CNS PHYSIOLOGY

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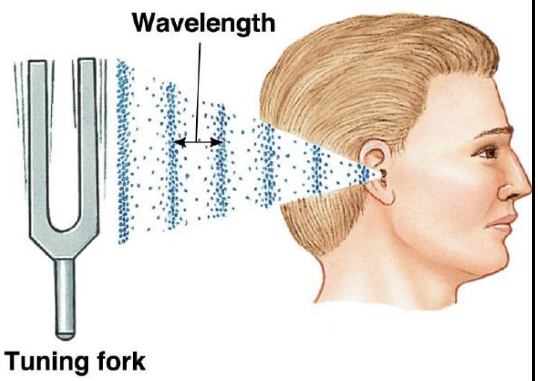
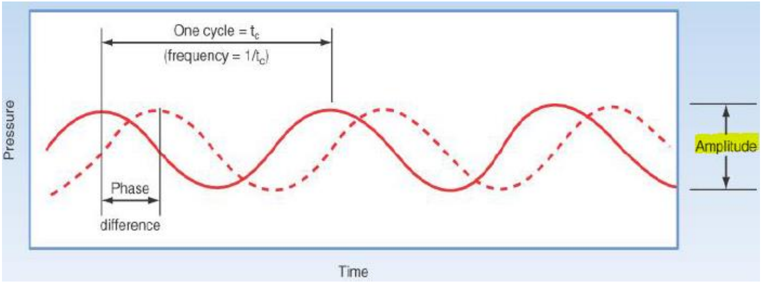
Auditory Sensation (Hearing)



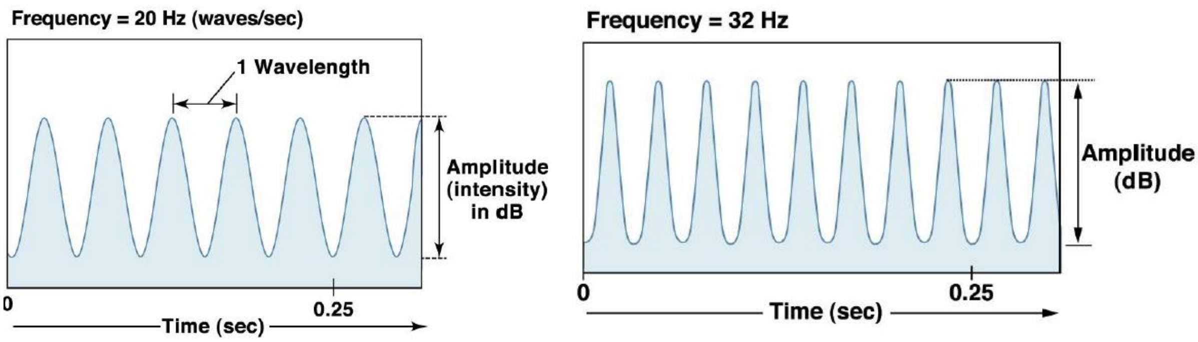
- The stimulus of auditory sensation are the sound waves; these waves are what we hear.
- A wave's limit is from one peak to the other peak.
- The sound waves can be described according to certain physical characteristics:
    1) Frequency: Also called Hertz (Hz), which is the number of repeated wave cycles per unit of time. It depends on the distance between the two peaks.

    The frequencies of audible sound is between (20-200,000 Hz).

    2) Amplitude of a sound is the intensity (loudness), measured in decibel (dB).
    3) The speed of a wave: the speed of sound is 335 m/sec in air, which is much less than the speed of light in air which is around 300,000 km/sec.



- Here we have 2 waves with different wavelengths, thus different frequencies (pitches) and the same amplitude (loudness).



- Decibel: is a logarithmic scale that describes a sound's amplitude (intensity/strength).

Decibel= 10 log I/I_R

I: Intensity of sound. I_R: Reference intensity

Decibel= 1\10 of a bel.

- ✓ The sound intensity (acoustic intensity) is proportional to the square of sound pressure level. Therefore, it is better to measure the intensity in terms of pressure as it is easy to measure.
  - ⇒ Sound pressure level (SPL) unit is decibel.
    SPL (dB) = 20 log P/P_R

Dyne is a unit of pressure

P= the sound pressure in N/m^2 (N=Newton, m = meter)

P_R= reference pressure (0.0002 dynes/cm^2, the absolute threshold for human hearing (This equals 20 micro pascal), or 1 dyne/ cm^2)

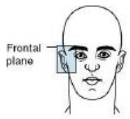
- ✓ So, the intensity is measured in decibels which is a logarithmic scale.
- ☞ But why do we use a logarithmic scale?

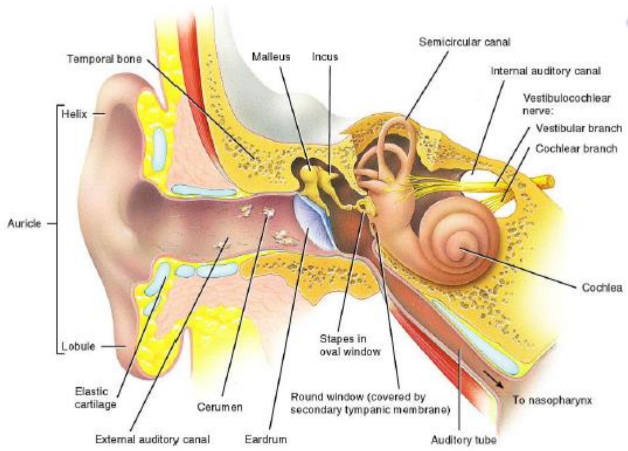
To increase the intensity level → Humans can hear sound intensities between (0-120 dB).

Which means we can hear sounds between (10^0-10^{120}).

[Using logarithm, we can express large values using small numbers]

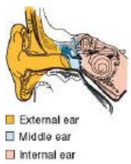
The Anatomy of the Ear

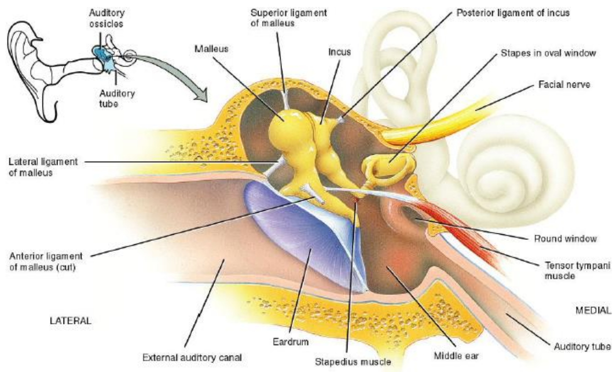




Frontal section through the right side of the skull showing the three principal regions of the ear

1) The external ear consists of:
   - ⇒ The ear pinna (auricle).
   - ⇒ External auditory canal: contains ceruminous glands that secrete cerumen (wax).
   - ⇒ Tympanic membrane (Ear drum).





Frontal section showing location of auditory ossicles

2) The middle ear: contains the ossicles.
   - ⇒ Malleus: resting on the top of the tympanic membrane.
   - ⇒ Incus
   - ⇒ Stapes: lies on the oval window (Membranous window) and is a part of the cochlea.

The auditory canal (Eustachian tube): connects the middle ear to the nasopharynx.

3) The inner ear:

⇒ The cochlea: innervated by the cochlear part of the vestibulocochlear nerve (8th cranial nerve).

⇒ The vestibule.

The Tympanic membrane and the ossicular system

- ✓ The tympanic membrane's function is to transmit vibrations from the air to the cochlea.
- ✓ The area of the tympanic membrane= 55 sq.mm while the area of the oval window = 3.2 sq.mm [the tympanic membrane is 17 times larger than the oval window].
- ✓ The transmission of vibrations from a relatively large area to a much smaller one leads to the amplification of sound waves (17 times).
- ✓ The tympanic membrane is connected to the ossicles (malleus, incus and stapes).
- ✓ The ossicular system works as a lever system and amplifies the sound 1.3 times.

⇒ Total amplification= 17x1.3=22 times. The sound waves are amplified 22 times when transmitted from the air, until it reaches the oval window.

- ✓ Why do we need to increase the sound pressure?

The amplification of sound waves will increase the pressure enough to move the fluid inside the cochlea (in & outward movement).

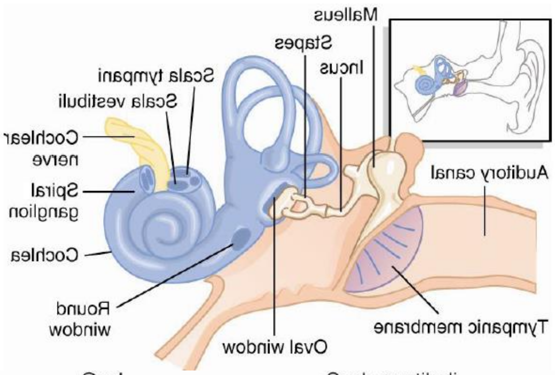
The pressure produced by sound waves while traveling through the air is not enough to move the fluid, so the function of the tympanic membrane & the ossicular system is to match the resistance of sound wave movement in the air (low resistance) to the resistance of movement in the fluid (very high resistance). This process is called *Impedance Matching.*

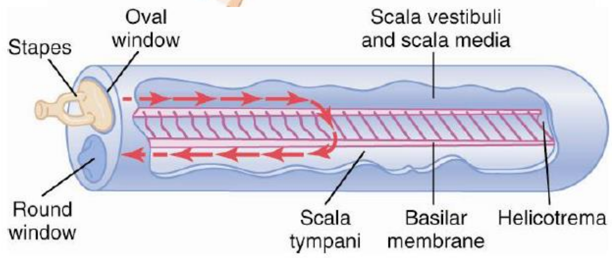
- ✓ After the pressure is increased by the tympanic membrane & the ossicular system, the pressure will be transmitted from the stapes to the cochlea, which are attached to each other through a small area (the cochlea is a relatively large membrane attached to stapes through a small opening) which also increases the sound pressure.
- ✓ We have 2 muscles (smallest muscles in our body) that are very important for protection from very loud sounds (high intensity sounds, not high frequency). Such loud sounds might cause perforation of the tympanic membrane or could damage the hearing receptors inside the cochlea.
- ☞ Tensor tympani muscle (trigeminal nerve/V): attached to the tympanic membrane, contracts and pulls the ossicular system & tympanic membrane inside.

☞ Stapedius muscle (facial/VII): attached to the stapes, contracts & pulls the stapes outward.

The ossicular system is now very hard to vibrate, so the strong vibrations will not be transmitted. This is a protective reflex called *Attenuation reflex*, it gets initiated after (40-80 millisecond) and masks low frequency sounds in a loud environment (your own voice).

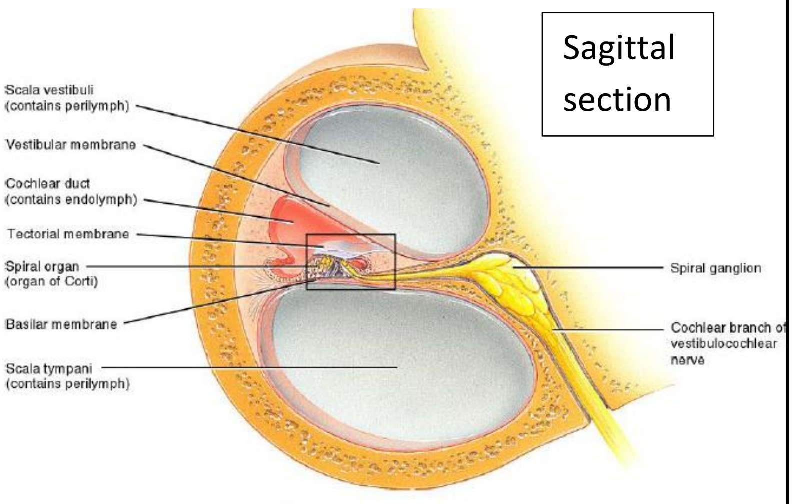
The cochlea





- ✓ Snail like structure which has the oval window & round window on its surface. It consists of 3 coiled tubes:

1) Scala vestibuli: the upper tube that is close to the vestibule, which contains fluid called Perilymph (similar to the extracellular fluid). The oval window is related to this tube.
2) Scala media (cochlear duct): separated from scala vestibuli by Reissner's membrane (vestibular membrane), and separated from scala tympani by the basilar membrane. Contains fluid called endolymph (similar to intracellular fluid).
3) Scala tympani: the lower tube, which contains perilymph. The round window is related to this layer.

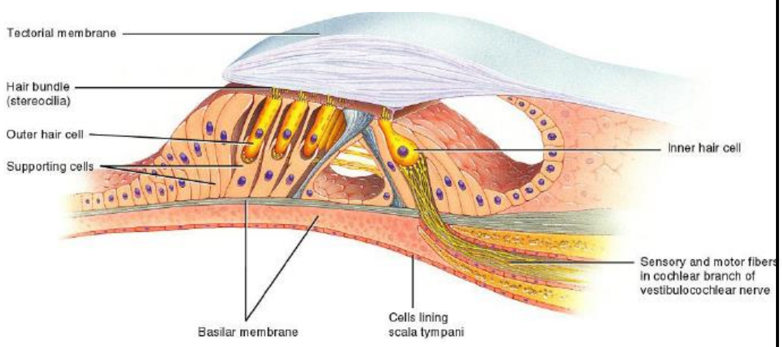


- ✓ Scala vestibuli & scala tympani are connected to each other at the end of the cochlea at a point called helicotrema. So, they have the same fluid.
- ✓ Organ of Corti: located on top of the basilar membrane, and consists of hair cell: 3 rows of outer hair cells & one row of inner hair cells.
- ✓ The row of inner hair cells contains around 3500 hair cells, so the outer rows contain 12000 hair cells.
- ✓ The basilar membrane's shape is triangular, with the base of the "triangle" located near the oval window, as the apex projects towards the helicotrema.
- ✓ The vibrations transmitted through stapes to the oval window causes movement of the fluid in Scala vestibuli, followed by the Scala tympani.

- ✓ The pressure caused by the moving fluid inside the cochlea is what causes the movement of the round window for the dissipation of pressure into the middle ear. The pressure in the middle ear will be dissipated through the Eustachian canal to the nose.
- ☞ That is what happens when you go to the dead sea. You feel the pressure build up inside your ears, so you attempt to reduce the pressure by swallowing.

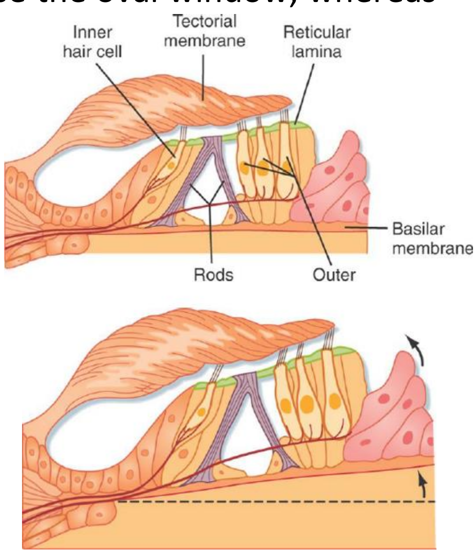
Organ of Corti

- ✓ Hair cells are supplied by the cochlear branch of vestibulocochlear nerve, note (on the previous figures) the spiral ganglion which consists of the cell bodies of the cochlear branch.
- ✓ The outer cell layers are *mainly* supplied by efferent neurons from the cortex. These are corticofugal fibers that transmit feedback signals that increase the sensitivity of the system.
- ✓ The inner cell layer is *mainly* supplied by afferent neurons, they transmit auditory signals.



(d) Enlargement of spiral organ (organ of Corti)

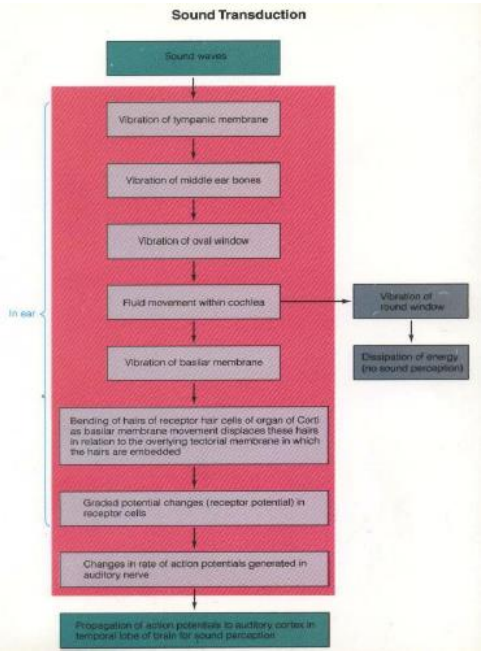
- ✓ Above the inner & outer hair cells, we have a proteinaceous membrane called *Tectorial membrane*.
- ✓ The basilar membrane contains about 30,000 fibers which project from the bony center of the cochlea (the modiolus).
- ✓ The fibers are stiff reed-like structures fixed to the modiolus and are embedded in the loose basilar membrane. Because they are stiff and free at one end, they can vibrate like a musical reed.
- ☞ The fibers that are located near the oval window are short & thick. As the fibers move towards the helicotrema, they become longer and thinner. Overall stiffness decreases from the base to the helicotrema by around 100 times.
- ☞ High frequency sound will vibrate the thick fibers close the oval window, whereas low frequency sound will vibrate the fibers close to the helicotrema, and moderate sound waves will vibrate the fibers in the middle.
- ☞ So the basilar membrane is organized tonotopically, which means that it is organized according to the tone.
- ✓ The movement of the fluid inside the cochlea will move the basilar membrane down & up which moves the stereocilia of hair cells back & forth against the tectorial membrane.

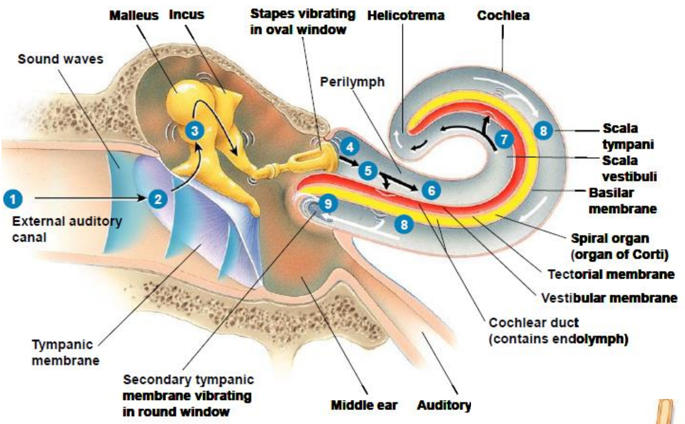


- ✓ Neural transduction of the auditory signal:
  - ☞ stretching the basilar membrane downwards will stop the friction of hair cells with the tectorial membrane, which causes hyperpolarization (inhibition) of the inner and outer hair cells -inner cells are more important- Afterwards, there is an upward stretch, leading to the depolarization of hair cells and secretion of the neurotransmitter (Presumably glutamate).
  - ☞ The bending of stereocilia in one direction causes hyperpolarization, and the bending in the opposite direction will cause depolarization.
- ✓ How many times does it go down & up? It depends in the intensity of the sound.

Sound transduction

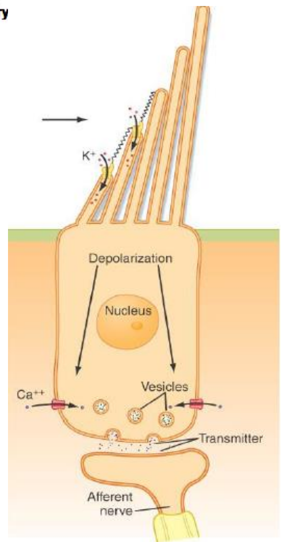
1) Sound waves passing through the external auditory canal will vibrate the tympanic membrane at the same frequency of the sound wave.
2) Tympanic membrane vibration is transmitted through malleus, incus and stapes.
3) Stapes vibration will be transmitted through the oval window to the cochlea.
4) Vibration of the perilymph.
5) Vibration of the basilar membrane (thus, organ of Corti).
6) Hyperpolarization, then depolarization of the hair cells and signal transmission.
7) The pressure inside scala vestibuli & Scala tympani will dissipate through the round window.





The hair cells

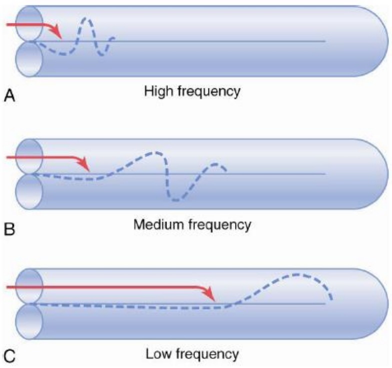
- ✓ The longest projections are called kinocilia.
- ✓ The smaller ones are called stereocilia.
- ✓ The membrane potential between the intracellular side of the cell & scala tympani (perilymph) is -70mV.



- ✓ The potential difference between the intracellular side & scala media (endolymph) is -150mV.
- ☞ Remember that the endolymph is similar to the intracellular fluid, so it contains high concentrations of K^+.
- ✓ The membrane of stereocilia contains K^+ channels, and since the equilibrium potential for K^+=-90mV, K^+ ions will enter the cell causing depolarization.
  [K^+ ions tries to make the membrane potential -90mV instead of -150mV, that's why it enter the cell].
- ✓ After depolarization occurs, voltage gated Ca^{++} channels will open and Ca^{++} ions enter the cell.
- ✓ Neurotransmitter vesicles will fuse with the membrane and release its contents.
- ✓ The membrane potential is called endocochlear potential.
- ☞ Note that what occurs here is not an action potential, it is graded potential (receptor potential). Action potential occurs in the neurons of the cochlear nerve.

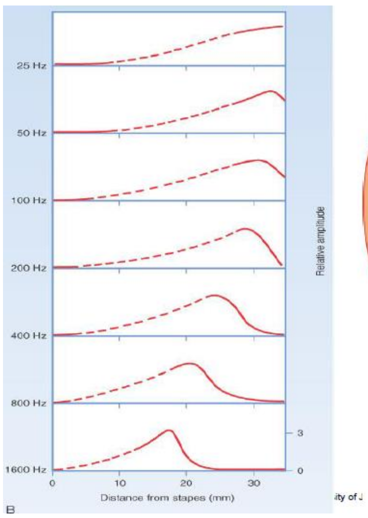
Determination of sound frequency and amplitude (sound intensity)

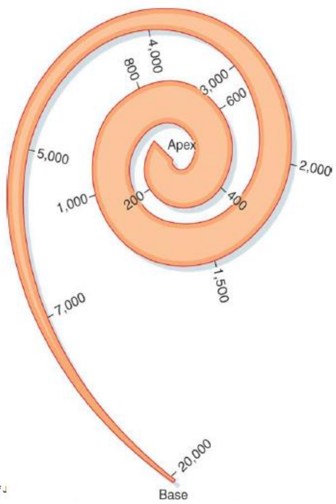
1) Place principle:



- ✓ Since basilar membrane is tonotopically organized, different frequencies of sound will cause the basilar membrane to oscillate at different positions.
- ✓ The position along the basilar membrane where hair cells are being stimulated determines the pitch of the sound being perceived.
- ✓ Vibration of the basilar membrane near the base is associated to high frequency sound, while vibration close to the helicotrema means low frequency.
- ✓ The intensity of the sound is determined depending on the number of fibers stimulated; high intensity sound stimulates a larger number of fibers around the peak.

  The range of sound frequencies we are able to hear is between 200-20,000Hz, but it gets narrower with age 400-8000Hz

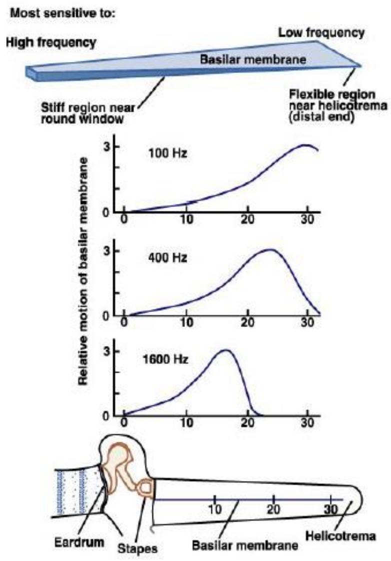




2) Phase-locked (volley) principle:

✓ At the helicotrema site of the basilar membrane, there is discrimination of sound waves at very high range. How?

☞ Sound waves have phases (peak, bottom..), and these phases differ among waves with different frequencies, so when the helicotrema is hit by 2 waves with different frequencies, the same area will be stimulated by different phases of sound waves. Depending on the site of the wave that hit that area of the membrane, a different rate of firing will be generated.



✓ Remember that the sensory system encodes for the intensity of the stimulus depending on 1) The number of neurons stimulated, 2) The frequency of action potentials.

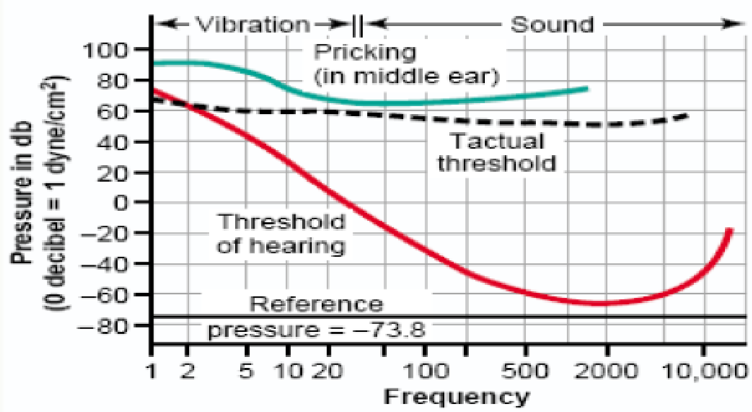
✓ High intensity sound waves increase the movement of the basilar membrane (up & down) which causes the generation of more action potentials.

Threshold of hair cells

✓ Different sound wave frequencies have different thresholds.

✓ The threshold is the lowest intensity (pressure) of a wave of a particular frequency that can be heard.

✓ The red graph here represents the values of sound wave pressure (in decibel) that can be heard for different values of sound wave frequencies.



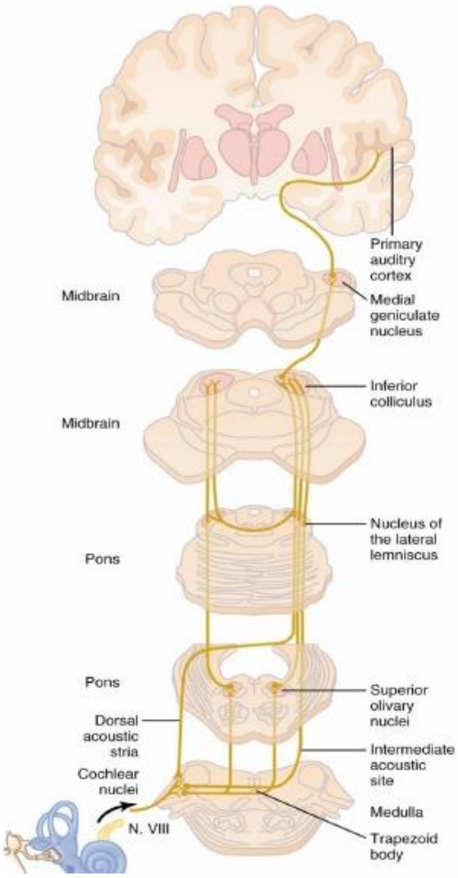
☞ The frequency is on the x axis, and the threshold is on the y axis.

The lowest threshold for 2000 frequencies= -60 dB. [This means that if you hear a sound, with a frequency of 2000 Hz, it doesn't necessarily have to be loud for you to hear it. In fact, you can hear it even if the pressure (loudness) is as low as -60dB].

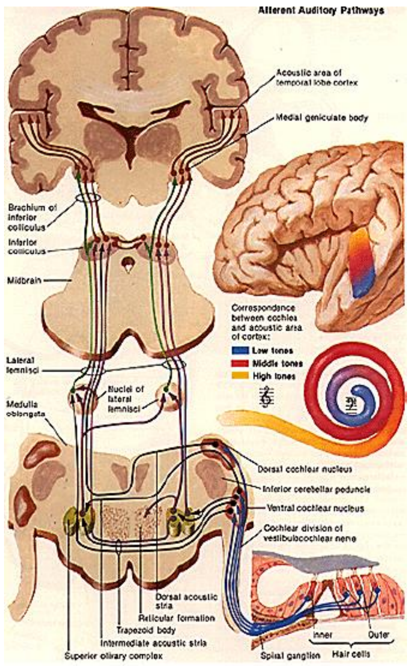
Decibel unit of sound

- ✓ Unit of sound expressed in terms of the logarithm of their intensity.
- ✓ 10 fold increase in energy is 1 bel.
- ✓ 0.1 bel is a decibel.
- ✓ 1 decibel is an increase in sound energy of 1.26 times.
- ✓ We can hear sounds between 0 to 120 dB.

Central Auditory pathway

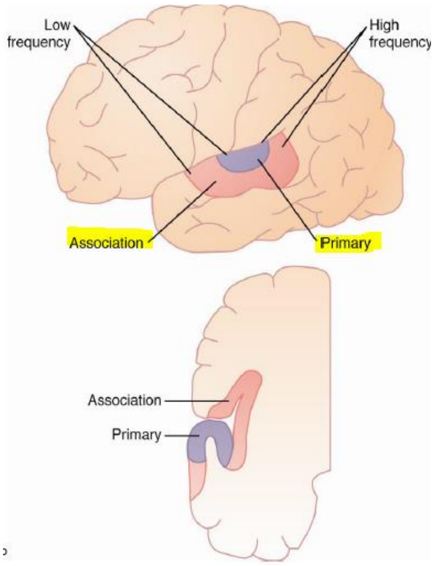


1) Starts from the *cochlear branch* of vestibulocochlear nerve (VIII).
2) Enters upper medulla oblongata where the *ventral & dorsal cochlear nuclei* are located, second order neurons ascend on both sides; ipsilateral & contralateral sides.
   The crossing fibers pass through a structure called *trapezoid body*.
3) The fibers go to the *superior olivary nucleus* and ascend in both sides.
4) Then to the *nucleus of the lateral lemniscus* in pons.
5) Then to the *inferior colliculus* in the midbrain where the tectospinal tract starts.
   Tectospinal tract is responsible for the movement of the neck in response to sound.
6) Then fibers synapse in the *medial geniculate nucleus* of the thalamus.
7) And finally it goes to the *primary auditory cortex* in the temporal lobe.



- ☞ Note that the auditory sensation that is transmitted from one side will eventually end up in both auditory cortices because there's crossing at many levels throughout the pathway.
- ☞ So, when the auditory cortex at one side gets damaged, the patient will not have unilateral deafness, because the other cortex receives input from both sides.
- ☞ Unilateral deafness occurs if the cochlear nerve or cochlear nuclei are damaged.

Auditory cortex and Association areas



- ✓ Tonotopic organization starts at the basilar membrane, and it continues throughout the whole pathway to the cortex.
- ✓ The tonotopic organization of the auditory cortex: low frequency area is located anteriorly, high frequency areas are located posteriorly, and moderate frequency is in the middle.
- ✓ The area around the primary auditory cortex is the secondary cortex (association cortex). Its function is to discriminate or interpret the meaning or importance of the primary sensation.
- ✓ If the secondary cortex is damaged, the patient will have *word deafness*; in which he can hear sounds but can't explain what he is hearing.

Determination of the direction of sounds

1) The first mechanism: difference in the intensity of sound.
   - ☞ When the sound comes from the right side, the intensity of the sound that is detected is higher in the right ear than the left ear.
   - ☞ So the *lateral* nuclei of the superior olivary nucleus is able to discriminate where the sound came from, depending on the intensity of sound coming from each side.
2) The second mechanism: time lag.
   - ☞ The *medial* nuclei of the superior olivary nucleus determines the direction by the time lag between acoustic signals entering the ears.
   - ☞ Sounds coming from the right side will reach the right ear before reaching the left ear.

Deafness

1) Nerve deafness: damage in the nerve that transmits the signals. The damage could be in the receptors (hair cells) as well.
2) Conduction deafness: there is no vibration of the system due to impairment in the tympanic membrane, the ossicles, or the cochlear duct.
   - ☞ Auto sclerosis: hardening of the ossicles, making them incapable of vibrating, so there no wave conduction. This may occur due to aging.

- ☞ The tympanic membrane could be perforated, so sound waves will not be transmitted to the ossicles through the tympanic membrane.

✓ The types of deafness are differentiated by audiometry (audiogram):

⇒ Sound waves of different frequencies are produced to assess air & bone conduction.

⇒ Bone conduction: the source of sound is placed on/against the mastoid bone, the sound waves will be transmitted through the bone to the cochlea directly without the need to pass through the external & middle ears, so the fluid inside the cochlea will move, and the basilar membrane will vibrate.

⇒ Air conduction: the source of sound is put near the ear.

☞ During the examination of one ear, the other one should be closed.

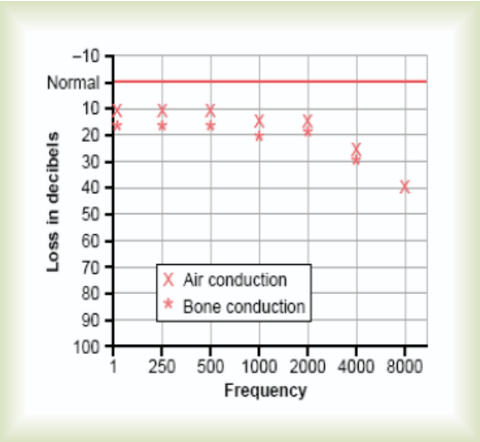


Figure 52–12

Audiogram of the old-age type of nerve deafness.

This patient has loss of decibels sensed through air & bone conduction of sound waves at high frequencies. Abnormality in both; air & .bone conduction (mixed)

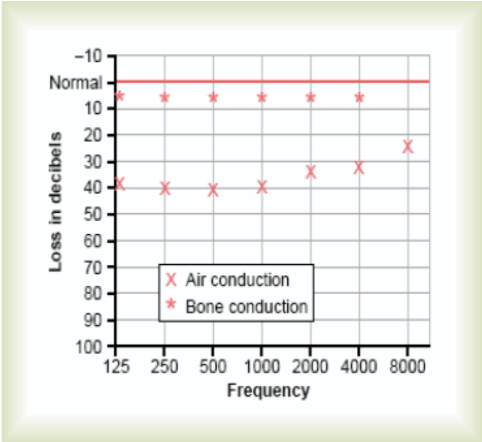


Figure 52–13

Audiogram of air conduction deafness resulting from middle ear sclerosi

This patient has loss of decibels sensed through air conduction of sound waves at low frequencies, and has normal bone conduction. Conduction deafness, probably in the middle ear, to low frequency sound.

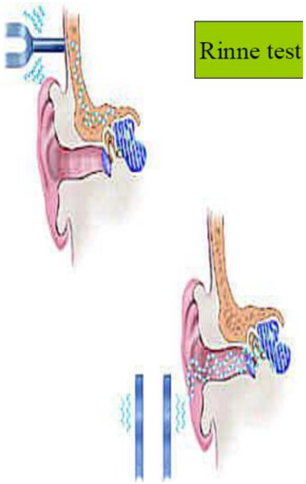
Rinne & Weber tests

✓ Both tests use 512 Hz tuning forks to test how you respond to sounds & vibrations near your ears.

✓ Noninvasive & cause no pain, and there are no risks associated with them.

✓ The information they provide determines the type of hearing loss, especially when the results of both tests are used together.

Rinne test



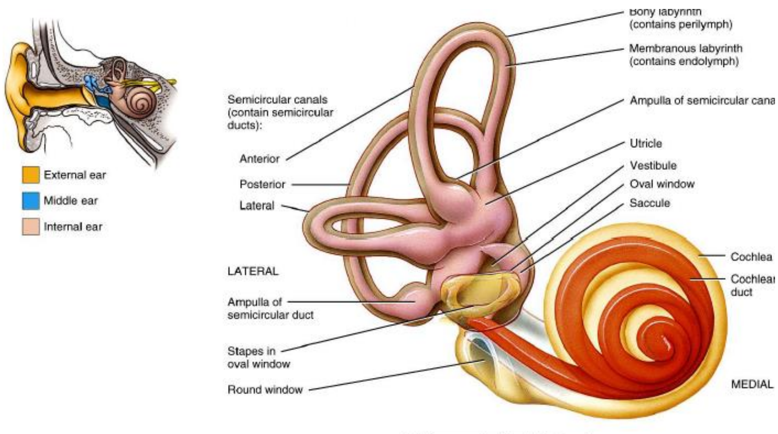
- ✓ The doctor strikes the tuning fork & places it on the mastoid bone behind one ear.
- ✓ When the patient can no longer hear a sound, they signal to the doctor.
- ✓ Then the doctor moves the tuning fork next to the ear canal.
- ✓ When the patient can no longer hear that sound, they signal to the doctor again.
- ✓ The doctor records the duration of time for which the patient heard each sound.
- ☞ Test results:
- ✓ Normal hearing will show an air conduction time that is twice as long as the bone conduction time. In other words, you will hear the sound next to your ear for twice as long as you would hear the sound behind your ear.
- ✓ If you have conductive hearing loss, the bone conduction is heard for longer than the air conduction sound.
- ✓ If you have sensorineural hearing loss, air conduction is heard for longer than bone conduction, but may not be twice as long.

Weber test

- ✓ The doctor strikes a tuning fork, and places it in the center of the patient's head.
- ✓ The patient notes where the sound is best heard: the left ear, the right ear or both equally.
- ☞ Test results:
- ✓ Normal hearing will produce equal sounds in both ears.
- ✓ Conductive loss will cause the sound to be heard the best in the abnormal/affected ear.
- ✓ Sensorineural loss will cause the sound to be heard best in the normal ear.

Equilibrium

- The vestibule of the inner ear is responsible for the equilibrium.
- The vestibule consists of: Utricle, Saccule and Semicircular canals.
- The utricle & saccule have receptors that are concerned with linear acceleration (forward & backward movement).
- The semicircular canals: Anterior & posterior & lateral.
- They contain receptors at the base (crista annularis), associated with angular acceleration.
- We have 2 vestibules: in the right ear and the left ear.
- The left & right *lateral* semicircular canals are at the same plane.
- The *anterior* semicircular canal on one side is aligned at the same plane of the *posterior* semicircular canal on the other side.
- The movement in all directions (X, Y, Z) is covered by the receptors.
- The receptor cells are very organized. This helps with the detection of movements in all directions.



(a) Components of the right internal ear

Good Luck