Physics of the Ear and Hearing

Speech and hearing are the most important means by which we communicate with our fellow man. Through hearing we receive speech sounds from others and also listen to ourselves! In some ways it is more of a handicap to be born "**stone deaf**" than to be born blind. Any child who cannot hear the sounds from his own vocal cords cannot learn to talk without special training. In earlier times a child deaf from birth was also **mute**, or **dumb**, and since so much of our learning takes place through hearing, he often was not educated.

While deaf people can now be taught to speak, their voices usually sound abnormal since they have no easy way to compare them to the voice sounds produced by other people.

If a sound is loud enough, it can be "**heard**" by a def person through the sense of touch; ***for example***, he may feel vibrations of the exposed hairs on his body and thus "**hear**" the loud sound through the nerve sensors at the roots of the hairs.

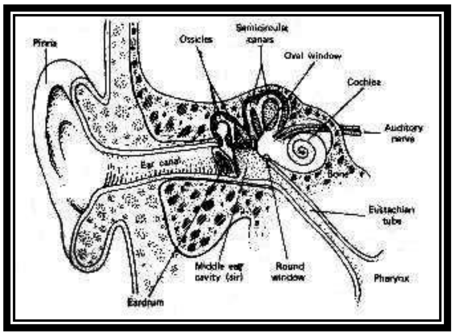
The sense of **hearing** is in some ways more remarkable than the sense of **vision**. We can hear a range of sound intensities of over a million million ($\mathbf{10^{12}}$), or **100** times greater than the range of light intensities the eye can handle. The ear can hear frequencies that vary by a factor of **1000**, while the frequencies of light that the eye can detect vary by only a factor of **2**.

<u>The sense of hearing involves: -</u>

1. The mechanical system that stimulates the hair cells in the cochlea.
2. The sensors that produce the action potentials in the auditory nerves.
3. The auditory cortex, the part of the brain that decodes and interprets the signals from the auditory nerves.

Deafness or **hearing loss** results if any of these parts **malfunctions**.

The ear is a cleverly designed converter of very weak **mechanical waves** in air into **electrical pulses** in the auditory nerve.



<u>**The ear is usually thought of as divided into three areas: -**</u>

- The **outer ear** consists of the ear canal, which terminates at the eardrum (**tympanic membrane**).
- The **middle ear** includes the three small bones (**ossicles**) and an opening to the mouth (**Eustachian tube**).
- The **inner ear** consists of the fluid-filled, spiral-shaped cochlea containing the organ of **Corti**. Hair cells in the organ of **Corti** convert vibrations of sound waves hitting the eardrum into coded nerve pulses that inform the brain of these sound waves.

The outer ear

The **outer ear** does not refer, as you might think, to the visible part of the ear, which in medical jargon is called the **external auricle** or **pinna**. The **outer ear** is the external auditory canal, which terminates at the **eardrum**. The outer structure, or **auricle**, is the least important part of the hearing system; it aids only slightly in funneling sound waves into the canal and can be completely removed with no noticeable loss in hearing, although its removal will not help anyone's appearance.

The **external auditory canal**, besides being a storage place for ear wax, serves to increase the ear's sensitivity in the region of **3000** to **4000 Hz**. The canal is about **2.5cm** long and the diameter of a **pencil**. You can think of the canal as an organ pipe closed at one end (**length=$\lambda/4$**) with a resonant frequency of about 3300Hz (**λ=10cm**).

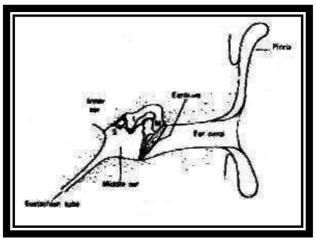
The **eardrum**, or **tympanic membrane**, is about **0.1mm** thick (**paper thin**) and has an area of about **65mm^2**. It couples the vibrations in the air to the small bones in the middle ear. Because of the off-center attachment of the **malleus**, the eardrum does not vibrate symmetrically like a drumhead.

However, it is clear that the actual movement of the eardrum is exceedingly small since it must be less than the movement of the air molecules in the sound wave. This movement at the **threshold of hearing** at **3000Hz** is about **10^{-9}cm**. At the **threshold of hearing** at the lowest frequencies that we can hear (**~20Hz**), the motion of the eardrum may be as large as **10^{-5}cm**.

It is possible for sound pressures above **160dB** to rupture the eardrum. A ruptured eardrum normally heals just as other living tissue does.

The middle ear

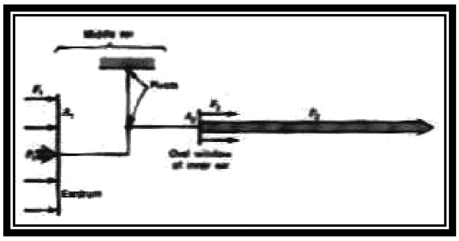
The dominant features of the middle ear are the **three** small bones (**ossicles**). These bones are full adult size before birth. (**The fetus can hear while it is still in the womb**).



The **ossicles** play an important role in matching the impedance of the sound waves at the eardrum to the liquid-filled chambers of the inner ear. The **ossicles** are named after the objects they resemble: the **malleus** (**hammer**), the **incus** (**anvil**), and the **stapes** (**stirrup**). They are arranged so that they efficiently transmit vibrations from the eardrum to the inner ear. They transmit poorly vibrations in the skull-even the large vibrations from the vocal cords. You hear your own voice primarily by transmission of sound through the air. Try plugging both your ears and listen to the reduction in your sound volume.

The **ossicles** amplify the pressure of the sound waves at the entrance to the inner ear. The **lever action** of the **ossicles** is such that the motion of the plate of the stapes at the **oval window** of the inner ear is about **0.7** that of the **malleus** at the eardrum.

Thus the **lever action** amplifies the force by a factor of about **1.3**. A much larger gain in pressure is obtained by the **piston action**.



The **eardrum**, which acts like a large piston, is mechanically coupled to the stapes, which acts like a small piston at the entrance to the inner ear. The ratio of the areas of the large eardrum and small oval window (A_1/A_2) increases the pressure by a factor of **15**.

$$\frac{A_1}{A_2}=\frac{\text{effective area of the eardrum}}{\text{effective area of the oval window}}=\frac{15}{1}=15$$

These factors produce a pressure P_2 at the oval window that is about **20** times higher than the sound pressure P_1 at the eardrum.

$$\textbf{total gain} = \textbf{lever gain x piston gain}$$
$$= \mathbf{1.3x15 \approx 20}$$

When a sound wave encounters a very different medium most of the sound energy is reflected. A sound wave in air striking a wall is about **99.9%** reflected; that is, only **0.1%** or **1** part in **1000** is transmitted! An attenuation of **1000** amounts to a sound loss of (**10 log 1000**) or **30dB**! The ear is designed to **reduce** this loss by **impedance matching**. In the ear, the factors that affect the impedance are primarily the **springiness** of the eardrum and its **mass**. The impedance in the ear is fairly well matched from about **400** to **4000 Hz**; below **400Hz** the "**spring**" is too stiff and above **4000Hz** the "**mass**" of the eardrum is too great. The middle ear aids the impedance match by **amplifying** the pressure by the **lever** and **piston** action.

The **ossicles** and their sensory ligaments play an important role in **protecting** the ear against loud sounds. A loud sound causes the muscles in the middle ear to pull sideways on the **ossicles** and reduce the sound intensity reaching the inner ear.

Persons living or working in an environment of loud sounds permanently loss some of their hearing sensitivity.

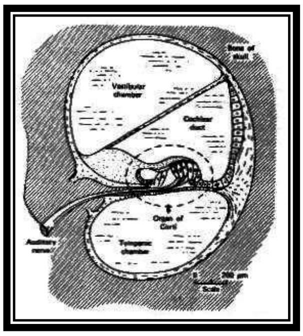
Another structure in the middle ear plays a protective role-the **Eustachian tube**, which leads down toward the mouth. It is considerably smaller and is normally closed rather than open. The middle ear contains air, and it is important for the air pressures on both sides of the thin eardrum to be essentially the same; the **Eustachian tube** serves to equalize the pressures. Air in the middle ear is gradually absorbed into the tissues, lowering the pressure on the inner side of the eardrum. The movement of the muscles in the face during **swallowing**, **yawning**, or **chewing** will usually cause a momentary opening of the **Eustachian tube** that equalizes the pressure in the middle ear with the atmospheric pressure. Pressure differences are usually noticed in situations in which the outside pressure changes rapidly in a short period of time, such as when **flying**, **riding**.

When for some reason the **Eustachian tube** does not open, the resulting pressure difference deflects the eardrum inward and decreases the sensitivity of the ear; at about **60mmHg** across the eardrum, the pressure difference causes pain. Common reasons for the failure of this equalizing system are the blockage of the **Eustachian tube** by the viscous fluids from a head cold and the swelling of tissues around the entrance to the tube.

The inner ear

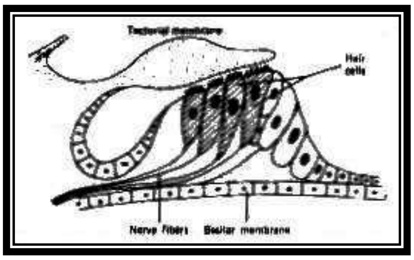
The **inner ear**, hidden deep within the hard bone of the skull, is man's best-protected sense organ. The **inner ear** consists a small spiral-shaped, fluid-filled structure called the **cochlea**. The **ossicles** of the middle ear communicate with the cochlea via a flexible membrane (**the oval window**); the stapes transmits its pressure variations of incoming sound waves across this membrane to the **cochlea**. The **cochlea** communicates with the brain via the **auditory nerve**-a bundle of about **8000** conductors that inform the brain via coded electrical pulses which parts of the **cochlea** are being stimulated by incoming sound waves. The auditory nerve provides information on both the **frequency** and the **intensity** of the sounds that we hear.

The **cochlea** is about the size of the tip of the little finger. If its spiral were straightened out, the cochlea would be about **3cm** (**~1.25in.**) long. It is divided into **three** small fluid-filled chambers that run its full length. The **oval window** is on the end of the **vestibular chamber**, the **middle chamber** is the **cochlear duct**, and the **third chamber** is the **tympanic chamber**.



The **vestibular** and **tympanic** chambers are interconnected at the tip of the spiral. Pressure produced at the **oval window** by the stapes is transmitted via the **vestibular chamber** to the end of the spiral and then returns via the **tympanic chamber**. Since fluid is almost incompressible; the cochlea needs a "**relief valve**"; the flexible **round window** at the end of the **tympanic chamber** serves this purpose.

A sound wave entering at the **oval window** produces a wave-like **ripple** in the basilar membrane of the **cochlear duct**. This duct contains the sensors that convert the sound into nerve signals.



The motions of this membrane are about **10 times** smaller in amplitude than the motions of the eardrum. Stimulation of nerves in the **cochlear duct** near the **oval window** indicates **high-frequency** sounds. **Low-frequency** sounds cause "**large**" motions in the basilar membrane and stimulation of nerves in the **cochlear duct** near the **tip of the spiral**.

The **transducers** that convert the **mechanical vibrations** into **electrical signals** are located in the bases of the fine hair cells in the organ of **Corti**. Apparently the small shear forces on these hair cells induce nerve impulses.

Sensitivity of the ears

The ear is not uniformly sensitive over the entire hearing range. Its best sensitivity is in the region of **2** to **5 kHz**. Sensitivity changes with **age**. The highest frequency you can hear will decrease as you get older, and the level of sounds will need to be greater for you to detect them. Hearing deteriorates more rapidly if the ears are subjected to continuous loud sounds.

The property of sound we call **loudness** is a mental response to the physical property called **intensity**. The **loudness** of a sound is roughly proportional to the logarithm of its intensity and this effectively compresses the huge range of sound intensities to which the ear responds (**$\sim 10^{12}:1$**). In addition, the **loudness** of a sound **depends** strongly on its **frequency**. A special unit has been designed for loudness-the **phon**. One **phon** is the loudness of a **1dB**, **1000Hz** sound; **10 phons** is the loudness of a **10dB**, **1000Hz** sound; and so forth. The **threshold of feeling** is about **120dB** at all frequencies.

The frequencies of most importance to us are those of the human voice. You can see that the ear is not optimized for the speech frequencies. However, it is possible to have a hearing loss of **40dB** and still hear most conversation.

If the ear were as sensitive at low frequencies as it is in the **3000Hz** region, we would be aware of many physiological noises, such as **blood flow** in the arteries in the head, **movement** of the joints, and possibly the small variations of pressure on the eardrum due to random motion of air molecules (**Brownian motion**). If you go into a special soundproof room used for testing hearing, you will be impressed by how many internal body sounds you hear. Most of these sounds are transmitted through **bone conduction** to the inner ear. These sounds are poorly detected by the ear, which is optimized for sounds coming via the **eardrum**. In general, a sound must be about **40dB** more intense to be heard by **bone conduction** than to be heard by **air conduction**.

Testing your hearing

If you have a hearing problem and consult an "**ear doctor**"-an **otologist** or **otolaryngologist**-he or she may send you to an audiologist to have your hearing tested. If you have a hearing loss, the **audiologist** will be able to determine whether it is curable; if it is not, your ability to use a hearing aid will be assessed.

The tests are normally done in a specially constructed soundproof testing room. Each ear is tested separately; test sounds can be sent to either ear through a comfortable headset. The subject is asked to give a sign when he hears the test sound. 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 can be compared to normal hearing thresholds. The normal **hearing threshold** at each frequency is taken to be **0dB**. The chart may show a general loss in one or both ears. Usually a hearing loss is **not uniform** over all frequencies.

Deafness and hearing aids

The frequency range most important for understanding conversational speech is from about **300** to **3000 Hz**. A person who is "**deaf**" above **4000Hz** but who has normal hearing in the speech frequencies is **not** considered deaf or even hard of hearing.

Hearing handicaps are classified according to the average **hearing threshold** at **500**, **1000**, **2000 Hz** in the better ear. A person with a hearing threshold **30dB** above normal would probably not have hearing problems. People with hearing thresholds of **90dB** are considered **deaf** or **stone deaf**. Hearing problems increase with **age**.

The average sound level of speech is about **60dB**. We adjust the sound level of our speech unconsciously according to the noise level of our surroundings.

<u>There are two common causes of reduced hearing: -</u>

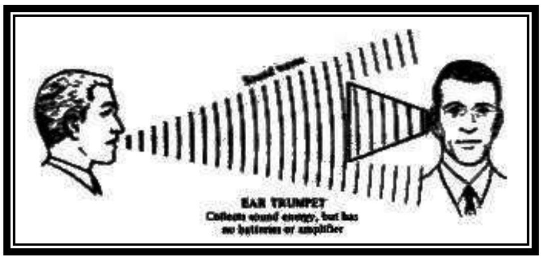
1. **Conduction hearing loss**, in which the sound vibrations do not reach the inner ear.
2. **Nerve hearing loss**, in which the sound reaches the inner ear but no nerve signals are sent to the brain.

Conduction hearing loss may be temporary due to a plug of wax blocking the eardrum or fluid in the middle ear. It may, however, be due to a solidification of the small bones in the middle ear. This condition can sometimes be corrected by an operation in which the stapes, which pushes on the oval window, is replaced with a piece of plastic. If a conduction hearing loss is not curable, a hearing aid can be used to transmit the sound through the bones of the skull to the inner ear.

Nerve hearing loss may affect only a narrow band of frequencies or it may affect all frequencies. At present there is no known cure or aid for nerve hearing losses.

The **hearing threshold** that requires a person to use a hearing aid is quite variable. Some people lip-read to help them understand speech. The simplest hearing aid, which is quite effective if your hearing loss is not large, is to cup your hand behind your ear. This reflects about **6** to **8 dB** of additional sound into your ear canal. In addition, you will usually gain another **10dB** when the speaker notices you and raises his voice.

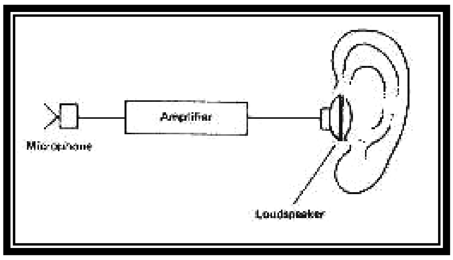
The earliest **artificial hearing aid** was the ear trumpet. The large opening catches the sound waves and the funnel concentrates the energy at the ear. The **size** and **shape** of the ear trumpet affect its efficiency.



The **auditory canal** has a resonance in the **2000** to **4000 Hz** region, at the upper end of the useful speech frequencies, while an ear trumpet has a resonance at the speech frequencies. A good ear trumpet will lower the **hearing threshold** by **10** to **15 dB**.

Electronic hearing aids are in common use today. Early electronic hearing aids were bulky, and the batteries wore out rapidly. The development of transistor amplifiers and miniaturized electrical components led to the development of hearing aids that can be concealed behind the ear or in the frames of glasses.

An **electronic hearing aid** is like a small public address system. It consists of a **microphone** to detect sound, an **amplifier** to increase its energy, and a **loudspeaker** to deliver the increased energy to the ear.



It is possible to obtain an amplification of **90dB** or an increase of **1 billion** in sound level. Even though a deaf person may have a hearing threshold of **70** to **80 dB**, his **discomfort threshold** is the same as that for a person with normal hearing, or about **100** to **120 dB**. Thus there is a practical upper limit on the sound output from an **electronic hearing aid**.

Hearing aids cannot return hearing to normal. They can only help compensate for the hearing loss. ***For example***, an abrupt hearing loss above **3000Hz** cannot be completely corrected with a **hearing aid**. Most **hearing aids** have a tone control that permits the wearer to adjust the frequency response, but its range of use is very limited.