Physics of the Ear and Hearing

The ear is the body's main receiver system for acoustic wave information.

The auditory system of the body is structured into a:

- **Mechanical system**, to catch and to amplify acoustical information (ear);
- **Sensory (electrical) system**, which converts mechanical pulses into electrical signals which are passed on the auditory nerves to the brain;
- **Auditory system**, to decode and analyze the electrical nerve signals in the auditory cortex (brain).

The ear itself can be structured into three sections with the purpose to receive acoustical signals and to amplify these signals, Fig.1:

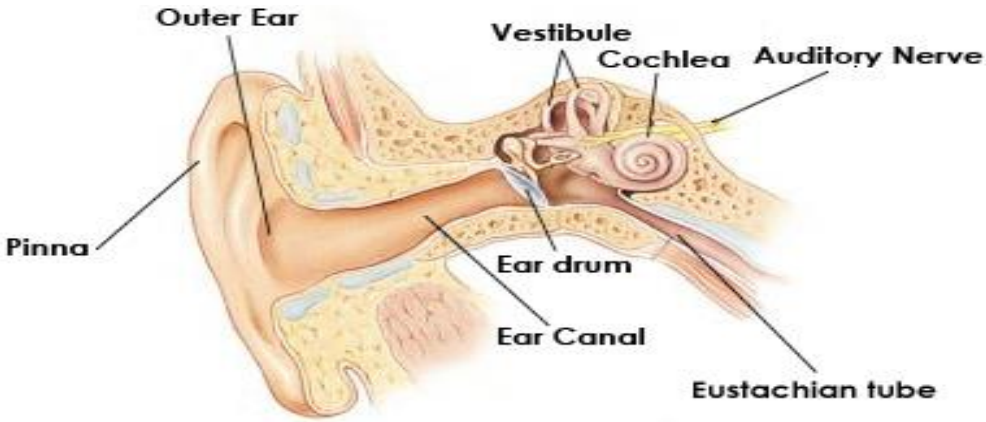


Fig. 1

Inner ear **Middle ear** **Inner ear**

Outer Ear	Middle Ear	Inner Ear
Description 2.5cm long ear canal terminated by the eardrum.	**Description** Cavity section containing by three bones (ossicles) with connecting tube to the mouth cavity (Eustachian tube).	**Description** Spiral-shaped, fluid-filled tube system (chochlea) with internal organ of Corti.
Function Serves to collect and channel sound to the middle ear.	**Function** Serves to transform the energy of a sound wave into the internal vibrations of the bone structure of the middle ear and transform these vibrations into a compressional wave in the inner ear.	**Function** Serves to transform the energy of the compressional wave within the inner ear fluid into nerve impulses which can be transmitted to the brain.

The three parts are separated by membrane windows, *eardrum* (between outer ear and middle ear), and *oval window* and round window (between middle ear and inner ear).

1. The outer ear

It consists of pinna, auditory canal and the eardrum. The outer ear acts as a funnel for sound waves,

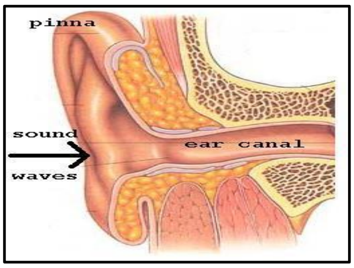
a. **The pinna;** The Pinna collects sound, acting as a funnel to amplify sound and directing sound toward the ear canal and adding directional information to the sound.

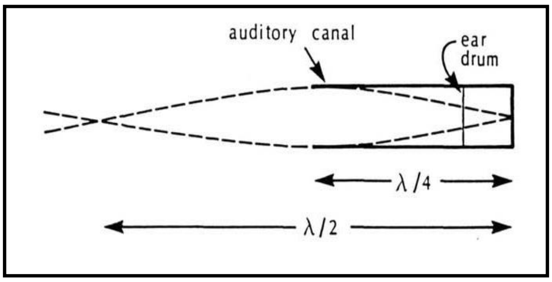
b. **The auditory canal**; (which is ~ 2.5 cm long and the diameter of a pencil) acts a resonator for certain range of frequencies ~ 3000 Hz. Also, the outer edge of the ear canal contains hair and wax to help prevent harmful items from entering the ear canal.

c. **The eardrum membrane**; is a ≈ 0.5 mm thick membrane with an area of ≈ 65 mm^2. It transfers sound (coming from the air) into the ossicles of the middle ear.

The natural or resonance frequency (creation a standing waves) for an air-filled tube of length **L** with one end closed is **λ = 4L**, as shown in Fig.2.

Fig. 2





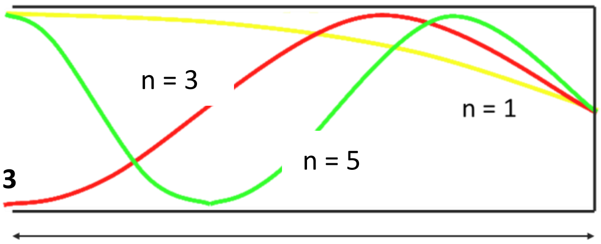
So, in regarding the outer ear, certain frequencies will resonated and amplified depending on the length of the ear canal (L = 25cm) and these frequencies are given by the following, Fig.3 :

$$f_n = n \cdot \frac{v}{4 \cdot L} \quad (n = 1, 3, 5, 7, \ldots)$$

So, $f_1 = 3300\ Hz,$
$f_3 = 9900\ Hz$

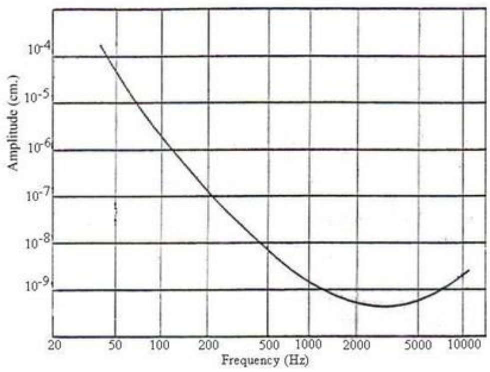
Where, (v) velocity of sound in air = 330 m/s

Fig. 3



This resonance will enhance the sensitivity of ear in the higher frequency range 2000-10000 Hz and the best sensitivity of the ear will be in the region 2000- 4000 Hz, Fig. 4.

Fig. 4



2. Reflection and Transmission at the Eardrum

The acoustical signal travels along the ear canal and hits the eardrum. This causes partial reflection and transmission of the signal. <u>To optimize the hearing sensitivity reflection should be minimized and transmission maximized</u>.

From measuring the intensity ratios for reflected and transmitted acoustical waves at the eardrum, we can obtain the following (where, Z_{air} = 430 kg/m^2.s, Z_{muscle} = 1.48 × 10^6 kg/m^2.s):

$$\frac{I_{ref}}{I_{in}} = 0.9988 \quad , \quad \frac{I_{trans}}{I_{in}} = 0.0012$$

From the above values, one can observe that most of the incoming wave intensity is reflected (bad impedance matching) and therefore lost for hearing process. <u>*Good impedance matching is necessary for good signal transmission.*</u>

3. The middle ear

The middle ear is a cavity containing the three bones of the middle ear. These are called the hammer, the anvil and the stirrup due to their shape. They transmit the vibrations of the tympanic membrane to the oval window of the inner ear. Pressure differences between the middle ear and outside are equalised by air flow through the Eustachian tube. This connects the middle ear to the pharynx (back of the throat).

- The ossicles act a lever system, in which amplify the pressure on the oval window by a factor of about 20, as shown in the following, Fig. 5:

- The force on the oval window (f_o) is about 1.5 times the force on the eardrum (f_m).
- The area of the oval window (A_o) is about 15 times smaller than the area of the ear drum (A_m).

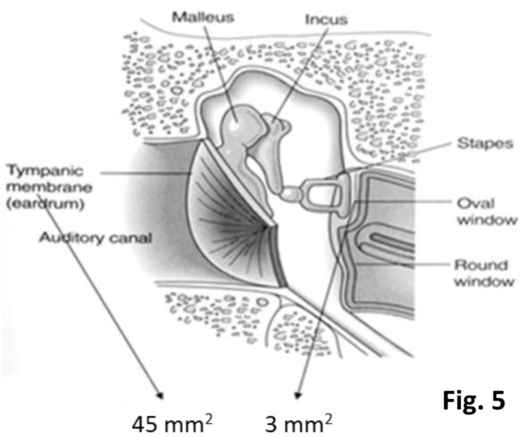


Fig. 5

Therefore,

$$\frac{Pressure\ on\ oval\ window\ (P_o)}{Pressure\ on\ ear\ drum\ (P_m)} = \frac{f_o}{A_o} \div \frac{f_m}{A_m}$$

$$= \frac{f_o}{f_m} \times \frac{A_m}{A_o} = 1.5 \times 15 \approx 20$$

4. The inner ear

- The hearing portion of the inner ear is the cochlea, a snail shaped structure that is connected to the stirrup (or stape). As the stapes moves in and out, it produces fluid waves within the cochlea.
- These waves in turn cause movement of tiny cells within the cochlea called the hair cells. As these hair cells vibrate, they send signals to the brain which can then be interpreted as sound, Fig. 6.

The basilar membrane has variable sensitivity to sound wave frequency along its length, Fig. 7. Since, the frequency of sound waves determines the displacement of the basilar membrane. The location of active hair cells creates a code that the brain translates as information about the pitch of sound.

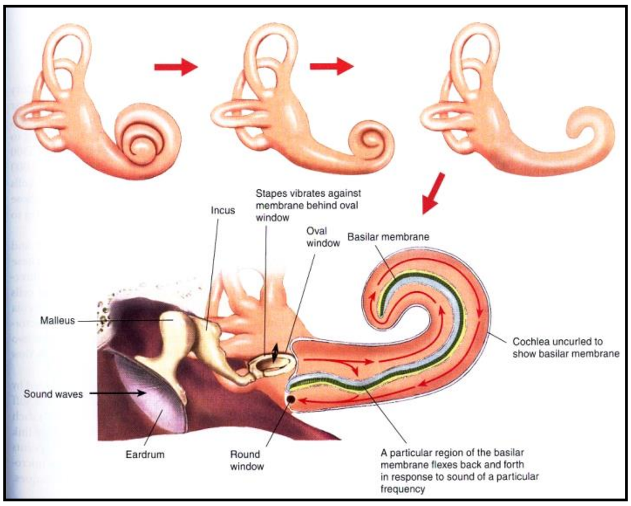


Fig. 6

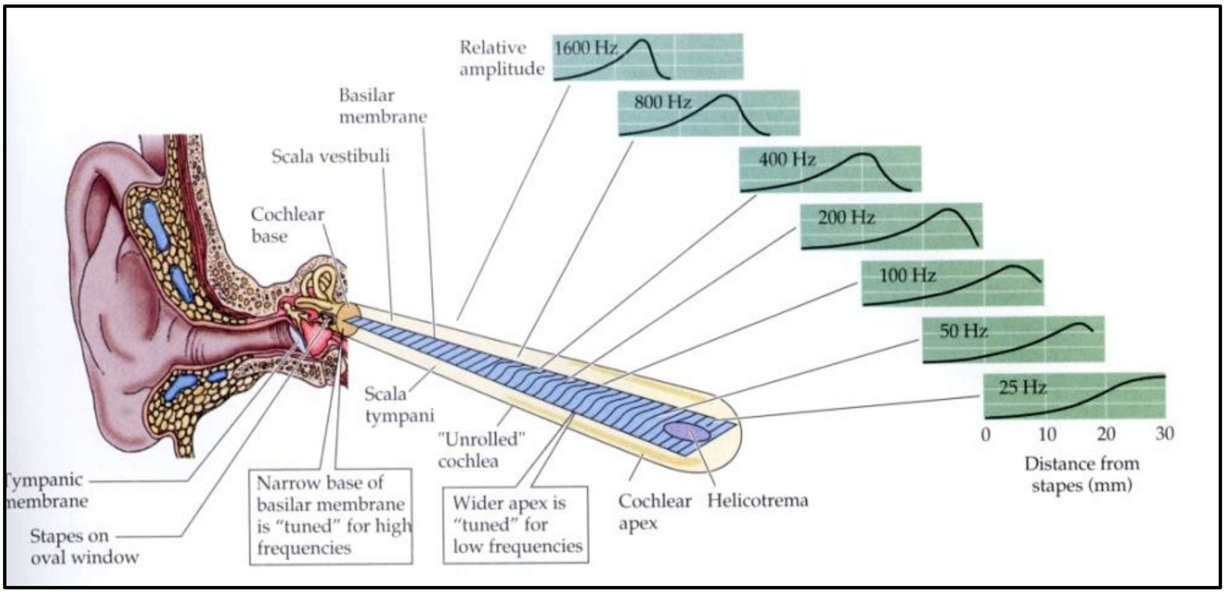


Fig. 7

5. Hearing loss (Deafness) and hearing aids

In more general terms, hearing loss can be grouped into two main types:

1- **Conduction hearing loss**, in which the sound vibrations do not reach the inner ear, this is may be due:
- Plug of wax blocking the eardrum.
- Fluid in the middle ear.

The result is an overall lowering of volume and inability to hear faint sounds. This hearing loss is usually temporary and can sometimes be reduced or eliminated by medical intervention or surgery.

2- **Nerve hearing loss,** in which the sound vibrations reach the inner ear but no nerve signals are sent to the brain. In most cases, nerve hearing loss is permanent and usually affects both ears. This type of hearing loss is commonly treated through the fitting of hearing aids.

In the case of nerve hearing loss, a hearing aid can be helpful by making sounds stronger and easier for you to hear. The components of a hearing aid include, Fig. 8:

- A microphone to gather in the sounds around the ear,
- An amplifier to make sounds louder,
- An earpiece to transmit sounds to the ear, and,
- A battery to power the device.

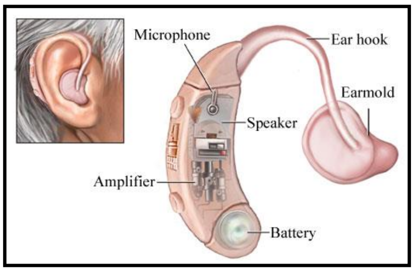


Fig. 8

Hearing aids cannot return hearing to normal. They can only help compensate for the hearing loss.