Sound in Medicine

General properties of sound:

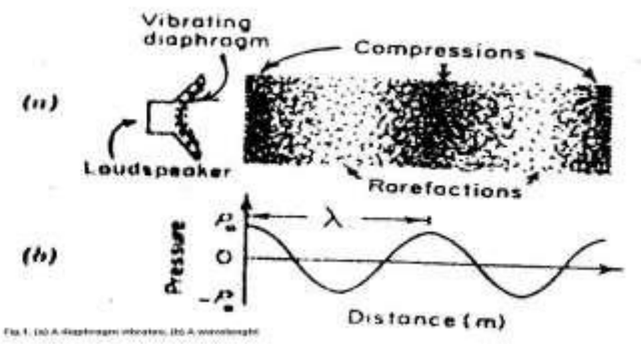
A sound wave is a mechanical disturbance in a gas, liquid, or solid that travels outward from the source with some definite velocity. We can use a loudspeaker vibrating back and forth in air at a frequency **f** to demonstrate the behavior of sound.

The vibrations cause local increases and decreases in pressure relative to atmospheric pressure(Fig 1). These pressure increases, called compressions, and decreases, called rarefactions, spread outward as a longitudinal wave, that is, a wave in which the pressure changes occur in the same direction the wave travels.

The compressions and rarefactions can also be described by density changes and by displacement of atoms and molecules from their equilibriums positions.

The relationship between the frequency of vibration **f** , the wavelength **λ**, and velocity **V** of the sound wave is:

$$V = \lambda f$$



Energy is carried by the wave as potential and kinetic energy. The intensity **I** of a sound wave energy passing through **$1m^2/s$**. Or watts per square meter for plane wave **I** is given by:

$$I = (1/2)\, \rho\, V A^2 (2\pi f)^2 = (1/2) Z (AW)^2$$

Where ρ is the density of the medium:

V: is the velocity of sound

f: is the frequency

W: is the angular frequency which equals **2π f**

A: is the maximum displacement amplitude of atoms from equilibrium position

Z : equals **ρ V**, is the acoustic impedance.

The intensity can also be expressed as

$$I = P_o^2 / 2Z$$

Where $\mathbf{P_o}$ is the maximum change in pressure.

Ex:1-a. The maximum sound intensity that the ear can tolerate at **1000 Hz** is approximately **1 W/m²**. What is the maximum displacement in air corresponding to this intensity?

sol.//

$A = 1/(2\pi f)(2I/z)^{1/2} = 1/6.28 \text{ x}10^3 \ (2 \ x \ I/4.3 \ x \ 100)^{1/2}$

$= 1.1 \text{ x } 10^{-5} m$

b. Calculate the sound pressure

$P_o = (2\ I\ Z)^{1/2} = (2\ x\ 4.3\ x\ 100\ x\ I)^{1/2}$

= 29 N/m² =0.0003 Atmosphere

For comparing the intensities of two waves (I_2 / I_1). This was named a after *Alexander bell*. The intensity ratio in bels equal to $\log_{10}(I_2 / I_1)$, and **(1 bel= 10 dB)** it is common to use the decibel comparing two sound intensities. Since I is proportional to P_2, the pressure ratio between two sound levels can be expressed as

$$10 \log_{10} (P_2^2/P_1^2) \quad \text{or} \; ..... \; 20 \log_{10} (P_2/p_1)$$

This can be used to compare any two sound pressures in the same medium.

For two sounds with pressures that differ by factor we 2 get

$$20 \text{ Log}_{10} (P_2/P_1) = 20 \text{ Log}_{10} 2 = 20(0.301) = 6 \text{ dB}$$

This variation would not be noticed by the average ear except under controlled laboratory conditions.

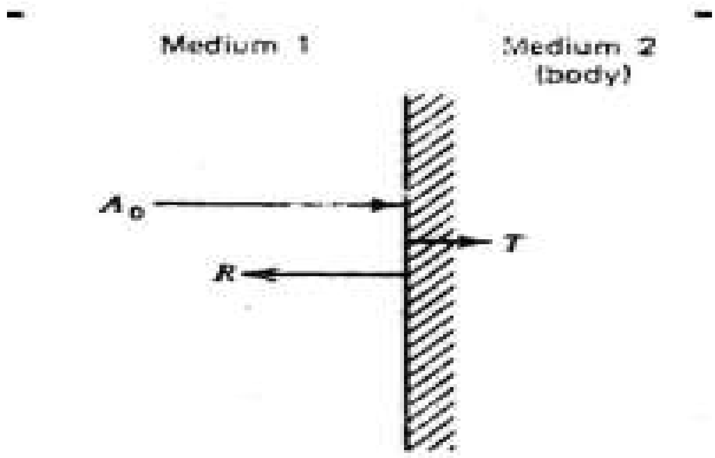
For hearing tests, it is convention to use a reference sound intensity or sound pressure to which other sound intensities can be compared. The reference sound intensity 10^{-16} W/cm², or 10^{-12} W/m²

$$P_o \doteq 2\text{x } 10^{-4} \text{ dyne/cm}^2$$

If a sound intensity is given in decibels with no reference to any other sound intensity, you can assume that I_o is the reference intensity.

<u>(H.W)</u>: The sound intensity levels of 10^4W/m² can cause damage of the eardrum diaphragm. What is the displacement of the diaphragm at such intensity adopting an average frequency 1000Hz? Where the acoustic impedance for tissue equal $1.64\text{x}10^4$Kg/m².s.

When a sound wave hits the body, part of the wave is reflected and part is transmitted into the body.



R : is the reflected pressure amplitude
$\mathbf{A_o}$:is the incident pressure amplitude
The ratio of $\mathbf{R/A_o}$ depends on acoustic impedance of the two media, $\mathbf{Z_1}$ and $\mathbf{Z_2}$.
The relationship is

$$R/A_o = Z_2 - Z_1 / Z_1 + Z_2$$

For a sound wave in air hitting the body, Z_1 is the acoustic impedance of air and Z_2 is the a acoustic impedance of tissue.
-If $\mathbf{Z_1 = Z_2}$
There is no reflected wave and transmission to the sound medium is complete
-If $\mathbf{Z_2 < Z_1}$
The sign change indicates a phase change of reflected wave.
The ratio of the transmitted pressure amplitude **T** to the incident wave amplitude $\mathbf{A_o}$ is

$$T/A_o = 2Z_2/Z_1 + Z_2$$

It is obvious that whenever acoustic impedances differ greatly there is almost complete reflection of sound intensity this is the reason heart sounds are poorly transmitted into the air adjacent to the chest.
Ex.2: Calculate the ratios of the pressure amplitudes and intensities of the reflected and transmitted sound waves from air to muscle.
$\mathbf{R/A_0} = (\mathbf{1.64 \; x \; 10^6 - 430}) / (\mathbf{1.64 \; x \; 10^6 + 430})$
= 0.9995
$T/A_o = 2(\mathbf{1.64 \; x \; 10^6}) / \mathbf{1.64 \; x \; 10^6 + 430} \simeq 1.9995$
Also we obtain the ratios of the reflected and transmitted intensities
$\mathbf{(R^2/2Z_1)/(A_0^2/2Z_1) = (R/A0)^2 = (0.9995)^2 = 0.9990}$
$\mathbf{(T^2/2Z_2)/(Ao^2/2Z_1) = Z_1/Z_2(T/A_o)^2 = 0.001}$
When the acoustic impedances of the two media are similar almost all of the sound is transmitted into the sound medium, choosing materials with similar

acoustic impedance is called impedance matching. Getting sound energy into the body requires impedance matching.

Example.3

Calculate the amplitudes and intensities of the reflected and transmitted sound waves from water to muscle using the values from Table

$\boldsymbol{R/A_o}=(\mathbf{1.64-1.48})\boldsymbol{x}\mathbf{10^6}/(\mathbf{1.64+1.48})\boldsymbol{x}\mathbf{10^6} = \mathbf{0.0513}$

$\boldsymbol{T/A_o}=\mathbf{2}(\mathbf{1.64})\boldsymbol{x}\mathbf{10^6}(\mathbf{1.64+1.48})\boldsymbol{x}\mathbf{10^6} = \mathbf{1.0513}$

The ratio of the reflected and transmitted intensities are now

$(\boldsymbol{R/A_o})^2 = (\mathbf{0.05013})^2 = \mathbf{0.0026}$

$\boldsymbol{Z_1/Z_2}(\boldsymbol{T}^{\,2}/\boldsymbol{A_o}) = (\mathbf{1.48}\ \boldsymbol{x}\mathbf{10^6}/\mathbf{1.64}\ \boldsymbol{x}\mathbf{10^6})\ (\mathbf{1.0513})^2 = \mathbf{0.9974}$

When a wave hits an angle Θ_i to a boundary between two media

$$\boldsymbol{sin}\Theta_1/\boldsymbol{V_1} = \boldsymbol{sin}\Theta_2/\boldsymbol{V_2}$$

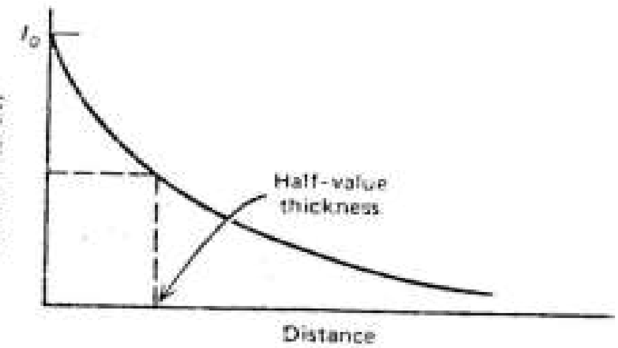
$\mathbf{V_1}$ and $\mathbf{V_2}$ are the velocities of sound in two media, $\boldsymbol{\Theta_1}$ is the angle of the incident wave, $\boldsymbol{\Theta_2}$ is the angle of the refracted sound wave. Because sound can be refracted, acoustic lenses can be constructed to focus sound waves.

When sound wave passes through tissue, there is some loss of energy due to frictional effects. The absorption of energy in the tissue cause a reduction in the amplitude of sound wave. The amplitude **A** at a depth **X** cm in medium is related to initial amplitude **A_o(x=0)** by the exponential equation

$$\boldsymbol{A} = \boldsymbol{A}_o\boldsymbol{e}^{-\alpha x}$$

Where α , is the absorption coefficient for the medium. Since the intensity is proportional to the square of the amplitude, its dependence with depth is

$$\boldsymbol{I} = \boldsymbol{I_0}\,\boldsymbol{e}^{-2\alpha x}$$



Where $\boldsymbol{I_0}$ is the incident intensity at **X = 0** and **I** is intensity at a depth **X2α** absorption coefficient. The half-value thickness (**HVT**) is the tissue thickness needed to decrease $\boldsymbol{I}$ to $\boldsymbol{I_0}$**/2.**

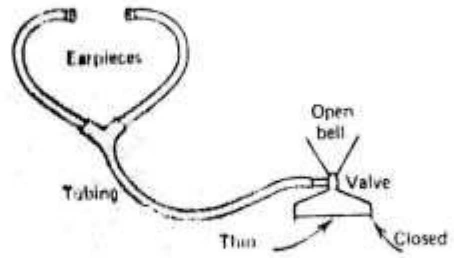
Ex.4: What is the attenuation of sound intensity by 1 cm of bone at 0.8, 1, 2, and 1.6 MHz?

-AT 0.8 MHz, the HVT is 0.34 cm, there for 1 cm is about 3 HVT and intensity is reduced by 2^3, or by factor 8 (i.e ~ 12% remains).

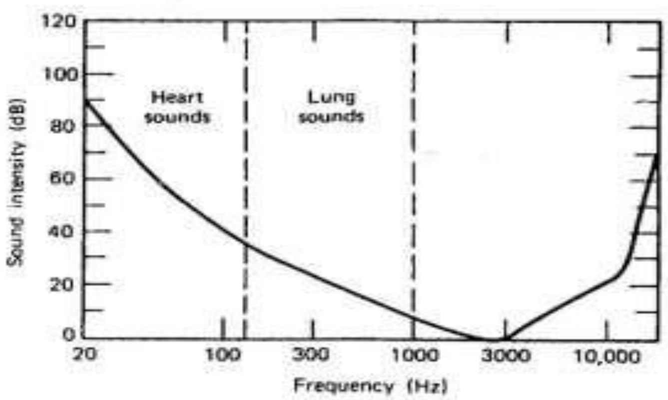
-AT 1.2 MHZ, the HVT is 0.21: 1 cm is nearly 5 HVT, and intensity is reduced by almost 25, or by factor 3^2 (i.e ~ 3%).

-AT 1.6 MHz, the HVT is 0.11 cm : 1 cm is about 9HVT, and intensity is reduced by 2^9, or by factor of 512 (i.e ~ 0.9%) remains.

The stethoscope:
The act of listening sounds with a stethoscope is called mediate auscultation or usually just auscultation.
The main parts of a modern stethoscope are bell, which is either open or closed by a thin diaphragm, the tubing and the earpieces.



The open bell is an impedance matcher between the skin and the air and accumulates sounds from the contacted area. The skin under the open bell behaves like a diaphragm. The skin diaphragm has a natural resonant frequency at which it most effectively transmits sound; it is possible to enhance the sound range of interest by changing the bell size and varying the pressure of the bell against the skin and the skin tension.
A low frequency heart murmur will appear to go away if the stethoscope is pressed hard against the skin.
A closed bell is merely a bell with a diaphragm of known resonant frequency, usually high, that tunes out-low frequency sound, it is resonant frequency is controlled by the same factors that control the frequency of the open bell pressed against the skin.
The closed bell stethoscope is primarily used for listening to lung sounds, which are of higher frequency ranges of heart and lung sounds.



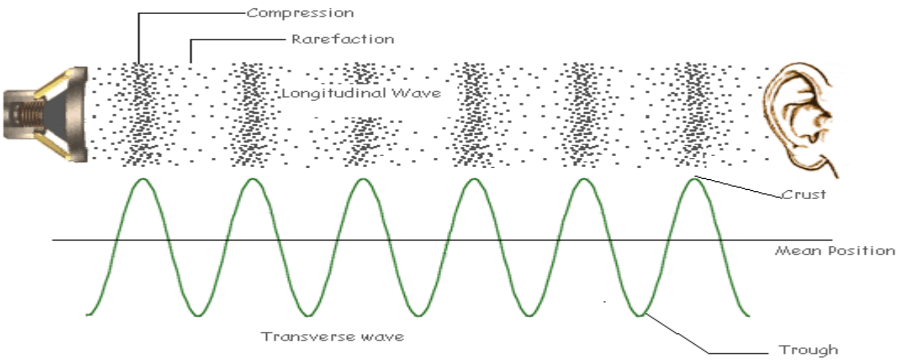
What is the best shape for the bell?
It is desirable to have a bell with as small a volume as possible.
The smaller the volume gas , the greater the pressure change for given movement of the diaphragm at the end of the bell.

The volume of tubes should also be small. And there should be little frictional loss of sound to the walls of the tube.
Below about 100 Hz tube length does not greatly affect the efficiency. But above this frequency decreases as the tube is lengthened.
AT 200 Hz 15 dB is lost in changing from tube 7.5 cm long to tube 66 cm long. A compromise is a tube with a length of about 25 cm and diameter of 0.3 cm.

Ultrasound in medicine :

-Infrasound
1. < 20 Hz 2. Earthquake, atmospheric pressure changes, blower in ventilator 3. Not audible 4. Headaches and physiological disturbances
- Sound
1. 20 ~ 20,000 Hz 2. Audible
- Ultrasound
1. > 20 kHz 2. Not audible 3. Medical imaging, blood flow measurements, …etc

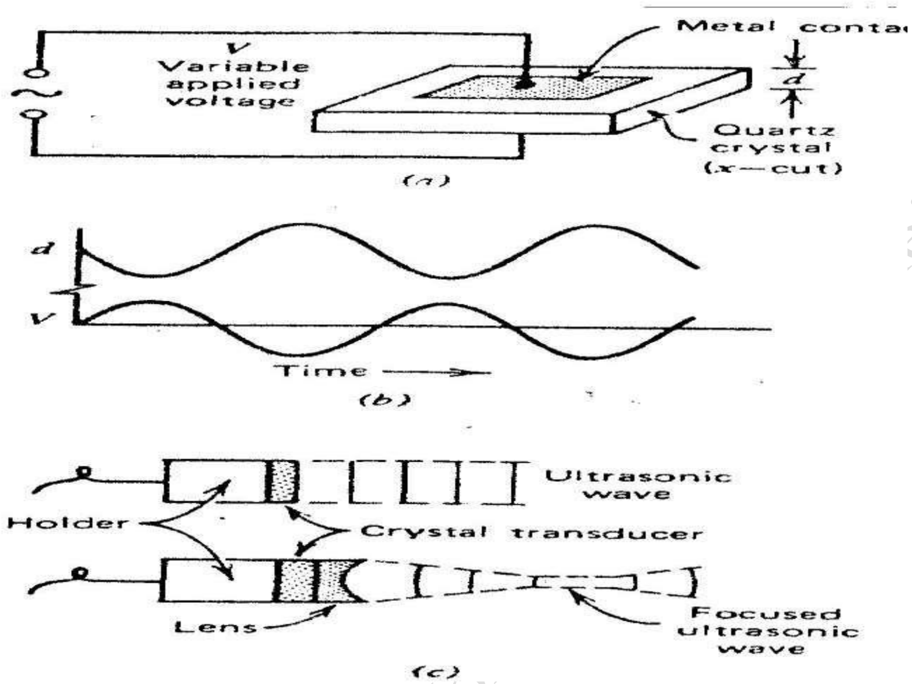
Ultrasound or sound waves are mechanical, longitudinal, pressure wave, requires medium for its transmission (gas or liquid or solid).



Human ears respond to sound in the frequency range of about **20** to **20000 Hz**, although many animals can produce & hear sounds of higher frequencies. For example, bats emits blips of ultrasonic frequencies(30Hz-100KHz) & navigate by listening to the echoes.
It was discovered, during "**world war Ⅱ**", that man can use ultrasound in much the same way bats can. The navy developed the (***SONAR***)" Sound Navigation & Ranging"
SONAR is a method of locating under water objects, such as "submarines", with ultrasound echoes.
Medical engineers developed techniques for using ultrasound for diagnosis. 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 distances to the various structures or organs in the path of the ultrasound beam.

There are several methods of generating ultrasound. The most important for medical applications involves the *piezoelectric effect*. Many *crystals* can be cut so that on oscillating voltage across the crystals will produce a similar vibration of the crystal, thus generating a sound wave.



Ultrasound Imaging:

The basis for the use of ultrasound in medicine is the partial reflection of sound at the surface between the two media that have different acoustical properties .

The amount of reflection depends on:

1- The difference in the acoustical impedances of the two materials.

2-The orientation of the surface with respect to the beam.

Since the transmitter & detector are the same unit, the most intense detected signals are due to the reflection from surface perpendicular to the beam (i.e., the perpendicular surfaces give more intense beam).

Medical Generation of Ultrasound

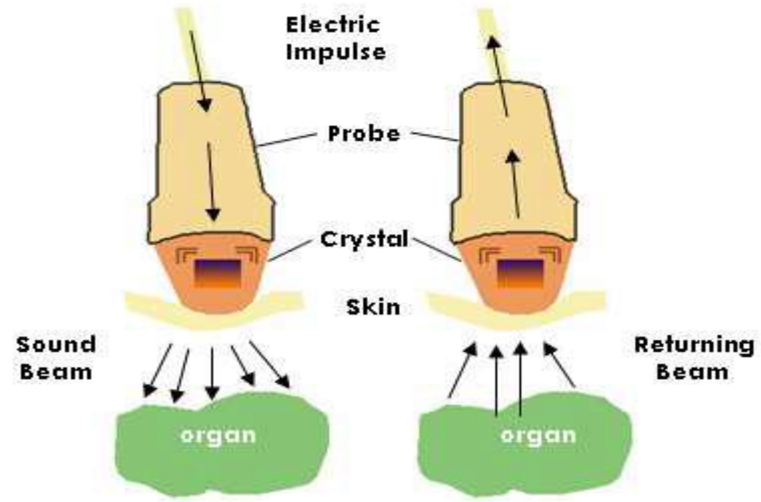
The most important method for generating ultrasound for medical applications involves the piezoelectric effect.

Many crystals can be cut so that an oscillating voltage across the crystal will produce a similar vibration of the crystal.

Transducer

A device that converts electrical energy to mechanical energy or vice versa is called *transducer*.

Each transducer has a natural resonant frequency of vibration. The thinner the crystal, the higher the frequency at which it will oscillate. For a *quartz crystal* cut long a certain axis (X – cut), a thickness of **2.85 mm** gives a resonant frequency of about **1 MHz**.
Typical frequencies for medical work are in the **1** to **5 MHz** range.



Pulses of ultrasound are transmitted into the body by placing the vibrating crystal in close contact with the skin, using water or a jelly past to element the air. This gives a good coupling at the skin and greatly increases the transmission of the ultrasound into the body and of the echoes back to the detector (because air and tissues have difference acoustic impedances)..
A short pulse of ultrasound is emitted from the transducer and after a short time delay an echo is obtained at the receiver. The weak signal are then amplified and displayed on oscilloscope.

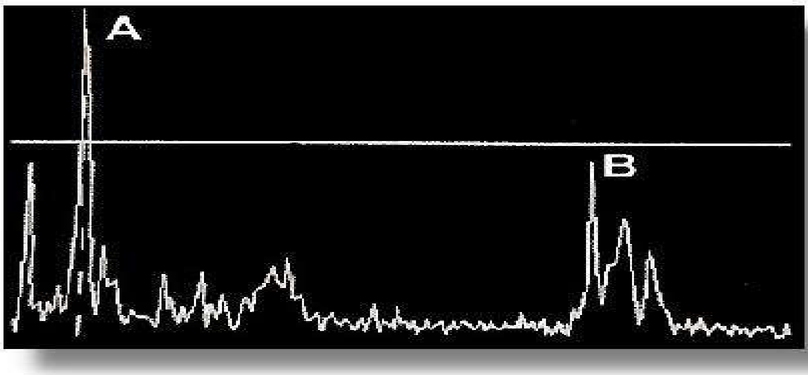
Modes of Imaging:

1- A-Mode (Amplitude mode)

To obtain diagnostic information about the depth of structure in the body, we send pulses of ultrasound in to the body & measure the time required to receive the reflected sound (echoes) from the various surfaces in it.

This procedure is called (A scan method) of ultrasound diagnosis. A scan gives one dimensional image.

Pulses for (A scan) work are usually emitted **400→ 1000 pulses/sec**.



The vibration of the crystal produced by the echoes generate a voltage across it – the signals are displayed on an oscilloscope. . Many of applications of ultrasound in medicine are based on the principles of sonar. In sonar a sound wave pulse is sent out and is reflected from an object, from the time required to receive the echo and the known velocity of sound in water, the distance to the object can be determined. This procedure is called the *A-scan* method of ultrasound diagnosis; pulses for A-scan work are typically a few microseconds.

A scan is used in…….

(1)- *Echoencephlography*

It is used in the detection of brain tumors. Pulses of ultrasound are sent in to a thin region of skull slightly above the ear & and echoes from the different structures within the head are displayed on an oscilloscope .The usual procedure is to compare the echoes from the left side of the head to the echoes from the right side & to look for a shift in the midline structure. A tumor in one side of the brain tend to shift the midline toward the other side.

Generally, a shift of more than (3mm) for an adult or (2mm) for a child is considered abnormal.

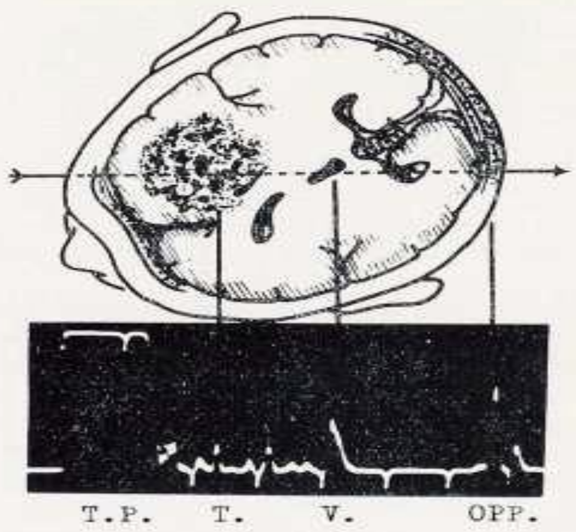


FIG. 16, 6
Tumour echo-pattern at right frontal (2·25 Mc).
T.P. = transmitted pulse.
T. = tumour echo.
V. = ventricle echo.
Opp. = opposite side of head.

(2)- *Ophthalmology*

Application of A scan in ophthalmology can be divided in to two areas:

a- The first one is concerned with obtaining information for use in the diagnosis of eye diseases.

b- The second one involves biometry.

Biometry:- measurements of distances in the eye such as the lens thickness, depth from cornea to lens, the distance to the retina & the thickness of the vitreous humor. which is a major determinant in common sight disorders.

The ultrasound that is used in ophthalmology has frequencies of up to (20 MHz). Theses high frequencies can be used in the eye to produce better resolution since there is no bone to absorb, most of the energy & absorption is not significant because the eye is small.

2- B-Mode (Brightness mode)

For many clinical purposes, A scans have been largely replaced by B scans.

The B scan method is used to obtain two dimensional views of parts of the body.

The principles are the same as for the A scan except that the transducer is moved.

As a result, each echo produces a dot on the oscilloscope at a position corresponding to the location of the reflecting surface.

B scan provide information about the internal structure of the body.

B scans have been used:-

1- In diagnostic studies of the eye, liver, breast, heart & fetus.
2- In detecting pregnancy as early as the fifth week.
3- In providing information about uterine anomalies
4- In giving information on the size, location & change with time of a fetus.
5-In giving information about abnormal bleeding & threatened abortion of pregnancy.

In many cases B scans can provide more information than x-rays & they present less risk.

For example, x-ray studies can only detect cysts that take up radiopaque solutions while ultrasound can be used to quantitatively image many types of cysts.

Gray Scale Display (B mode):

It is used to display the great variation of amplitudes of the echoes that arise from tissue.

I mean that the gray-scale display, electrically, changes the brightness on the cathode ray tube (CRT) so that large echoes appear brighter than weak echoes.

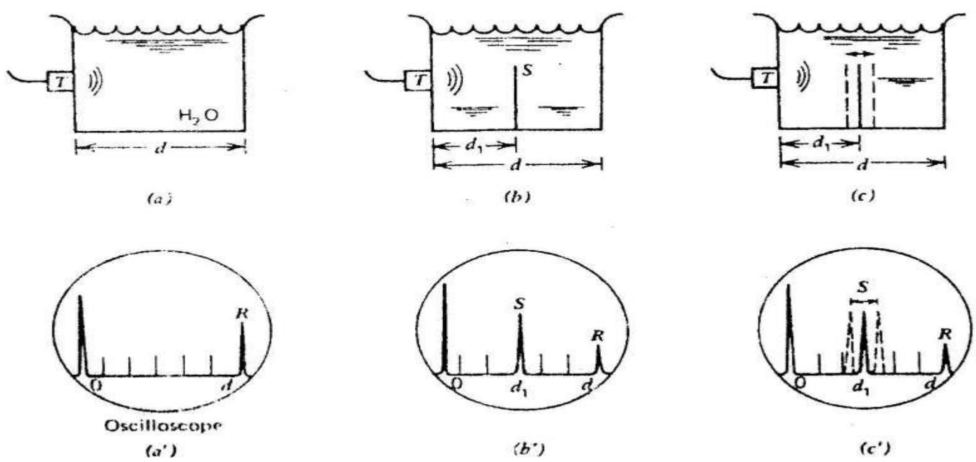
With the gray-scale display, tumors in the liver have been easily detected.

3-Real time scanning:

This mode displays motion by showing the images of the part of the body under the transducer as it is being scanned.

In this way a two dimensional B scan image is rapidly built up without lateral movement of the transducer head.

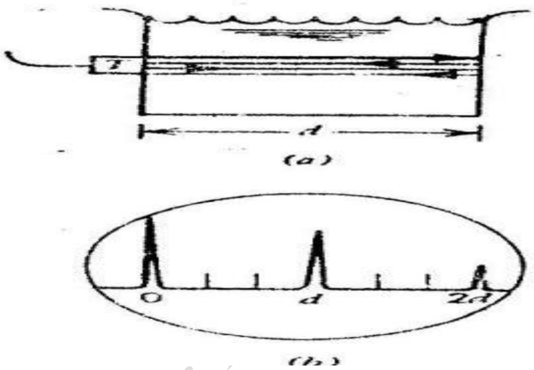
This happened when multiple B-mode images are watched in rapid sequence.



In(Fig a). a transducer **T** sends a pulse of ultrasound through a beaker of water of diameter **d**. The sound is reflected from the other side of the beaker and returns to the transducer, which also acts as a receiver. The detected echo is converted to an electrical signal and is displayed as the vertical deflection **R** on the Cathode Ray Tube (**CRT**) of an oscilloscope, fig a´ since the echo has been attenuated by the water, R is smaller in amplitude than the initial pulse shown in the oscilloscope at O.

In object in the beaker can be located with ultrasound. In (Fig b) a surface S at a distance d1 produces an additional echo.

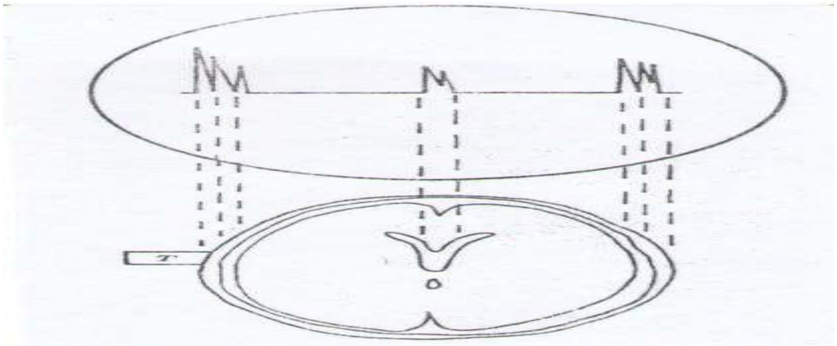
Which displayed on the oscilloscope as S at the position d_1 (Fig b´). Note that the echo R is now smaller. When the surface vibrates (Fig c), the position of the echo on the oscilloscope also moves Fig c´. It is also possible to have multiple reflections between surfaces. A pulse emitted at the transducer **T** is reflected from the far side and returns to the transducer, where apart is converted to a signal and apart is again reflected to the far side: this part returns to the transducer again and appears as a signal. Such a multiple echo appears in (Fig b) as an object at a distance **d** and a second object at **2d**.



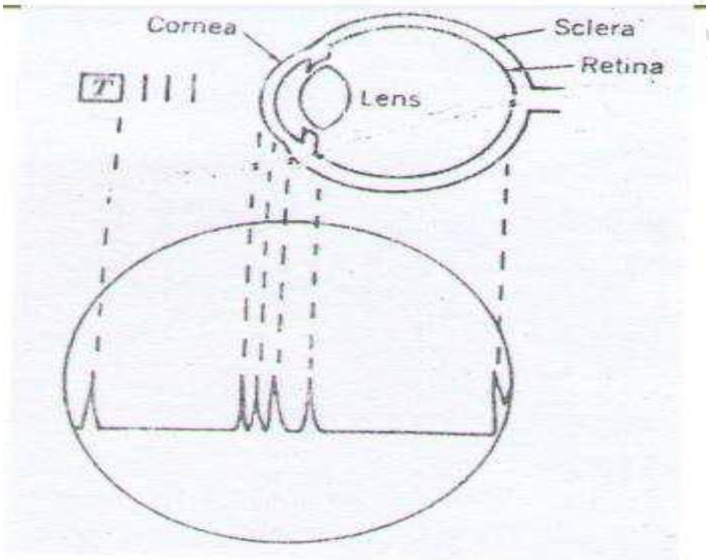
Another problem is the lack of resolution. Or the ability of the equipment to detect separate echoes from two objects close together. In general, structure smaller than the wavelength **λ** can not be resolved.

Since : $\lambda = V / f$

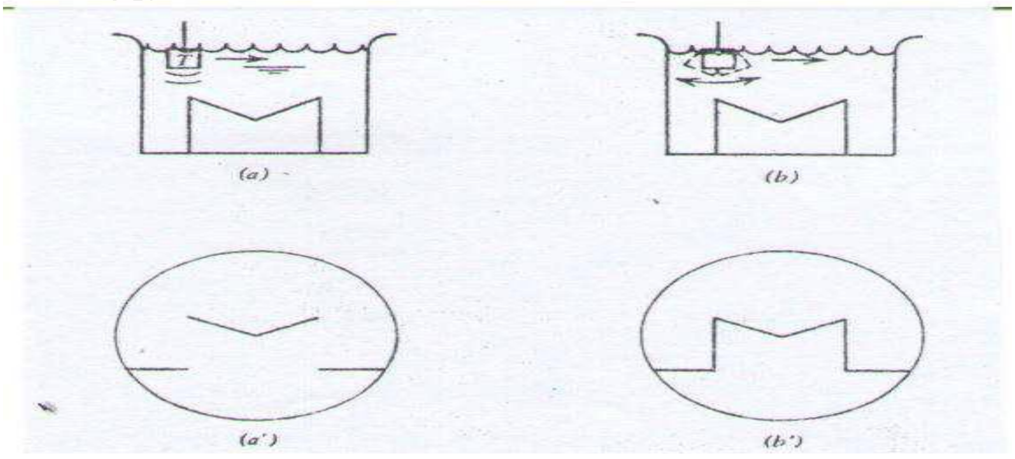
Where **V** is the velocity of sound and **f** is the frequency, the high frequency sound has shorter wavelengths and allows better resolution than low frequency sound. Since the absorption increases as the frequency increases. One scan procedure echo encephalography, has been used in the detection of brain tumors. Pluses of ultrasound are sent into thin region of the skull slightly above the ear and echo from the different structures with in the head are displayed on an oscilloscope. The usual procedure is to compare the echoes from the left side of the head to those from the right side and to look for a shift in the midline structure.



An ultrasound transducer **T** transmits sound through water into eye, and the reflected sound is displayed on an oscilloscope. It is possible to measure distance in the eye such as lens thickness, depth from cornea to the lens the distance to the retina.



The **B scan** method is used to obtain two-dimensional views of parts of the body.
The principles are the same as for **A scan** except that the transducer is moved as result each echo produces a dot on the oscilloscope at a position corresponding to the location of the reflection surface



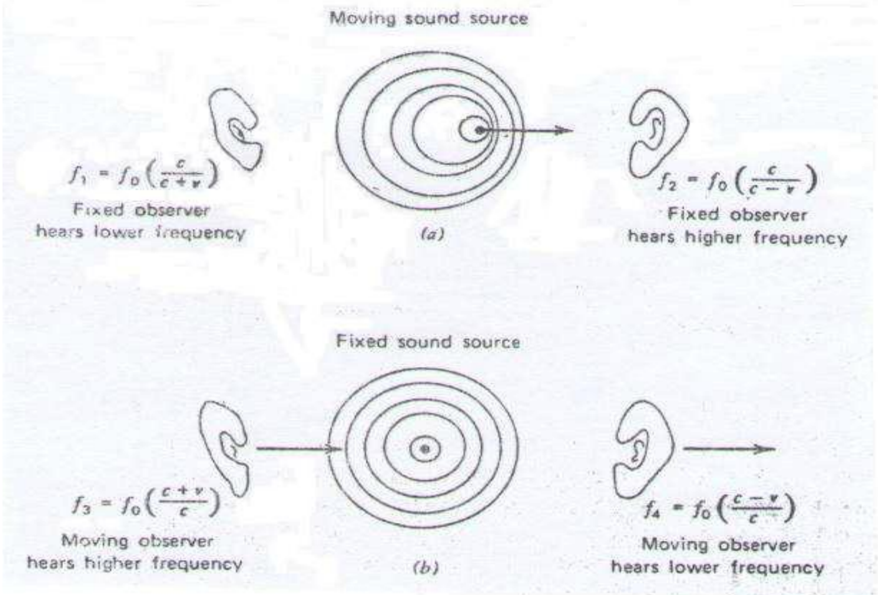
B scan provide information about the internal structure of the body. They have been used in diagnostic studies of the eye, liver, breast, heart and fetus. They can detect pregnancy as early as the fifth week.

Ultrasound to measure motion :

• Two methods are used to obtain information about motion in the body with ultrasound: the **M scan**, which used to study motion as that of the heart and the heart valves, and the ***Doppler*** *technique*, which is used to measure blood flow.

• The **M scan** combines certain features of **A scan** and **B scan**.
The transducer is held stationary as in the **A scan** and the echoes appear as dotes in the **B scan**.

• **M scan** are used to obtain diagnostic information about the heart. The rate of closing for a normal valve is indicated by the slope.
The frequency change is called the ***Doppler*** *shift*. When the sound source is moving toward the listener or when he is moving toward the source, the sound waves are pushed together and he hears a frequency higher than f_o.
When the source is moving away from the listener or when he is moving away from the source, he hears a frequency lower than f_o.

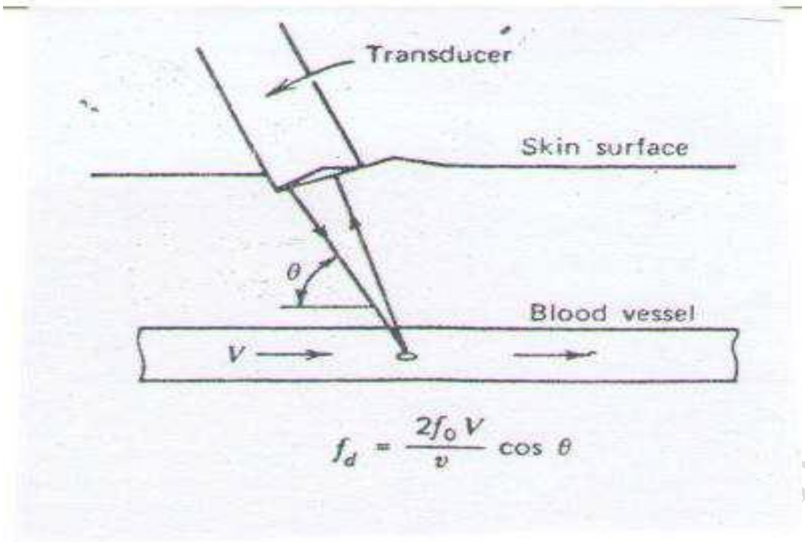


The *Doppler Effect* can be used to measure the speed of moving objects or fluids within the body, such as the blood.
When the blood is moving at an angle θ from the direction of the sound waves, the frequency change f_d is

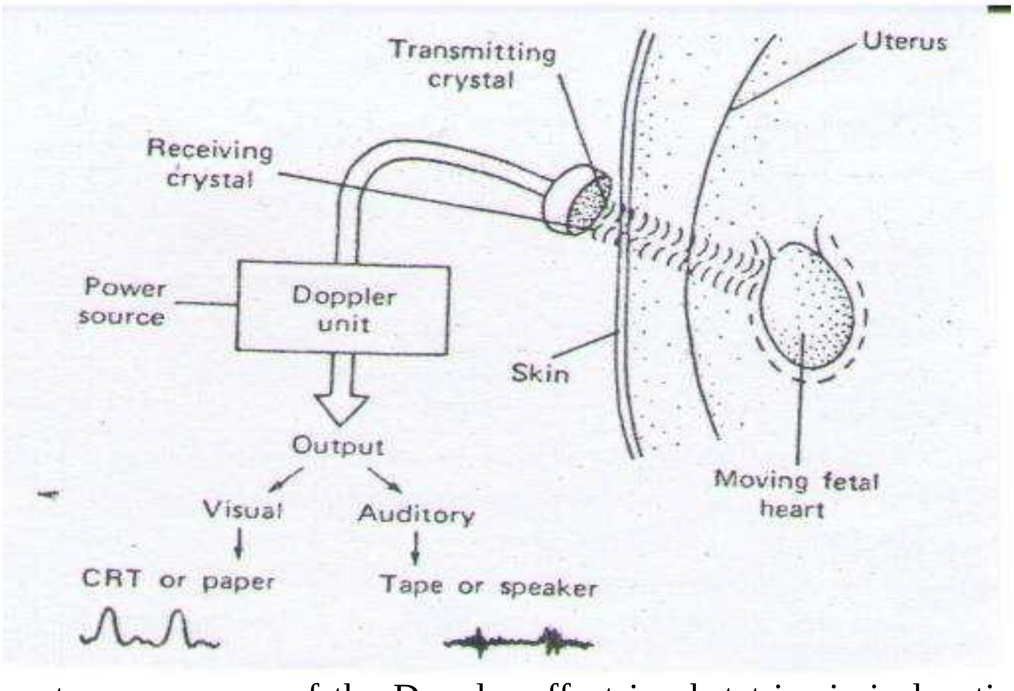
$$f_d=(2f_o V/\gamma)\cos\theta$$

Where f_o is the frequency of initial ultrasound wave
V is the velocity of blood

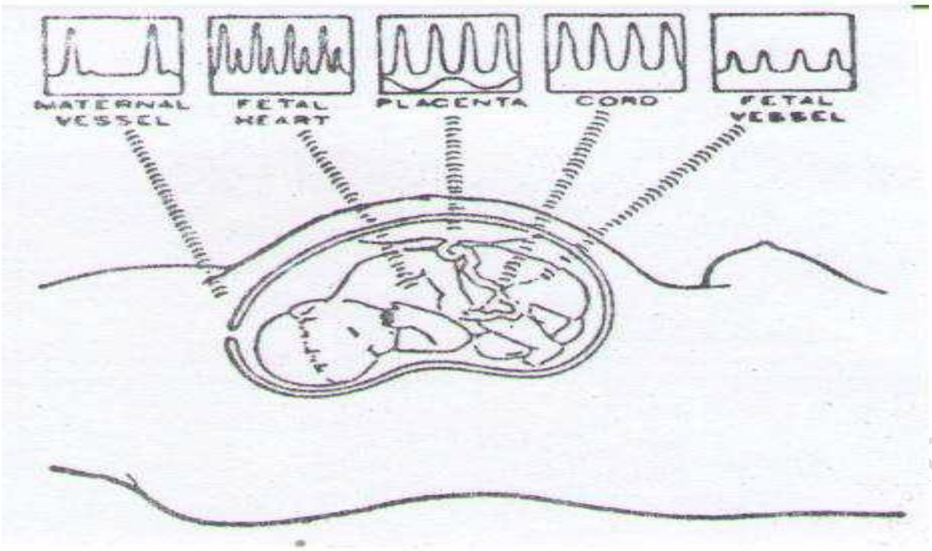
$\boldsymbol{\gamma}$ is the velocity of sound…..$\boldsymbol{\theta}$ is the angle between V and $\boldsymbol{\gamma}$



The Doppler Effect is also used to detect motion of the fetal heart, when a continuous sound wave of frequency f_o is incident upon the fetal heart, the reflected sound is shifted to frequencies slightly higher than f_o when 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 rate.



The most common use of the Doppler effect in obstetrics is in locating the point of entry of the umbilical cord (artery) into placenta.



Physiological effects of ultrasound in therapy :

Various physical and chemical effects occur when ultrasonic pass through the body, and they can cause physiological effects. The magnitude of the physiological effects depends on the frequency and amplitude of the sound.

At the very low intensity used for diagnostic work **(0.01W/cm^2).**

Average power and **(20 W/cm^2)** peak power ultrasound is used as a deep heating agent at continuous intensity levels of about **1 W/cm**^{2}.

A tissue-destroying agent at intensity levels of **10^3 W/cm^2**.The primary physical effects produced by ultrasound are temperature increase and pressure variations. The primary effect used for therapy is the temperature rise to the absorption of a acoustic energy in the tissue.

Ultrasound waves differ completely from electromagnetic waves, they interact with tissue primarily by microscopic motion of the tissue particles. As a sound wave moves through tissue, the region of compression and rarefaction cause pressure differences in adjacent region of tissue. Stretching occurs in these regions. If the stretching exceeds the elastic limit of the tissue, tearing results. This is why an eardrum can be ruptured by a very intense sound. In physical therapy the typical intensity is about **1** to **10 W/cm^2** and the frequency about **1** MHz.

Using equation $\mathbf{I} = (1/2) Z\, (\mathbf{A\, W})^2$

We find that amplitude of displacement **A** at **10 W/cm^2** in tissue is about **10^{-6} cm**. The maximum pressure amplitude $\mathbf{P_o}$

Equation : $\mathbf{I} = P_o{}^2/2Z$

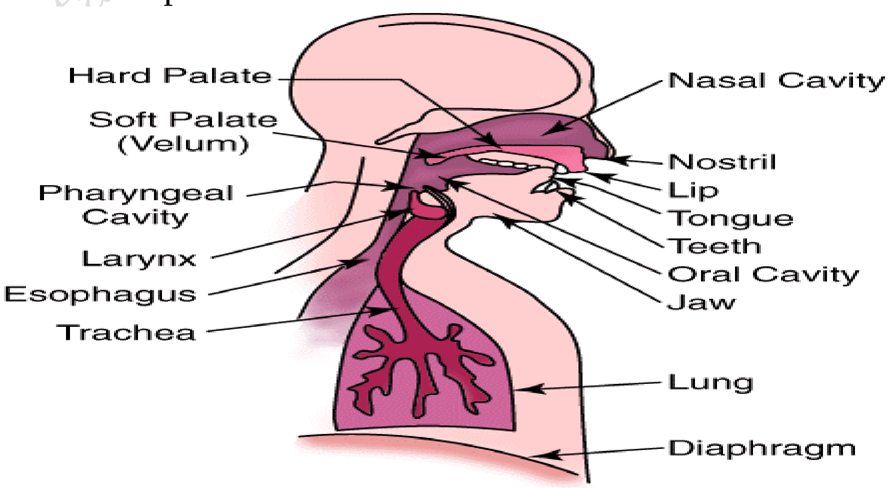
Is approximately **5 atom**

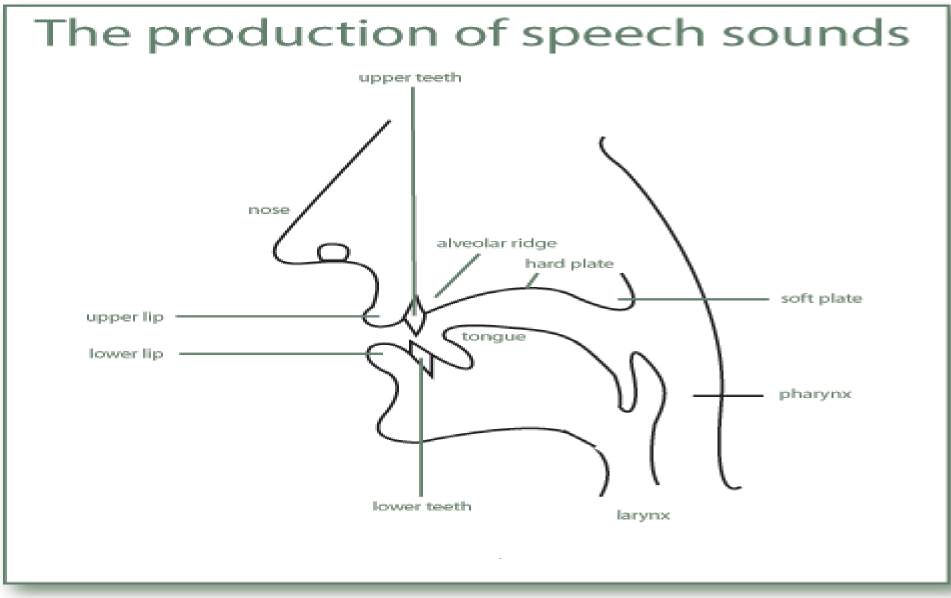
The Production of Speech (Phonation):

- Modulation of outward flow of air →speech

- Stream of air in voiced sound: lungs →vocal folds (cords, glottis) → several vocal cavities →mouse and nostrils

- Unvoiced sounds are produced in the oral portion of the vocal tract without the use of vocal folds: air flow through constrictions or past edges formed by the tongue,teeth, lips, and palate
+ Plosive sound: p, t
+ Fricative sound: s, f, th
+ Combination sound: ch
- Source-filter model of vocal tract
- Vocal folds
1. Within the *larynx* or *adam's apple*.
2. Normal respiration: large triangular openning
3. Speech production: drawn close together by muscles →air pressure below the vocal folds rises →closed folds are forced apart →rapid upward air flow →decrease in pressure between folds →elastic forces in the tissue →move folds together →partial blockage of passage →reduced air velocity →increase the air pressure below the vocal folds →recycle …→complex vibration
- Fundamental frequency of vibration: mass and tension of the vocal folds
1. Men: longer and heavier vocal folds →125 Hz
2. Women: 250 Hz
3. Lowest frequency by base singer: 64 Hz
4. Highest frequency by a soprano: 2,048 Hz
- Vocal cavities: pharyngeal (throat), oral, and nasal cavities
1. Throat and nasal cavity: well fixed to each individual and determine the sound of voice
2. Oral cavity: can be changed by tongue, palate, and cheeks
- Production of speech:





- Speaking "Joe took Father's workbench out"
1. Energy: 3´10-5 ~ 4´10-5 J
2. Time: 2 s
3. Average power: 10 ~ 20 mW
4. Energy of continuous talking for a year < energy to boil a cup of water
5. Energy in vowel sound >> energy in consonant sound →vowels are easier to understand

(H.W)

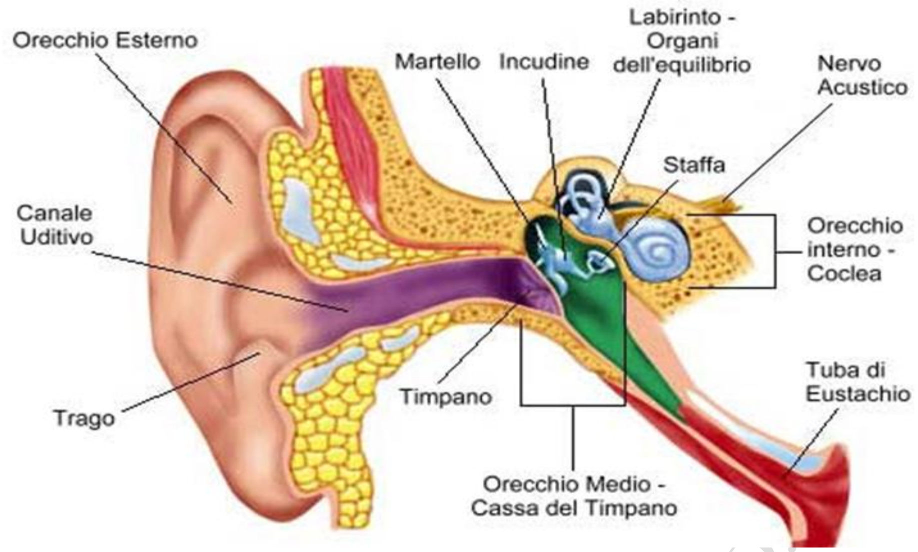
1.What is infrasound ?Ultrasound? Acoustic impedance? Transducer?
2.What is the attenuation of sound intensity in 15 cm of bran tissue ?(*Ans.0.037*) .
3.How is the ultrasound Doppler effect used to monitor fetal heart rate?
4.What is the difference between an ultrasound A scan and an ultrasound B scan?
5.What is the typical fundamental frequency of the vocal folds of men and women?

Physics of the Ear and Hearing:

- Hearing
1. 100 times greater dynamic range than vision
2. Wide frequency range (20 ~ 20,000 Hz)
- Sense of hearing
1. Mechanical system that stimulates the hair cells in the cochlea
2. Sensors that produce action potentials in the auditory nerves

3. Auditory cortex in the brain

- Ear:



conversion of weak mechanical waves in air into electrical pulses in the auditory nerve

1. *Outer ear*: ear canal and eardrum (tympanic membrane)
2. *Middle ear*: three small bones (ossicles) and Eustachian tube
3. *Inner ear*: cochlea (hair cells in the origin of Corti in the cochlea)

- Medical specialists

1. Otologist, MD: disease of the ear and ear surgery
2. Otorhinolaryngologist or ENT specialist, MD: disease of the ear, nose, and throat
3. Audiologist, non-MD: measuring hearing response, diagnosing hearing disorders, hearing aids

1. The Outer Ear

- External auricle or pinna: not a part of the outer ear

1. Negligible effect on hearing
2. Cupping hand behind the ear →6 ~ 8 dB gain

- External auditory canal

1. Storage of ear wax
2. 2.5 cm long with the diameter of a pencil (l/4 = 10 cm)
3. Increase the sensitivity in the region of 3000 ~ 4000 Hz
4. Resonance frequency of 3300 Hz (l = 10 cm):

- Eardrum or tympanic membrane

1. 0.1 mm thick (paper thin) and 65 mm^2
2. Couples the vibrations in the air to ossicles
3. Non-symmetric vibration .
4. At 3000 Hz, 10^{-9} cm movement for the sound intensity of the threshold of hearing

5. At lower frequency, longer movement
6. Sound pressure over 160 dB rupture the eardrum
7. Ruptured eardrum normally heals like other living tissues

2. The Middle Ear

- Three small bones or ossicles (Fig. 13.3): full adult size before birth, fetus can hear in the womb

- *Ossicles*

1. Impedance matching between the eardrum and the liquid-filled chamber of the inner ear
2. Malleus (hammer), incus (anvil), stapes (stirrup)
3. Force amplification by a factor of about 20

(**a**) Lever action amplifies the force by a factor of about 1.3 between M and S

(**b**) Piston action amplifies the force by a factor of about 15 between the eardrum and S

- *Ossicles and their sensory ligaments*

1. Protection against loud sounds: loud sound →muscles in the middle ear pull sideways on the ossicles in 15 ms or longer →reduce sound intensity by 15 dB
2. Noise pollution →may result in hearing loss

- *Eustachian tube*

1. Normally closed
2. Muscle movement during swallowing, yawing, or chewing causes a momentary opening

1. Equilibrate air pressure on both sides of the eardrum
2. Rapid pressure change →pressure difference across the eardrum →decreased sensitivity of the ear
3. 60 dB across the eardrum Þ pain
4. Viscous fluid from a head cold and the swelling of the tissue around the entrance of the tube →blockage of the Eustachian tube

3. The Inner Ear

- Best-*protected sense organ* (hidden deep within the hard bone of the skull)

- *Oval window*

1. Flexible membrane
2. Interface between the ossicles and the cochlea
3. Stapes transmits pressure vibrations to the cochlea through the oval window

- *Cochlea*

1. Small, spiral-shaped, fluid-filled structure
2. About the size of the tip of the little finger
3. About 3 cm long when straightened out

4. Produce coded electric pulses
5. The organ of Corti and three small fluid-filled chambers:
 vestibular chamber, cochlear duct, tympanic chamber
6. Vestibular chamber and tympanic chamber are interconnected at the end of the spiral
7. Pressure transmission: stapes →oval windows →vestibular chamber →end of the spiral →tympanic chamber →flexible round window at the end of tympanic chamber
8. Action potential generation: oval window →wave-like ripple in the basilar membrane →small shear force on hair cells in the organ of Corti →action potentials
9. Encoding
(**a**) Cochlear duct near the oval window →high-frequency sound
(**b**) Cochlear duct near the tip of the spiral →low-frequency sound
(**c**) < 10,000 Hz: frequency of nerve pulses is the same as sound frequency
(**d**) > 10,000 Hz: frequency of nerve pulses < 10,000 Hz, location is encoded
- *Auditory nerve*
1. Interface between the cochlea and the brain
2. Bundle of about 8000 conductors
3. Carries electric pulses from the cochlea containing frequency and intensity information of the sound.

Sensitivity of the Ear:
- Not uniform over 20 ~ 20,000 Hz
- Most sensitive range: 2 ~ 5 kHz
- Sensitivity is decreased for old people
1. 45 years old: no perception for over 12 kHz, need 10 dB more at 4 kHz than 20 years old
2. 65 years old: 25 dB loss for > 2 kHz
- Loudness
1. Proportional to the logarithm of intensity
2. Unit: phone, one phone = 1 dB sound at 1000 Hz, 10 phones = 10 dB sound at 1000 Hz
3. Frequency dependent

Testing Your Hearing
- Soundproof room
- Test sound: 250 ~ 8000 Hz
- Hearing threshold plot (Fig. 13.8)

Deafness and Hearing Aids

- Deaf or hard of hearing: problem in hearing 300 ~ 3000 Hz, hearing threshold of 90 dB
- Sound level: average 60 dB, 45 dB in a quiet room, 90 dB in a noisy party
- Conduction hearing loss
1. May be temporary
2. May be due to solidification of the small bones in the middle ear
3. Surgery: replace the stapes with a piece of plastic
4. Use a hearing aids
- Nerve hearing loss
1. May affect only a limited frequency range
2. Use a cochlear implant (artificial ear)
- Hearing aids
1. Ear trumpet
2. Electronic hearing aids: microphone, amplifier, loudspeaker