Dr.Ghania Salim Al-Thaher Medical physics Physiology Department

College of Medicine

L28- Physics of the Ear and Hearing

Hearing: is the ability to perceive sound by detecting vibrations, changes in the pressure of the surrounding medium through time, through an organ such as the ear. It is one of the traditional five senses

In humans and other vertebrates, hearing is performed primarily by the auditory system: mechanical waves, known as vibrations are detected by the ear and transducer into nerve impulses that are perceived by the brain.

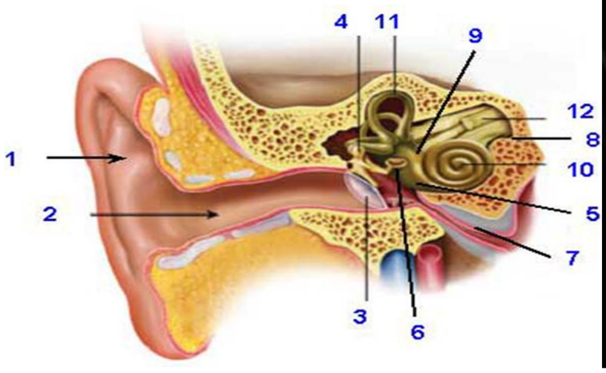
Structure of the ear

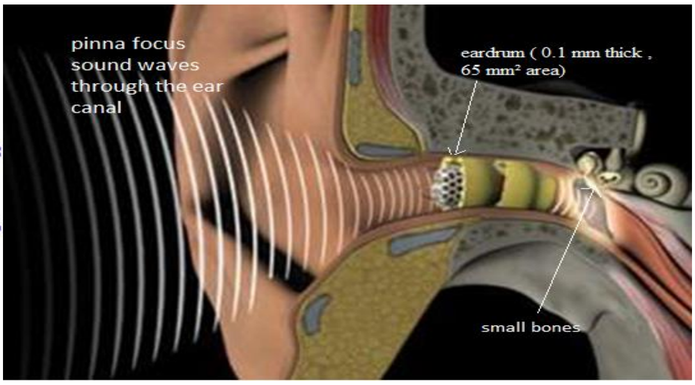
The human ear can be divided into three sections. Each section performs a different role in transmitting sound waves to the brain.

1. **Outer ear**
2. **Middle ear**
3. **Inner ear**

1. Outer ear

The outer ear consists of the visible portion on the side of the head, known as the pinna [1], and the external auditory canal (ear canal) [2]. The purpose of the pinna is to catch sound waves, amplify them slightly, and funnel them down the ear canal to the tympanic membrane (eardrum) [3]. The tympanic membrane is a very thin structure that separates the outer ear canal from the middle ear space.





The eardrum is about 0.1 mm thick and has an area of about 65 mm². It couples the vibrations in the air to the small bones in the middle ear.

The eardrum is an airtight membrane, and when sound waves arrive there, they cause it to vibrate following the waveform of the sound.

2. Middle ear

The middle ear is an air-filled cavity that sits between the tympanic membrane(eardrum) [3] and the inner ear. The hollow space of the middle ear has also been called the tympanic cavity, or *cavum tympani*.

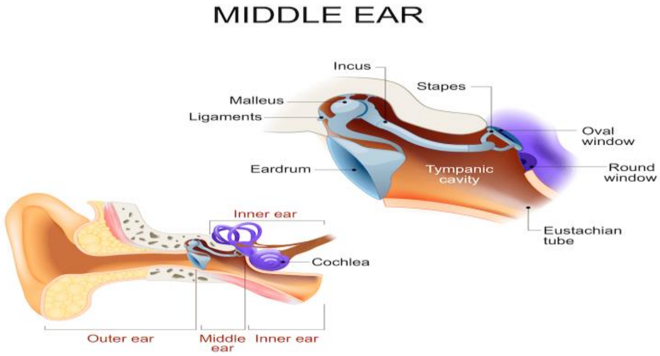
The middle ear also consists of three tiny bones called ossicles [4], the round window [5], the oval window [6], and the Eustachian tube [7].

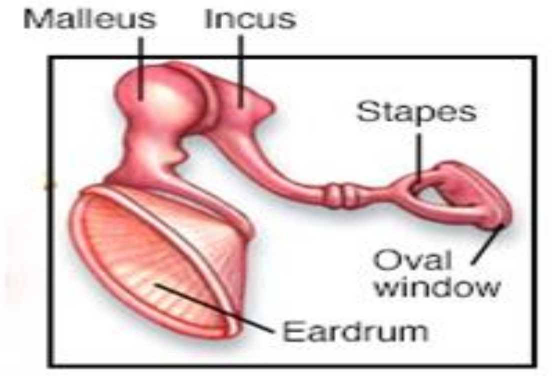
Ossicles and Their Function (there are the three smallest bones in the body),

- **Malleus (commonly known as the hammer)**
- **Incus (commonly known as the anvil)**
- **Stapes (commonly known as the footplate, or stirrup)**

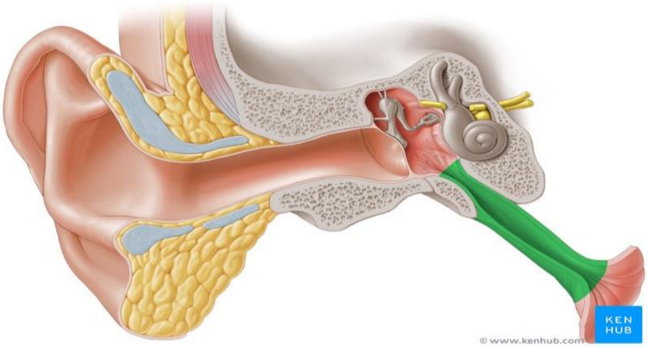
One end of the malleus is attached to the tympanic membrane and the other end is attached to the incus. The incus is attached to the stapes. The base of the stapes is located in a depression called the oval window [6].

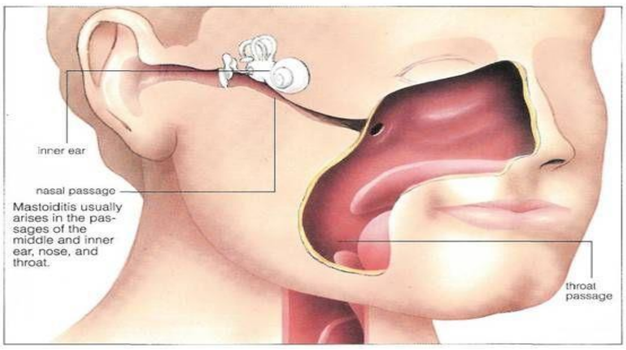
The function of these bones transfers the vibrations of the eardrum into waves in the fluid and membranes of the inner ear.





The Eustachian tube [7] connects the middle ear space to the upper part of the throat. In its normal state, the Eustachian tube stays closed, but it will open when you yawn, swallow, chew, or hold your nose and blow. The purpose of the Eustachian tube is to provide fresh air to the middle ear space and to equalize pressure between the outer ear and the middle ear. Ever wonder why your ears "pop" when you go up or down in an airplane or an elevator in a tall building? That sound is your Eustachian tube(s) opening and closing to equalize the air pressure in your ears.





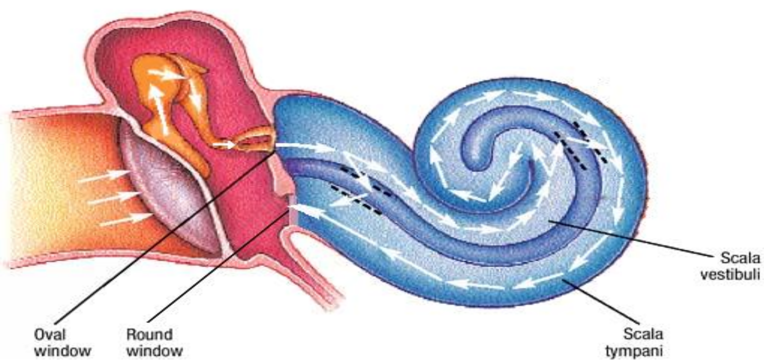
The oval window membrane is one of two membranes that separate the middle ear space from the inner ear. The other is the round window membrane.

The oval window

The stapes transmits sound waves to the inner ear through the oval window, a flexible membrane separating the air-filled middle ear from the fluid-filled inner ear.

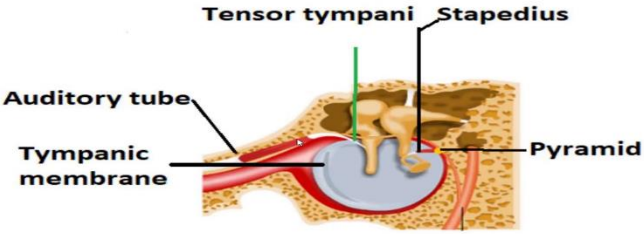
The round window

The round window, another flexible membrane, allows for the smooth displacement of the inner ear fluid caused by the entering sound waves.



What is the function of the middle ear?

1. **Efficiently transfer acoustic energy from compression waves in air to fluid–membrane waves within the cochlea**
2. **Pressure to equalize between the middle ear and throat.**
3. **Also located in the middle ear are the stapedius and tensor tympani muscles which protect the hearing mechanism through a stiffening reflex.**



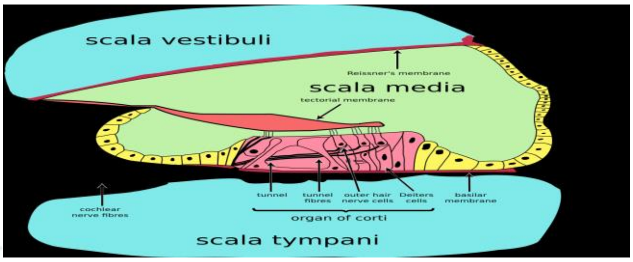
3. The Inner Ear

The inner ear is encased in the temporal bone [8] and consists of three parts:

1. **Vestibule [9]: the central inner ear cavity**
2. **Cochlea [10]: the organ of hearing**
3. **Semicircular Canals [11]: part of the balance system**

Parts of the Cochlea

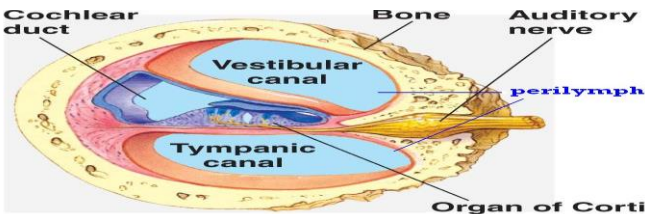
The cochlea is made up of three compartments (scala tympani, scala media, scala vestibuli) that are separated from each other by two membranes (basilar membrane and Reissner's membrane).

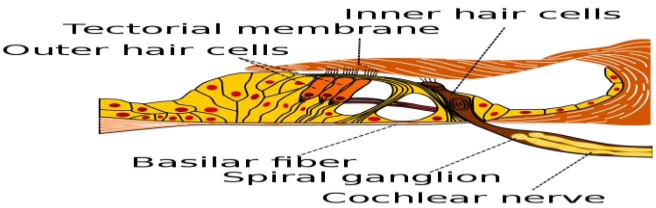


The basilar membrane, a structure that vibrates when waves from the middle ear propagate through the cochlear fluid – endolymph. The basilar membrane is tonotopic, so that each frequency has a characteristic place of resonance along it.

Organ of Corti

A tiny organ (organ of Corti) (is the sensory receptor inside the cochlea which holds the hair cells, the nerve receptors for hearing) it is sits on top of the basilar membrane. This hair cells, convert the mechanical energy from the vibrations of the basilar membrane into electrical impulses. Those electrical impulses are sent to the auditory nerve [12], which transmits the information up the brainstem to the auditory cortex.

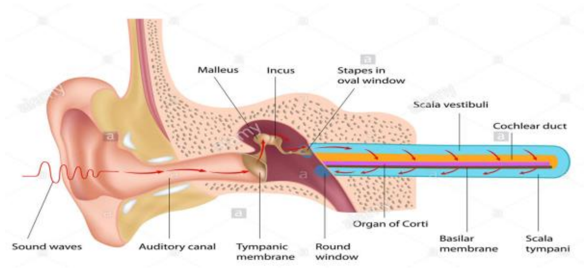


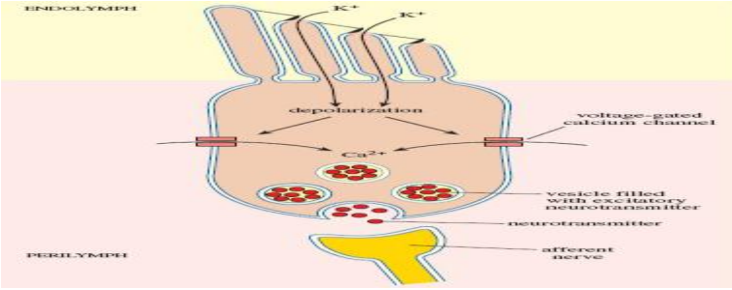


Hearing mechanism

- **The pinna catches sound waves and channels them down the external auditory canal, where they hit the tympanic membrane and make it vibrate.**
- **Those vibrations cause the three ossicles to move.**

- The stapes footplate pushes on the oval window membrane, which sets the cochlear fluid in motion.
- This wave-like motion causes the basilar membrane to vibrate.
- As the basilar membrane moves up and down, the tiny “hairs” (stereocilia) on top of the hair cells open and close to change the electrical charge of the cell (depolarization).
- Depolarisation of a hair cell leading to the release of chemical transmitter to the afferent nerve fibre contacting the hair cell which does produce action potentials.
- In this way, the patterns of oscillations on the basilar membrane are converted to spatiotemporal patterns of electrical signal which transmit information about the sound to the brainstem.(The auditory nerve sends these impulses up to the brain, where the signal is interpreted as sound.)





The analysis of sound frequencies by the basilar membrane.

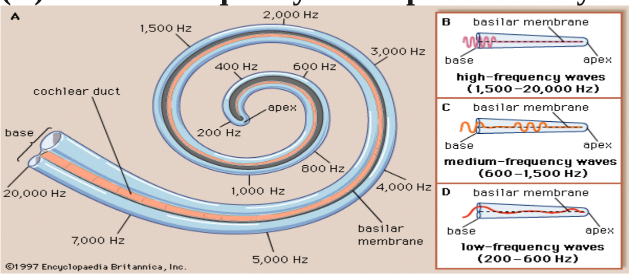
Characteristic frequencies are high at the basal entrance to the cochlea, and low at the apex. Basilar membrane motion causes depolarization of the hair cells,

(A) The fibres of the basilar membrane become progressively wider and more flexible from the base of the cochlea to the apex. As a result, each area of the basilar membrane vibrates preferentially to a particular sound frequency.

(B) High-frequency sound waves cause maximum vibration of the area of the basilar membrane nearest to the base of the cochlea;

(C) medium-frequency waves affect the centre of the membrane;

(D) and low-frequency waves preferentially stimulate the apex of the basilar membrane.



The Range of Human Hearing (Sensitivity of the Ear)

- The human ear can respond to minute pressure variations in the air if they are in the audible frequency range, roughly 20 Hz - 20 kHz
- It is capable of detecting pressure variations of less than one billionth of atmospheric pressure.

The human hearing range depends on both

- The pitch of the sound(frequency) – whether it is high or low – and
- The loudness of the sound.(Amplitude)

Pitch is measured in Hertz (Hz) and loudness is measured in decibels (dB)

Our ears can compress sound waves

- The middle ear has a mechanism which can adjust the intensity of sound waves striking our eardrums.
- This adjustment enables us to discriminate very small changes in the intensity of quiet sounds, but to be much less sensitive to volume changes in louder noises.
- This means that the human ear can safely hear a huge range of very soft to very loud sounds.

What is the threshold of human hearing?

- **In order for us to be able to hear a sound at all, it has to be above a certain level.**
- **This level is called the auditory threshold or hearing threshold.**
- **The threshold of hearing corresponds to air vibrations about a tenth of an atomic diameter.**
- **The hearing threshold I_o (10^{-12} w/m^2)**
- **This incredible sensitivity is enhanced by an effective amplification of the sound signal by the outer and middle ear structures.**
- **Contributing to the wide dynamic range of human hearing are protective mechanisms that reduce the ear's response to very loud sounds. Sound intensities over this wide range are usually expressed in decibels.**

Human hearing occurs in two dimensions:

Frequency and intensity.

- **In the frequency domain, the range of human hearing is between approximately 20 to 20,000 Hz.**
- **In the intensity domain, there is roughly 120 dB dynamic range.**

What do decibel and hertz mean

- **The volume or loudness of a sound is determined by the sound pressure level.**
- **The higher this is, the louder the sound is.**
- **Sound pressure level is measured in decibels (dB). The word "decibel" comes from "deci" (meaning "one tenth") and the name of the man who invented the decibel unit, Alexander Graham Bell.**
- **The frequency describes how high the pitch of a sound is. It is measured in hertz (Hz).**
- **The frequency is how many vibrations there are per second. For instance, 20 hertz means 20 vibrations per second. This very slow vibration can barely be heard as a very low pitch.**
- **The higher the frequency, the higher the pitch.**

A threshold shift is an increase in the hearing threshold for a particular sound frequency. It means that the hearing sensitivity decreases and that it becomes harder for the listener to detect soft sounds. Threshold shifts can be temporary or permanent.

- **PTS (Permanent Threshold Shift) is a permanent change of the hearing threshold (the intensity necessary for one to detect a sound) following an event, which will never recover. PTS is measured in decibels.**
- **TTS (Temporary Threshold Shift) is a temporary change of the hearing threshold the hearing loss that will be recovered after a few hours to couple of days. Also called auditory fatigue. TTS is also measured in decibels.**

The hearing threshold: is the sound level below which a person's ear is unable to detect any sound.

For adults, 0 dB is the reference level.

The hearing threshold Io (10^{-12} w/m^2),

Hearing Intensity level threshold 0 dB=10log (I/I_o)= 10 log(10^{-12} / 10^{-12}) =0

- **Above this threshold, sounds with higher sound pressure levels are heard as louder noises.**
- **Sounds above 90 dB can lead to chronic hearing damage if people are exposed to them every day or all the time.**
- **Hearing becomes uncomfortable if the sound pressure level is above 110 decibels (threshold of discomfort),**
- **Hearing becomes painful above 130 decibels (threshold of pain).**