Sound and Ultrasound in Medicine

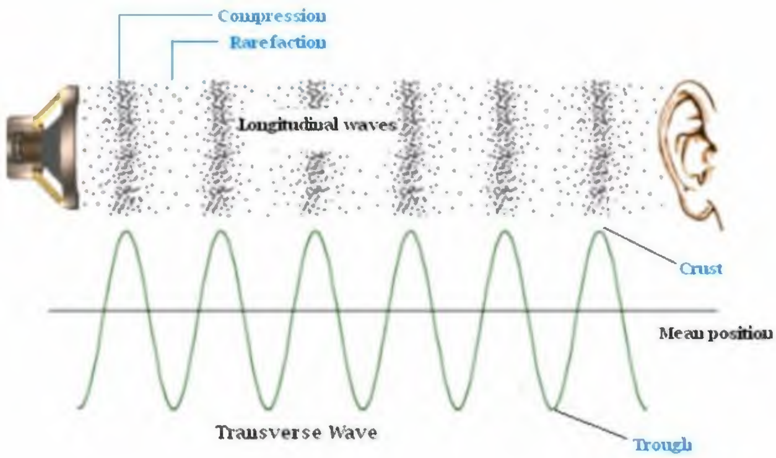
Introduction

In this chapter we discuss the physical properties of sound and the applications of sound in medicine. These applications range from the use of the stethoscope to the use of modern ultrasonic techniques to study heart valve motion.

1. Nature and characteristics of sound

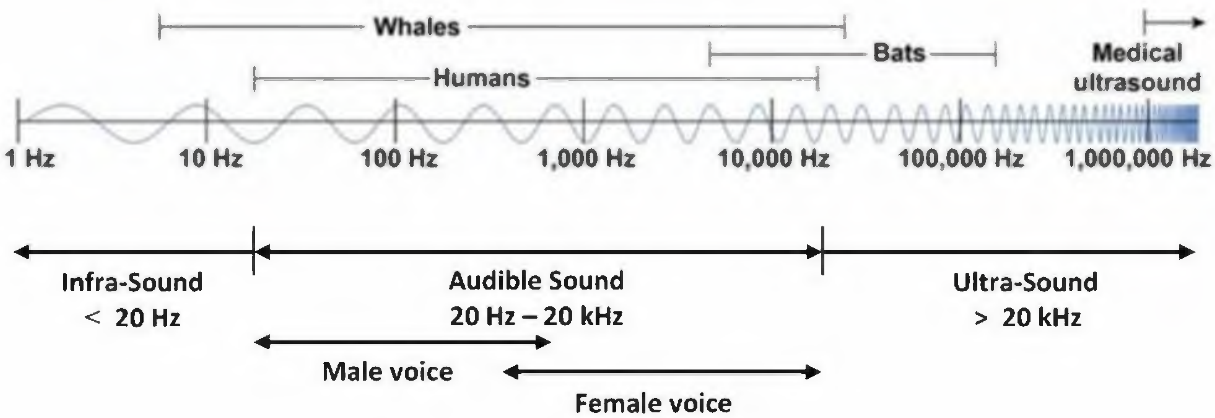
Sound wave

It is a mechanical disturbance or vibration in a gas, liquid, or solid travels from a source with some definite velocity. In air it can be defined as a local increase (compression) or decrease (rarefaction) of pressure relative to atmospheric pressure.



Sonic spectrum

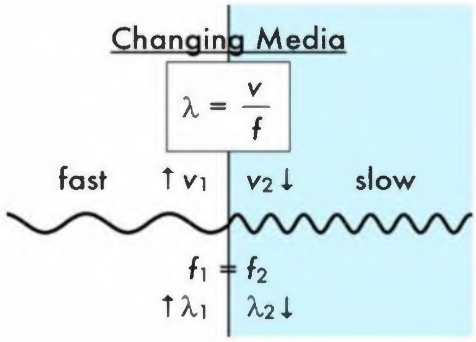
Sonic spectrum can be classified (according to its frequency) as human sound system operates within a certain frequency range:



Speed of Sound Wave

Sound waves can travel through various materials at different speeds. Velocity of sound is given by: $v = \lambda f$

When sound passes from one medium to another, speed and wavelength change while frequency stays the same. The more elasticity of the medium, the faster the sound speed tends to be as shown in the table.



Intensity that carried by sound wave

Intensity is defined as the power carried by sound waves per unit area W/m^2. It may be expressed by the maximum change in pressure; P_o as following: $I = \frac{P_o^2}{2Z}$ $(I \propto P_o^2)$

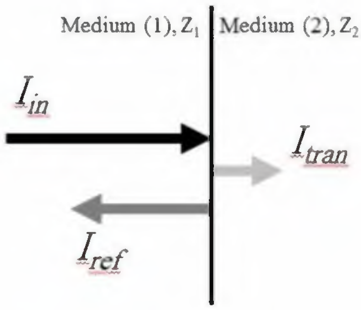
Where, I: intensity and $Z = \rho v$ acoustic impedance of the medium.

Acoustic impedance (Z) is the measure of the opposition that a system presents to the sound when flow through a medium.

Sound reflection and transmission on interfaces

Sound waves, in different material, move with different speeds. When the sound wave is applied in perpendicular way on the interface between two media which have different acoustic impedance (Z_1 and Z_2) a portion of this wave will pass through and another one will reflect (large difference in Z ⟶ high reflection ratio).

The ratio of reflected; I_{ref} (or transmitted; I_{tran}) and the incident waves (I_{in}) can be measured as following,



$$R = \frac{I_{ref}}{I_{in}} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \quad , \quad T = \frac{I_{trans}}{I_{in}} = \frac{Z_1}{Z_2}\left(\frac{2\,Z_1}{Z_2 + Z_1}\right)^2$$

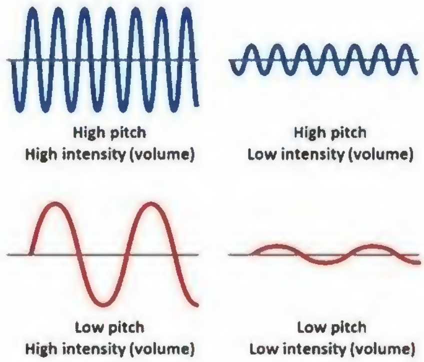
If the materials show large impedance differences, only a small portion of the intensity is transmitted to the medium (**bad impedance matching** or **mismatch**).

Values of *ρ*, *v* and *Z* for various substances

Medium	*ρ* (kg/m^3)	*v* (m/s)	*Z* (kg/m^2.s)
Air	1.29	330	430
Water	1.00×10^3	1480	1.48×10^6
Muscle	1.04×10^3	1580	1.64×10^6
bone	1.9×10^3	4040	7.68×10^6

2. Effect the nature of sound on human hearing

The human ear can distinguish two characteristics of sound. These are the loudness and pitch, and each refers to a sensation in the consciousness of the listener.



1. **Loudness:** (or volume) is defined as the degree of sensation of sound produced in the ear. The loudness of sound depends on its intensity but the relationship is not linear.

2. **Pitch:** The pitch of a sound refers to whether it is high (sharp), like the sound of a violin, or low, like the sound of a bass drum. The physical quantity that determines pitch is the frequency.

3. Units of sound intensities for auditory system

To measure the sound (such as human hearing) a comparison between intensities of two sound waves (I_2/I_1) has been used (called as sound intensity level or dB scale). It is given by:

$$10\log\frac{I}{I_0} = \textit{Intensity ratio } (dB)$$

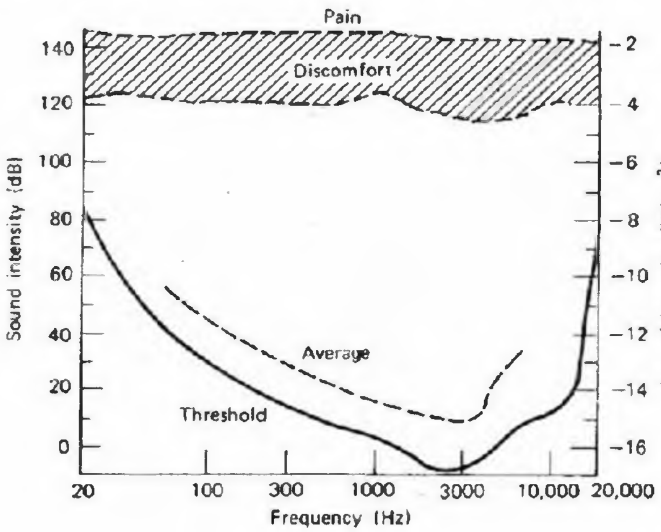
Because $I \propto P_o^2$. → So, In terms of pressure, the ratio becomes as:

$$20\ \log\frac{P}{P_0} = \textit{Intensity ratio } (dB)$$

Where $I_o = 10^{-12}$ w/m^2
$P_o = 2\times10^{-4}$ dyne/cm^2

Sound	Intensity W m^{-2}	$\frac{I}{I_0}$	Decibels dB	Description
Just detectable	10^{-12}	10^0	0	Hearing threshold
Whisper	10^{-10}	10^2	20	
Library	10^9	10^3	30	Very quiet
Normal office	10^7	10^5	50	Quiet
Normal conversation (2m)	10^6	10^6	60	
Machine shop	10^2	10^{10}	100	Constant exposure impairs hearing
Rock concert	10^0	10^{12}	120	Pain threshold
Overhead thunder	10^1	10^{13}	130	
Nearby jet take-off	10^3	10^{15}	150	

Where I_o (or P_o) is the reference intensity at frequency 1000Hz, I_o called as Hearing threshold which is the barely audible sound for a person with good hearing;
An audiogram for the normal human ear is given as in the below figure, where:



- The lower curve gives the faintest sounds that can be heard (hearing threshold), and
- The upper curve gives the loudest sounds that can be heard without pain (pain threshold).

The test is normally done in a specially constructed soundproof testing room. Each ear is tested separately , test sounds can be sent to each ear through a comfortable headset.Selected frequencies from 250 to 8000 Hz are used. At each frequency the operator raises and lowers the volume until a consistent hearing threshold is obtained.

The hearing thresholds are then plotted on a chart and then be compared to normal hearing thresholds (Fig. a). The normal hearing threshold at each frequency is taken to be 0 dB. The chart may show a general loss in one or both ears (Fig. b).

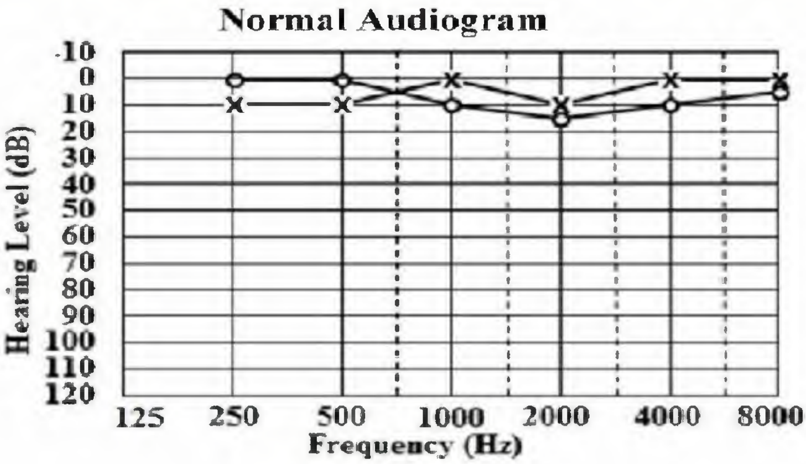


Fig a : Normal hearing

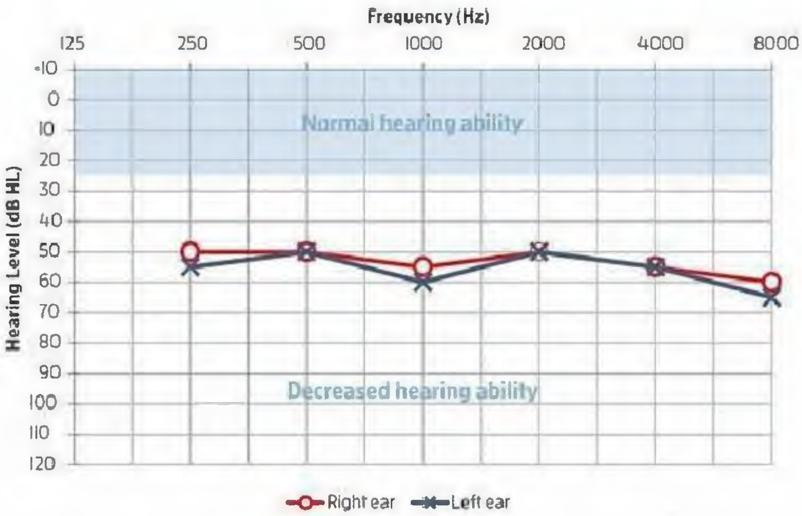


Fig b : hearing test shows lossing in both ears

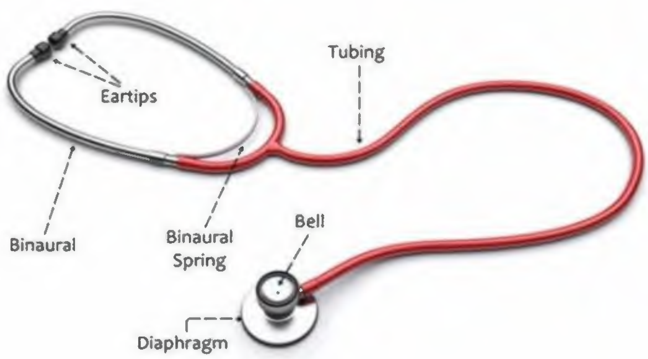
4. Applications of audible sound in medicine

a. Percussion

Sounds produced by striking body surface. Percussion is a method of tapping on a surface to determine the underlying structure. There are many types of percussion sounds: resonant, hyper-resonant, and stony dull or dull. A dull sound indicates the presence of a solid mass under the surface. A more resonant sound indicates hollow, air-containing structures.

b. Stethoscope

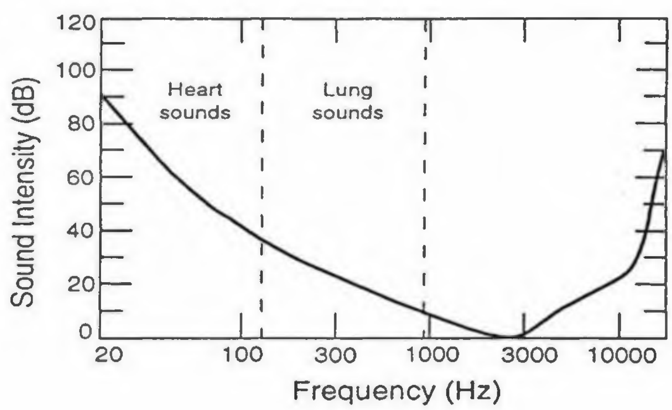
Stethoscopes are diagnostic instruments that amplify sounds made by the body from the heart, lungs, abdomen and intestinal tract, or other body sites.



Modern stethoscope consists of, bell which closed by a thin diaphragm, tubing and earpieces. The bell serves as impedance matcher between body and the air in the tube. This requires that the frequency of the sounds must resonate in the bell membrane.

The natural frequency F_{res} of the bell depends on bell diameter d and tension T of the diaphragm as following:

$F_{res} \propto \frac{\sqrt{T}}{d}$, To selectivity pick up certain frequency ranges (low frequency heart murmur, high frequency lung sounds) the appropriate bell size and diaphragm tension must be chosen.

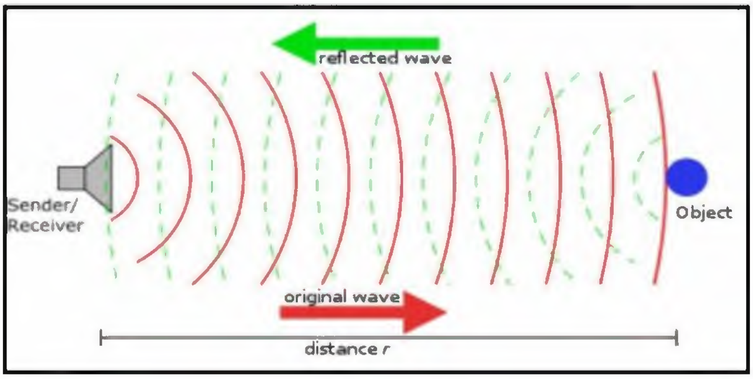


5. Ultrasound in Medicine

Ultrasound (US) is sound with a frequency greater than the upper limit of human hearing.

SONAR (***SO***und ***NA***vigation and ***R***anging)- It is a device that uses an US to generate an image of a particular soft tissue structure in the body. Since, reflections from soft tissue interfaces of homogenous, fluid-filled, or solid organs, tumor masses, and muscles located within the body may be imaged with US.

In medical diagnosis, pulses of ultrasound are transmitted into the body by placing the US transducer (vibrating crystal) in close contact with the skin, using water or a jelly paste to eliminate the air and create a good impedance matching between the transducer and skin.



The backed echoes are detected as a weak signal that amplified and displayed on an oscilloscope.

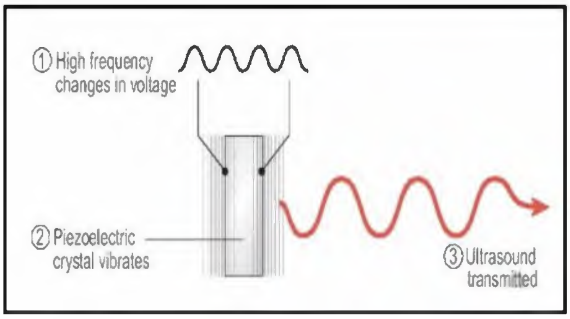
US Generation (*Piezoelectric principle*)

The ultrasound signal is generated and detected by the transducer (or probe or sensor). The transducer based on piezoelectric principle. Many crystals can be used so that AC voltage (electrical energy) across the crystal will produce a vibration of the crystal (mechanical energy), thus generating an ultrasound wave and vice versa.

The frequency that will produce from the piezoelectric element with thickness t is given by:

$$f(MHz) \approx \frac{2}{t\ (mm)}$$

For example; a 0.4 mm thick crystal resonates at a frequency of 5 MHz.



6. Quality of ultrasound imaging

The quality of ultrasound imaging is determined by the interaction of the acoustic wave with the body tissue, theses interactions includes:

1. Spatial resolution, which depends on wavelength of US.
2. Attenuation, which depends on absorption and scattering of US waves.
3. Reflection and transmission, which depend on the impedance of the medium.

Spatial Resolution

The spatial resolution is limited by wavelength of sound: $\Delta s \approx \lambda = \frac{v}{f}$

For low frequencies in the audible range 10 kHz → $\lambda = \frac{1540\,(m/s)}{10^4\left(\frac{1}{s}\right)} = 0.154\ cm$

Frequencies in the ultrasound range 10 MHz → $\lambda = 0.154\ mm$

So, **low f → high Δs → Bad resolution → Bad image**

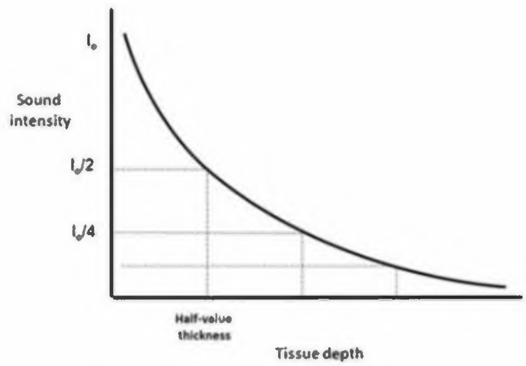
Attenuation

All media attenuate ultrasound due to absorption and scattering effects as following:

$\alpha = \alpha_{abs} + \alpha_{scat}$

α depends on the tissue characteristics (density) and on frequency. The attenuation in a sound wave is given by: $I = I_0 e^{-2\alpha x}$

Where I is intensity at depth x, I_0 initial intensity , α is the absorption coefficient



So, **high f → high attenuation**

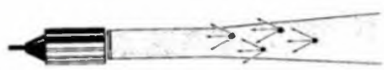
Reflection and transmission

Perpendicular reflection originates the echo signal, while non-perpendicular reflection causes an intensity loss in echo signal, as shown in the figure.

Smooth surface → low scattering → good image

Rough surface → high scattering → bad image

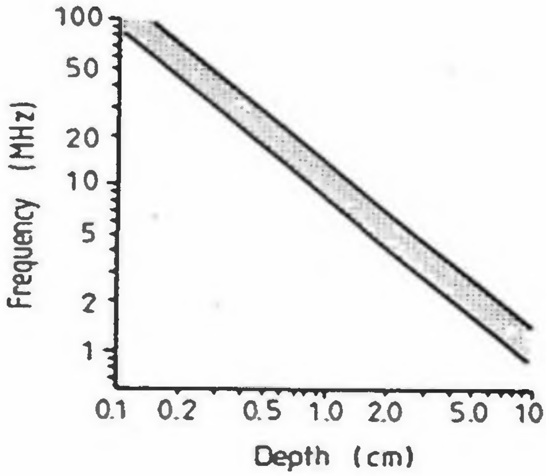
Specular boundary: *Smooth surface* and *very little scatter*



Non-Specular boundary: *Rough surface* and *Diffuse scatter*

The choice of the ultrasound is determined by a compromise between **good resolution** and **deep penetration.** The attenuation of high frequency acoustic waves limits the penetration depth; low frequency waves decrease resolution.

This figure represents the relationship between the frequencies that used in the diagnosis and depth of penetration in the body. Frequencies in the 3-5 MHz range with better resolution are used to probe smaller structures, like thyroid, arteries infant organs etc.



Ultrasound picture of the body:

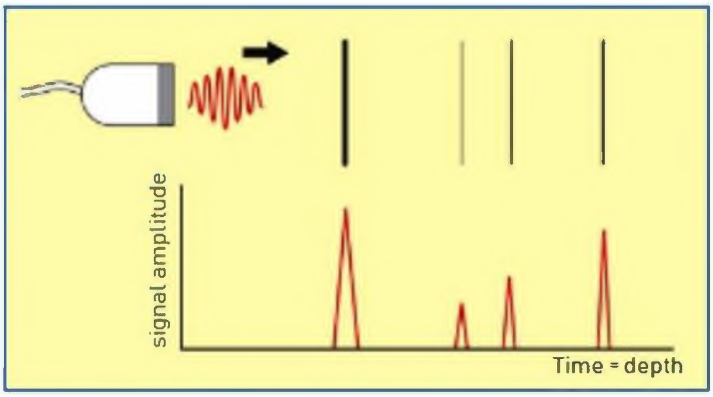
Basically, an ultrasound source sends a beam of pulses of 1 to 5 MHz sound into the body. The time required for the sound pulses to be reflected gives information on the distance to the various structures or organs in the path of the ultrasound beam.

Types of US imaging

1. A - Mode (1D)

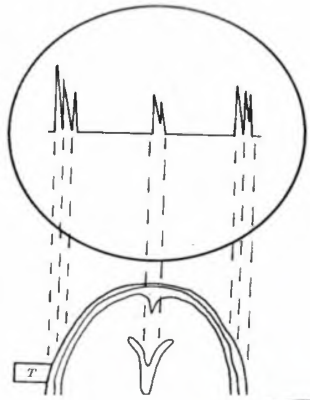
To obtain diagnostic information about the depth of structures in the body, we send pulses of ultrasound into the body and measure the time required to receive the reflected sound (echoes) from the various surfaces in it. This procedure is called the A Scan method of ultrasound diagnosis. It is used to obtain diagnostic information about the depth of structure (image with 1-dimention).

In this mode an US waves send into the body and measure the time required to receive the reflected sound (echoes) from the interface between the different tissues. In A-mode the transducer is held stationary without movement.



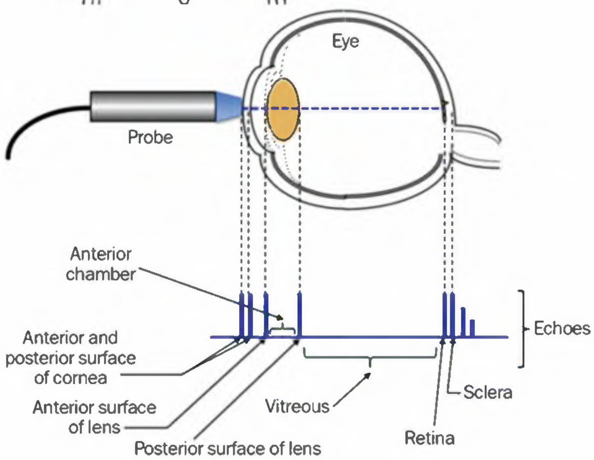
Applications of A Scans

1- Applications of A Scans in echoencephalography, has been used in the detection of the brain tumors. Pulses of ultrasound are sent into a thin region of the skull slightly above the ear and echoes from the different structures within the head are displayed on an oscilloscope



2- Applications of A Scans in ophthalmology can be divided into two areas:

- Obtaining information for use in the diagnosis of eye diseases;
- Biometry or measurements of the distances in the eye.



2- B-mode (2D image):

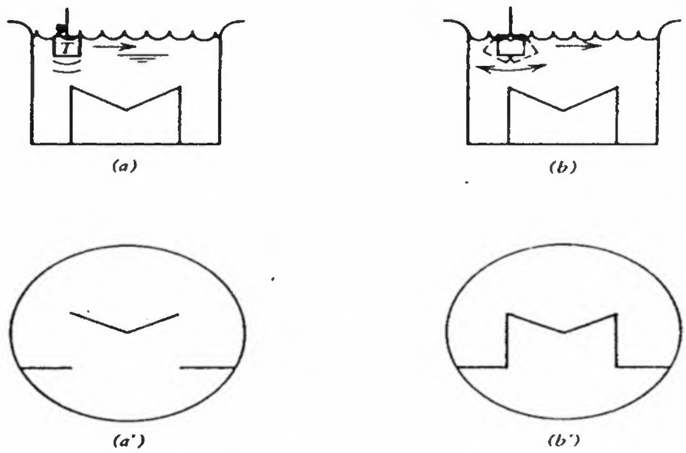
The principles are the same as for the A Scan except that the transducer is moved. Each echo produces a dot on the monitor at a position corresponding to the location of the reflecting surface.

B Scans have been used in

1- Diagnostic studies of the eyes, liver, breast, heart, and fetus.
2- Detecting pregnancy as early as the fifth week
3- Determining the size, location, and change with time of a fetus.

In many cases B Scans can provide more information than X-ray, and they present less risk.

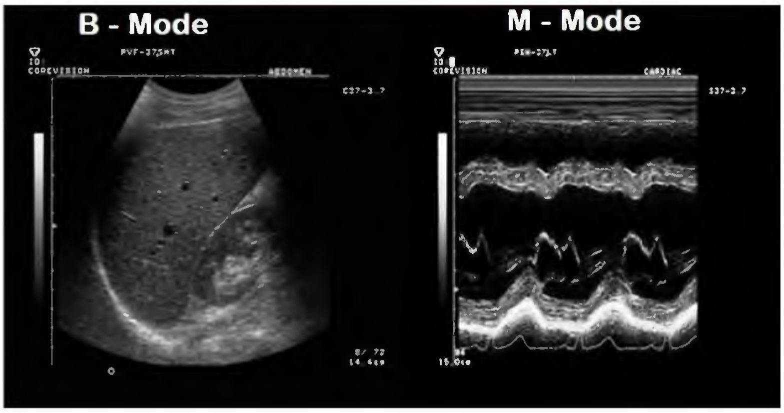
Figures (a) as the transducer T moves to the right it produces echoes from the submerged object (a') Dots corresponding to the location of each echo (b) rocking transducer as it moves produces echoes from other surfaces (b') the scan shows the sides of the object.



3.M-mode (2D + motion):

It is used to study motion such as that of heart and heart valves (image with 2D + motion). M-mode combines between features of A-mode and B-mode. The transducer is held stationary as in A-mode and the echoes appear as dots as in B-mode.

M-mode is used in diagnostic information about the heart (mitral valve) and detection of pericardial effusion.



Doppler principle:

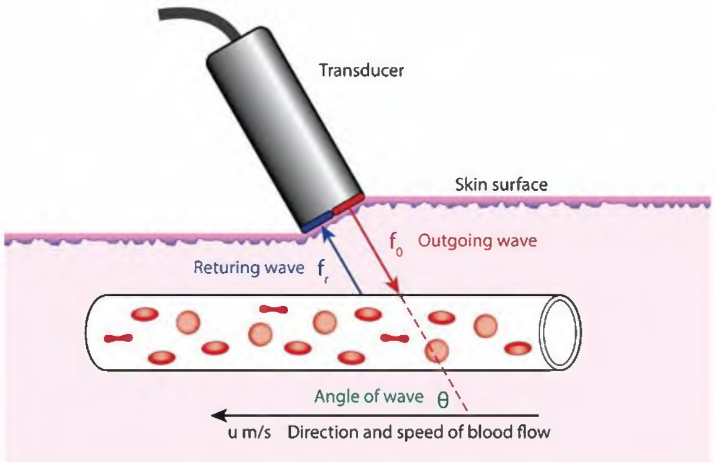
A source of sound of frequency f_o has a higher pitch when it is moving toward a listener and a lower pitch when it is moving away from him. The frequency change is called the Doppler Shift.

Measuring the speed of blood

When a continuous ultrasound beam is "received" by some red blood cells in an artery moving away from the source, the blood "hears" a slightly lower frequency than the original frequency f_o. The blood sends back scattered echoes of the sound it "hears" but since it is now a source of sound moving away from the detector, there is another shift to a still lower frequency. The detector receives a back-scattered signal that has undergone a double Doppler Shift. When the blood is moving at an angle θ from the direction of the sound waves, the frequency change f_r is: -

$$f_r = \frac{2 f_o V}{\upsilon} \cos\theta$$

Where f_o is the frequency of the original US wave, V is the velocity of the blood, v is the velocity of sound and θ is the angle between V and v.



motion of the fetal heart:

In order to establish fetal life during the 12 to 20 week period of gestation . A continuous sound wave of frequency f_o is incident upon the fetal heart. When is shifted to frequencies slightly higher than f_o , the fetal heart is moving toward the source of sound and slightly lower than f_o when the fetal heart is moving away from it. Variations in the frequency give the fetal heart rate.

Physiological effects of ultrasound in therapy

The magnitude of the physiological effects depends on the frequency and amplitude of the ultrasound (intensity) as following:

1. Low intensity US (~ 0.01 W/cm^2) → no harmful effects are observed → used for diagnostic work (as in the SONAR).
2. Continuous US (~1 W/cm^2) → deep heating effect (diathermy) → temperature raise due to the absorption of acoustic energy in the tissue .
3. Continuous US (1-10 W/cm^2) → sound moves through tissues → region of compression and rarefactions → pressure differences in adjacent regions of tissues (micromassage). If the amplitude of the sound is over elastic limit of tissue → tissue tearing.
4. Continuous US (~35 W/cm^2) → tissue destroying effect.
35 W/cm^2 → 10 atm over a very short distance → molecules cannot disperse the energy to its surrounding by vibration → breakage of chemical bonds → rupture DNA molecules.
5. Continuous and focused US (~ 103 W/cm^2)→ selective destroying of deep tissue using a focused ultrasound beam.