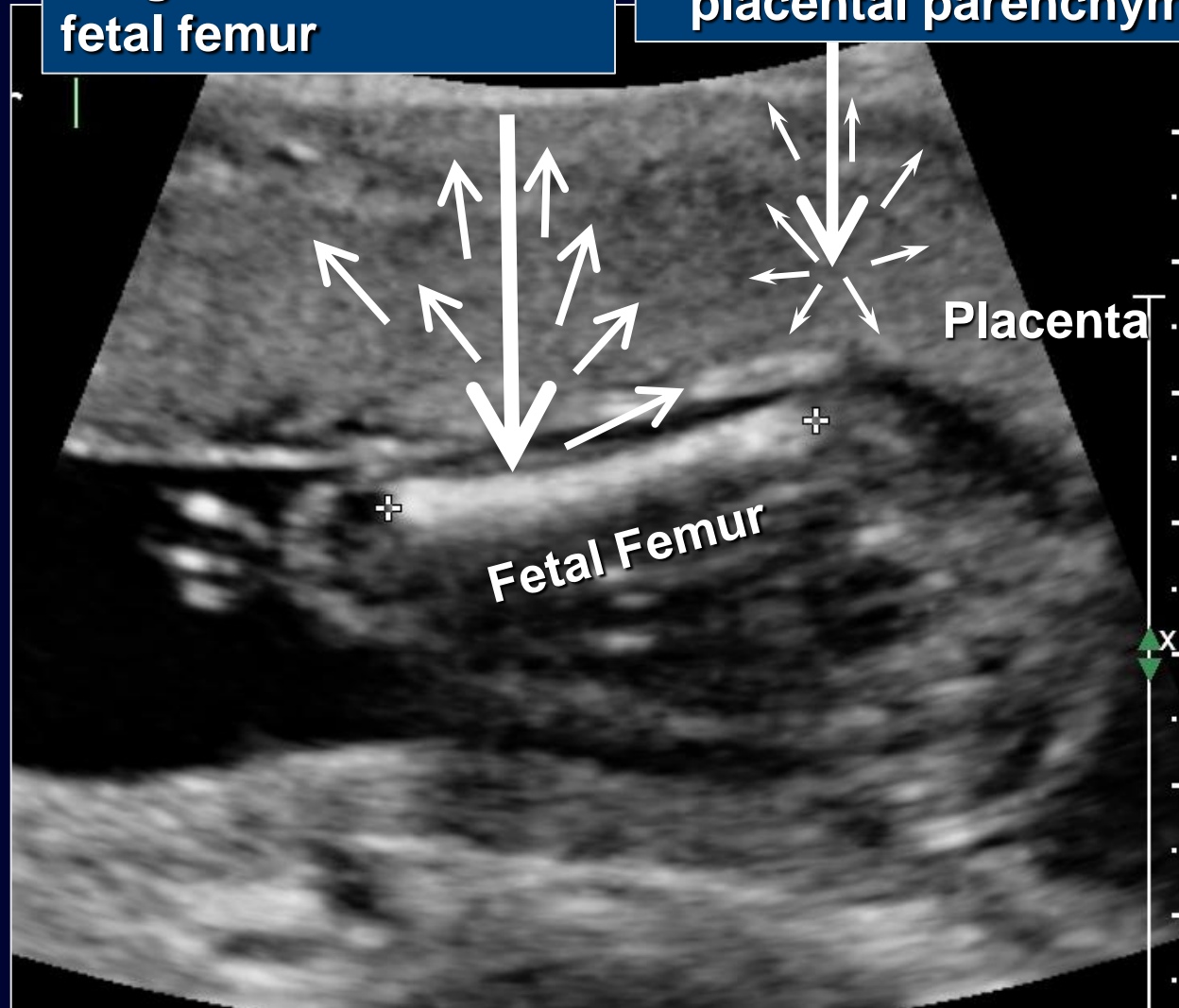
Scattering

- **Ultrasound is reflected in many directions when it encounters large irregular surfaces such as bone or organ surfaces or a heterogeneous medium containing small reflectors equivalent to or smaller than the wavelength. This is known as scattering or diffuse reflection.**
- **The small scatterers reflect weak echoes which get reinforced through mutual interaction (positive interference) and return to the transducer as backscattered echoes.**
- **Scattering reflection is the primary mechanism for imaging organ boundaries and tissue parenchyma.**
- **Backscattering of transmitted ultrasound from the red cells is the basis for measuring the Doppler shift.**
- **Examples of scattering are given in the next slide.**

Scattering

Scattering from irregular surface of fetal femur

Scattering from placental parenchyma



Ultrasound: The Basics
Modes of Diagnostic
Ultrasound

Modes of Ultrasound

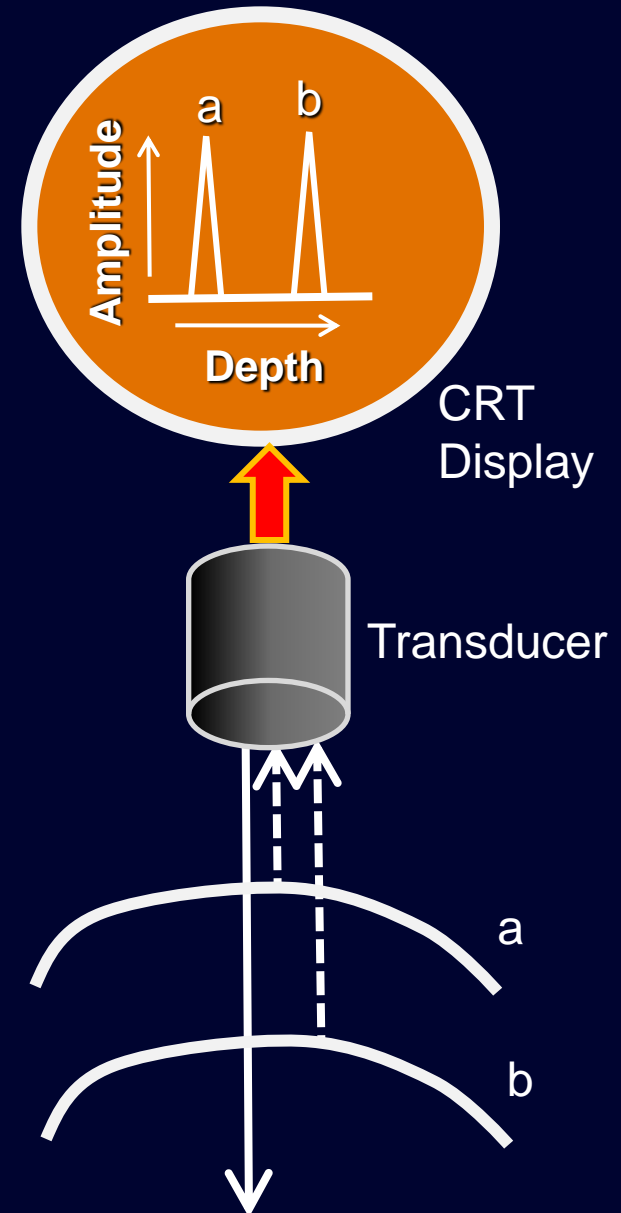
Diagnostic ultrasound is available in several modes depending on the fundamental technology, image acquisition, and display:

- A-mode
- M-mode
- B-mode
- Doppler modes
- 3- and 4-dimensional modes

These are further discussed in the subsequent slides.

A-Mode Ultrasound

- A-mode is the amplitude mode.
- A single piezoelectric element sends ultrasound pulses.
- Returning echo signals along the beam path are uni-dimensionally displayed as spikes according to the depth of the reflectors.
- Echoes from deeper reflectors are displayed to the right of the screen along the horizontal axis.
- Stronger echoes have taller spikes.
- This mode is currently NOT used in ob/gyn imaging.



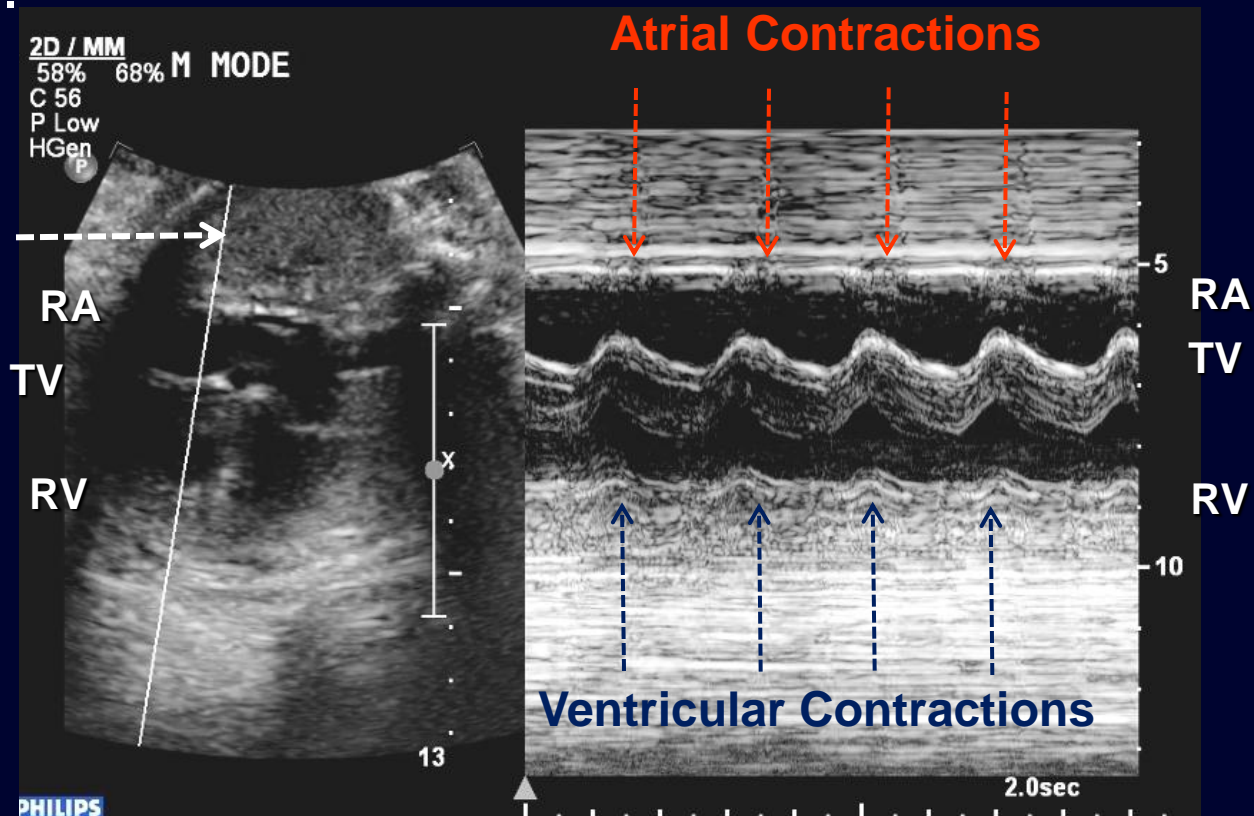
M-Mode Ultrasound

- M-mode is the motion mode or the time motion mode.
- A single piezoelectric element sends ultrasound pulses.
- Echo signals along the beam path are uni-dimensionally displayed as dots or pixels in the vertical axis according to the depth of the reflectors.
- The brightness of the dots is determined by the echo strength.
- The display is scrolled over time with the new echoes displayed on the right.
- This produces bright lines indicating vertical positional changes of the reflectors over time.
- The next slide provides an example.

M-Mode Ultrasound

M-mode assessment of fetal cardiac rhythm is shown below. In this example there is concordance of the atrioventricular rhythm. The fetal heart rate can be calculated from an M-mode image.

M mode cursor line indicating the beam path.



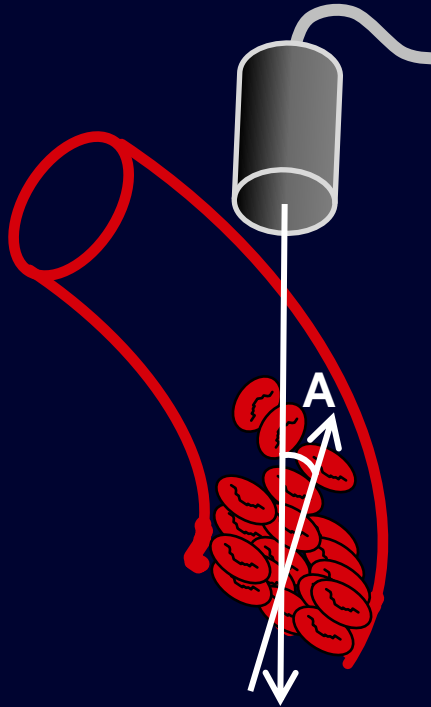
RA = right atrium, RV = right ventricle, TV = tricuspid valve

B-Mode Ultrasound

- B-mode is the brightness mode of pulse echo ultrasound.
- A B-mode image is created by sweeping the ultrasound beam through the target area and detecting echoes along the scan lines.
- The returning echoes are displayed 2-dimensionally as bright dots or pixels.
- The strength of echoes determines the brightness of the dots.
- The sweeping beams produce images or frames that constitute real-time images.
- The number of frames per unit time is called the frame rate. Multiple focal points or greater depth slow the frame rate.



Principles of Doppler Sonography



- In Doppler ultrasound, the transmitted ultrasound waves are backscattered by the moving red cells and undergo Doppler shift.
- The frequency shift is proportional to the speed of blood flow as shown in the Doppler equation:
$$fd = 2ft v/c$$
where fd = Doppler frequency shift, ft = transducer frequency, v = velocity of blood flow, c = propagation speed of sound.
- The velocity of blood flow can be determined if the angle of insonation between the Doppler beam and the direction of flow is known (**A** as shown in the figure on the left).

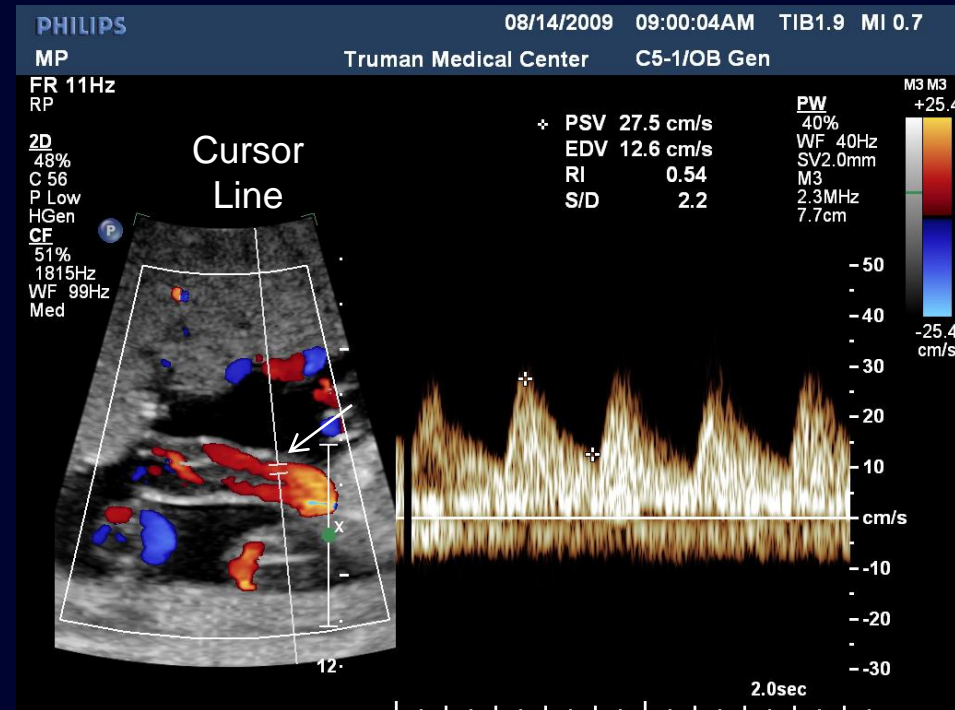
Doppler Ultrasound

There are 4 types of Doppler ultrasound:

1. **Spectral Doppler shows the magnitude of the Doppler frequency shift over time with the power or the amplitude displayed as brightness. There are 2 types of spectral Doppler: continuous wave and pulsed wave.**
2. **Color flow Doppler shows color-coded blood flow patterns superimposed on gray scale B-mode images. The Doppler information is based on mean frequency shift, and color denotes the flow direction.**
3. **Power Doppler is similar to the color flow images except the flow patterns are based on the amplitude or power of the Doppler shift signals.**
4. **Tissue Doppler shows tissue motion such as the cardiac wall movements .**

Example of Color and Spectral Doppler Ultrasound

- The left panel shows color Doppler of umbilical circulation.
- Flow to the transducer is shown in red and away in blue.
- The cursor line indicates the beam path.
- The Doppler sample volume (oblique arrow) shows the sampling site for pulsed Doppler interrogation.
- The right panel shows spectral Doppler of umbilical artery flow. As the flow is toward the transducer, it is depicted as positive or upward deflections.



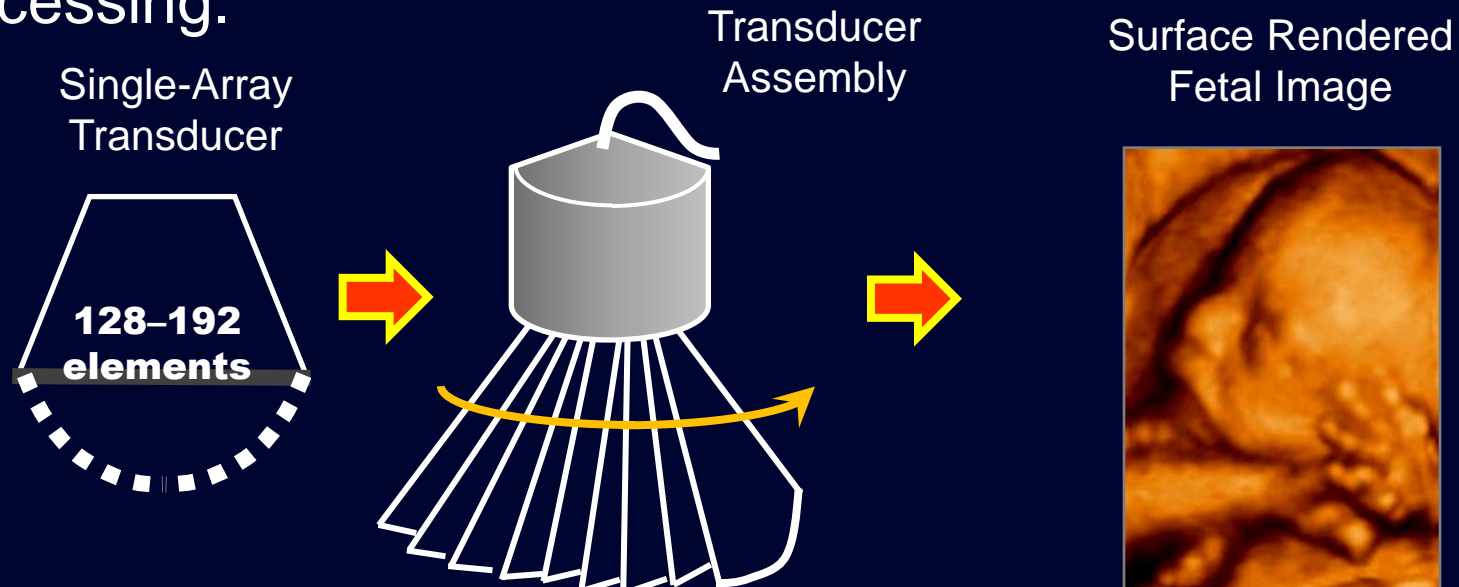
Umbilical artery Doppler waves

Three- and 4-Dimensional Sonography

- **Three dimensional (3D) ultrasound depicts ultrasound images in the 3D planes along the x, y, and z axes (Cartesian).**
- **The display unit for a 3D ultrasound image is a voxel (see the figure).**
- **The process involves 3D acquisition, processing, and display.**
- **3D ultrasound in real time constitutes 4D ultrasound.**
- **There are 2 approaches to 3D/4D ultrasound imaging:**
 - **Reconstruction out of sequential 2D images**
 - **3D imaging in real time using a 3D ultrasound beam**

Reconstructed 3D Ultrasound

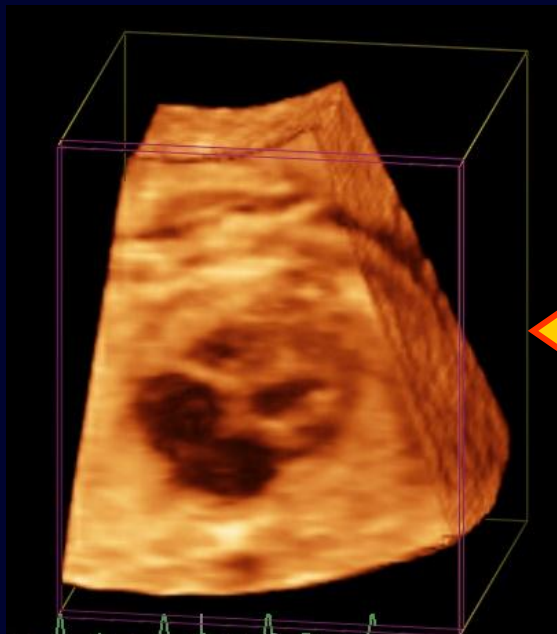
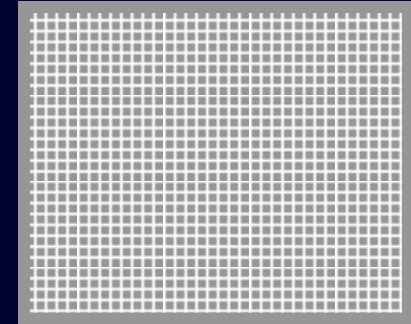
- Three-dimensional images are reconstructed from a series of 2D images.
- Uni-dimensional array transducers with a motor drive for transducer sweep are used to acquire 3D volume information.
- Subsequent image processing produces surface-rendered 3D fetal images.
- A fetal cardiac image can also be obtained by special processing.



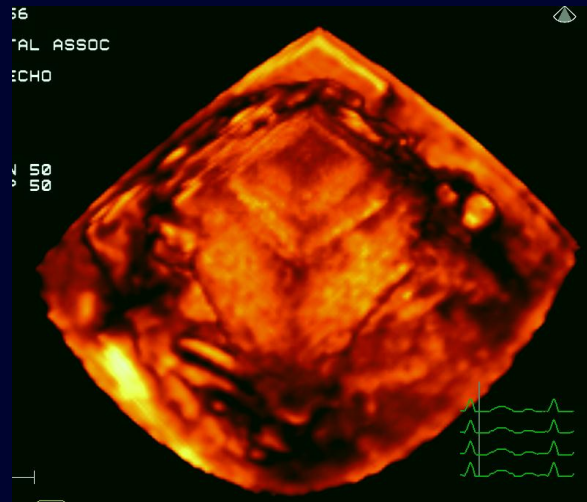
Real-Time 3D/4D Ultrasound

- 2D phased array transducers with 2-3000 piezoelectric elements arranged in columns and rows.
- Generates a pyramidal pulse of ultrasound to create 3D images in real time.

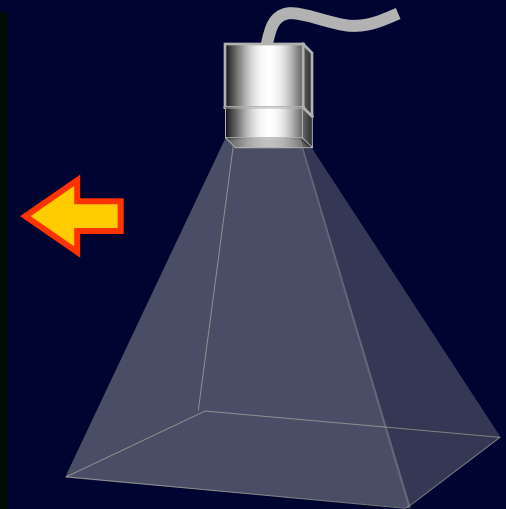
2D Array



4D Fetal Cardiac Image



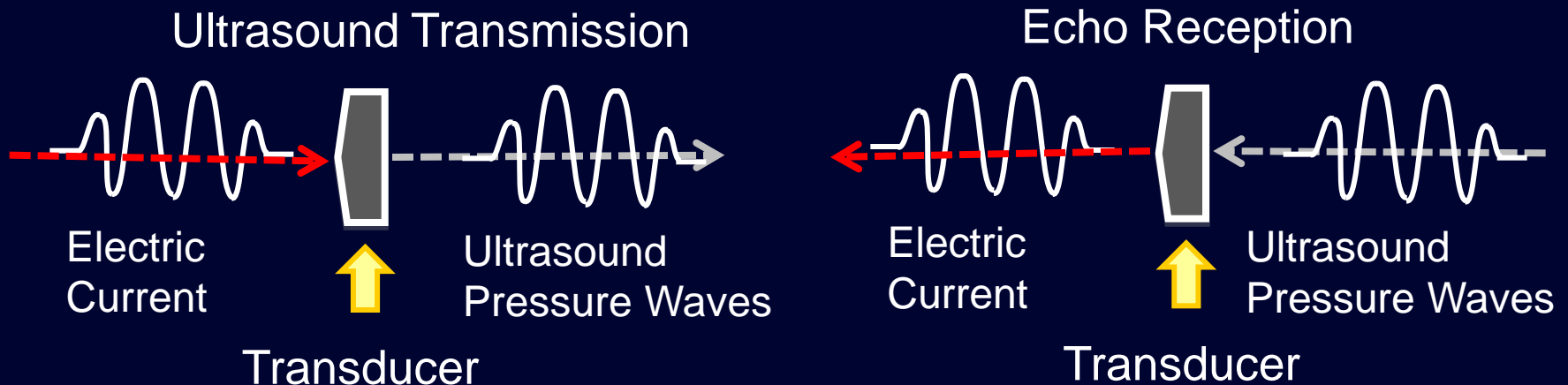
3D Image Data Set



Ultrasound: The Basics
Diagnostic Ultrasound
Instrumentation

Piezoelectric Effect and Transducers

- Certain materials when exposed to an electrical field undergo physical distortion and generate pressure waves.
- Conversely, changes in the mechanical pressure on these materials will lead to a polarity change and electrical voltage generation. This is called the *piezoelectric effect*.
- The piezoelectric effect allows conversion of electric current to ultrasound and reconversion of the returning echoes to electricity. This forms the basis for ultrasound transducers.



Electronic Array Transducers

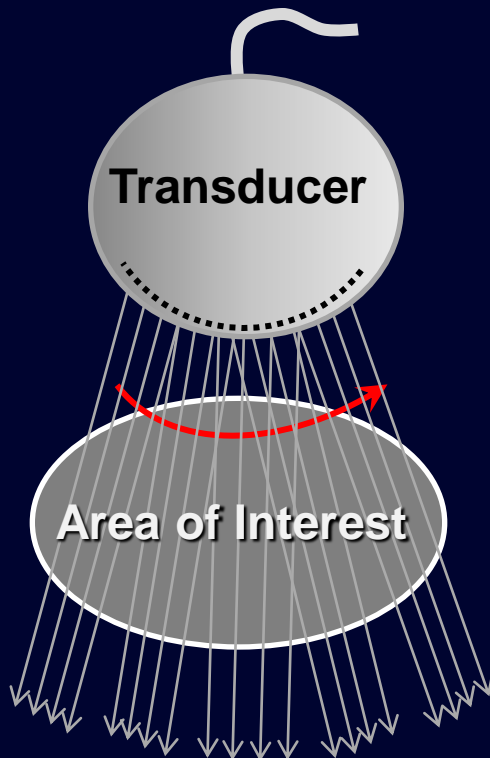
- **These transducers are used for real-time B-mode imaging.**
- **In electronic array transducers, excitation of the adjacently arranged piezoelectric elements generates the ultrasound beam.**
- **The beam automatically sweeps across the target area and generates the image.**

Electronic Array Transducers

- There are 4 types of arrangements of the elements:
 - Linear
 - Curved or curvilinear
 - Annular
 - 2D matrix
- There are 2 basic types of electronic array transducers depending on their mechanism of beam generation and scanning:
 - Sequential array
 - Phased array

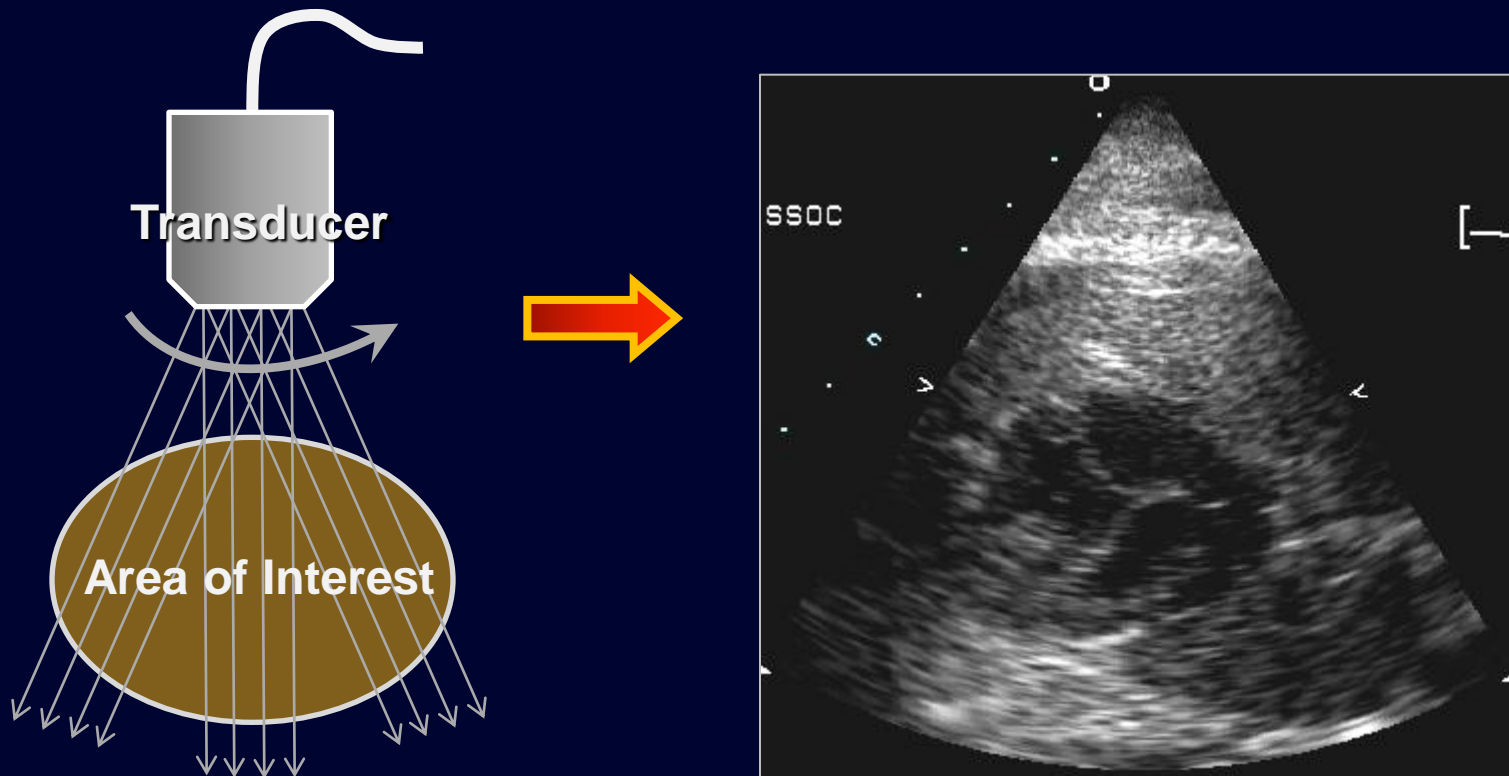
Sequential Array Transducer

- In this system, the transducer elements are arranged in a line, which can be straight or curved.
- The elements are sequentially activated in groups sweeping the target area to generate the image, and the process is automatically repeated.



Phased Array Transducers

In this system, all the elements are activated simultaneously, and the beam is electronically steered by a precise delay in the activation sequence to sweep the target area to generate the image. The process is automatically repeated.

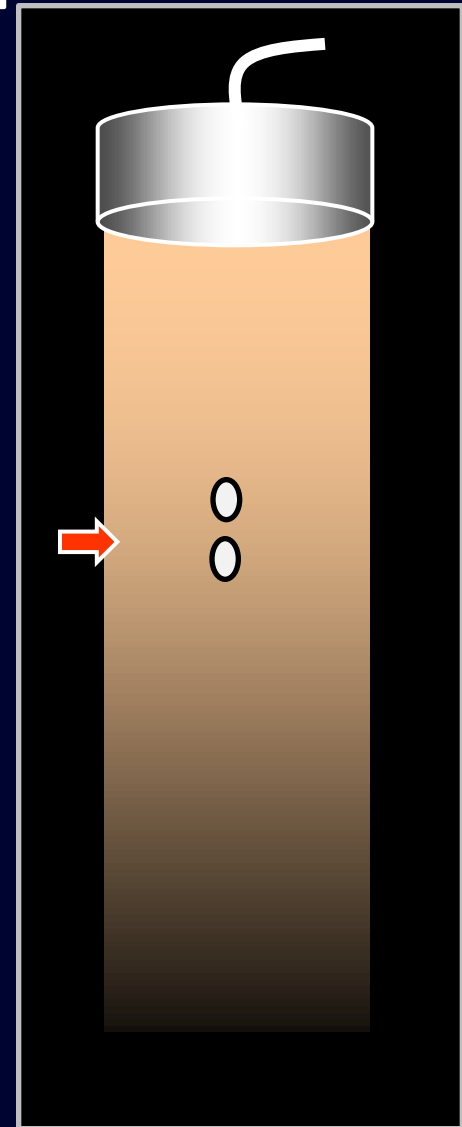


Ultrasound Image Resolution

- Resolution is of 2 types: spatial and temporal.
- Spatial resolution is the ability to separate reflectors in space. This is also known as the detailed resolution.
- Spatial resolution is of 2 types: axial and lateral
- Temporal resolution is the ability to separate events in time as in cardiac cycle.

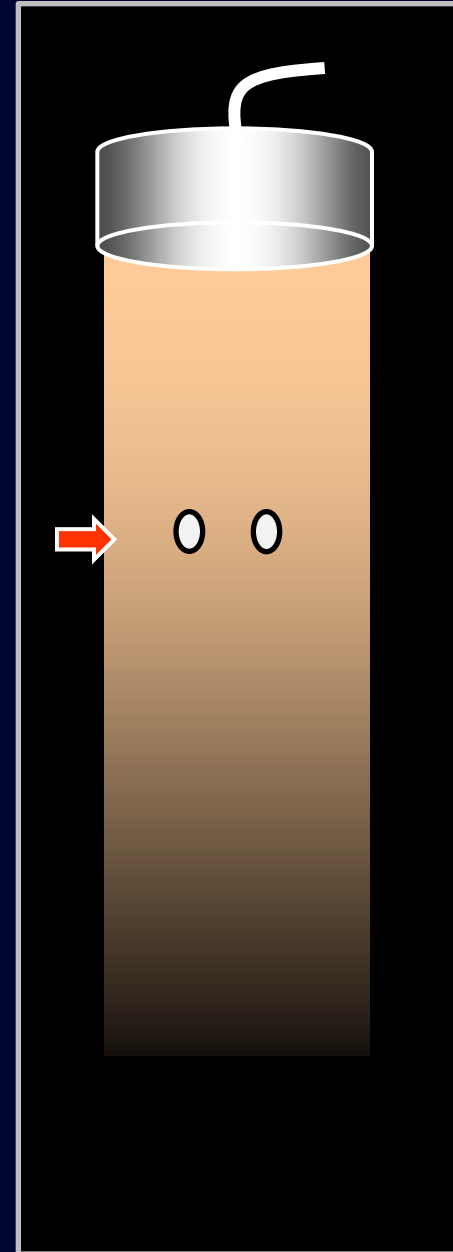
Ultrasound Image Resolution

- Axial resolution is the minimal distance between 2 reflectors at which their echoes can be distinctly seen along the ultrasound scan lines.
- Axial resolution improves with higher transducer frequencies.



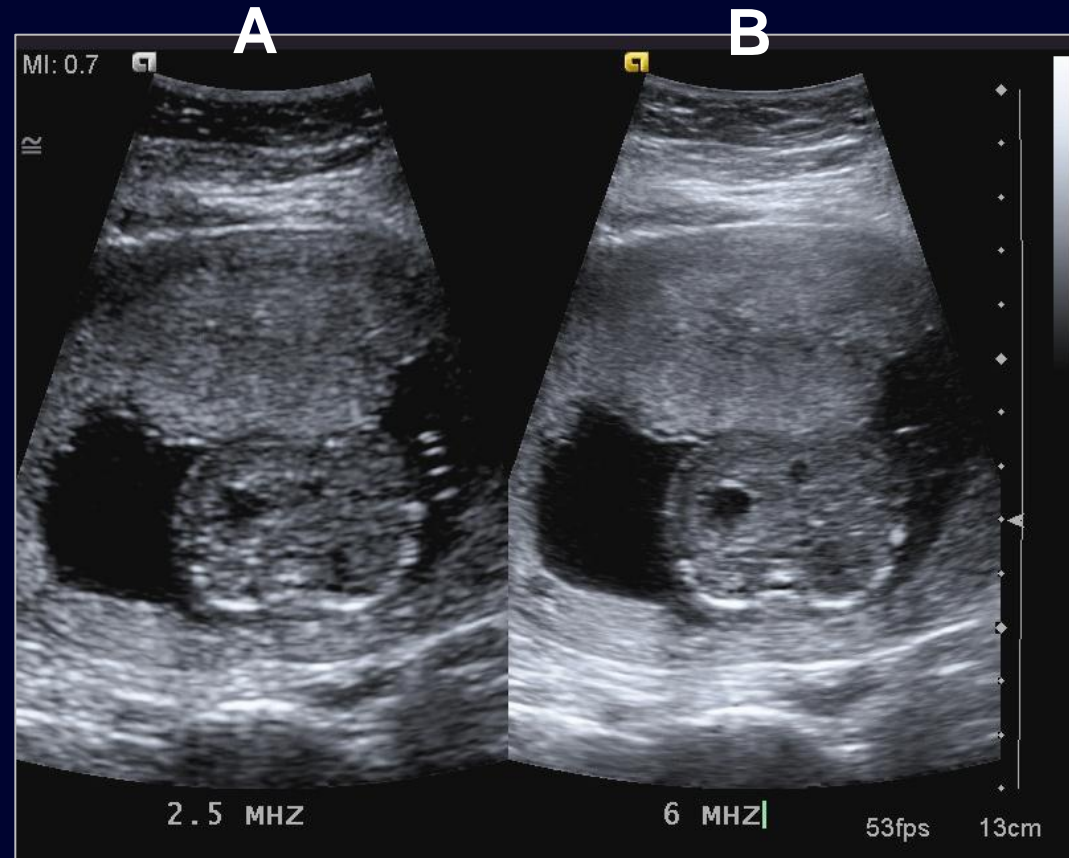
Ultrasound Image Resolution

- Lateral resolution is the minimal distance between 2 reflectors at which their echoes can be distinctly seen perpendicular to the ultrasound scan lines.
- Lateral resolution depends on the beam diameter. A narrower beam improves lateral resolution.
- Lateral resolution is best at the focal zone.

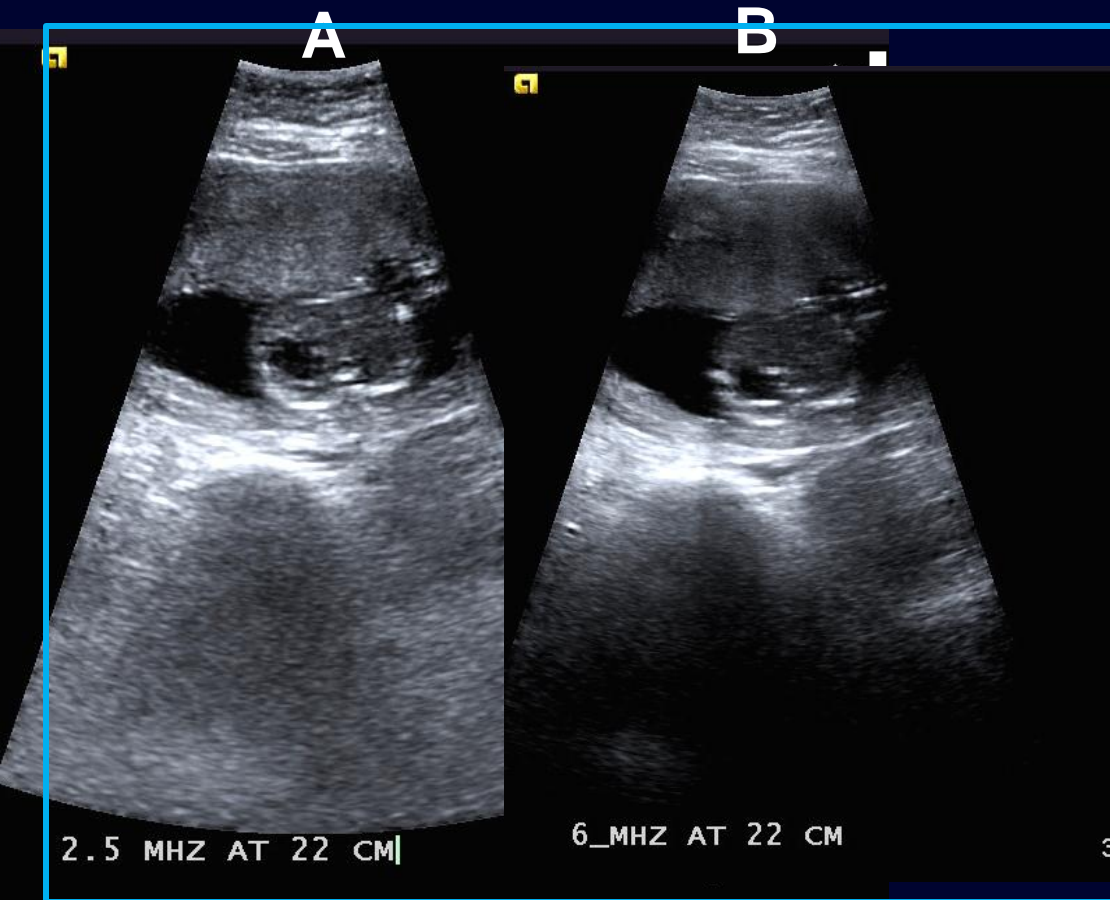


Transducer Frequency and Spatial Resolution

- The higher the frequency, the better the axial resolution. This is exemplified in these images.
- Both images are from the same area.
- Image A is taken with a 2.5-MHz transducer.
- Image B is taken with a 6-MHz transducer and demonstrates higher detail resolution.



Transducer Frequency and Depth



- The higher the frequency, the lower the depth penetration by the ultrasound beam.
- Image A is taken with a 2.5-MHz transducer.
- Image B is taken with a 6-MHz transducer and shows much less depth of image.

Gain Control

- Gain control allows increasing the intensities or brightness of the image.
- There are 2 types of gain control:
 - Total or main gain
 - Time gain compensation
- Total gain control amplifies the image intensity at all depths. Examples are shown in figures A, B, and C:
 - A shows highly suppressed gain.
 - B shows very high gain.
 - C shows appropriate gain.
- Time gain compensation is discussed in the next slide.



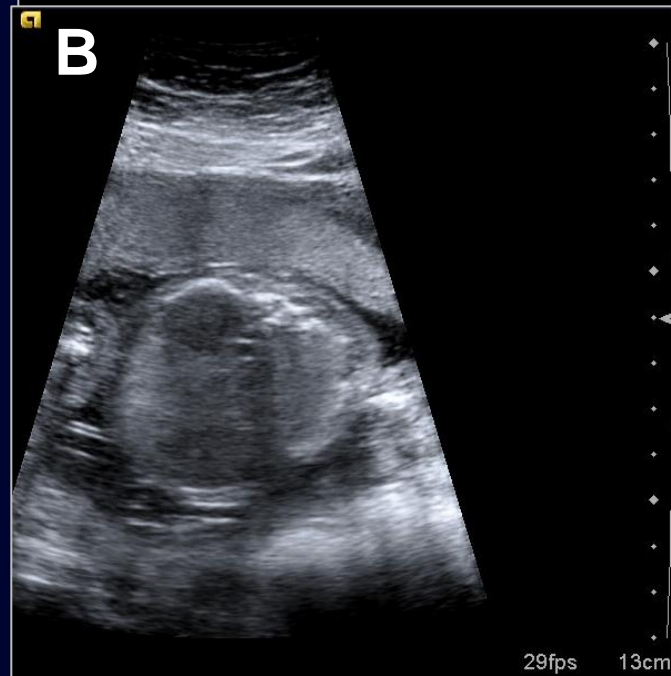
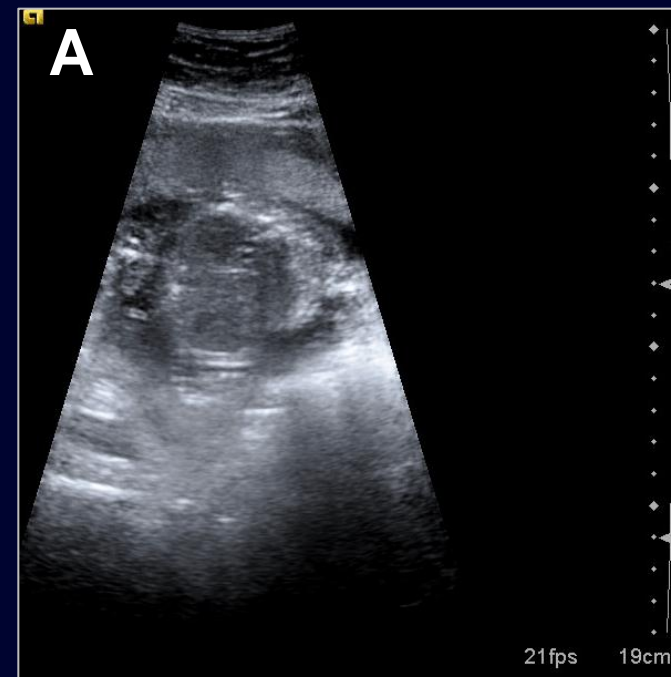
Time Gain Compensation



- This allows manually adjusting the gain can selectively at different depths.
- Multiple separate depth adjustment controls are available on the device control panel.
- This is used to compensate for strong attenuation or enhancement in image areas.
- An example is given in the figure showing the TGC indicator line (white arrows) and uniform appropriate image intensity.

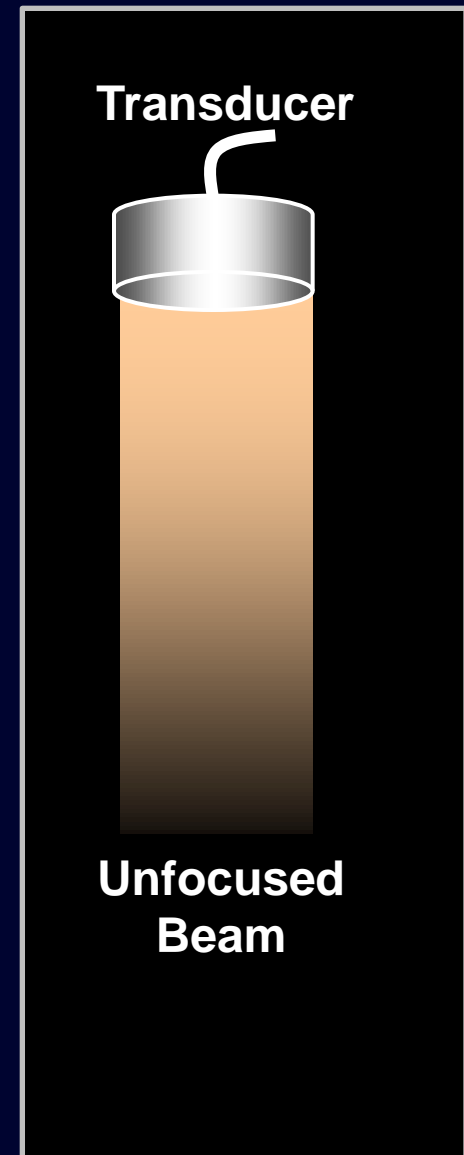
Depth Control

- This control allows adjusting the depth from which images can be obtained.
- The transducer frequency limits the depth. The lower the frequency, the greater the depth of imaging.
- The depth control can be used to enlarge the image size. The depth of image A on the right is 19 cm. Reducing the depth to 13 cm substantially increases the target image in B.



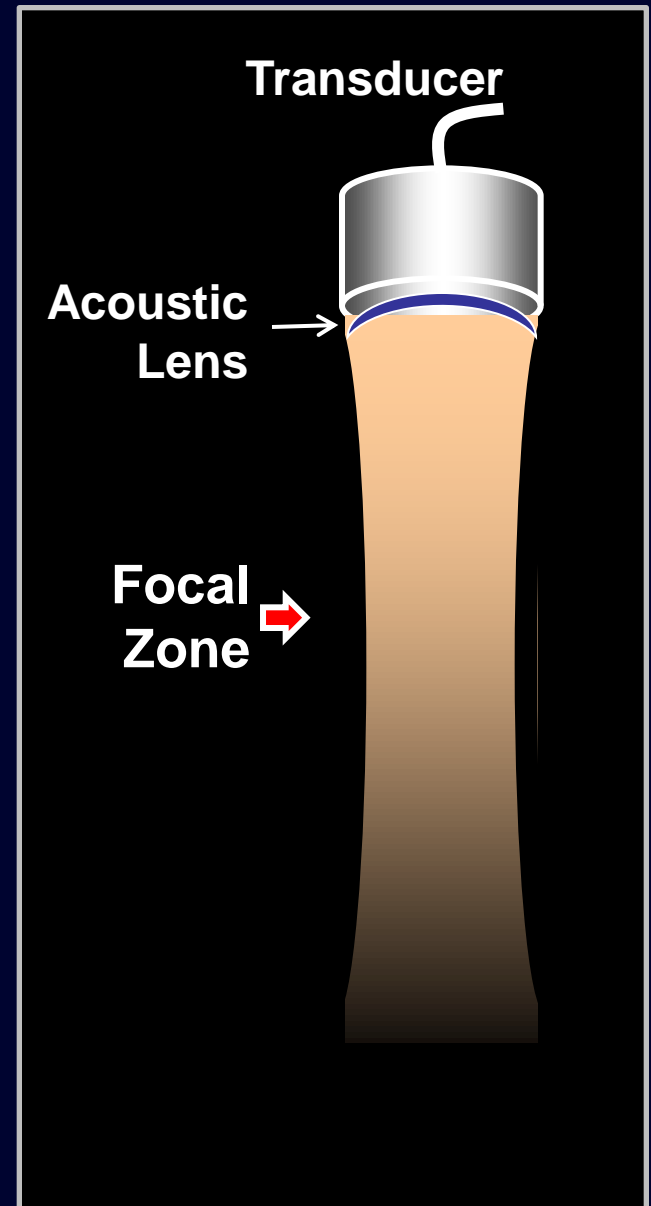
Focusing

- The ultrasound beam is formed by the simultaneous triggering of a group of elements; the beam wavefront is parallel to the array of transducer elements, and the beam is unfocused in the image plane.
- The ultrasound beam can be adjusted to be focused at a particular depth.
- Focusing allows improved lateral image resolution.
- Simultaneous focusing at many levels slows the frame rate.
- The ultrasound beam is focused by an acoustic lens or electronic focusing.



Focusing by an Acoustic Lens

- An acoustic lens is formed of special polymer or resin material that transmits ultrasound faster than soft tissue.
- The lens is concave, which allows peripheral wavelets to travel faster than the central ones, thus forming a concave wavefront.
- This leads to a focused beam over an area or zone.



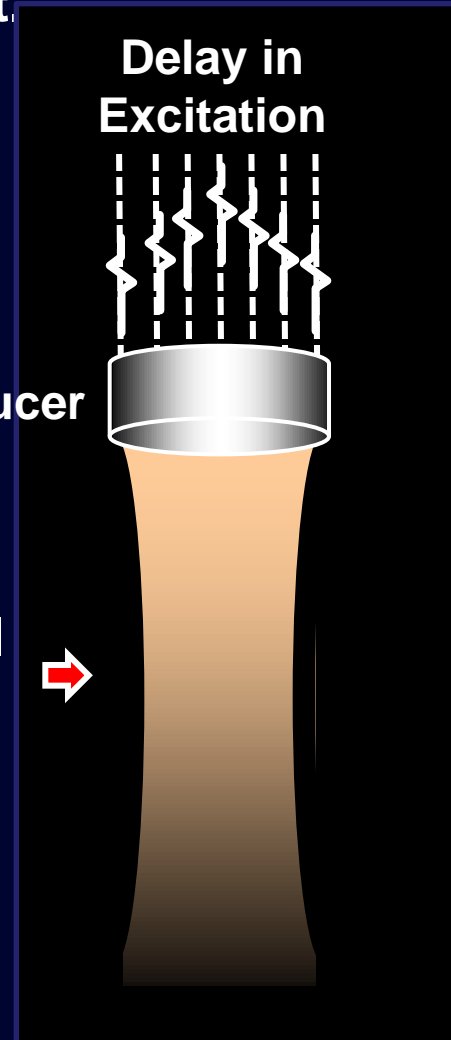
Focusing by an Electronic Array

- An electronic array focuses the beam in the image plane by controlled delay in excitation pulses to the transducer elements producing a concave wavefront.
- Focusing can also be done by delay in receiving the echoes.
- The user can control electronic focusing.



Transducer

Focal
Zone



Conclusions: 1

- **Sound is mechanical energy and propagates in waves.**
- **Frequency, amplitude, reflection, and attenuation are some of the important considerations for its diagnostic use.**
- **Transducers are based on the piezoelectric phenomenon that allows interconversion of electrical and mechanical energies.**

Conclusions: 2

- **Most current transducers use electronic control of transducer elements to generate images.**
- **Diagnostic ultrasound operates in several modes, including B and Doppler modes.**
- **Working knowledge of ultrasound imaging devices is essential for optimal utilization of this technology.**

Recommended Bibliography

- **Kremkau F, et al. Diagnostic Ultrasound: Principles and Instruments. 7th ed. Elsevier Science; 2005.**
- **Maulik D, Zalud I. Doppler Ultrasound in Obstetrics and Gynecology. 2nd ed. Springer; 2005:chapters 2-5.**