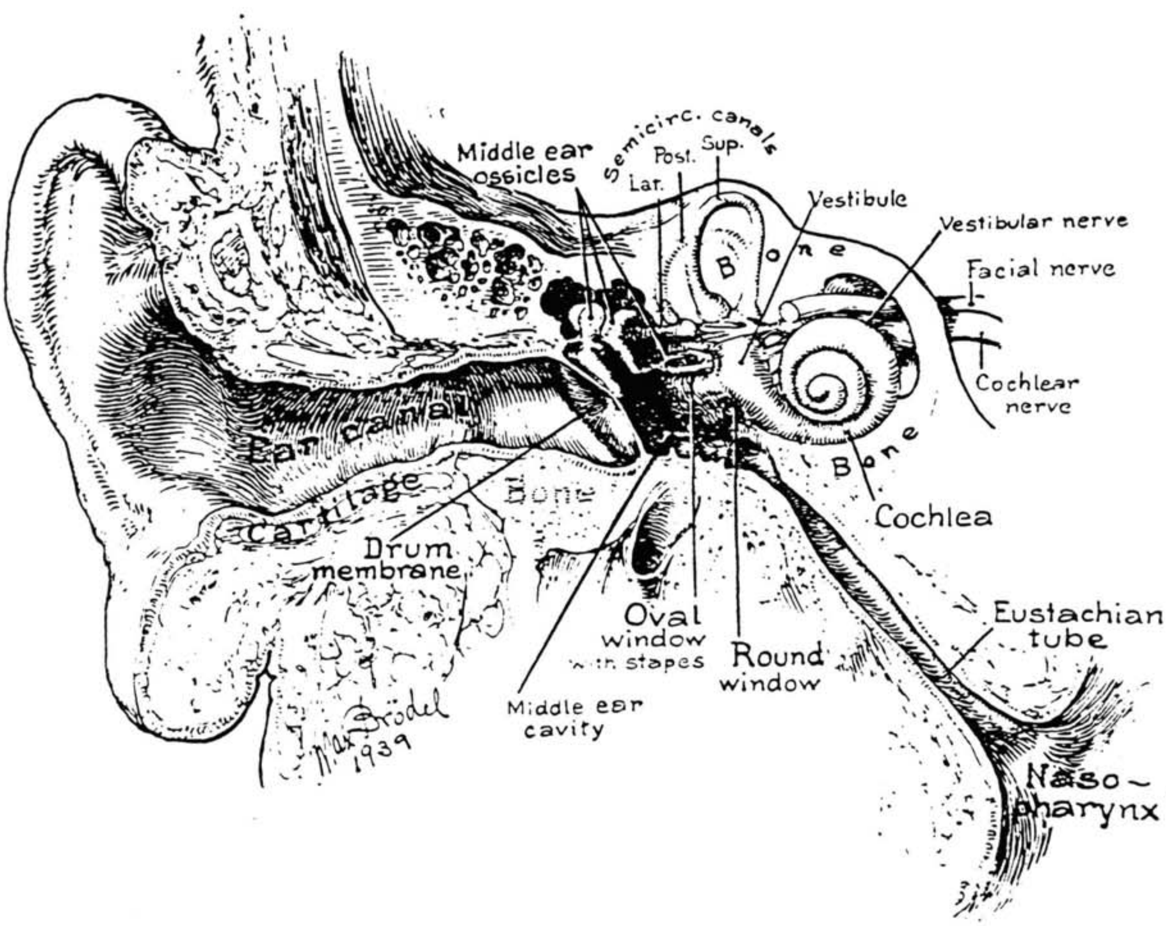
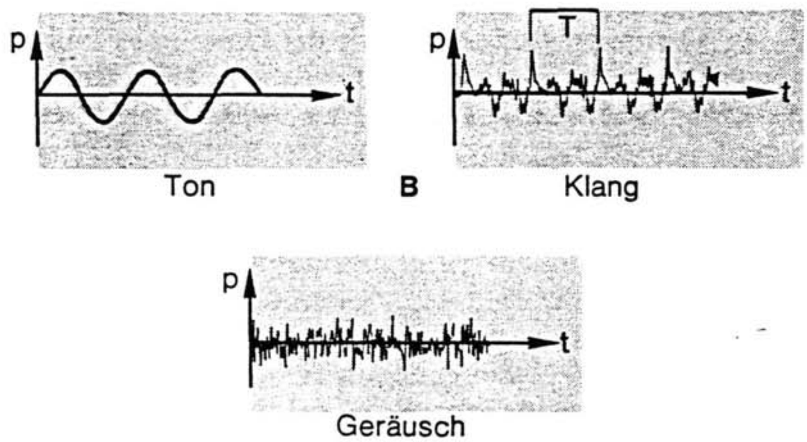


Middle ear ossicles
Semicirc. canals
Post.
Sup.
Lar.
Vestibule
Vestibular nerve
Bone
B
Facial nerve
Cochlear nerve
Ear canal
Bone
Cartilage
Bone
Cochlea
Drum membrane
Oval window with stapes
Round window
Eustachian tube
Middle ear cavity
Max Brödel 1939
Naso-pharynx

The ear is the body's main receiver system for acoustic wave information. The main objective of the ear is to receive, the acoustic waves, to amplify the intensity, to analyze the frequency and intensity structure of the wave, and to reject random background noise.

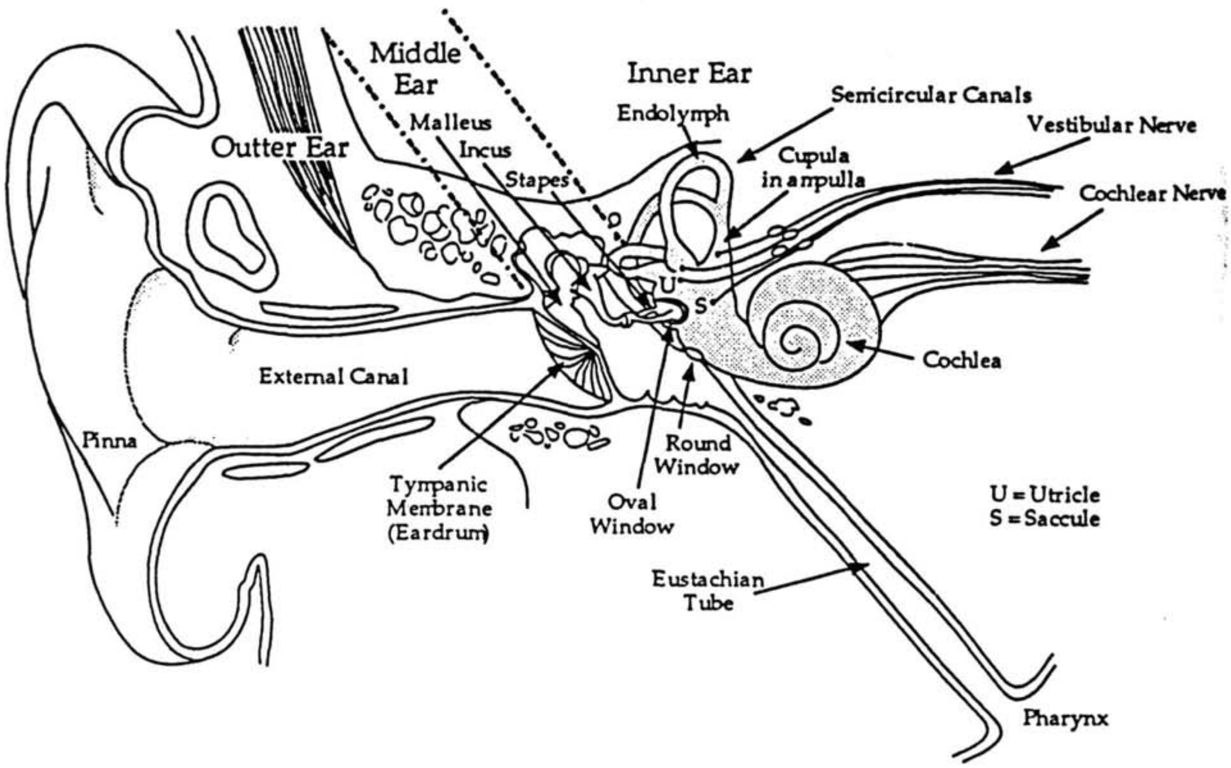


The auditory system of the body is structured into a:

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

The following section will be mainly concerned with the mechanical aspects of the hearing process, the physics of the ear. The electrical aspects of information transfer will be discussed in section 6.

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



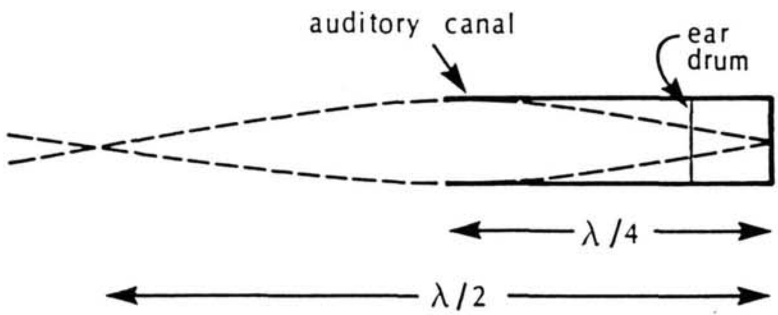
- *OUTER EAR*, ≈ 2.5 cm long ear canal terminated by the eardrum.
- *MIDDLE EAR*, cavity section containing by three small bones (ossicles with connecting tube to the mouth cavity (Eustachian tube).
- *INNER EAR*, spiral-shaped, fluid-filled tube system (chochlea) with internal organ of Corti.

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

THE OUTER EAR

The visible part of the outer ear (pinna) is nearly negligible for the hearing process. Removement would lead only to insignificant consequences as far as the auditory sensibility is concerned.

The critical part of the outer ear is the auditary canal which is ≈ 2.5 cm long. The canal is closed by the eardrum membrane. It represents a tube closed on one side. Therefore incoming acoustic waves of certain frequency can resonante.



The natural frequency for an air-filled tube of length L with one end closed is:

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

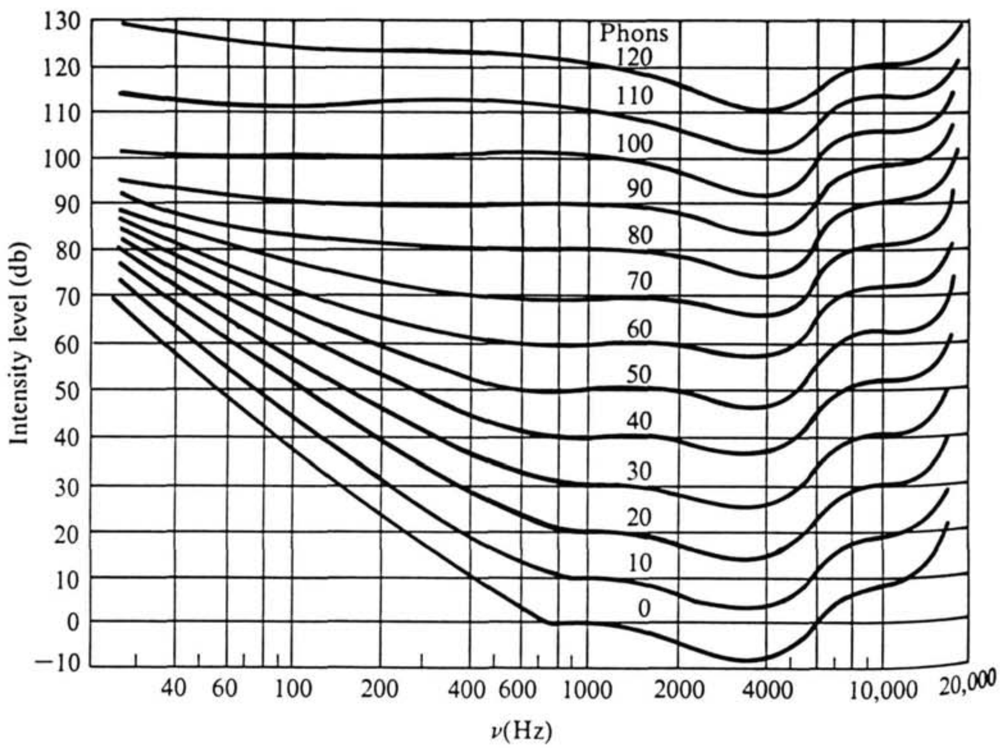
$$f_1 = \frac{330\ [m/s]}{4 \cdot 0.025\ [m]} = 3300\ Hz$$

$$f_2 = 2 \cdot \frac{330\ [m/s]}{4 \cdot 0.025\ [m]} = 6600\ Hz$$

This enhances the sensitivity of ear in the higher frequency range 2000 - 8000 Hz.

The sensitivity of the ear changes with frequency and can be described in terms of the **loudness**. Constant loudness (isophon) varies with intensity and frequency. The unit for the loudness is the **phon** which is normalized to the intensity at the fixed frequency of f=1000 Hz.

$$1\ [phon]\ \equiv\ 1\ [db] \quad at\ \ f\ =\ 1000\ [Hz]$$



The solid lines indicate the isophones, curves of constant loudness as a function of intensity and frequency. All sounds along the isophone appear equally loud to the listener. The lowest isophone represents the hearing threshold.

The dips in the isophones at frequencies around 3000 Hz and 8000 Hz signalize that lower intensities correspond to higher loudness, this results from the increased sensitivity of the ear due to the resonance effect in the outer ear canal.

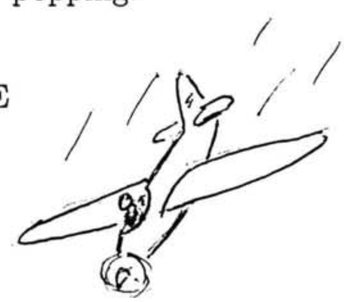
The Eardrum

The eardrum is a ≈0.5 mm thick membran with an area of ≈ 65 mm^2. It separates the outer ear canal from the middle ear cavity. The main purpose of the membrane is to absorb and transmit the pressure variations caused by acoustical waves in the outer ear canal.

Because the thinness of the membrane large pressure variations due to intense noise, 160 db (see example) or large pressure differences between outer and middle ear cavities ($\Delta P \approx 8 \cdot 10^3$ Pa) can cause its rupture.

To avoid rapid development of pressure gradients (for example by rapid change of atmospheric pressure, Eustachian tube connects middle ear and mouth cavity for pressure equilibrization. Eustachian tube is normally closed, but opens when swallowing.
A pressure gradient develops during the start and landing of aircraft, in rapidly moving elevators,
swallowing avoids ear-popping!

EXAMPLE



An small aircraft drops rapidly from its initial height h_1 to height h_2, the rapid change in atmospheric pressure causes rupture of the pilot's eardrum. Calculate the height difference.

$$\Delta P = \rho \cdot g \cdot (h_1 - h_2)$$

$$(h_1 - h_2) = \frac{\Delta P}{\rho \cdot g} = \frac{8 \cdot 10^3\ [Pa]}{1.29\ [kg/m^3] \cdot 9.81\ [m/s^2]} = 632\ m$$

The free fall takes ≈11 s (see Mechanics of the Body, section 1.3), rapid swallowing should prevent rupture of the eardrum.

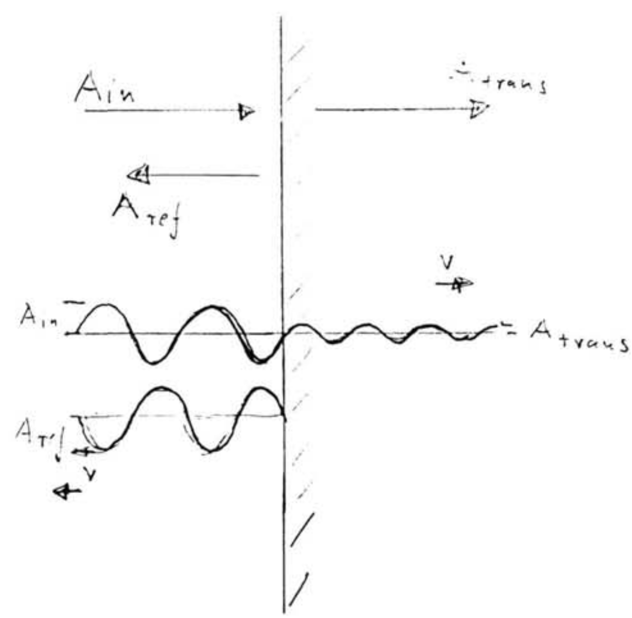
Reflection and Transmission at the Eardrum

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

Sound waves in different material moves with different speed. The density of the material and the speed of sound determine the impedance for the sound transmission in the material: $Z = \rho \cdot v$

If sound waves traveling through material with impedance Z_1 hit the surface of a material with different impedance Z_2 only part of the sound wave transmits into the material, most of the sound wave is reflected at the surface. Considering the amplitudes of the incident wave A_{in}, the reflected wave A_{ref} and the transmitted wave A_{trans}, we get the relation:

$$\frac{A_{ref}}{A_{in}} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad ; \quad \frac{A_{trans}}{A_{in}} = \frac{2 \cdot Z_2}{Z_1 + Z_2}$$



The ear receives and processes the intensity of the acoustical signal:

$$I \propto A^2.$$

To investigate the transmission of the acoustical signal inside the ear it is necessary to consider the intensity ratios rather than the amplitude ratios.

$$\frac{I_{ref}}{I_{in}} = \frac{Z_1}{Z_1} \cdot \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

$$\frac{I_{trans}}{I_{in}} = \frac{Z_1}{Z_2} \cdot \left(\frac{2 \cdot Z_2}{Z_1 + Z_2}\right)^2$$

If the material show large impedance differences, most of the signal is reflected, only a small portion of the intensity is transmitted into the higher impedance material: **impedance mismatch.**

This yields for the intensity ratios for reflected and transmitted acoustical waves at the eardrum!
Z_{air}=430 $kg/m^2 \cdot s$, Z_{muscle}=1.48·10^6 $kg/m^2 \cdot s$

$$\frac{I_{ref}}{I_{in}} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 = 0.9988$$

$$\frac{I_{trans}}{I_{in}} = \frac{Z_1}{Z_2} \cdot \left(\frac{2 \cdot Z_2}{Z_1 + Z_2}\right)^2 = 0.0012$$

Most of the incoming wave intensity is reflected and therefore lost for the hearing process.

$$10 \cdot log_{10}\frac{I_{trans}}{I_{in}} = 10 \cdot log_{10} 0.0012 = -29 \; db$$

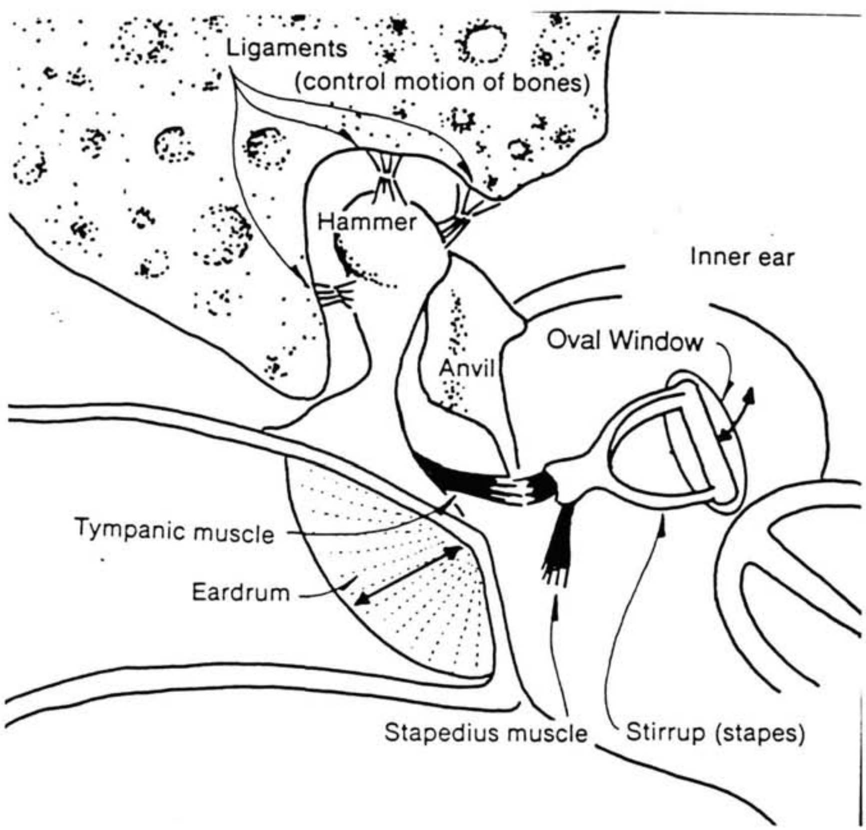
Better conditions for transmission between water and muscle: **impedance matching**
(Z_{water}=1.64·10^6 $kg/m^2 \cdot s$, Z_{muscle}=1.48·10^6 $kg/m^2 \cdot s$)

$$\frac{I_{ref}}{I_{in}} = 0.0026 \quad ; \quad \frac{I_{trans}}{I_{in}} = 0.9974$$

Good impedance matching is necessary for good signal transmission!

THE MIDDLE EAR

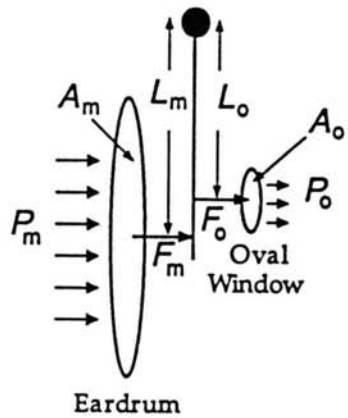
The middle ear is an air filled cavity which is connected by the Eustachian tube with the mouth cavity. Dominant feature of the middle ear are three small bones, the ossicles, malleus (hammer), incus (anvil), and stapes (stirrup). Purpose of the bones is to serve as mechanical impedance matching and amplifying system for the transmission of the eardrum vibrations towards the inner ear.



The malleus is attched directly to the eardrum membrane to absorb the vibrations, the incus couples the malleus with the stapes which in turn is attached to the oval window membrane which separates the middle ear cavity from the inner ear.

The ossicles act as a lever system causing a substantial amplification of the eardrum membrane vibrations.

The pressure variation P_m induce a force $F_m = P_m \cdot A_m$ at the eardrum with area A_m which causes a torque τ_m at the incus. This torque in turn transmits a force F_o and pressure P_o onto the oval window with area A_o.



$$\tau_m = F_m \cdot L_m = F_o \cdot L_o = \tau_o$$

$$P_m \cdot A_m \cdot L_m = P_o \cdot A_o \cdot L_o$$

$$\frac{P_o}{P_m} = \frac{A_m}{A_o} \cdot \frac{L_m}{L_o}$$

This pressure ratio for the vibrations on eardrum and oval window represents a significant amplification of the initial acoustical system:

For $L_m/L_o \approx 1.3$ and $A_m/A_o \approx 15 \Rightarrow P_o/P_m \approx 19.5!$

This represents an increase in decibels of:

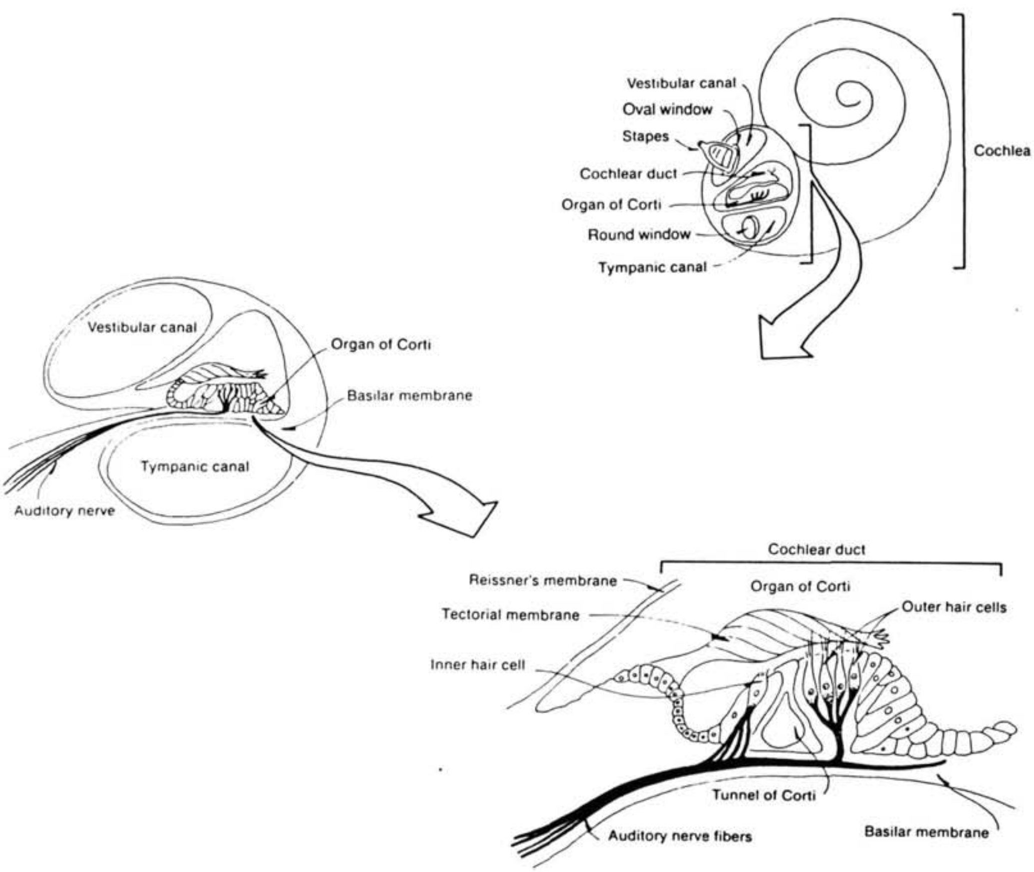
$$20 \cdot log_{10}\frac{P_o}{P_m} = 20 \cdot log_{10}19.5 = 26\ db$$

Ossicle lever system in the middle ear provides efficient coupling between the vibrating eardrum membrane and the oval window membrane without intensity losses. The coupling (impedance matching) is most efficient in the frequency range from 400 Hz to 4000 Hz.

For higher and lower frequencies, stiffness and mass of the ossicle system limit the impedance match.

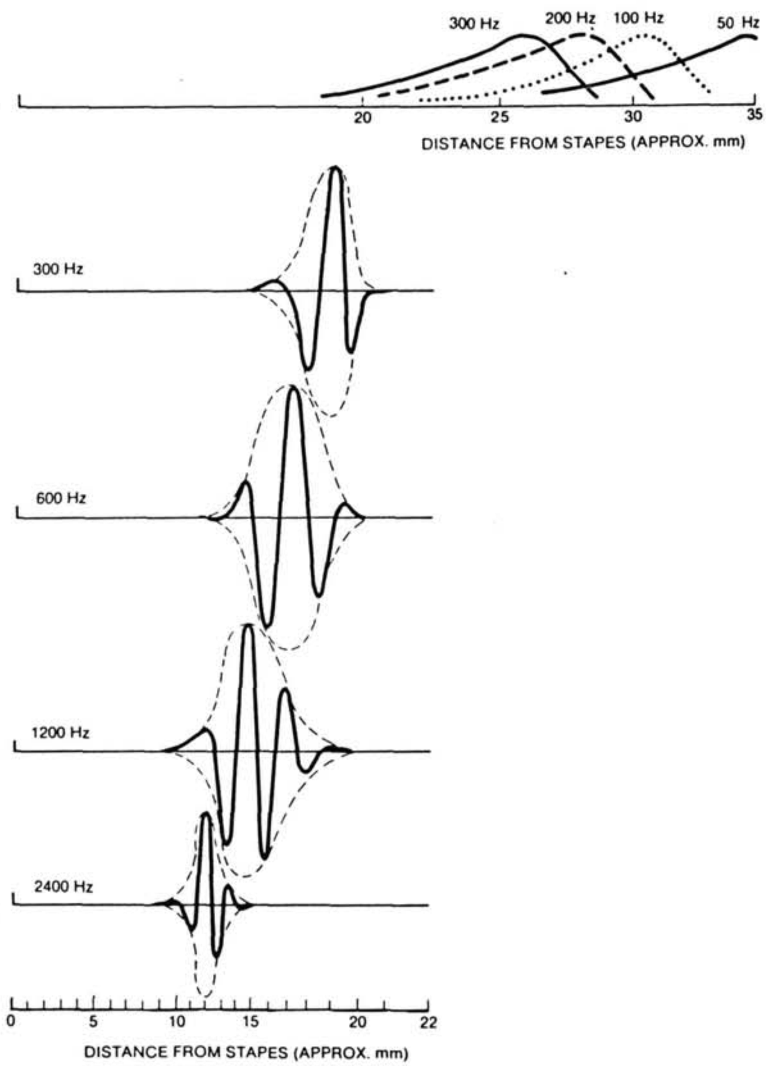
THE INNER EAR

The inner ear is well protected within the skull.
The inner ear consists of a spiral shaped system of three parallel tubes, the cochlea, filled with an anionic liquid. The two outer tubes (tympanic chamber and vestibular chamber) are connected at the tip of the cochlea. The inner tube (cochlear duct) is separated by the basilar membrane from the outer tubes.



The stapes is attached to the oval window which separates the vestibular chamber from the middle ear. The round window separates the tympanic chamber from the middle ear. Vibrations of the oval window transmit pressure variations to the fluid in the closed vestibular and tympanic chambers of the cochlea.

The movement of the liquid causes a wave-like vibration in the basilar membrane of the cochlear duct moving toward the tip of the cochlea. Due to the decreasing stiffness of the basilar membrane tones of certain intensity and frequency cause local maximum of wave amplitude along the basilar membrane.



The basilar membrane carries the organ of Corti, covered by fine hair sensors which gets locally excited at the amplitude maximum of the vibration of the basilar membrane. This position dependent excitation of sensors causes frequency dispersion.