Handout # 8 Ultrasound

8.1 Fundamentals

(1) Concept

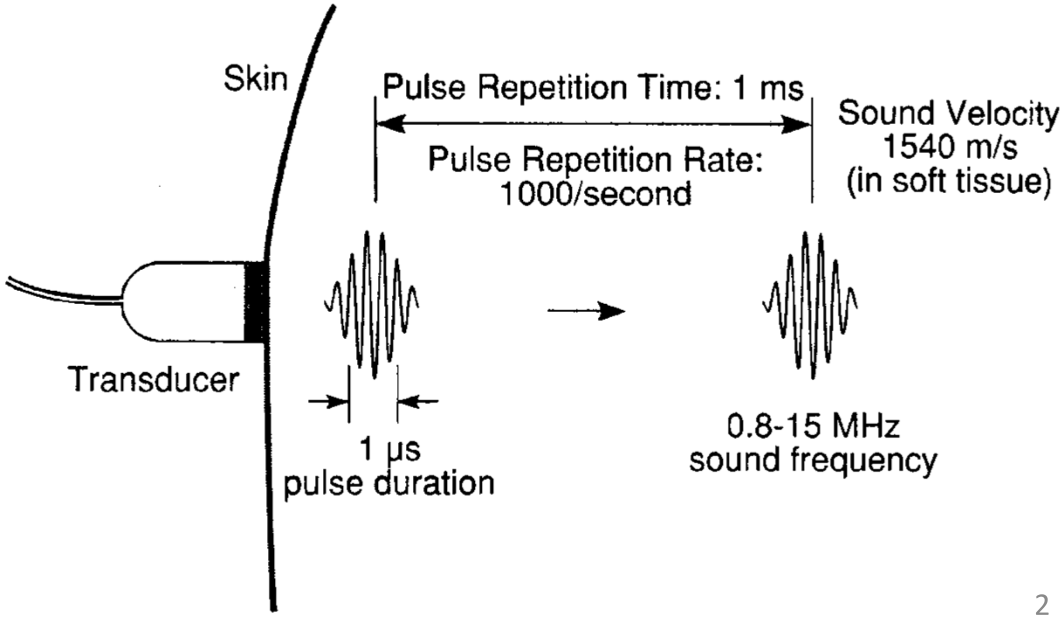
Audible sounds: 20Hz to 20KHz

Clinical ultrasound: 0.8 ~ 15 MHz

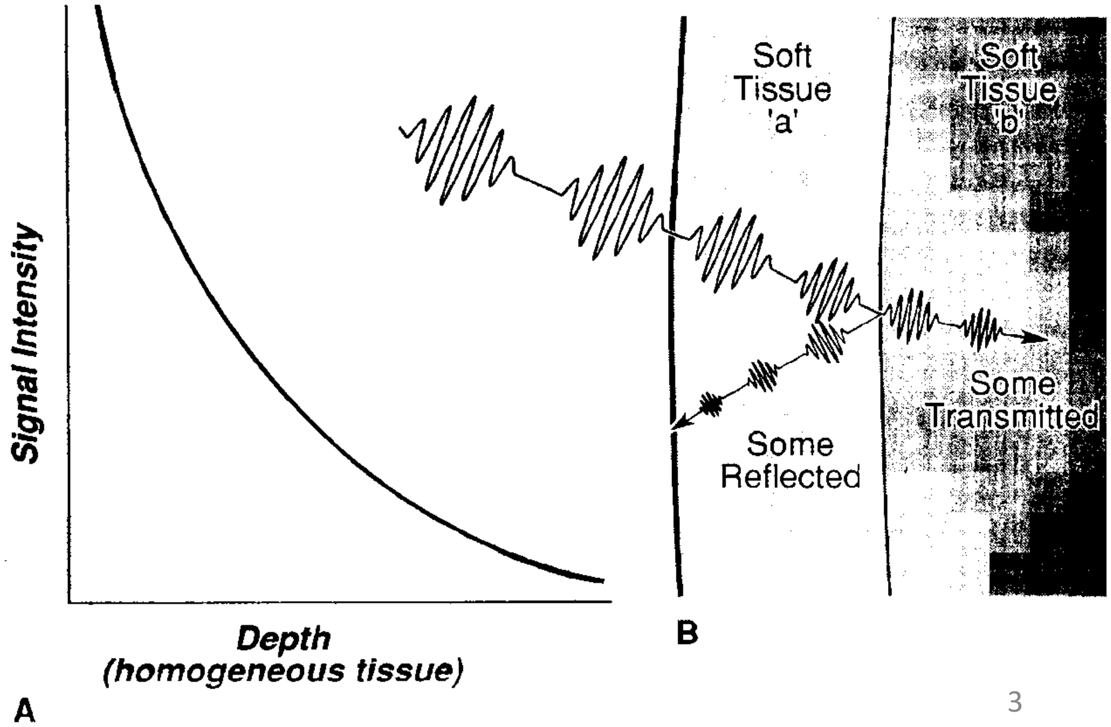
- **Sound** is mechanical energy that propagates through medium, is absorbed by medium; undergoes refraction and reflection at an interface between two different media.
- **Ultrasound** is the term that describes sound waves of frequencies exceeding the range of human hearing and their propagation in a medium.
- **Medical diagnostic ultrasound** is a modality that uses ultrasound energy and the acoustic properties of the body to produce an image from stationary and moving tissues.

(2) Working principle of medical diagnostic ultrasound

- ❖ The pulse generator and transmitter produce a train of short, identical pulses of high frequency electrical voltage oscillations.
- ❖ A **transducer** transforms the electronic signal into brief pulses of mechanical vibrations.
- ❖ The **transducer** is pressed against the patient's body, acoustically coupled to it by means of a suitable coupling medium such as mineral oil.
- ❖ The **pulses** of ultrasound energy can then enter the body, with relatively little reflection at the skin.
- ❖ The **intensity** of a ultrasound pulse is attenuated exponentially when passing through homogeneous medium---no echo is produced.



- What is of clinical significance is that a **reflection** will occur at a sharp boundary between two body tissues with sufficiently different acoustic properties--**an echo** is produced.
- The **lapse of time** until detection of the echo is proportional to the depth within the patient to the tissue interface.
- The **intensity of the echo signal** increase with the degree of **physical difference** (in **compressibility** and **density,** primarily) between the two tissues.
- **Echo signal strength** also depends on **the depth of the interface within the patient**, but ultrasound imaging systems have ways to compensate from much of that dependence.



- The echoes created in the body from a set of ultrasound pulses are detected by the **same transducer**, where they are transformed back into electrical signal.
- As the transducer **sweeps** the ultrasound beam back and forth within the patient's body, the computer keeps track of its relative position and orientation at any instant and of the return times and the amplitudes of the various echo signals, and from this information it creates an image.

8.2 Characteristics of Sound

(1) Wavelength, frequency and speed of sound

$$c = \lambda f$$

where:

c (m/s): is the speed of sound in the medium -- it is strongly **dependent** on the propagation medium and varies widely in different material.

f (Hz): is the frequency of sound -- it is basically a constant for different medium (f is **independent** of the medium). It is unaffected by changes in sound speed as the acoustic beam propagates through various media.

λ(m): is the wavelength. (The ultrasound wavelength λ is **dependent** on the medium.)

❖ The speeds of sound for a number of media of clinical interest are listed in the following table.

Speed of sound in some media

Medium	Speed, c (m/s)
Air	331
Water	1430
Sea Water	1510
Fat	1450
Soft Tissue	1540
Blood	1570
Muscle	1585
PZT (Transducer)	4000
Bone (skull)	4080
Metal	5000

Note again: The speed of sound **depends** on the nature of the medium through which it is traveling.

Example:

The speed of sound ***c*** in soft tissue is 1540 m/s:

A 2 MHz beam has a wavelength in soft tissue of:

$$\lambda = \frac{c}{f} = \frac{1540\ m/s}{2\times10^{6}\ /\ s} = 770\times10^{-6}(m) = 0.77mm$$

A 10 MHz ultrasound beam has a corresponding wavelength in soft tissue of:

$$\lambda = \frac{c}{f} = \frac{1540\ m/s}{10\times10^{6}\ /\ s} = 154\times10^{-6}(m) = 0.154mm$$

So, higher frequency sound has shorter wavelength.

Exercise:

A 5 MHz beam travels from soft tissue into fat. Please calculate the wavelength in each medium.

Solution:

The speed of sound in soft tissue is 1540 m/s, and in fat is 1450 m/s:

For 5 MHZ beam:

In soft tissue:

$$\lambda_{tissue} = \frac{c_{tissue}}{f} = \frac{1540\ m/s}{5 \times 10^6\ /\ s} = 308 \times 10^{-6}(m) = 0.308mm$$

In fat:

$$\lambda_{fat} = \frac{c_{fat}}{f} = \frac{1450\ m/s}{5 \times 10^6\ /\ s} = 290 \times 10^{-6}(m) = 0.29mm$$

(2) Intensity and dB scale

Intensity (I): The amount of power per unit area (W / m^2)

Relative intensity (dB):

$$dB = 10\log_{10}\left(\frac{I_1}{I_0}\right)$$

where:

I_0: Input intensity,

I_1: Output intensity.

Here the decibel (dB) serves as the **RELATIVE** (rather than absolute) measure for comparing the intensities of two signals.

Example:

The threshold of audibility of a 1000 Hz tone occurs at an intensity of about 10^{-12} W/m^2, and if a whisper is 10^{-10} W/m^2, the ratio of these two intensity values is:

$I_1 / I_0 = 100$, a whisper is 100 times louder than the threshold.

or

$$dB = 10\log_{10}\left(\frac{I_1}{I_0}\right) = 10\lg 100 = 20\,dB$$

So a whisper is 20 dB higher in intensity than the threshold of audibility.

(3) Interactions of ultrasound with matter

- As ultrasound energy propagates through a medium, interactions that occur include:
  - Reflection
  - Refraction
  - Attenuation (Tissue scatting and absorption)

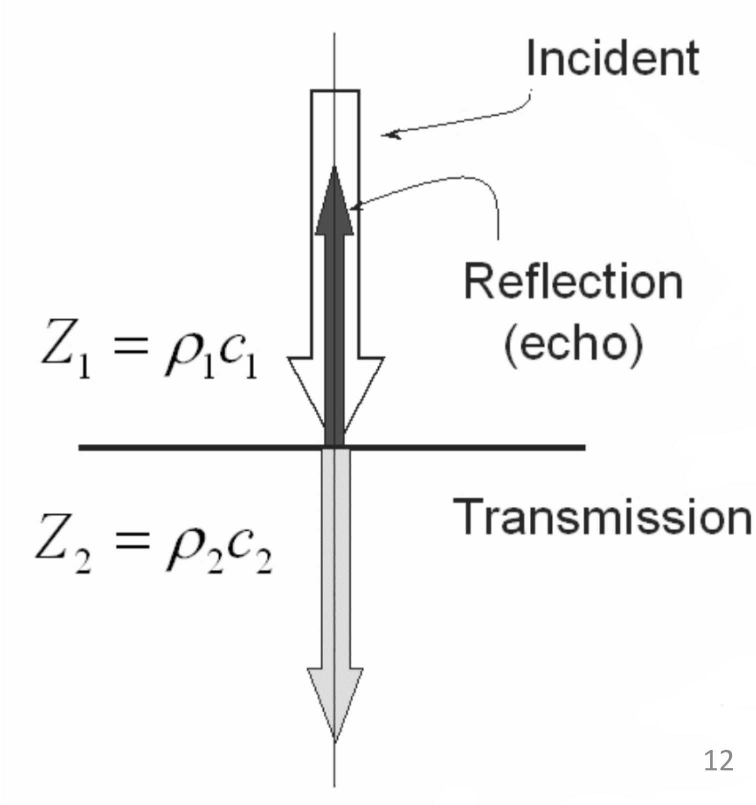
(a) **Reflection** of ultrasound at an interface between media with different **acoustic impedance**

❖ **Acoustic impedance** of a material is defined as:

$$Z = \rho \times c$$

where ρ is the density in kg/m^3, and c is the speed of sound in m/s, the SI unit for Z is $Kg/(m^2\ sec)$.

❖ **The reflection coefficient (R)** is the fraction of the energy or intensity of incoming ultrasound that is **reflected** at an interface.



For normal incidence, on a large and flat interface surface:

$$R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2$$

The rest, **T=1-R** is transmitted.

where **T is transmission coefficient**.

- Generally, only those waves that reflected back through about 180^0 can contribute to an ultrasound image (the same transducer is used to produce ultrasound and detect echo signal).

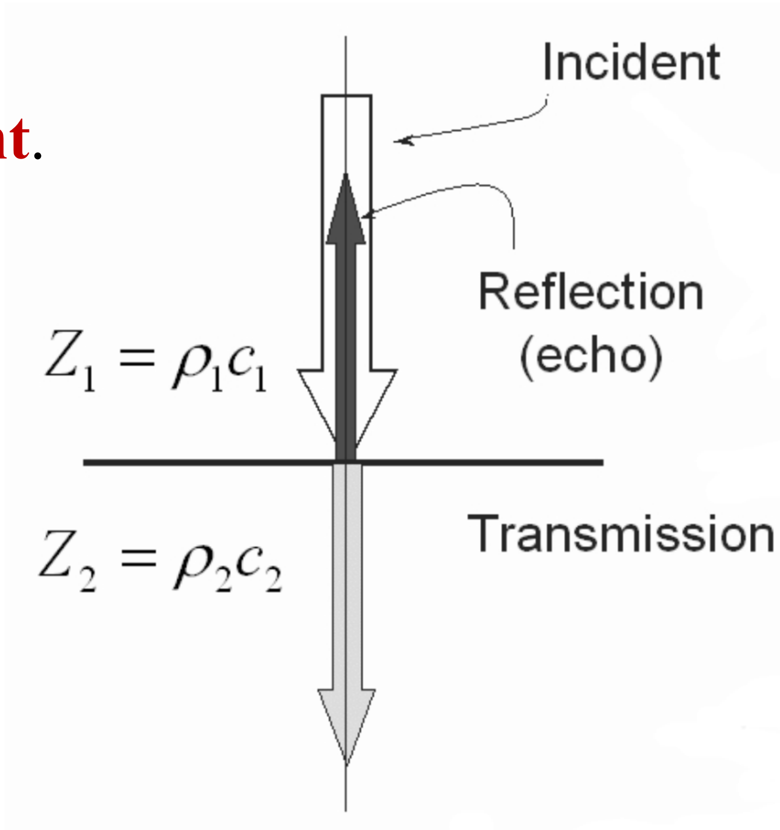


Table: Acoustic impedance $Z=\rho\times c$ for air, water and selected tissues

Tissue	**Z (kg/(m^2 sec)**
Air	0.0004×10^6
Lung	0.18×10^6
Fat	1.34×10^6
Water	1.48×10^6
Kidney	1.63×10^6
Blood	1.65×10^6
Liver	1.65×10^6
Muscle	1.71×10^6
Skull bone	7.8×10^6

Exercise:

Two media are with Z values of $Z_1=1.34\times10^6$ kg/(m^2 sec) and $Z_2=1.71\times10^6$ kg/(m^2 sec) respectively. For normal incidence, please determine the reflection coefficient *R* and transmission coefficient *T* of an ultrasound beam that are transmitted from one medium to another through the interface?

Solution: For normal incidence

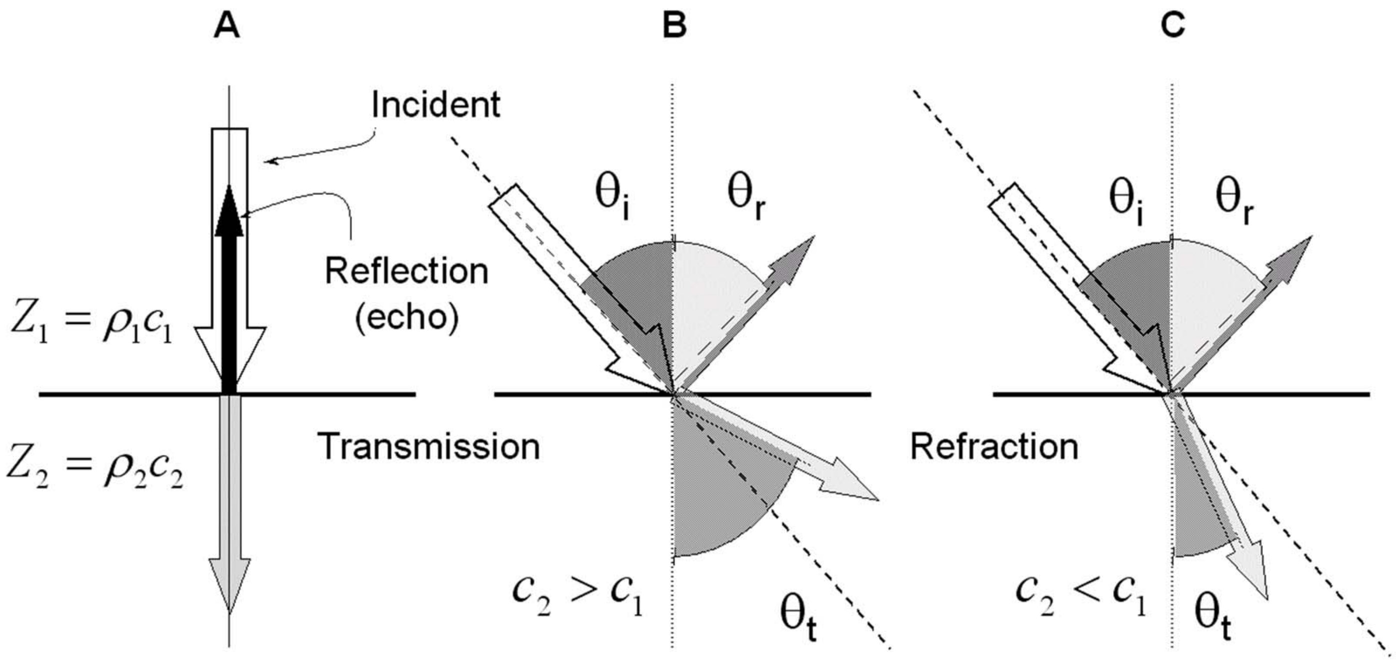
$$R = [(Z_2 - Z_1)/(Z_2 + Z_1)]^2$$
$$= (1.71\times10^6 - 1.34\times10^6)^2 / (1.71\times10^6 + 1.34\times10^6)^2$$
$$= 0.015=1.5\%$$

$$T=1 - R = 1 - 1.5\% = 98.5\%$$

(b) Refraction of ultrasound at an interface between media with different speed of sound.

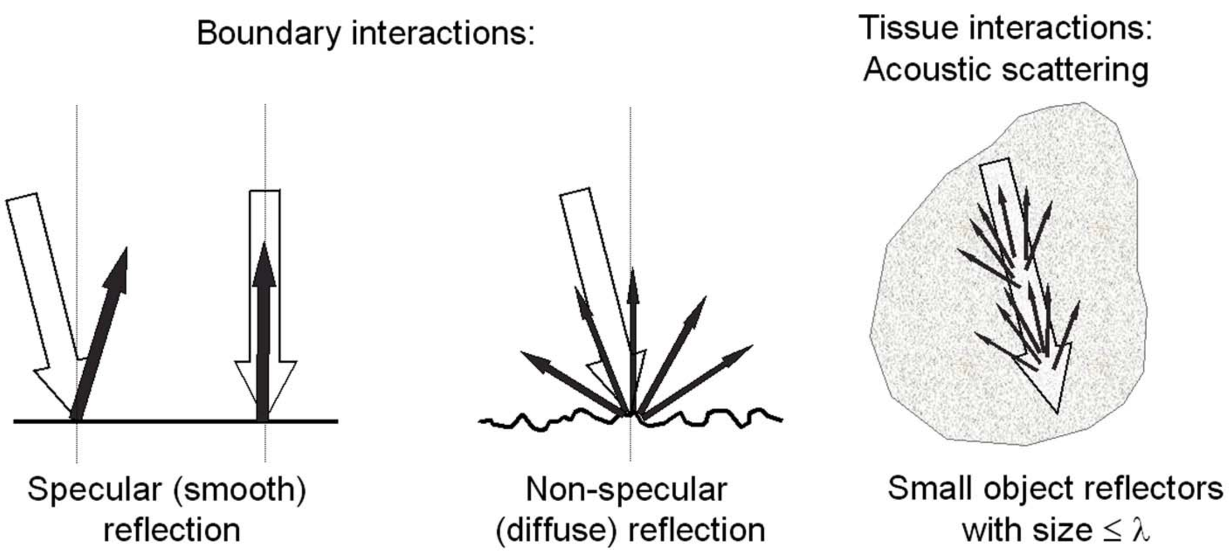
Snell's law: The angle of incidence θ_i is equal to the angle of reflection θ_r . The angle of transmission θ_t , however, is dependent on the propagation speed of the two materials:

$$\frac{\sin\theta_t}{\sin\theta_i} = \frac{c_2}{c_1}$$



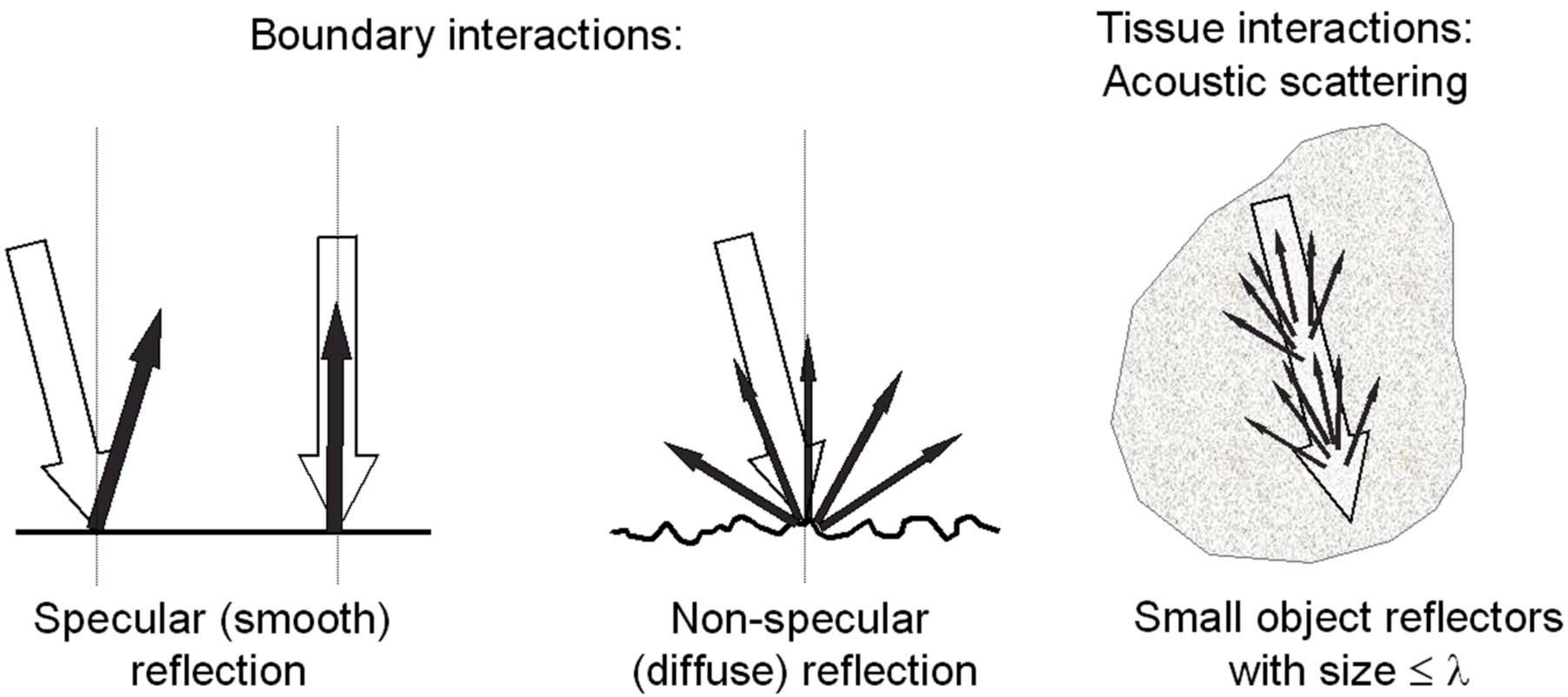
(c) Scattering

- ❖ Acoustic scattering arises from objects within a tissue that are about the size of the wavelength or smaller, and represent a rough or non-specular reflector surface.
- ❖ Most organs have a characteristic structure that gives rise to a defined scatter "signature" and provides much of the diagnostic information contained in the ultrasound image.
- ❖ Because non-specular reflectors reflect sound in all directions, the amplitudes of the returning echoes are significantly weaker than echoes from tissue boundaries.



❖ Fortunately, the dynamic range of the ultrasound receiver is sufficient to detect echo information over a wide range of amplitudes.

❖ Differences in scatter amplitude that occur from one region to another cause corresponding brightness changes on the ultrasound display.



(d) Absorption

Absorbed acoustic energy is converted to heat in the tissue.

(e) Attenuation: the loss of acoustic energy with distance traveled, is caused mainly by scattering and tissue absorption of the incident beam.

Exponential attenuation with depth in a homogeneous medium

$$I_1 = I_0 e^{-2\mu x}$$

where: μ (1/cm) is attenuation coefficient.

Recall: exponential attenuation with depth in a homogeneous medium:

$$I_1 = I_0 e^{-2\mu x}$$

It is a common practice to characterize attenuation of ultrasound in terms of decibels of intensity loss per **cm** of tissue (*dB/cm*),

$$\boldsymbol{dB} = (\boldsymbol{dB/cm}) \times \boldsymbol{x}$$

where $\boldsymbol{x}$ is the depth (thickness) of the tissue in cm

Relationship between μ and *dB/cm*:

$$dB = 10 \times \log_{10}\left(\frac{I_1}{I_0}\right) = 10 \times \log_{10}\left(e^{-2\mu x}\right)$$

$$= -20 \times \mu \times x \times \log_{10} e$$

$$= -8.686 \times \mu \times x$$

$$\therefore \quad dB/cm = dB/x = -8.686 \times \mu$$

where attenuation coefficient $\boldsymbol{\mu}$ is in 1/cm.

Exercise:

A 50 mW /cm^2 ultrasound beam have a 5 dB/cm overall intensity attenuation while traveling through soft tissue. Please determine the "output" intensity if the beam travels a total of 3cm through the homogeneous soft tissue.

Solution:

The input intensity I_0 is 50mW/cm^2, what is "output" intensity I_1?

The total loss in dB is: -5(dB/cm)×3(cm)=-15dB

$$-15dB = 10 \times \log_{10} \frac{I_1}{50mW/cm^2}$$

$$-1.5 = \log_{10} \frac{I_1}{50mW/cm^2}$$

$$10^{-1.5} = 10^{-3/2} = \frac{I_1}{50mW/cm^2}$$

$$I_1 = \frac{1}{\sqrt{1000}} \times 50mW/cm^2 = 1.58mW/cm^2$$

- Tissues and fluids have widely varying attenuation coefficients.
- Ultrasound attenuation expressed in ***dB/cm*** is approximately proportional to frequency.

Attenuation coefficients for selected tissues at 1 MHz

Medium	**Attenuation coefficients (1 MHz beam, dB/cm)**
Water	0.0002
Fat	0.5~1.8
Soft Tissue	0.3~0.8
Blood	0.18
Smooth Muscle	0.2~0.6

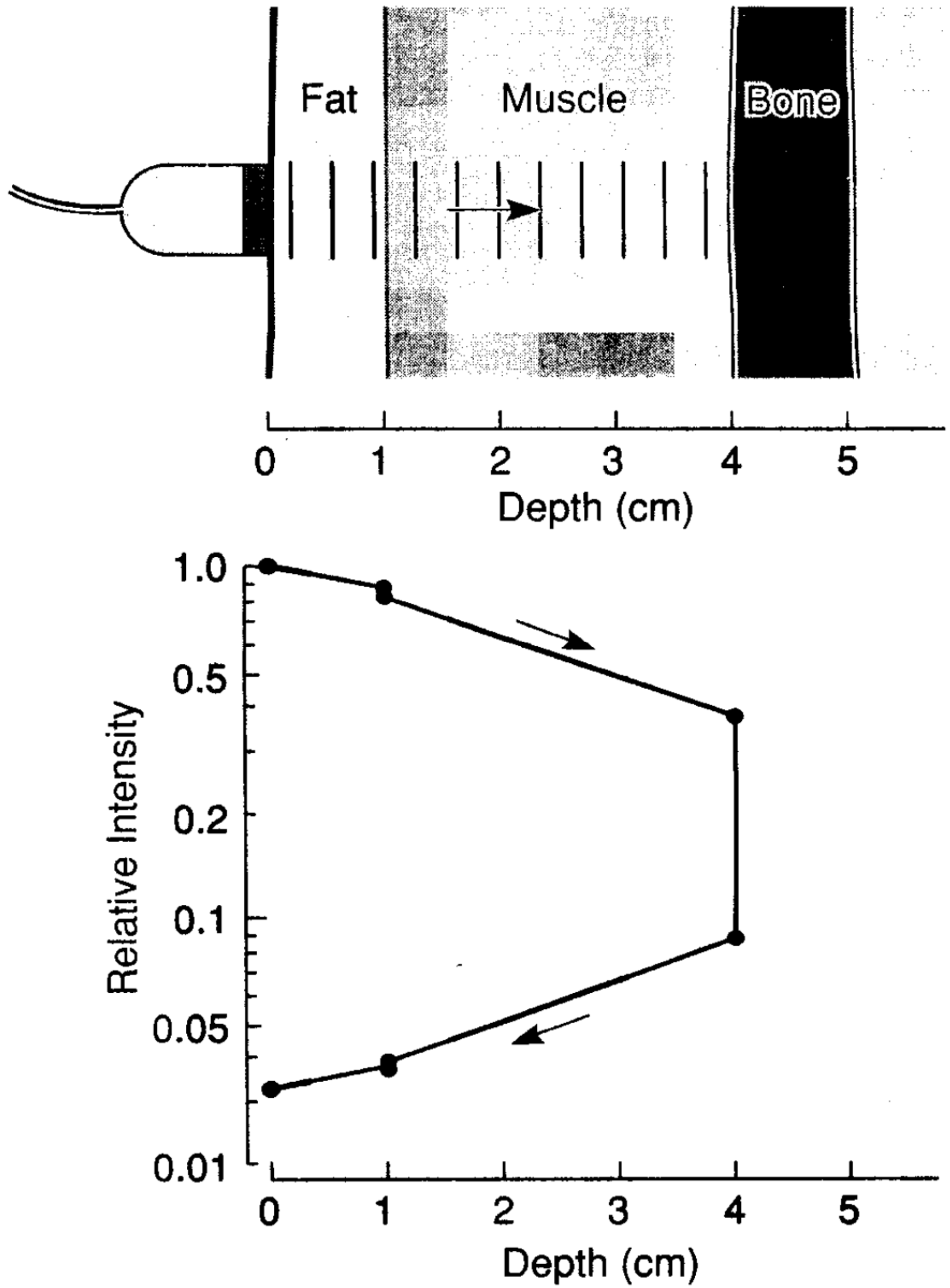
Example:

An approximate ultrasound attenuation in dB/cm for "soft tissue" is 0.5 dB per cm per MHz, or 0.5 (dB/cm)/MHz.

Thus, a 10 MHz ultrasound beam will have approximately ten times ultrasound attenuation of a 1 MHz beam per unit distance (dB/cm) for "soft tissue":

$$\left(\text{dB/cm}\right)_{10\,MHz} = \frac{0.5\,(\text{dB/cm})}{1\,MHz} \times 10\,MHz = 5\,(\text{dB/cm})$$

(f) Case study: Echoes from a bone embedded in tissue



Exercise:

To image a blood vessel beneath soft tissue, an ultrasound transducer receives an echo 20 μs after the signal is sent. What is the depth, *D*, of the tissue-vessel interface?

Solution:

$$2D = c \times \text{time}$$

The speed of sound c in soft tissue is 1540 m/s; time = 20 μs

$$D = c \times \text{time} / 2.$$

$$D = 1540 \text{ (m/s)} \times 20 \times 10^{-6} \text{ (s)} / 2 = 0.0154\text{m} = 15.4 \text{ mm}.$$

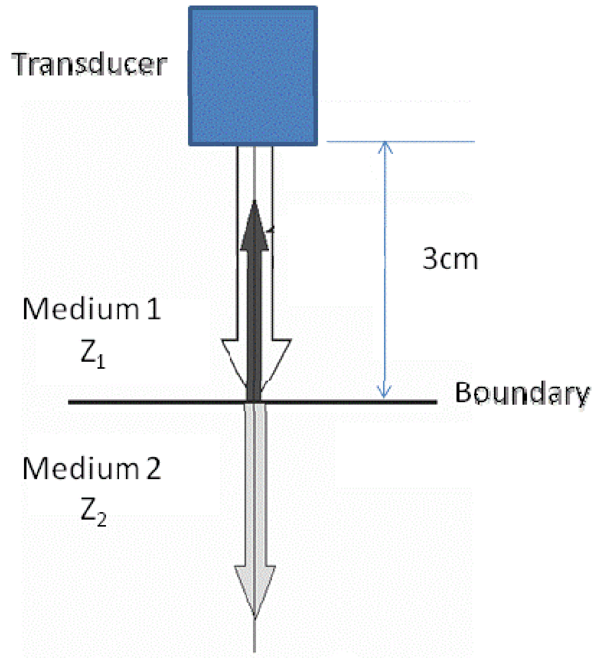
Exercise:

As shown by the figure, that medium 2 [acoustic impedance Z_2 is 1.71×10^6 kg/(m^2 sec)] is embedded by medium 1 [acoustic impedance Z_1 is 1.34×10^6 kg/(m^2 sec)].

A transducer emits an ultrasound beam of 2 MHz with an intensity of 16 mW/cm^2. Assume a 50% beam intensity transmittance when the beam enters the medium 1, and travels a distance of 3cm to reach normally on the flat boundary between medium 1 and medium 2. The ultrasound beam has a 0.5 dB/cm per MHz overall intensity attenuation while traveling through the medium 1.

(1) What is the intensity reaching the boundary?

(2) The same transducer is used to detect the ultrasound beam reflected from the boundary. What is the intensity to be received by the transducer?



Solution:

(1) The transducer emits an ultrasound beam with an intensity of $16\mathrm{mW/cm^2}$; the transmittance is 50% when the beam enters the medium 1:

$$I_0 = 16\mathrm{mW/cm^2} \times 50\% = 8\mathrm{mW/cm^2},$$

The 2 MHz ultrasound beam for 0.5dB/cm per MHz is:

$$-0.5\mathrm{dB/cm\ per\ MHz} \times 2\ \mathrm{MHz} = -1\ \mathrm{dB/cm}$$

Therefore, the intensity loss in dB when the ultrasound beam travels 3cm to reach a flat boundary of medium 1 & 2:

$$-1\mathrm{dB/cm} \times 3\mathrm{cm} = -3\ \mathrm{dB}$$

The incident intensity of ultrasound reaching the boundary is:

$$-3dB = 10\log_{10}\left(\frac{I_1}{I_0}\right)$$

$$\Rightarrow I_1 = I_0 \times 10^{-0.3} = 8 \times 10^{-0.3} = 4\left(\mathrm{mW/cm^2}\right)$$

(2) The reflected intensity from boundary can be calculated as:

$$R = \frac{I_2}{I_1} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 = \left(\frac{1.71\times10^6 - 1.34\times10^6}{1.71\times10^6 + 1.34\times10^6}\right)^2 = 1.5\%$$

$$\Rightarrow I_2 = I_1 \times 1.5\% = 4 \times 1.5\% = 0.06(mW/cm^2)$$

The intensity loss in dB when the ultrasound beam travels 3cm through medium 1 is:

-1 dB/cm × 3cm = -3 dB

$$-3dB = 10 \times \log_{10}\left(\frac{I_R}{I_2}\right)$$

$$\Rightarrow I_R = I_2 \times 10^{-0.3} = 0.06 \times 10^{-0.3} = 0.03(mW/cm^2)$$

Consider the 50% transmittance at the interface of medium 1 and the transduce, the ultrasound beam intensity received by the transducer is :

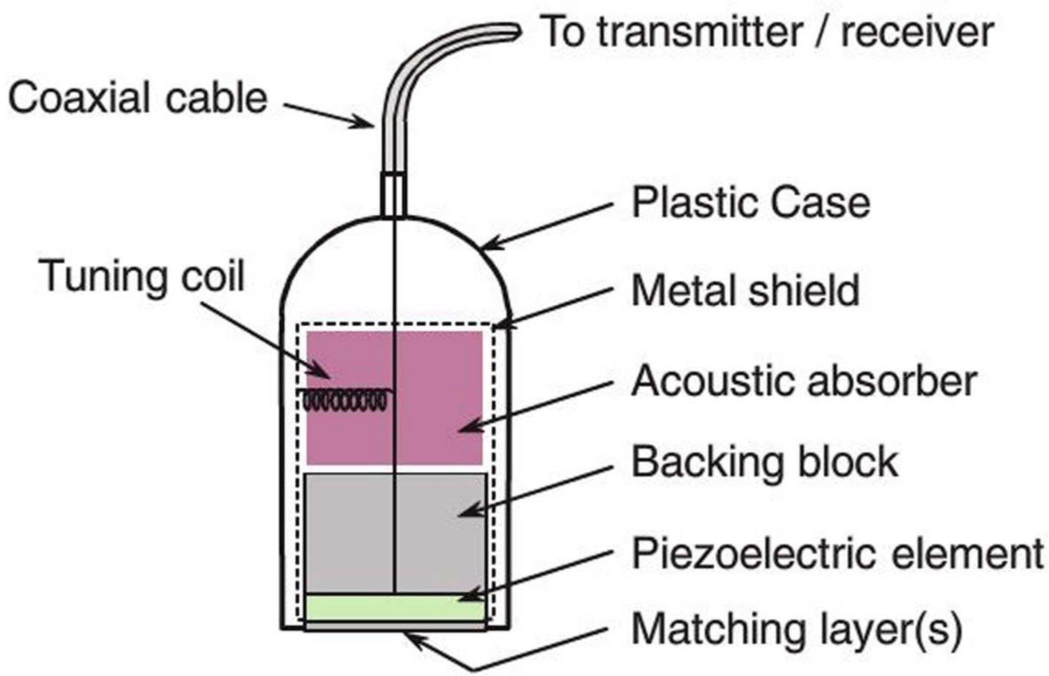
$$I_{transducer} = I_R \times 50\% = 0.03 \times 50\% = 0.015 \quad (mW/cm^2)$$

8.3 Transducer and Beam Characteristics

(1) Transducers

Ultrasound is produced and detected with a transducer, composed of one or more ceramic elements with electromechanical properties.

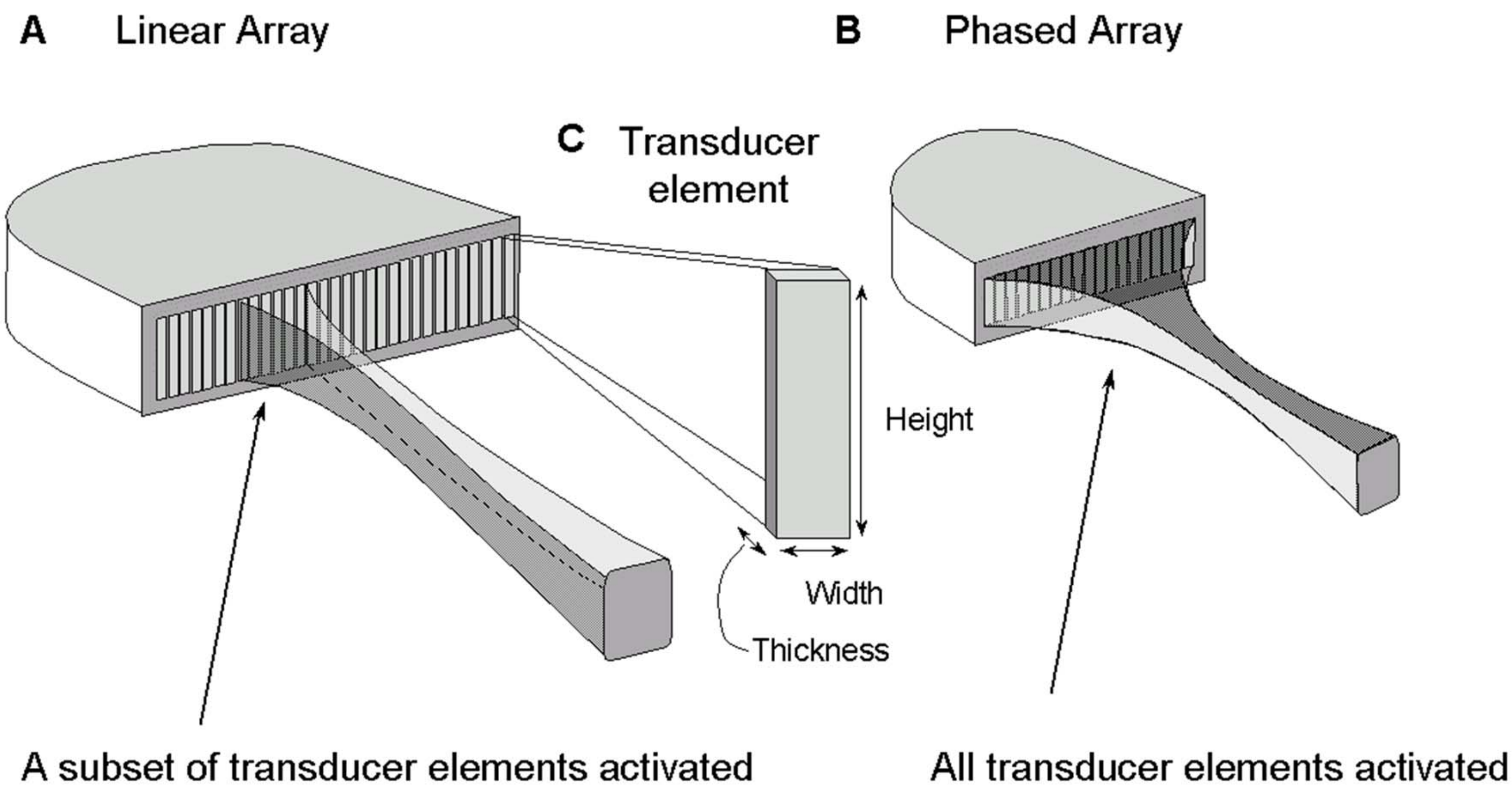
- The ceramic element converts electrical energy into mechanical energy to produce ultrasound and mechanical energy into electrical energy for ultrasound detection.
- A simple single element, plane piston source transducer is illustrated in following figure.
- Major components include the piezoelectric material, matching layer, backing block, acoustic absorber, insulating cover, sensor electrodes, and transducer housing.



(2) Transducer arrays

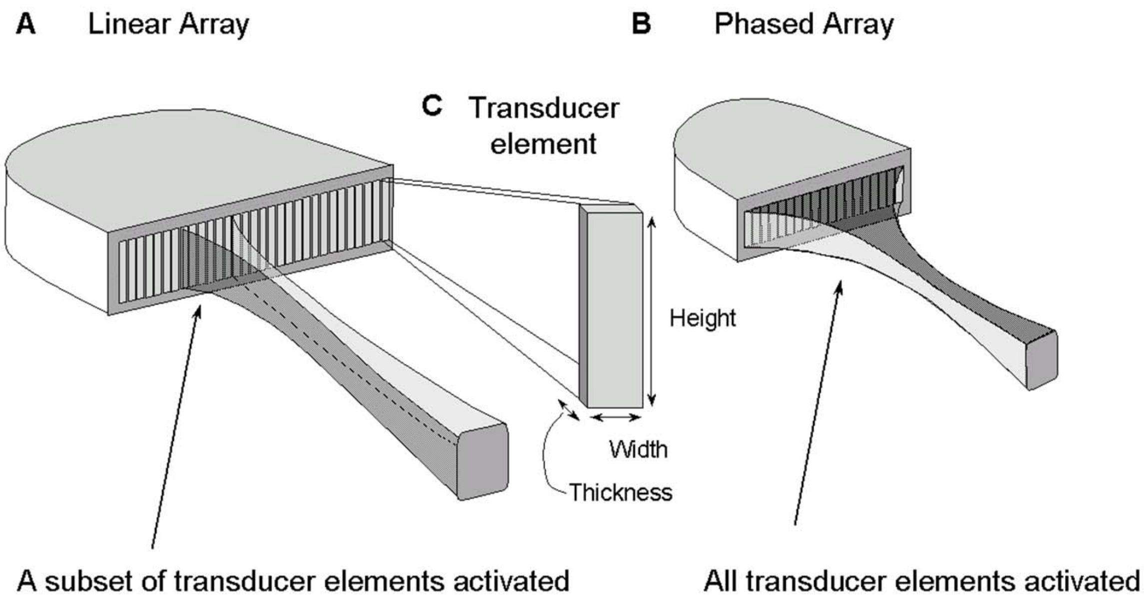
- ❖ The majority of ultrasound systems employ transducers with many individual rectangular piezoelectric elements arranged in linear or curvilinear arrays.
- ❖ Typically, 128 to 512 individual rectangular elements compose the transducer assembly.

- Two modes of activation are used to produce a beam.
- These are the "**linear**" (sequential) and "**phased**" activation/receive modes.



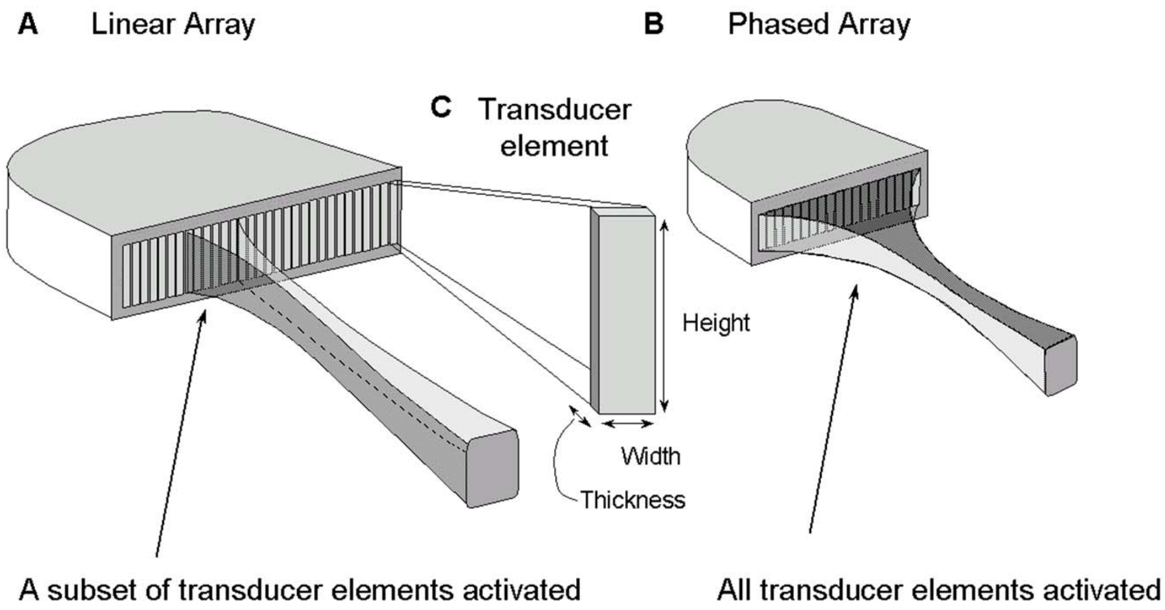
(a) Linear arrays

- ❖ Linear array transducers typically contain 256 to 512 elements; physically these are the largest transducer assemblies.
- ❖ In operation, the simultaneous firing of a small group of about 20 adjacent elements produces the ultrasound beam.
- ❖ The simultaneous activation produces a synthetic aperture (effective transducer width) defined by the number of active elements.
- ❖ Echoes are detected in the receive mode by acquiring signals from most of the transducer elements.
- ❖ A rectangular field of view is produced with this transducer arrangement.

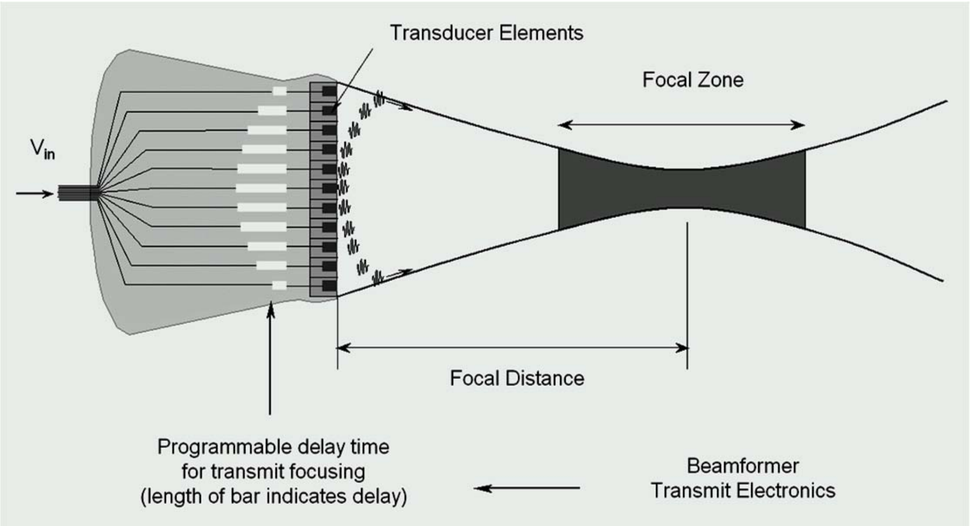


(b) Phased arrays

- ❖ A phased-array transducer is usually composed of 64 to 128 individual elements in a smaller package than a linear array transducer.
- ❖ All transducer elements are activated nearly (but not exactly) **simultaneously to produce a single ultrasound beam.**
- ❖ By using time delays in the electrical activation of the discrete elements across the face of the transducer, the ultrasound beam can be steered and focused electronically without moving the transducer.
- ❖ During ultrasound signal reception, all of the transducer elements **detect the returning echoes** from the beam path, and sophisticated algorithms synthesize the image from the detected data.



- A phased array transducer assembly uses all elements to produce the ultrasound beam.
- Focusing is achieved by implementing a programmable delay time (beam-former electronics) for the excitation of the individual transducer elements (focusing requires the outer elements in the array be energized first).
- Phase differences of the individual ultrasound pulses result in a minimum beam diameter (the focal distance) at a **predictable depth**.



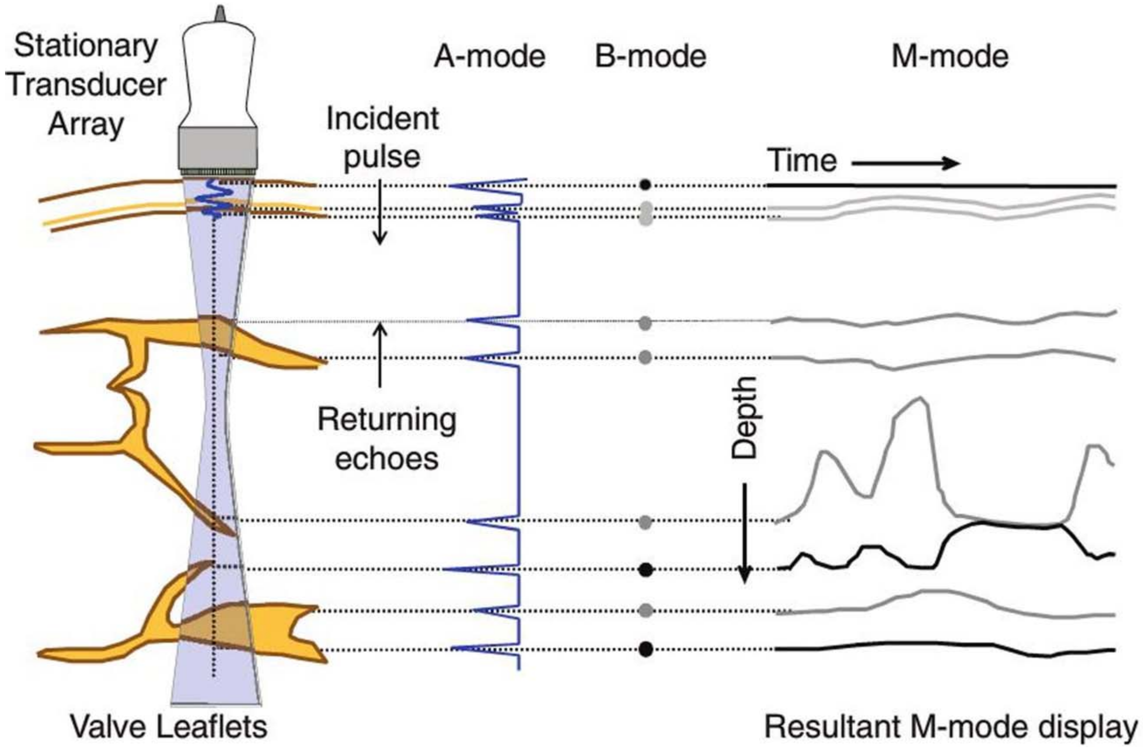
- In a phased array transducer, the echoes received by all of the individual transducer elements are summed together to **create the ultrasound signal from a given depth.**
- Echoes received at the edge of the element array travel a slightly longer distant than those received at the center of the array.

8.4 Echo Display Modes and Scan Convertor

An ultrasound transducer creates high frequency mechanical oscillations out of an electrical signal, and vice versa.

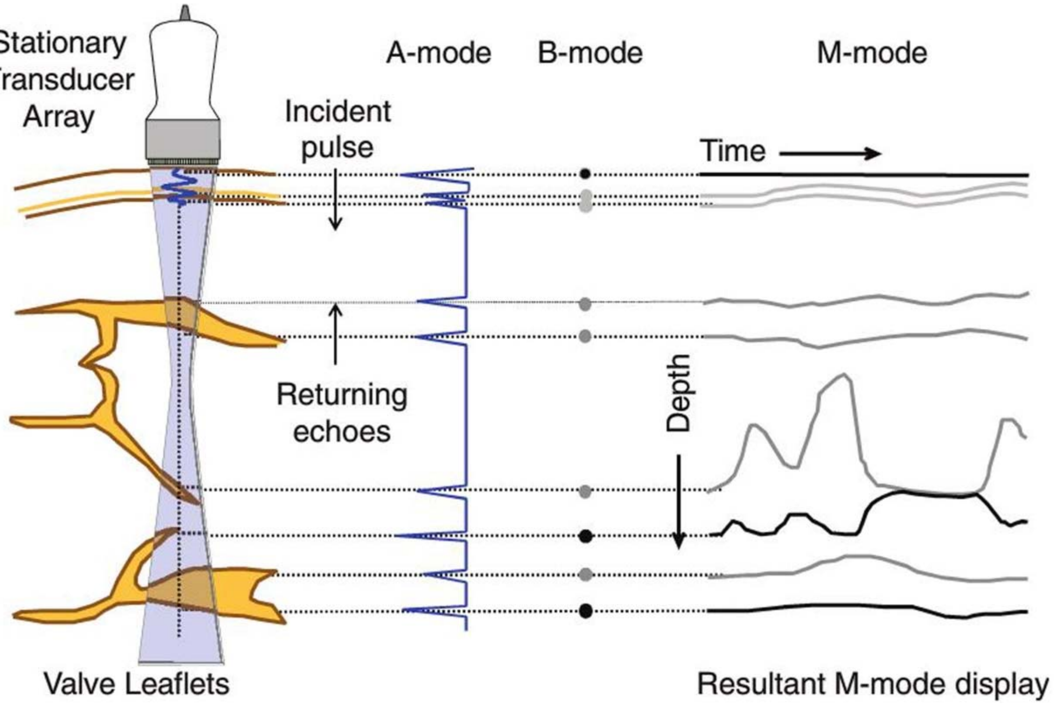
(1) A-mode

- ❖ **A-mode** (A for amplitude) is the display of the processed information from the receiver versus time.
- ❖ As echoes return from tissue boundaries and scatters (a function of the acoustic impedance differences in the tissues), a digital signal proportional to echo amplitude is produced as a function of time.
- ❖ One "**A-line**" of data per pulse repetition period is the result.



❖The depth of a tissue interface can be determined from the arrival time of an echo.

❖Signals are displayed along a line (of the depth of the tissue).

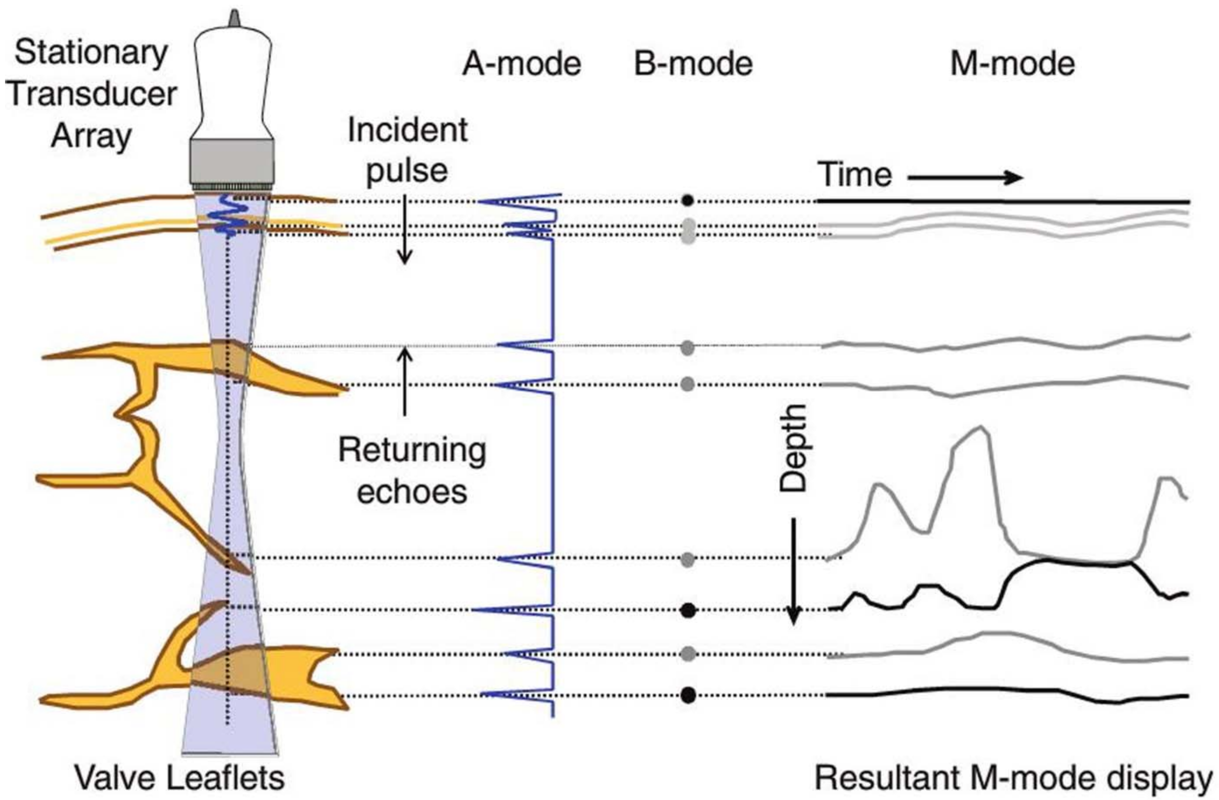


❖The earliest uses of ultrasound in medicine used A-mode information to determine the midline position of the brain for revealing possible mass effect of brain tumors.

❖A-mode and A-line information is currently used in ophthalmology applications for precise distance measurements of the eye.

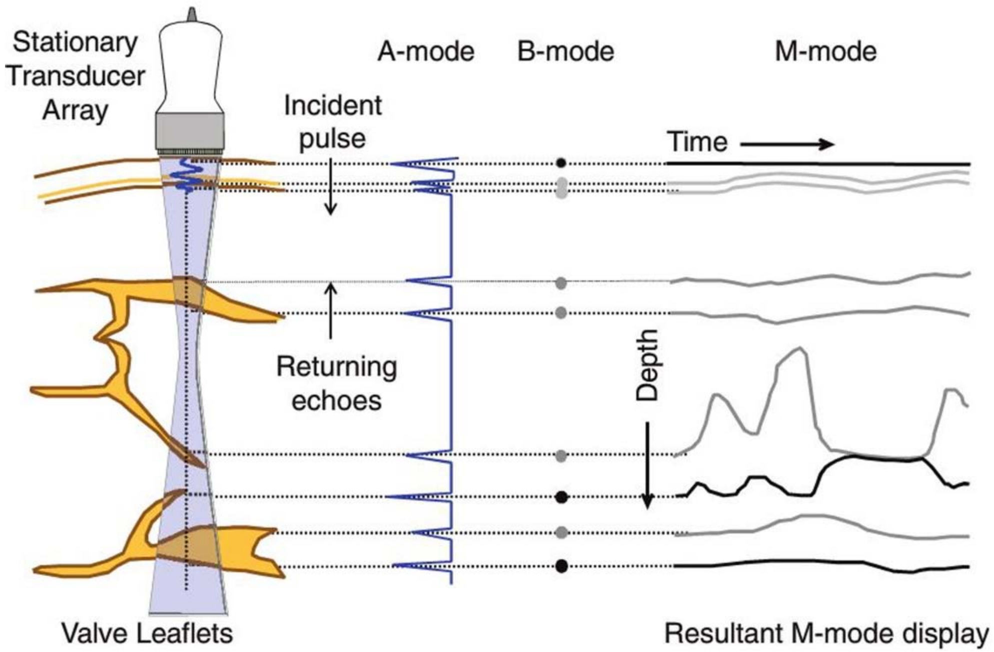
(2) B-mode

- **B-mode** (B for brightness) is the electronic conversion of the A-mode and A-line information into brightness-modulated dots on a display screen.
- In general, the brightness of the dot is proportional to the echo signal amplitude (depending on signal processing parameters).
- The B-mode display is used for M-mode and 2D gray-scale imaging.



(3) M-mode

- **M-mode** (M for motion**)** is a technique that uses B-mode information to display the echoes from a moving organ, such as the myocardium and valve leaflets, from a fixed transducer position and beam direction on the patient.
- To reveal motion, **signals are displayed along a line** (of the depth of the tissue), **plus a series of "frames"**
- The echo data from a single ultrasound beam passing through moving anatomy are acquired and displayed as a function of time, represented by reflector depth on the vertical axis (beam path direction) and time on the horizontal axis.
- **M-mode** can provide excellent **temporal resolution of motion patterns**, allowing the evaluation of the function of heart valves and other cardiac anatomy.



(4) Scan converter

- The function of the **scan converter** is to create 2D images from echo information from distinct beam directions, and to perform scan conversion to enable image data to be viewed on video display monitors.
- Scan conversion is necessary because the image acquisition and display occur in different formats.
- Early scan converters were of an analog design, using storage cathode ray tubes to capture data.
- Modern scan converters use digital technology for storage and manipulation of data.
- Digital scan converters are stable, and allow subsequent image processing with application of a variety mathematical functions.

With a rapid pulsing sequence and beam sweep, it is possible to produce up to 30 or so frames per second.

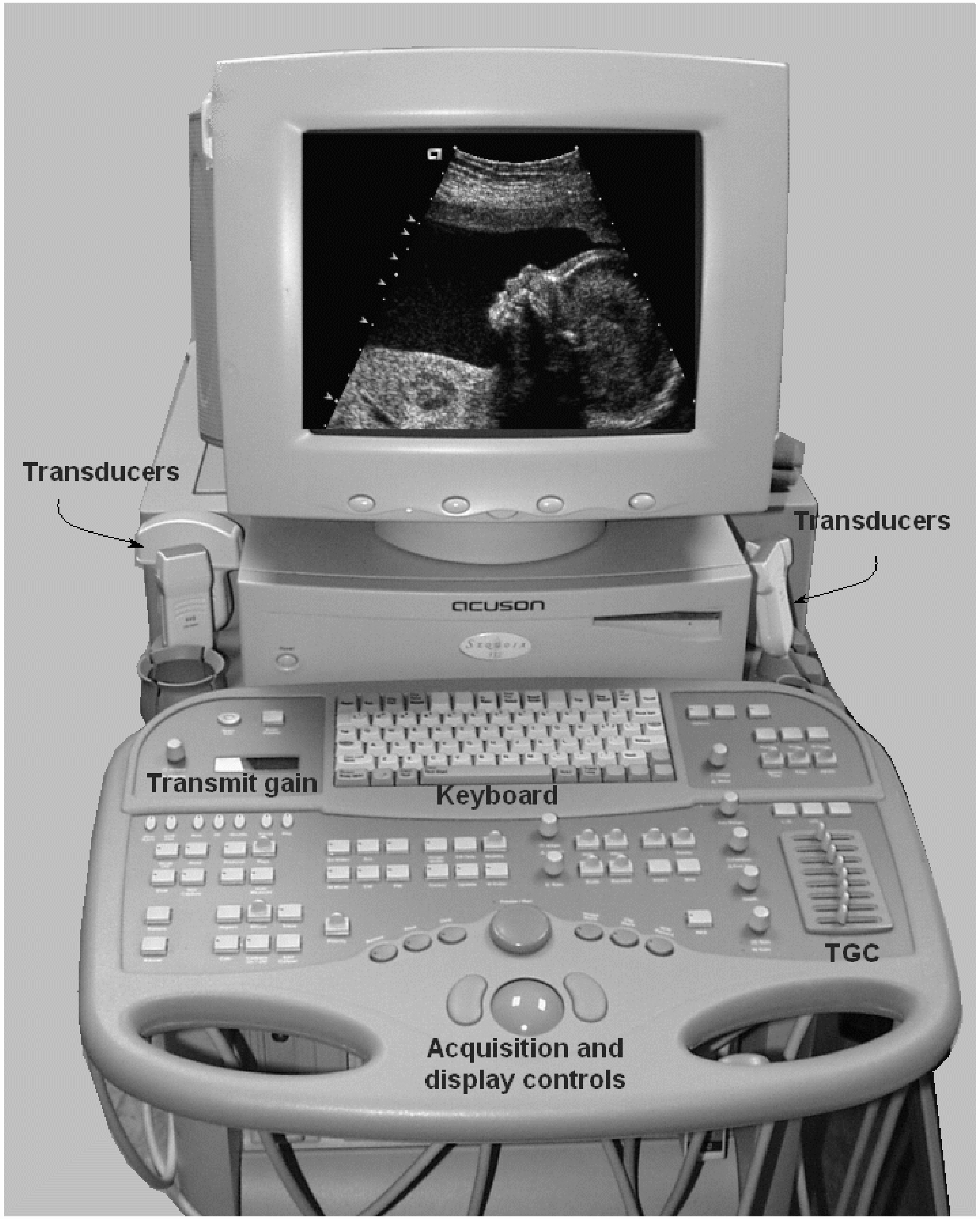


Figure: A commercial ultrasound scanner system is composed of a keyboard, various transducer selections, an image display monitor, and other components/interfaces.

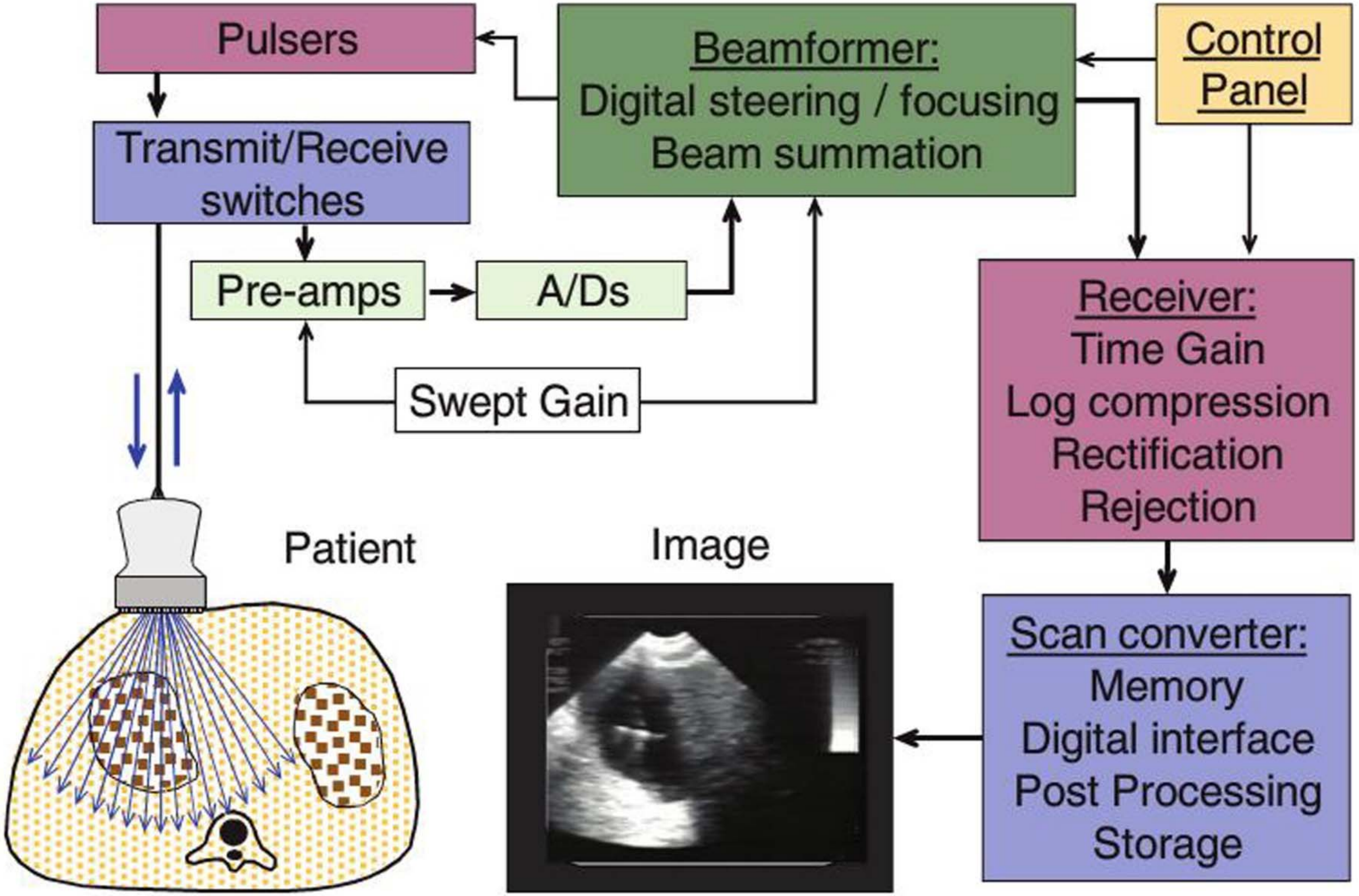
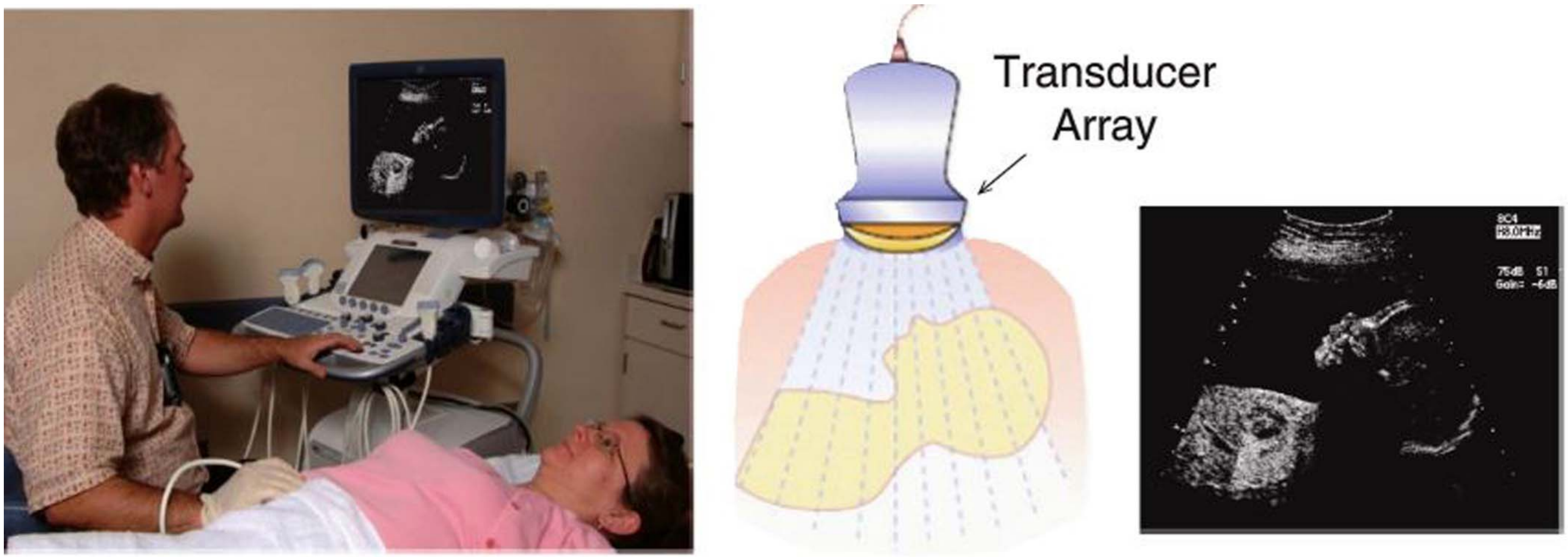


Figure: Components of the ultrasound imager. This schematic depicts the design of a digital acquisition/digital beam former system, where each of the transducer elements in the array has a pulser, transmit-receive switch, preamplifier, and analog-to-digital converter (A/D). The beam former provides focusing, steering, and summation of the beam; the receiver processes the data for optimal display, and the scan converter produces the output image rendered on the monitor.



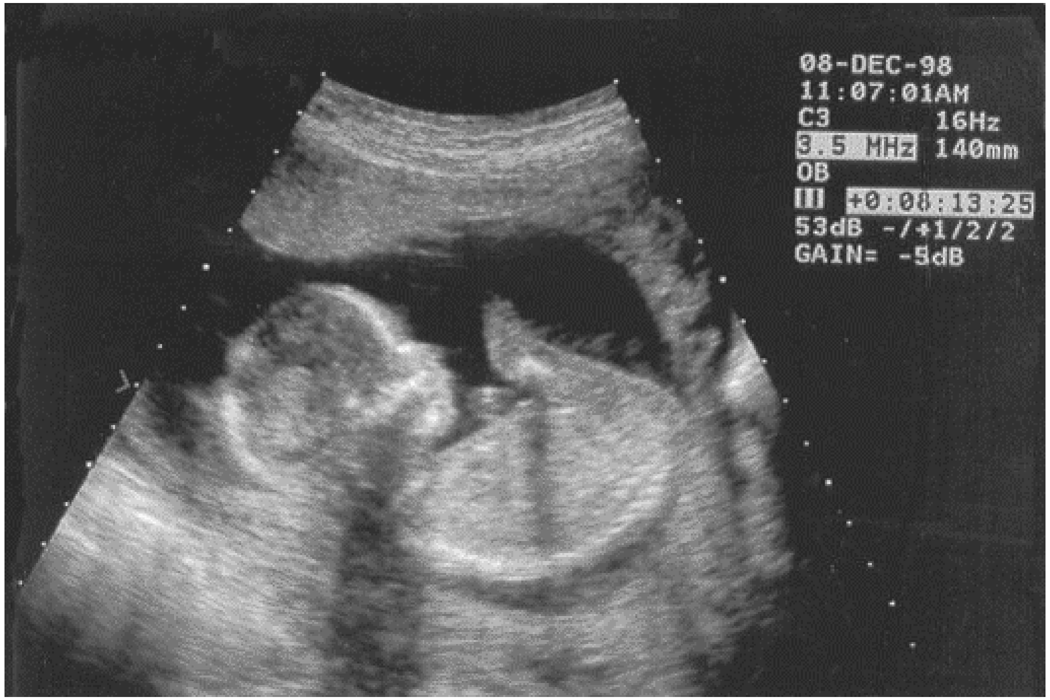
Interrogate body with acoustic "pulses" generated by transducer array

Acquire and record echoes arising from tissue interfaces

Construct "acoustic image" of tissues

Figure: A major use of ultrasound is the acquisition and display of the acoustic properties of tissue. A transducer array (transmitter and receiver of ultrasound pulses) directs sound waves into the patient, receives the returning echoes, and converts the echo amplitudes into a 2D tomographic image.

Ultrasound



J.T. Bushberg, J.A. Seibert, E.M. Leidholdt, Jr., J.M. Boone, *The Essential Physics of Medical Imaging,2002*

- The ultrasound image is a map of the echoes from tissue boundaries of high frequency sound wave pulses gray-scale encoded into a two dimensional tomographic image.
- A phased-array transducer operating at 3.5 MHz produced this normal obstetrical ultrasound image.
- Increased use of ultrasound is due to low equipment cost, portability, high safety, and minimal risk.

Fetal head diameter and circumference measurements

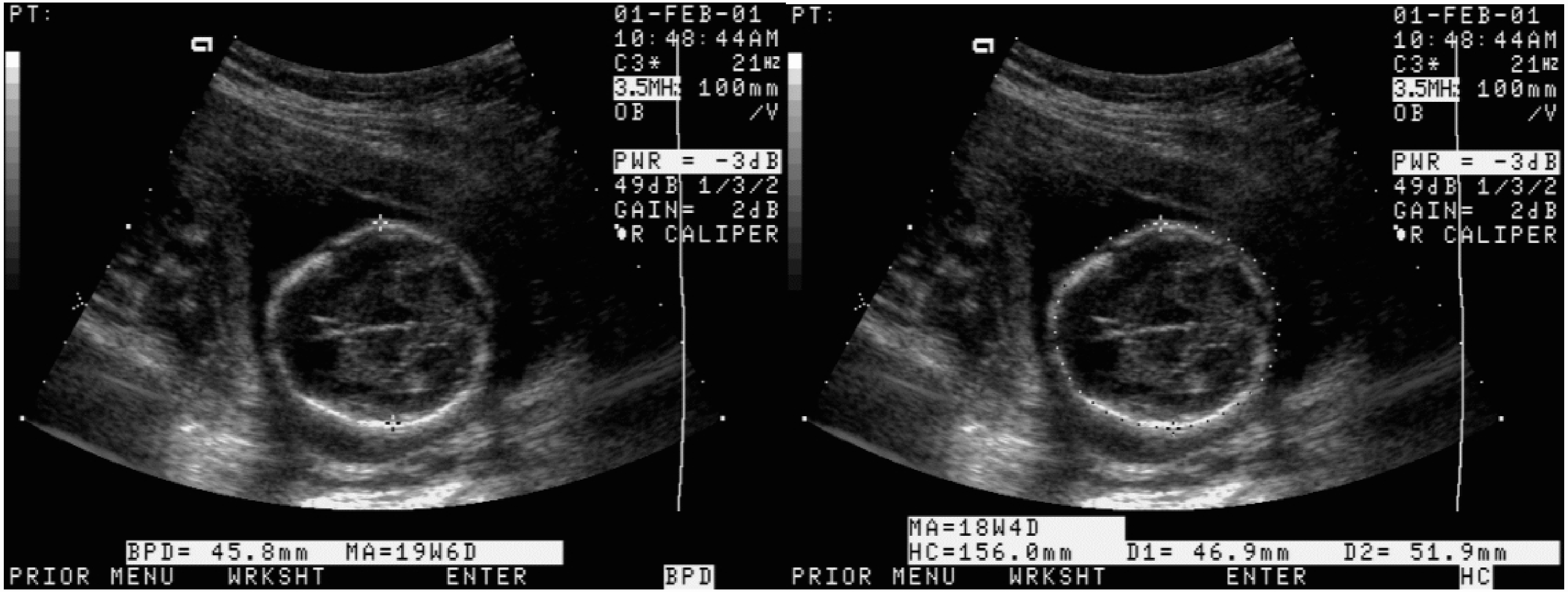


Figure: Ultrasound provides accurate distance measurements. Fetal age is often performed by biparietal (diameter) measurements (left) or circumference measurements (right). Based on known correlations, the age of the fetus in the image above is estimated to be 19 weeks and 6 days by the diameter assessment, and 18 weeks and 4 days by the circumference measurement.

8.5 Doppler Ultrasound

(1) Basic concepts

Doppler techniques are unique in ultrasound because they have the potential to offer information related to **function** of an organ through blood flow studies, and not just morphology.

- Doppler ultrasound is based on the shift of frequency in an ultrasound wave caused by a moving reflector.
- The moving reflectors in the body are the blood cells. By comparing the incident ultrasound frequency with the reflected ultrasound frequency from the blood cells, it is possible to discern the velocity of the blood.
- Not only can blood velocity (and indirectly blood flow) be measured, but also the information provided by the Doppler techniques can be used to create color blood flow use's of the vasculature.

(2) Doppler frequency shift

The Doppler shift is the difference between the incident frequency and reflected frequency.

Assume:

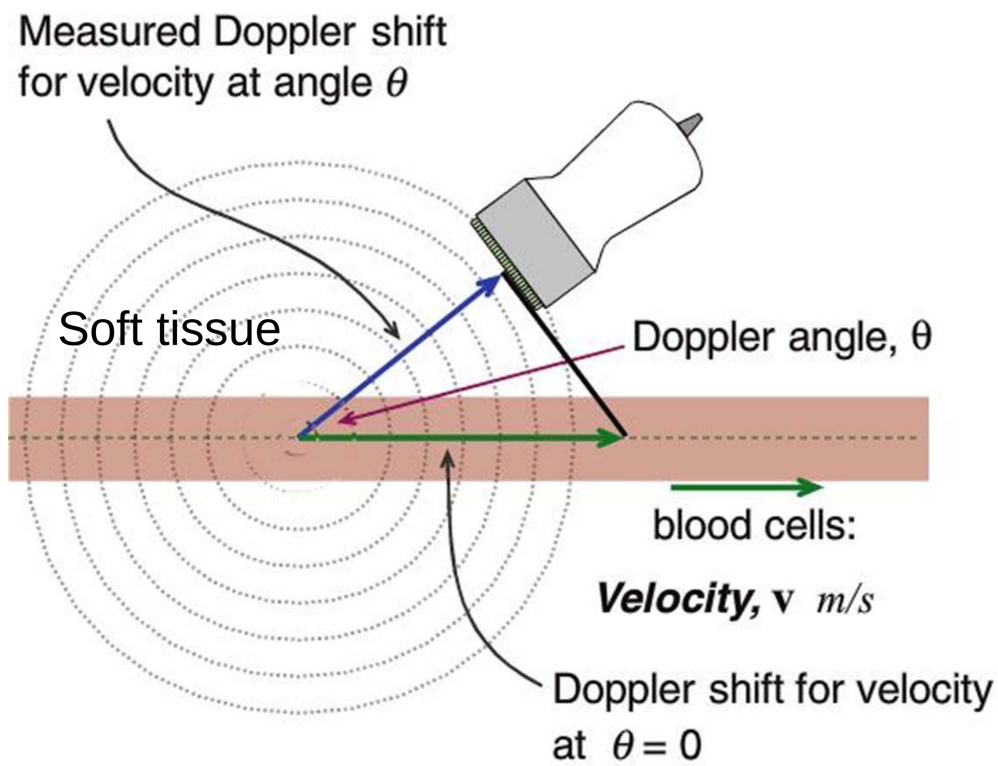
Incident frequency, f_i

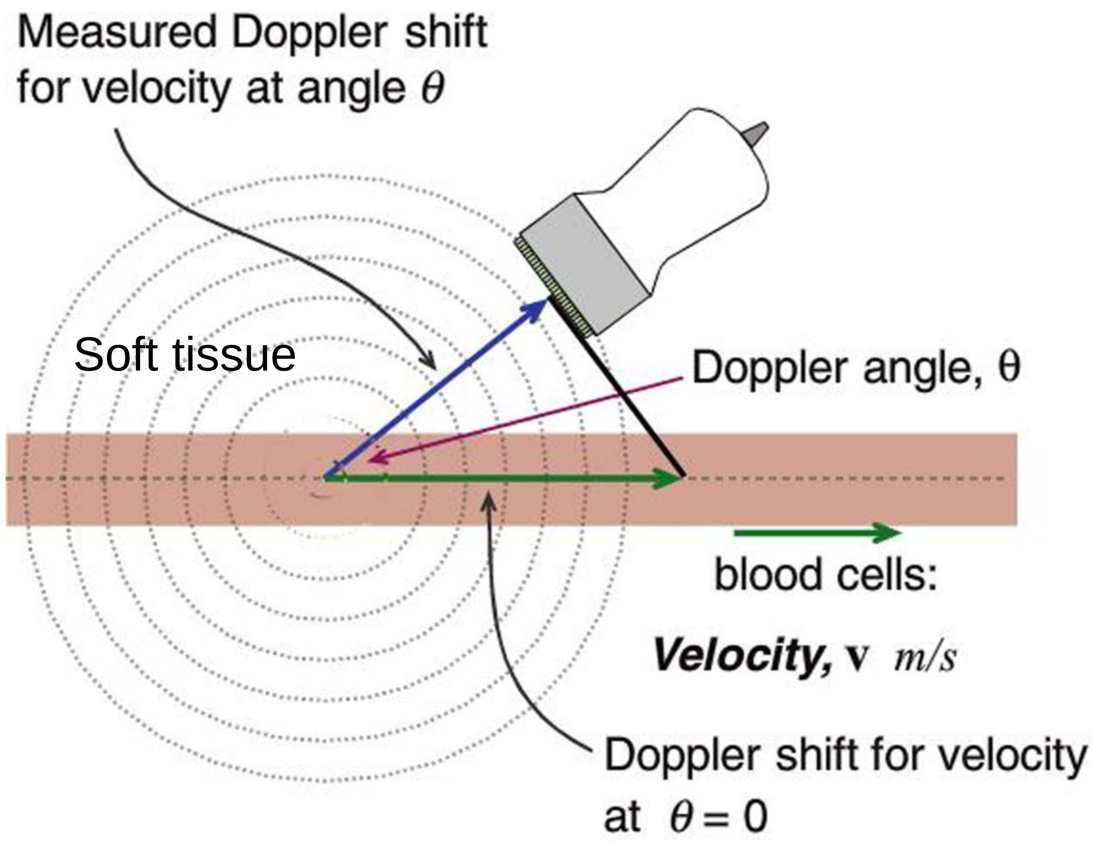
Reflected frequency, f_r

$$\Delta f = f_r - f_i = \frac{2 f_i \times (\text{reflector speed})}{\text{reflector speed} + \text{speed of sound}}$$

Generalized Doppler shift equation:

- ❖ As the velocity of blood cells (~2 m/sec) is significantly less than the speed of sound (1540 m/sec in soft tissue), the denominator can be simplified with extremely small error by neglecting the velocity of the blood.
- ❖ The angle between the direction of blood flow and the direction of the sound is called the **Doppler angle** (θ in the figure).
- ❖ The component of the blood velocity in the direction of the sound is equal to the actual blood velocity, V (hypotenuse) multiplied by ***cosθ***.





❖ This results in the generalized Doppler shift equation:

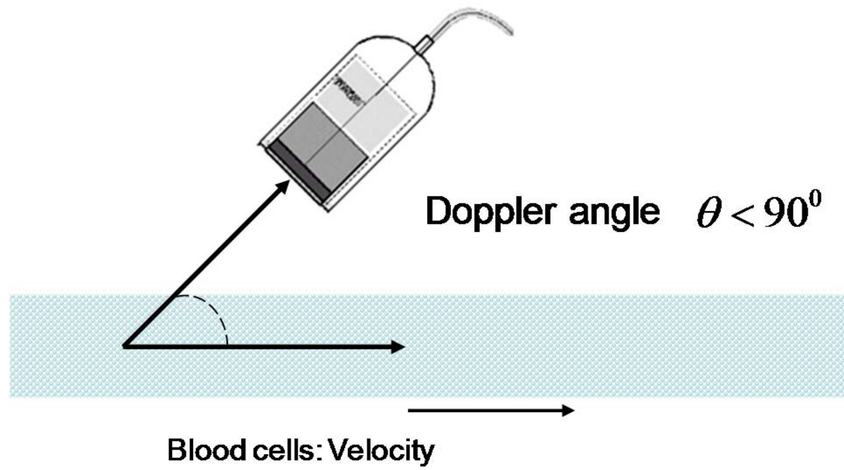
$$\Delta f = f_r - f_i = \frac{2 f_i V \cos\theta}{c}$$

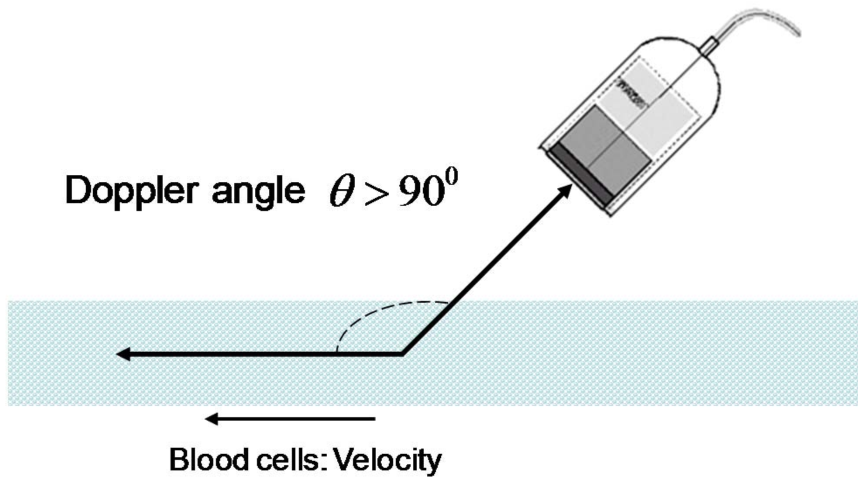
c: is the speed of sound (propagation speed of soft tissue);

V: is the speed of reflector (speed of blood)

More discussion about Δf and Doppler angle

- When the blood flowing toward the transducer (as shown in the following figure), $\theta<90^0$, $\Delta f = f_r - f_i > 0$, the reflected frequency, f_r, is large than the incident frequency, f_i.
- When the blood flow is away from the transducer (as shown in the following figure), $\theta>90^0$, $\Delta f = f_r - f_i < 0$, the reflected frequency, f_r, is less than the incident frequency, f_i.





Example:

Blood flows through a portion of an artery away from a transducer at V= 0.35m/s. the incident frequency is, f_i=*5MHz* and the **Doppler angle** is ***θ=45^0***, To calculate the Doppler frequency shift (the sound speed in soft tissue is 1540 m/s), we have.

$$\Delta f = \frac{2 f_i V \cos\theta}{C} = \frac{2\times 5\times 10^6 \times 0.35\times \cos 45^0}{1540} = 1.6\times 10^3 (Hz)$$

The frequency shift of 1.6 kHz is in the audible range (15 Hz to 20 kHz).

The Doppler frequency shifts for moving blood occur in the audible range. It is both customary and convenient to convert these frequency shifts into an audible signal through a loudspeaker that can be heard by the sonographer to aid in positioning and to assist in diagnosis.

Exercise:

Doppler ultrasound technique can be used to measure the speed of blood flow. Assume a ultrasound transducer is positioned so that the direction of the blood flow is at a 30^0 angle (Doppler angle: $\theta=30^0$), relative to the direction of the ultrasound beam. The incident frequency is 5000 KHz, and reflected frequency is detected as 5003 KHz. What is the speed of blood flow? (The speed of sound in soft tissue is C =1540 m/s).

Solution:

$$f_i = 5000\ KHz \quad f_r = 5003\ KHz \quad \theta = 30^0 \quad C = 1540\ m/s$$

The Doppler shift is:

$$\Delta f = f_r - f_i = 5003 - 5000 = 3 \quad (KHz)$$

Therefore, the speed of blood flow is:

$$V = \frac{\Delta f \times C}{2 f_i \cos\theta} = \frac{3 \times 1540}{2 \times 5000 \times \cos 30^0} = 0.533(m/s)$$

(3) Continuous Doppler operation

❖ The continuous-wave Doppler system is the simplest and least expensive device for measuring blood velocity.

❖ Two transducers are required, with one transmitting the incident ultrasound and the other detecting the resultant continuous echoes

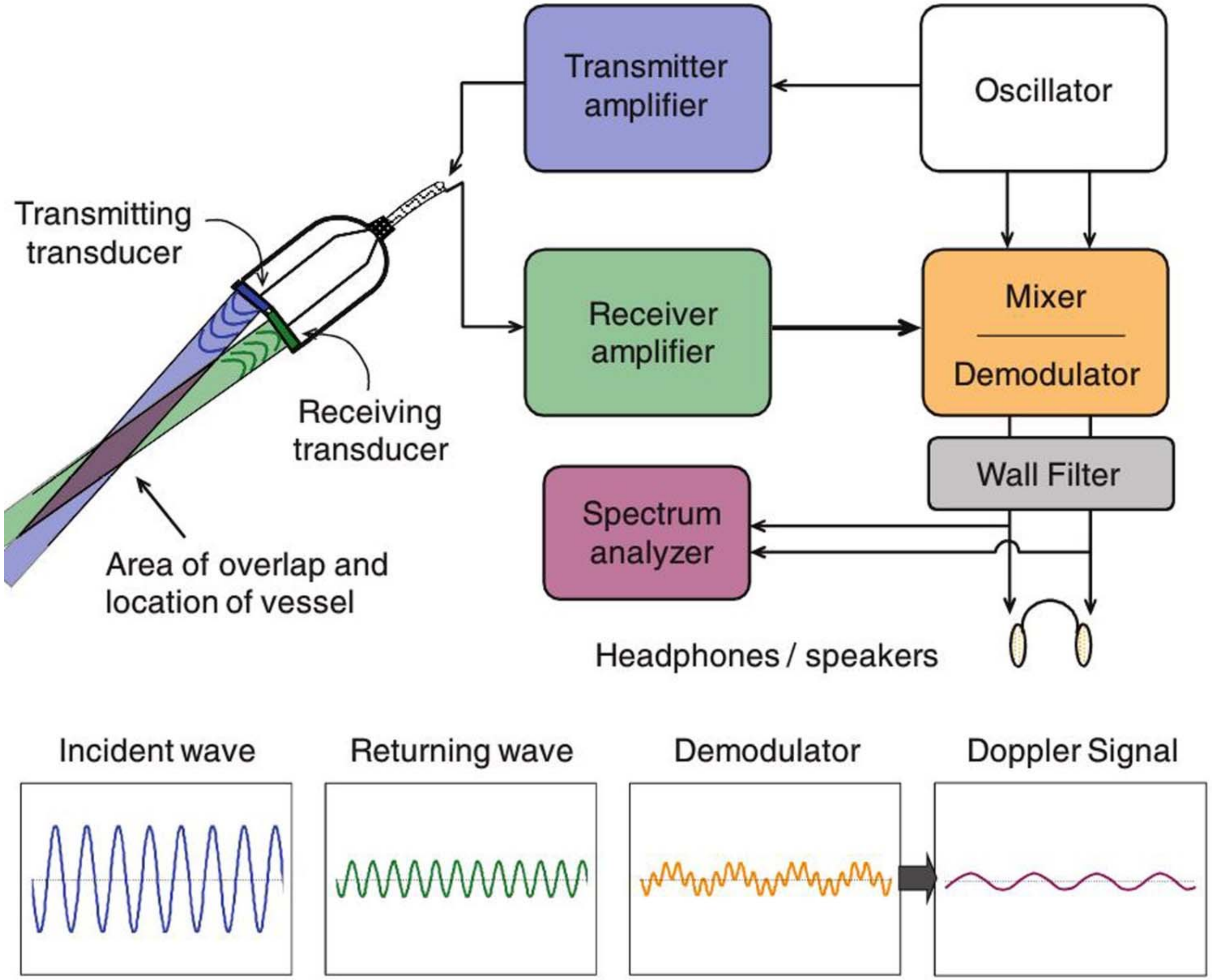


Figure: Block diagram of a continuous-wave Doppler system.

- An oscillator produces a resonant frequency to drive the transmit transducer and provides the same frequency signal to the demodulator, which compares the returning frequency to the incident frequency.
- The receiver amplifies the returning signal, and the mixer demodulator extracts the Doppler shift frequency by using a **"low-pass"** filter, which removes the superimposed high frequency oscillations.
- The Doppler signal contains very low frequency signals from vessel walls and other moving specular reflectors that a "wall filter" selectively removes.
- An audio amplifier amplifies the Doppler signal to an audible sound level, and a recorder tracks spectrum changes as a function of time for analysis of transient pulsatile flow.

- Here the block diagram of a continuous-wave Doppler system is shown again.

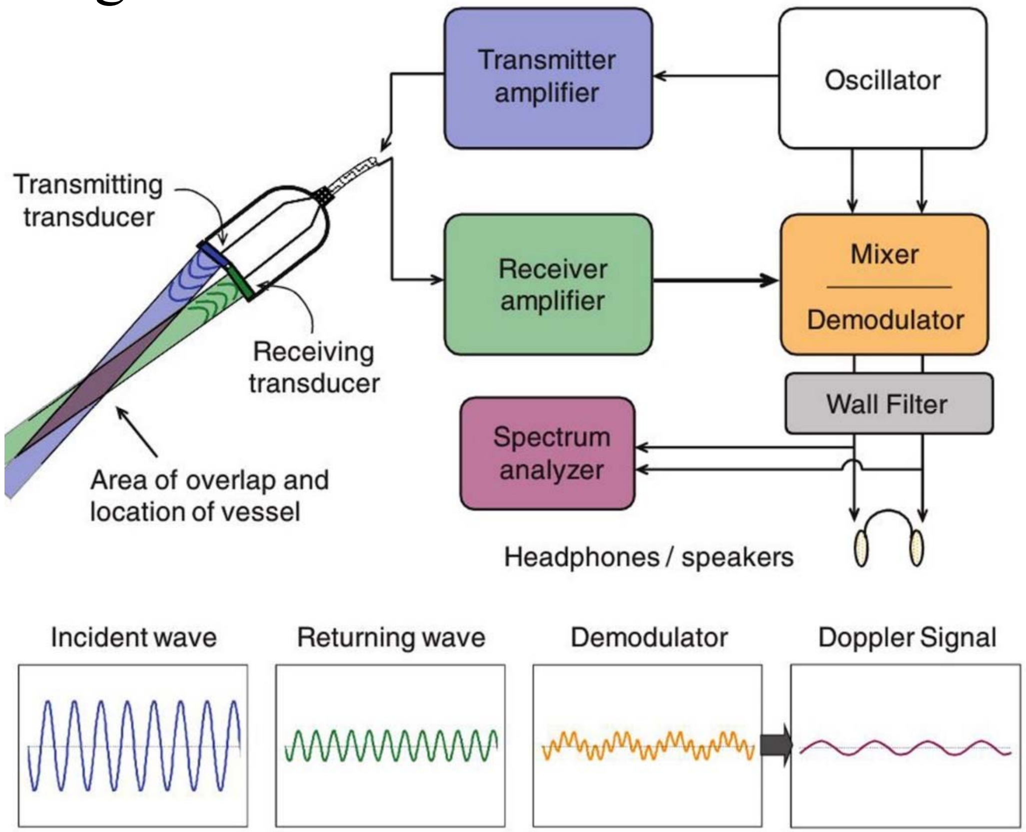


Figure. Two transducers are required: one as a transmitter and the other as a receiver. The area of overlap determines the position of blood velocity measurement. Signals from the receiver are mixed with the original frequency to extract the Doppler signal. A low-pass filter removes the highest frequencies in the demodulated signals, and a high-pass filter (Wall filter) removes the lowest frequencies due to tissue and transducer motion to extract the desired Doppler shift.

(4) Pulsed Doppler operation

- ❖ Pulsed Doppler ultrasound combines the velocity determination of continuous-wave Doppler systems and the range discrimination of pulse echo imaging.

- ❖ A transducer tuned for pulsed Doppler operation is used in a pulse echo format, similar to imaging.

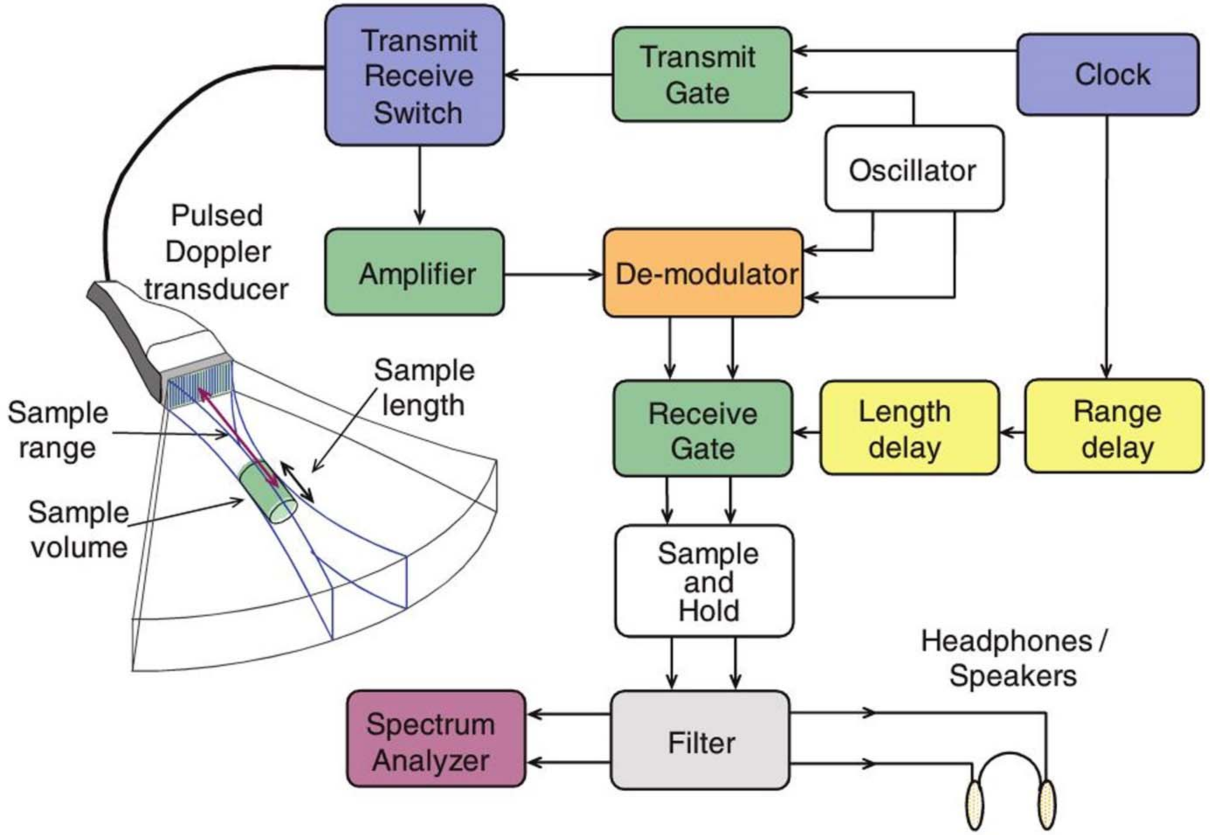


Figure: Block diagram of a pulsed Doppler system.

- The spatial pulse length is longer (a minimum of 5 cycles per pulse up to 25 cycles per pulse) to improve the measurement accuracy of the frequency shift (although at the expense of axial resolution).
- Depth selection is achieved with an electronic time gate circuit to reject all echo signals except those falling within the gate window, determined by the operator.
- In some systems, multiple gates provide profile patterns of velocity values across a vessel.
- A block diagram of a pulsed Doppler system is shown again in the next slide.

❖Here the block diagram of a pulsed Doppler system is shown again.

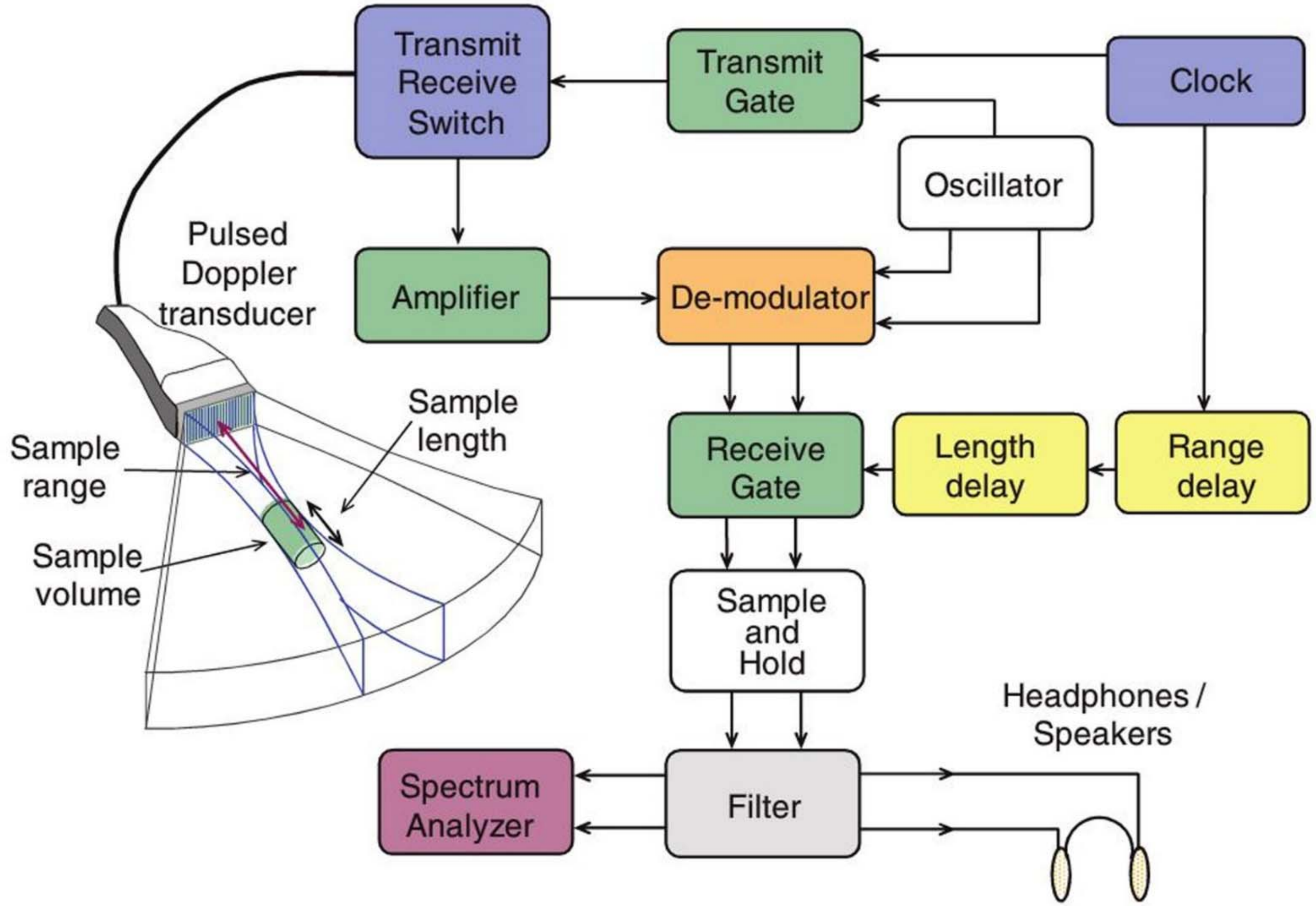
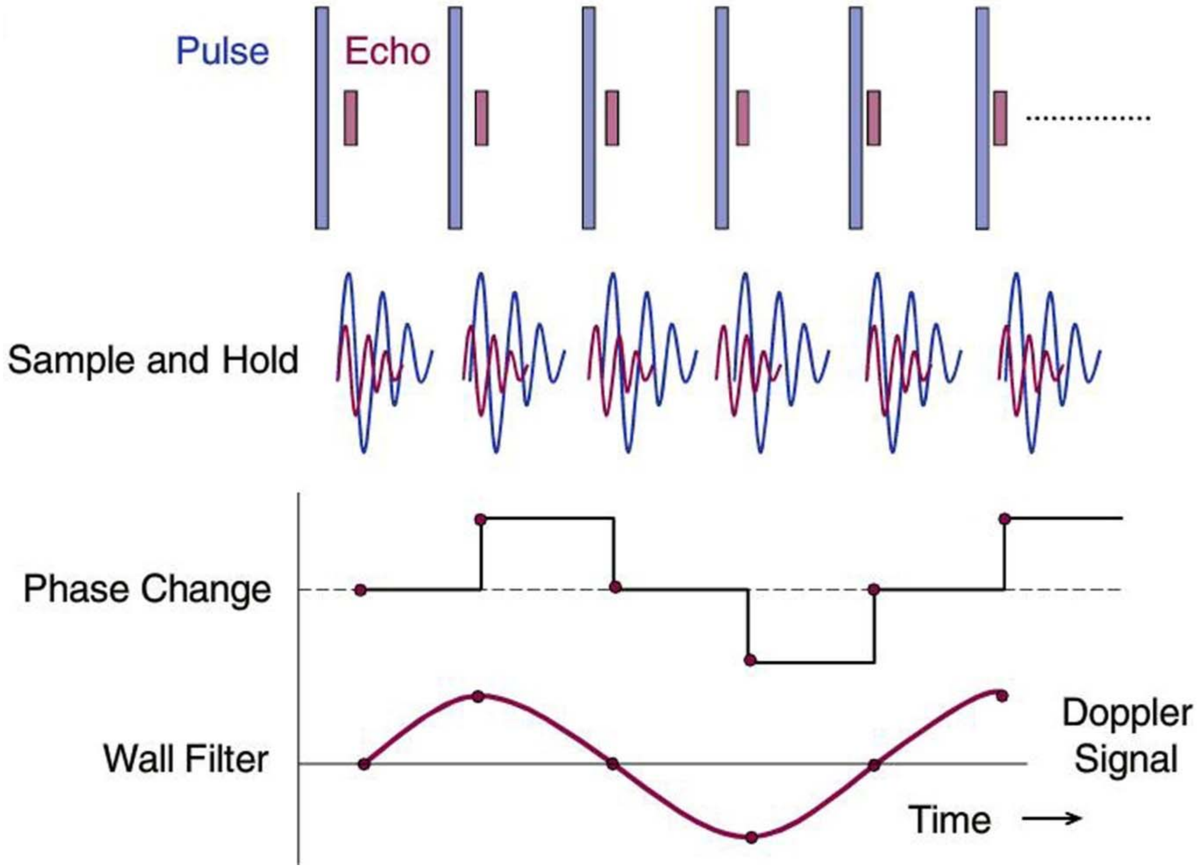


Figure: Isolation of a selected area is achieved by gating the time of echo return, and analyzing only those echoes that fall within the time window of the gate. In the pulse mode, the Doppler signal is discretely sampled in time to estimate the frequency shifts occurring in the Doppler gate.

- ❖ Each Doppler pulse does not contain enough information to completely determine Doppler shift, but only a sample of the shifted frequencies measured as a phase change.
- ❖ The phase of the returning echoes from a stationary object, relative to the phase of the transmitted sound, does not change with time.
- ❖ However, the phase of the returning echoes from moving objects does vary with time.
- ❖ Repeated echoes from the active gate are analyzed in the sample/hold circuit, and a Doppler signal is gradually built up (figure).



- The discrete measurements acquired at the **pulse repetition frequency (PRF)** produce the synthesized signal.
- According to **sampling theory**, a signal can be reconstructed unambiguously as long as the true frequency (e.g., the Doppler shift) is less than half the sampling rate.
- Thus, the PRF must be at least twice the maximal Doppler frequency shift encountered in the measurement.

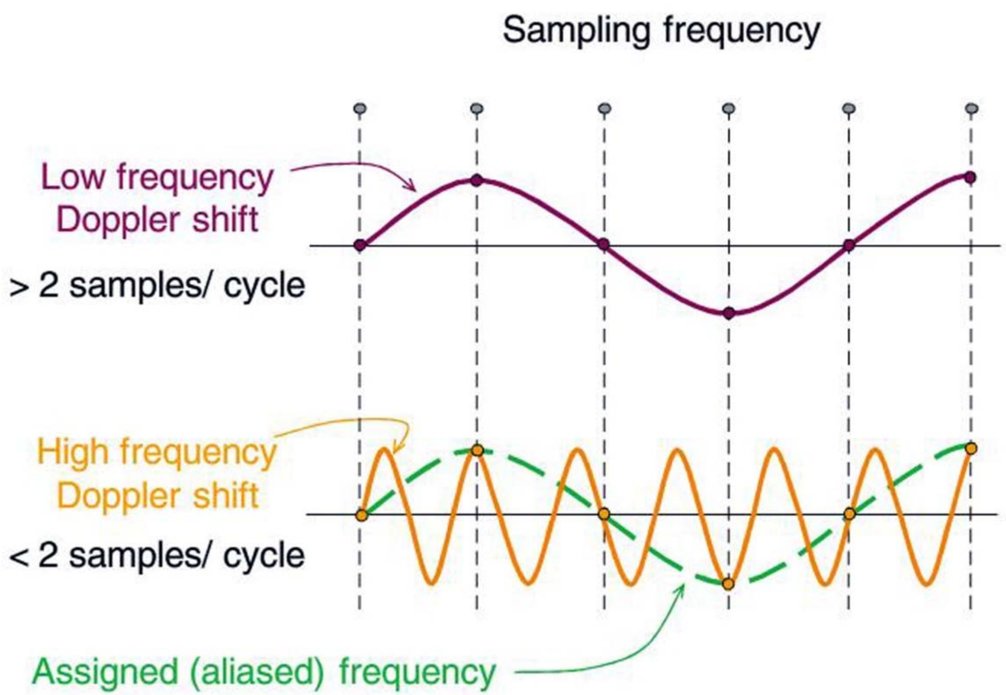
The maximum Doppler shift Δf_{max} that is unambiguously determined in the pulsed Doppler acquisition follows directly from the Doppler equation by substituting V_{max} for V:

$$\Delta f_{\max} = \frac{PRF}{2} = \frac{2 f_i V_{\max} \cos\theta}{c}$$

Rearranging the equation and solving for V_{max} :

$$V_{\max} = \frac{c \times PRF}{4 f_i \cos\theta}$$

- For Doppler shift frequencies exceeding one-half the PRF, aliasing will occur, causing a potentially significant error in the velocity estimation of the blood (Figure).
- A 1.6 kHz Doppler shift requires a minimum PRF of 2 × 1.6 kHz = 3.2 kHz.
- One cannot simply increase the PRF to arbitrarily high values, because of echo transit time and possible echo ambiguity.
- Use of a larger angle between the ultrasound beam direction and the blood flow direction reduces the Doppler shift.
- Thus, higher velocities can be unambiguously determined for a given PRF at larger angles.



Summary

a) Audible sounds: 20Hz to 20KHz; Clinical ultrasound: 0.8~15MHz
b) Echo signal: What is of clinical significance is that a **reflection** will occur at a sharp boundary between two body tissues with sufficiently different acoustic properties--an echo is produced.
c) Relative intensity (dB):

$$dB = 10 \log_{10}(I_1/I_o)$$

I_o: Intensity of a pulse originally transmitted,

I_1: Intensity of its echo

d) Exponential attenuation, reflection and refraction.
e) Transducer.
f) A-mode, B-mode and M-mode.
g) Doppler ultrasound: Doppler techniques are unique in ultrasound because they have the potential to offer information related to **function** of an organ through blood flow studies, and not just morphology.

Homework #07

1. It is known that the speed of ultrasound in soft tissue is about 1540 m/s. (1)What is the wavelength of 1 MHz ultrasound in soft tissue? (2) what is the wavelength of 10 MHz ultrasound in soft tissue?
2. Two ultrasound signals differs in intensity by 20 dB, what is the ratio of their intensities?
3. An ultrasonic wave of 10 MHz with an intensity of 5 mW/cm^2 is incident on a flat boundary normally between two media with acoustic impedance Z_1 and Z_2. Assume that the attenuation in the two media can be neglected. The reflected power is $0.4 mW/cm^2$. (a) What is the transmitted intensity, (b) If impedance Z_1 is 1.34×10^6 kg/(m^2 sec) , find Z_2 .

4. An ultrasound echo signal is half as intense as the original signal. Express the drop in intensity in decibels.

5. An 8 MHz ultrasound pulse Doppler flow meter is used to monitor blood flow in a carotid artery. The probe is marking an angle 25^0 with respect to the direction of flow. Suppose the speed of the blood flow in the artery is uniform throughout the lumen and is approximately 50 cm/sec. Please calculate the Doppler frequency shift. The speed of sound in the soft tissue is 1540 m/s.