NSII
Spring 2024
Neurophysiology lecture 4 and 5
The sense of hearing and auditory neurophysiology

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Lecture objectives

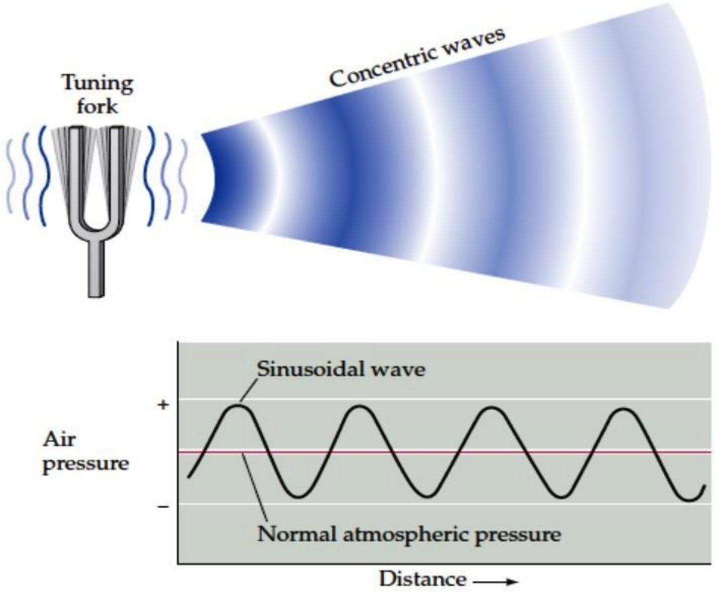
- Describe the components and functions of the external, middle, and inner ear.
- Explain the roles of the tympanic membrane, the auditory ossicles (malleus, incus, and stapes), and scala vestibule in sound transmission.
- Describe the way that movements of molecules in the air are converted into impulses generated in hair cells in the cochlea. (Auditory transduction)
- Explain how pitch, loudness, and timbre are coded in the auditory pathways.
- Describe the components of the auditory pathway from the cochlear hair cells to the cerebral cortex.
- Compare the causes of conductive and sensorineural hearing loss and the tests used to distinguish between them (lab objective)

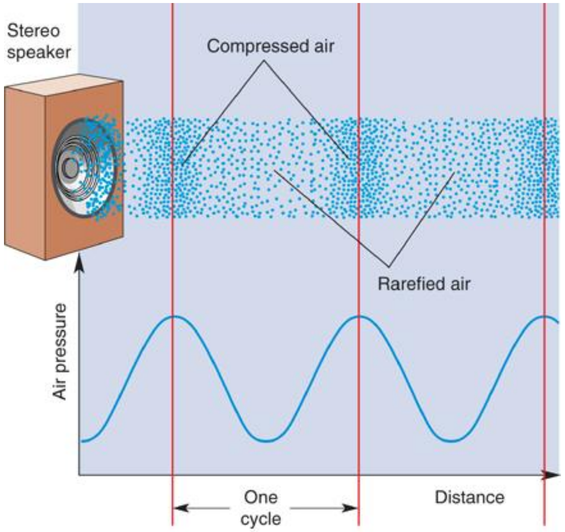
Sound definition and properties

- Definition: sound is a vibration that propagates as an acoustic wave, through a transmission medium such as a gas, liquid or solid.
- Sound =waves of compression (increase in pressure) and decompression (decrease in pressure) i.e. Audible variations in air pressure
- It is a form of energy ”mechanical force”, with our ears functioning as mechanoreceptive organs.
- Sound can travel through all types of media, excluding a vacuum.
- Sound is created by a vibrating object

The Nature of Sound

- Sound
  - Audible variations in air pressure
  - Sound frequency: Number of cycles per second expressed in units called hertz (Hz)
  - Cycle: Distance between successive compressed patches



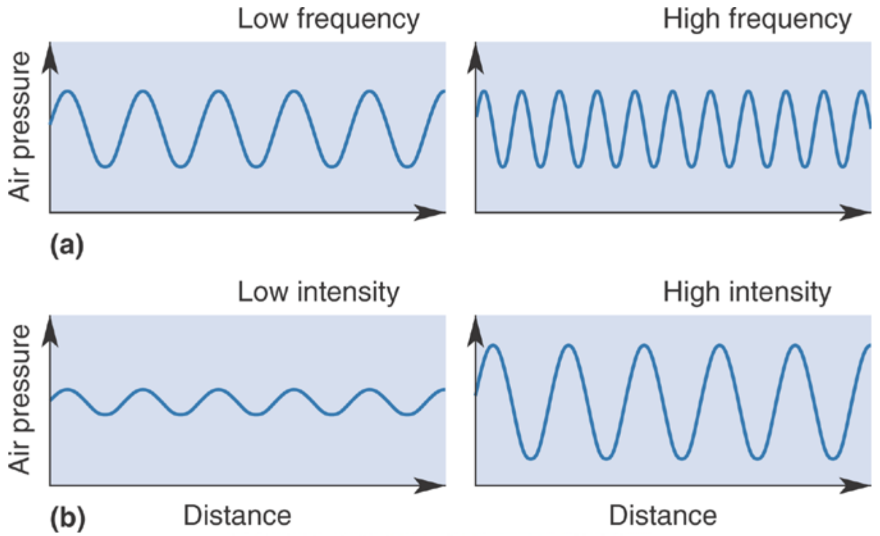


The Nature of Sound

- Sound
  - Range: 20 Hz to 20,000 Hz
  - Pitch: High pitch = high frequency; low frequency = low pitch
  - Intensity: High intensity louder than low intensity

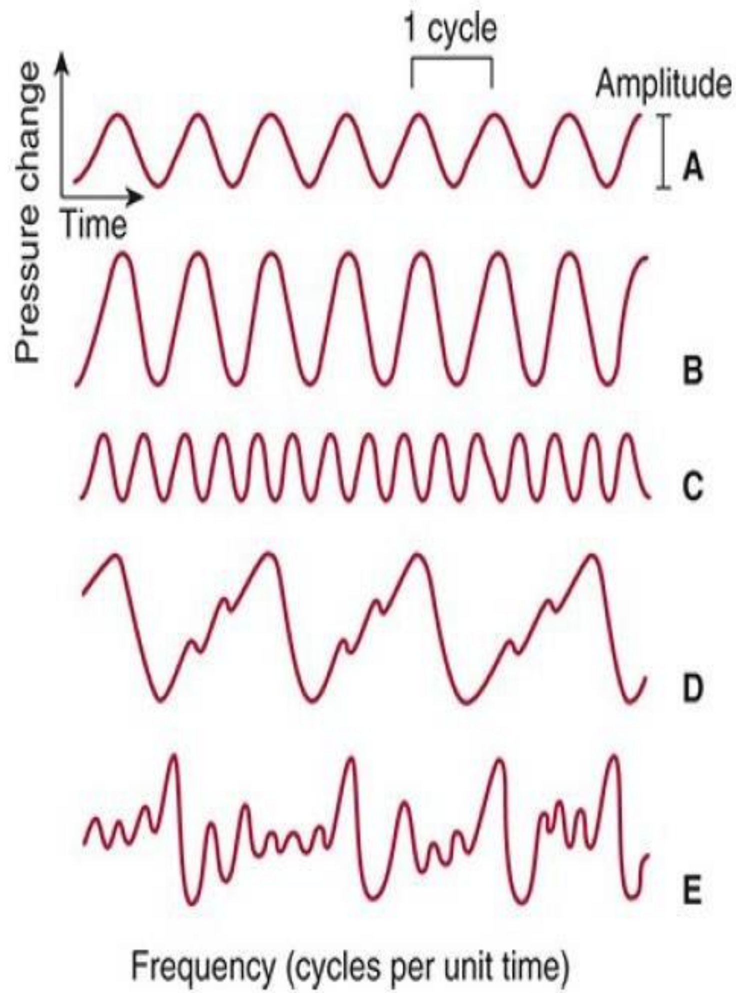
Sound intensity is measured in logarithmic units called decibels (dB)

dB= Log 10X Sound intensity/ Intensity of standard sound



Characteristics of sound waves.

- **A** is the record of a pure tone.
- **B** has a greater amplitude and is louder than **A.**
- **C** has the same amplitude as **A** but a greater frequency, and its pitch is higher.
- **D** is a complex wave form that is regularly repeated. Such patterns are perceived as musical sounds
- waves like shown in **E,** which have no regular pattern, are perceived as noise



Decibel scale

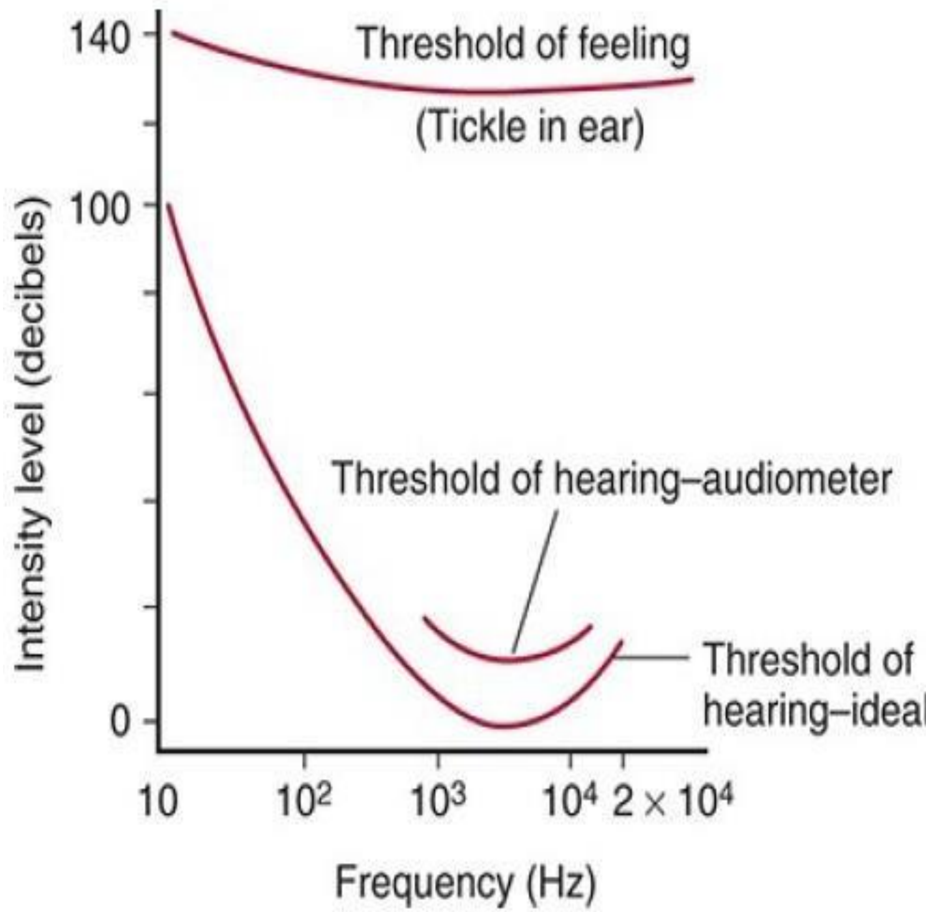
- Auditory physiologists express the intensity or amplitude of a sound wave in on **decibel scale**
- The intensity of a sound in **bels** is the logarithm of the ratio of
- the intensity of that sound and a standard sound.
- A decibel (dB) is 0.1 bel.
- The standard sound reference level adopted by the Acoustical Society of America corresponds to 0 dB at a pressure level of 0.000204 × dyne/cm2, a value that is just at the auditory threshold for the average human.
- A value of 0 dB does not mean the absence of sound but a sound level of an intensity equal to that of the standard.
- The 0- to 140-dB range from threshold pressure to a pressure that is potentially damaging to the organ of Corti
- It represents 10^7 (10 million)-fold variation in sound pressure.

Human audibility curve.

- Human ear is sensitive frequencies between 20 and 20,000 Hz and is most sensitive between 2000 and 5000 Hz.

- The usual range of frequencies in **human speech** is between **3000 and 3500 Hz-** sound intensity is about 65 dB.

- Sound intensities > 100 dB can damage the auditory apparatus>120 dB can cause pain.



- The ear: Wide dynamic range: 20 Hz – 20000 Hz

- Three major components:
  - Outer ear
  - Middle ear
  - Inner ear

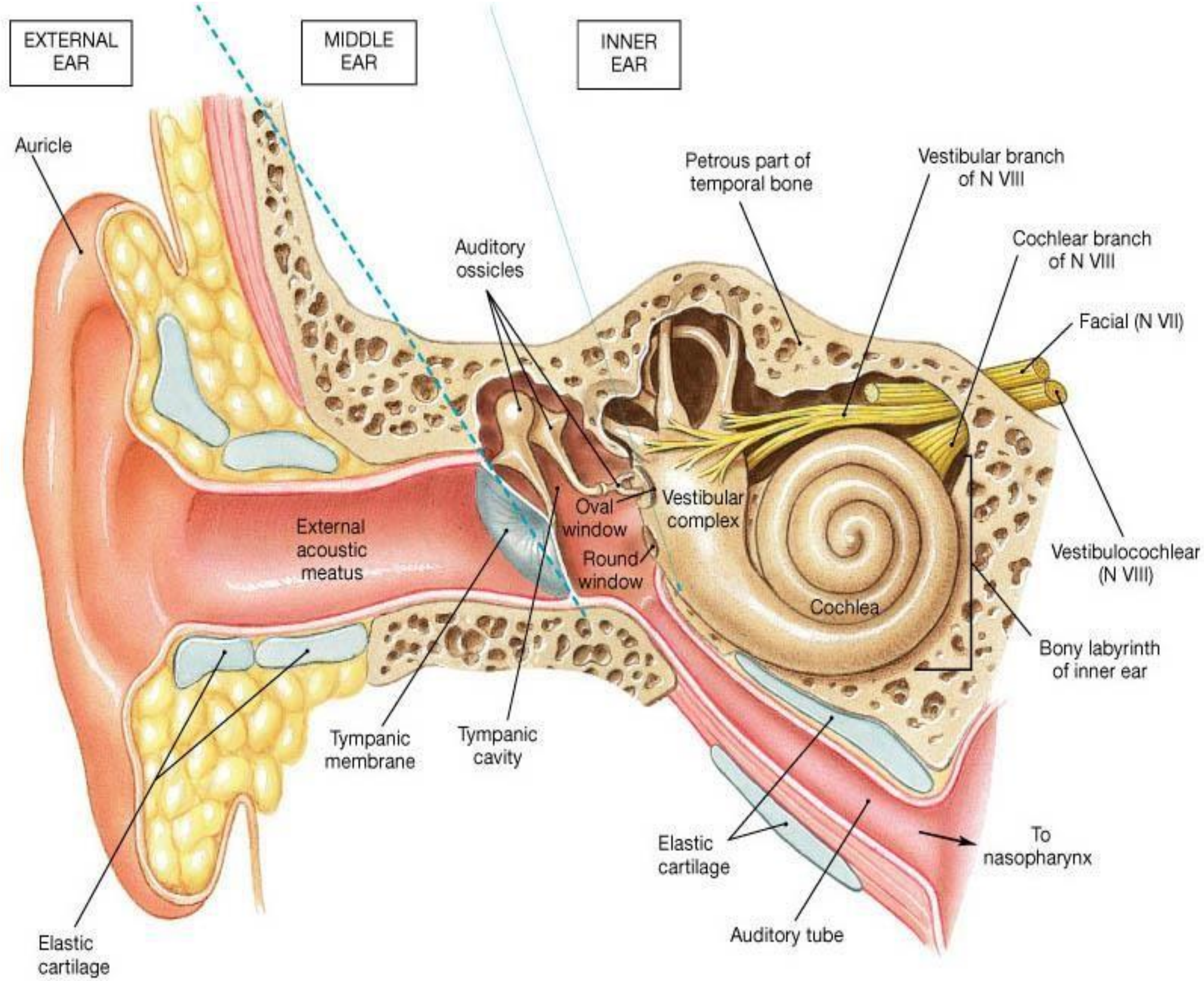
The Structure of the Auditory System

- Primary function of the ear
  - Transmission of sound waves and additory transduction
  - Sound waves are directed to the middle ear by the external ear.
  - These sound waves get converted into vibrations of the middle ear ossicles.
  - These vibrations are then transmitted to the cochlea, which converts them into electrical signals.
  - These signals are sent to CNS via the cochlear nerve's axons of auditory pathways
- Balance and equilibrium
- Auditory signals pathway stages
  - Sound waves
  - Tympanic membrane
  - Ossicles
  - Oval window
  - Cochlear fluid
  - Sensory receptor and neuron response

Basic anatomy of the ear and primary functions of the ear

transduction of sound vibrations

Balance and equilibrium



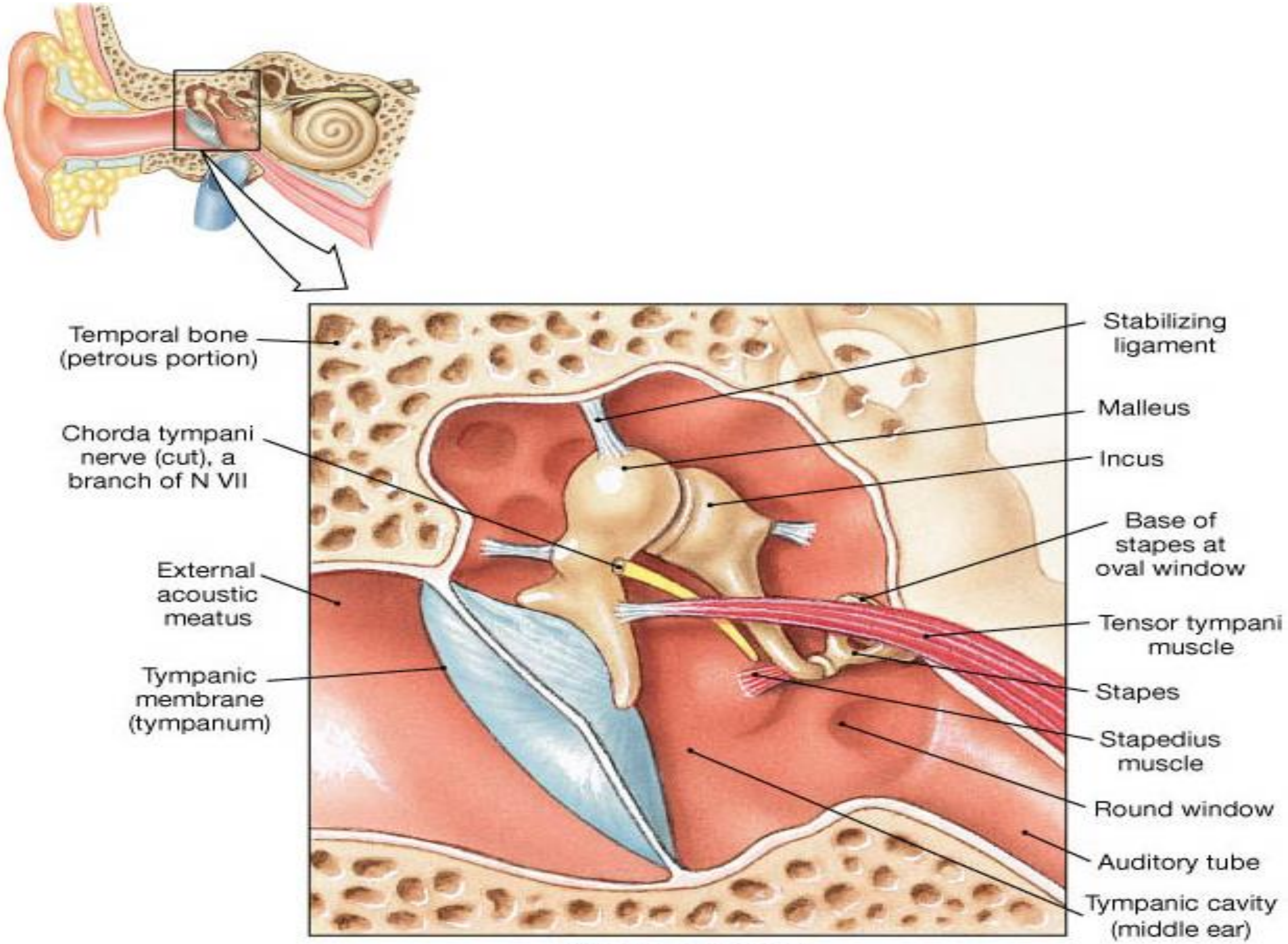
Functions of the ear

- Function of external ear
  - **External (outer) ear** contains the **auricle (pinna)**, **external auditory canal**
  - Functions to captures & direct sound waves towards external acoustic meatus
  - Conducts sound waves to tympanic membrane
  - Localization of sound
  - **Ceruminous glands** secrete **cerumen (earwax)** to protect the canal and eardrum.
  - Air filled

Middle Ear
Medial view

- **Three Auditory Ossicles: Malleus, Incus, Stapes**
- **Eustachian Tube = Auditory Tube**

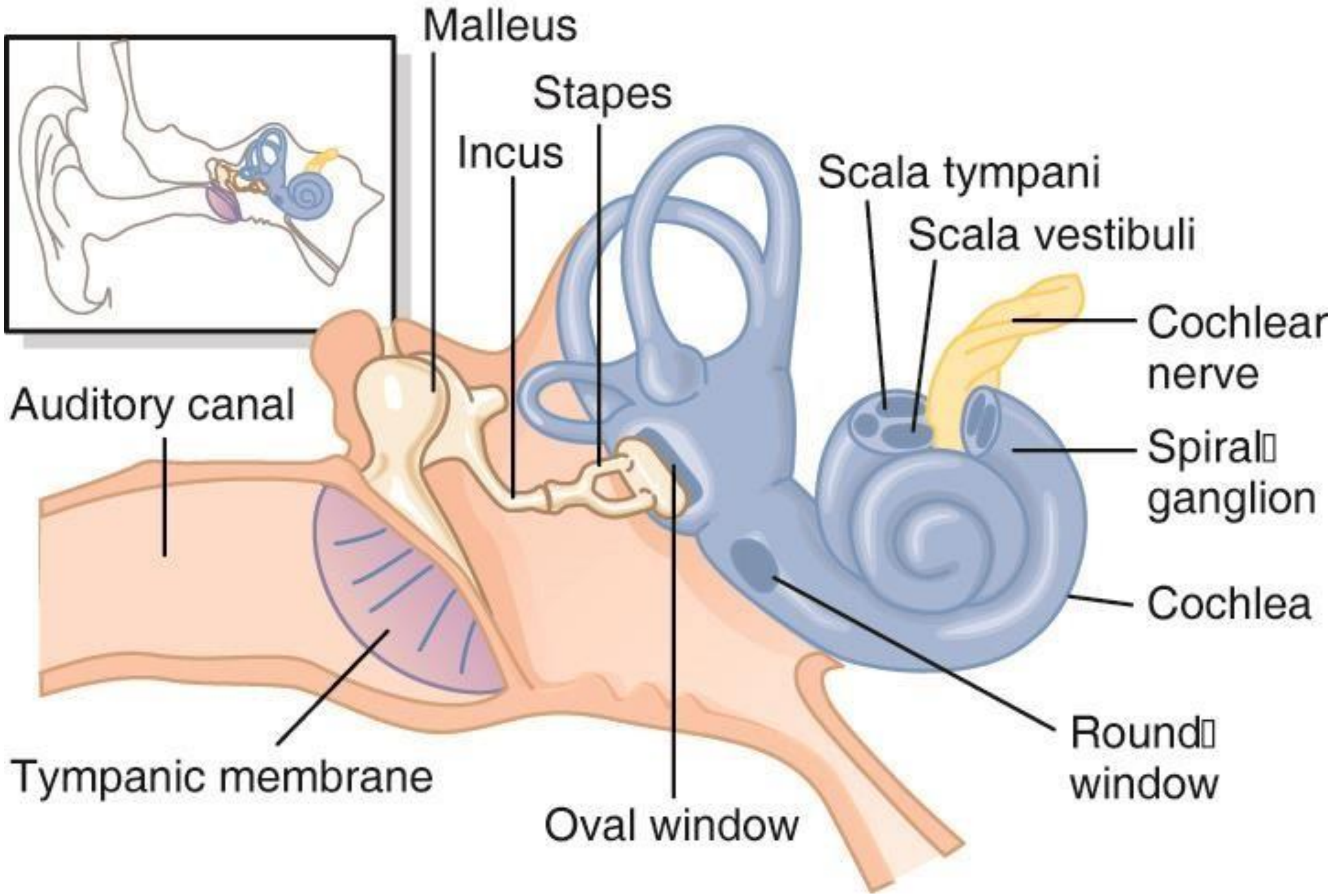
Tympanic (attenuation) reflex



(b) The middle ear

Tensor Tympani (Vth CN) Stapedius (VIIth CN).
When contract (loud noise, or self-generated vocalization) stiffen the ossicles and reduce transmitted energy to cochlea for protection.
In Bell's palsy, paralysis of Stapedius leads into **Hyperacusis**

Physiological anatomy



Function of the middle ear

- The **middle ear** contains 3 **auditory ossicles** (smallest bones in the body).
- They are the **malleus** the **incus** which and the **stapes**.
- Sound vibrations are transmitted from the eardrum through these 3 bones to the **oval window** into which the stapes fits.
- The **auditory tube (pharyngotympanic tube, eustachian tube)** extends from the middle ear into the nasopharynx to regulate air pressure in the middle ear And equalize pressure of the middle ear and the atmosphere

Functions of the ossicular System and tympanic membrane

- Transmits of sound waves to the cochlea
- Impedance of sound waves transmission occurs when from air filled media (external ear and middle to fluid filled media cochleae).
- Middle ear is used as a way of reducing the impedance mismatch so as to improve sound energy transmission to the cochlea . This is due to
- The area of the tympanic membrane is 17 times larger than the oval window
- Lever action amplification is 1.3 times

Impedance Matching and The Middle Ear

- **M**iddle ear is used as a way of reducing the impedance mismatch so as to improve sound energy transmission to the cochlea . This is due to
- **T**he area of the tympanic membrane is 17 times larger than the oval window
- The human tympanic membrane has a surface area approximately 17 times larger than the stapes footplate
- Lever action amplification is 1.3 times (*lever ratio)*
- *lever ratio :*refers to the difference in length of the manubrium of the malleus and the length process of the incus
- a small force applied to the long arm of the lever (manubrium) results in a larger force on the short arm of the lever (incus long process). In humans, the lever ratio is about 1.31

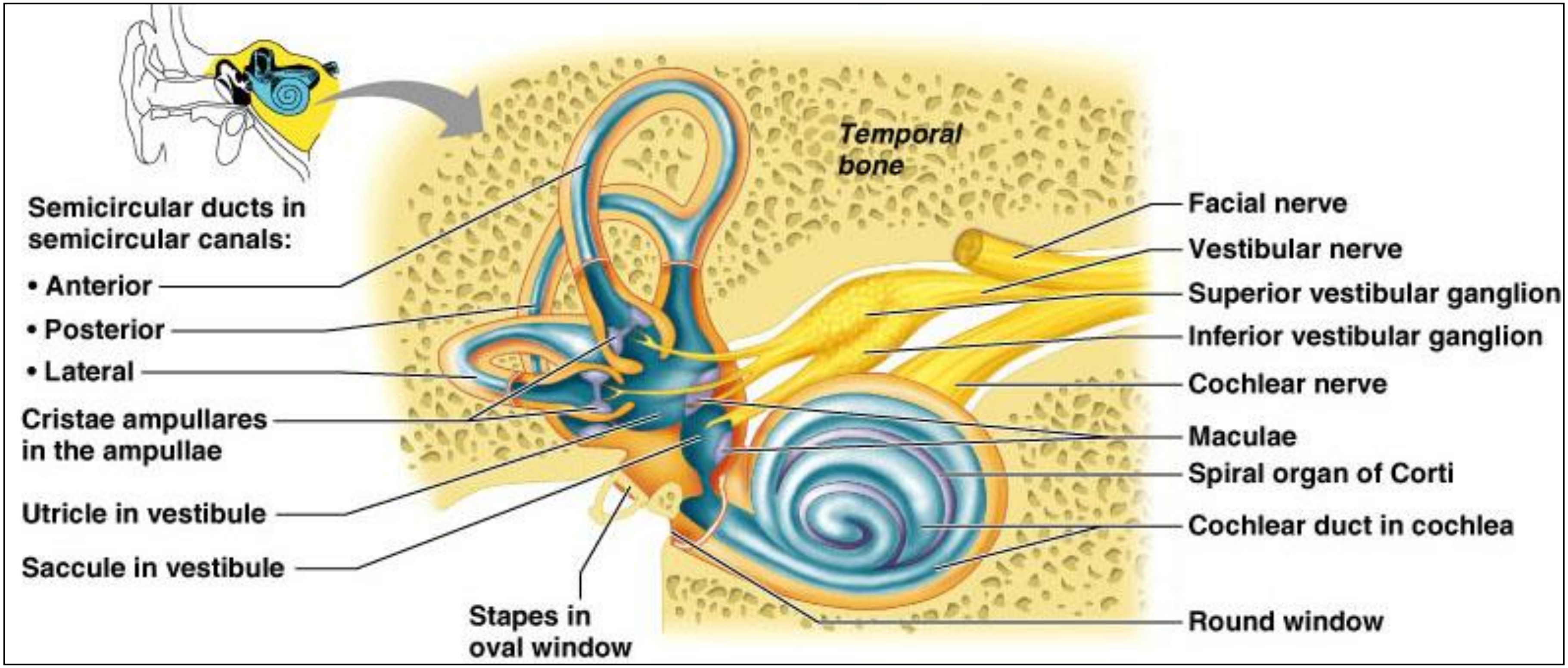
Attenuation of Sound by Muscle Contraction

- Two muscles attach to the ossicles
  - ***Stapedius*** *(stapes)*
  - ***tensor tympani*** *(malleus)*
- Stapedius is smallest skeletal muscle in body (1 mm long)
- ***Attenuation reflex***: a loud noise initiates reflex contraction, causing ossicular system to develop rigidity.
- *Both muscles involved*.
- Loud noise initiates **tympanic reflex cause** contraction of:
  - Tensor tympani- (innervated by mandibular nerve division of nerve V) pulls the handle of the malleus **inward**
  - Stapedius-(innervated by facial nerve pulls the stapes **outward**
  - **This makes the ossicular system more rigid**
- attenuates vibration intensity going to cochlea.
- Can reduce sound transmission by 30-40 decibels.
- Serves to ***protect cochlea*** and dampens low frequency sounds as well your own voice (~1000 Hz) or the voice of others.
- Takes 40-80 msec to activate
- In Bell's palsy, paralysis of Stapedius leads into **Hyperacusis**

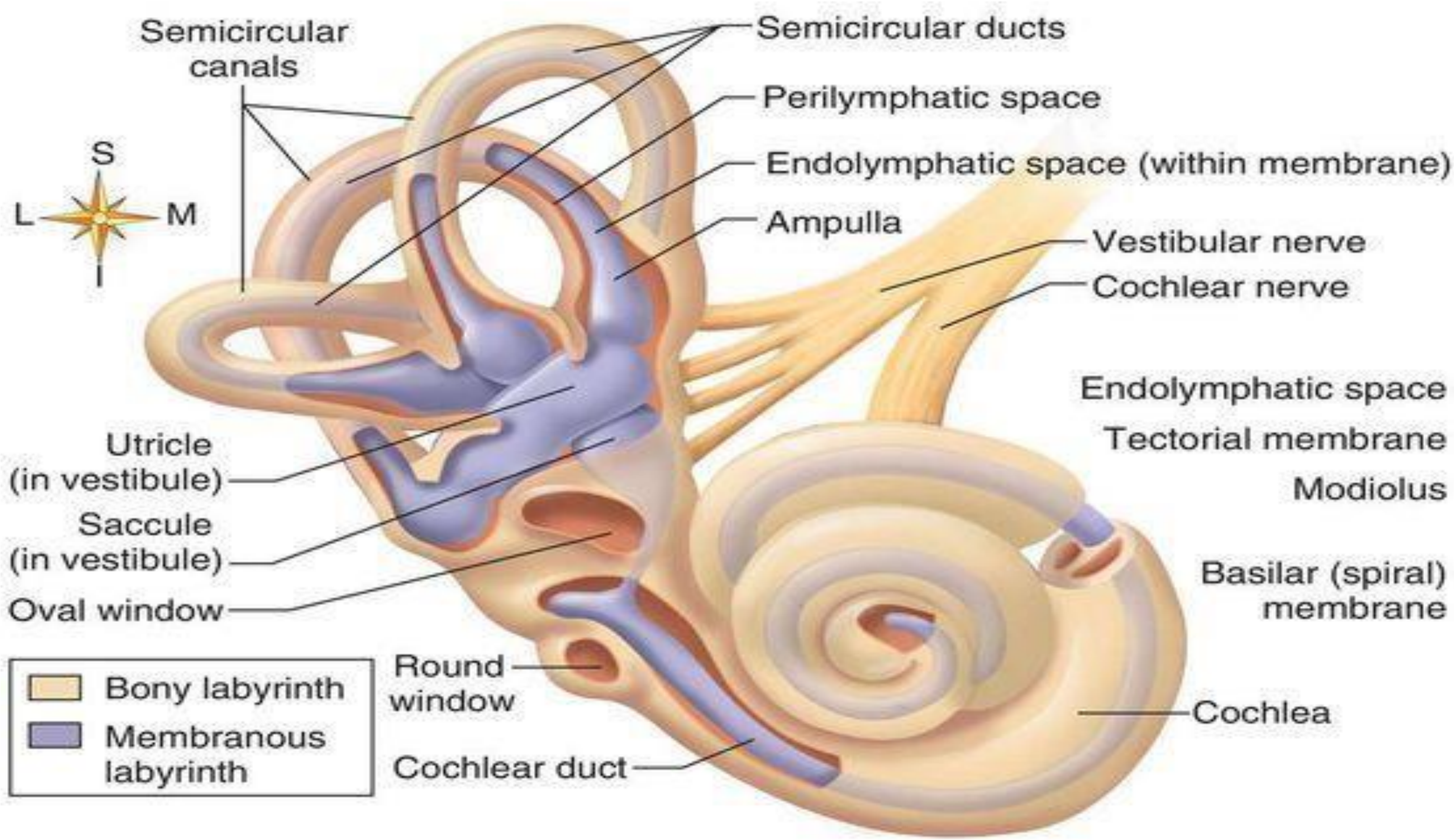
Inner Ear – Bony and Membranous Labyrinth

Bony Labyrinth - channels in temporal bone filled perilymph - 3 regions: vestibule, cochlea, and semicircular canals

Membranous Labyrinth - series of membranous sacs and ducts within the bony labyrinth filled with endolymph



Inner ear



The cochlea (from the Latin for “snail”) has a spiral shape resembling a snail’s shell.

Physiological Anatomy of Cochlea

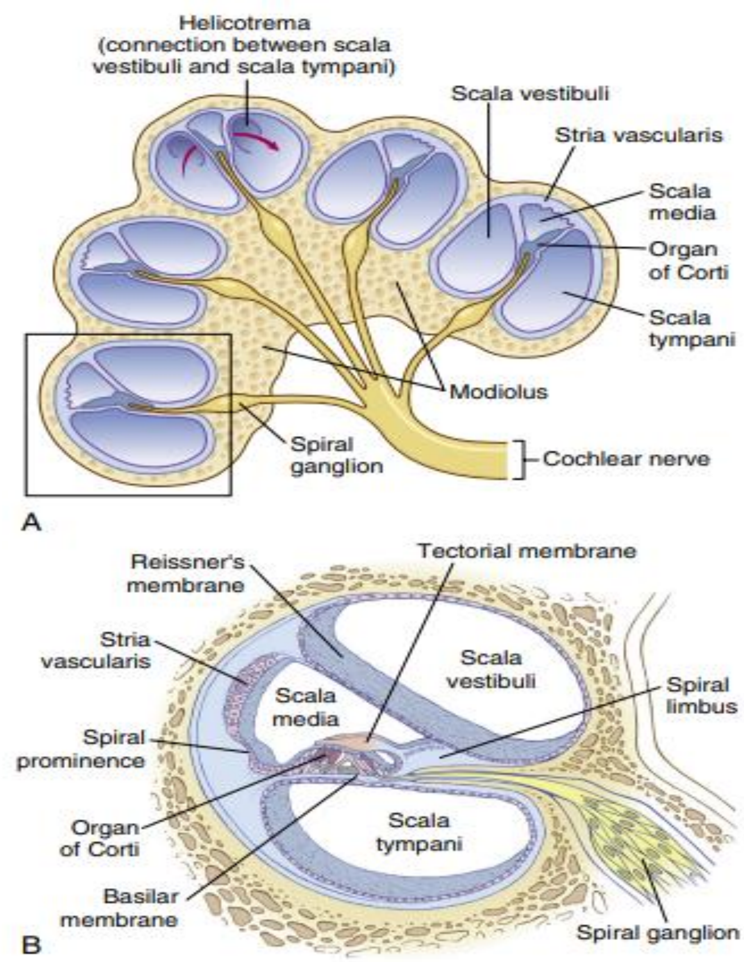
The cochlea is a system of coiled tube 33 mm length cochlea with 3 fluid compartments.

The Scala media, an endolymph-filled tube with 16000 hair cells mounting on a basilar membrane

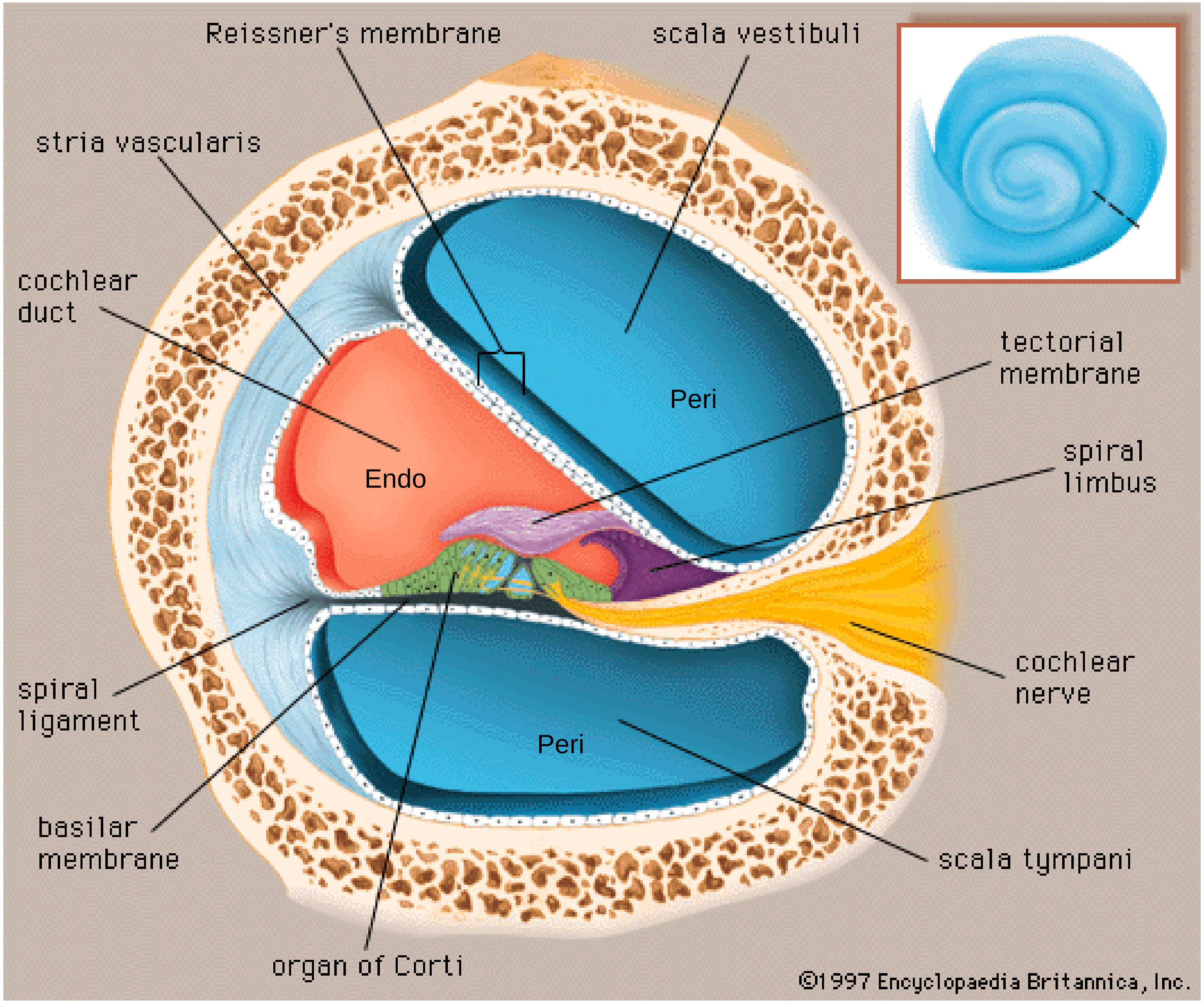
Seen in cross it is composed of three coiled tubes (chambers) separated by membranes

- ✓ *scala tympani-perilymph*
- ✓ *scala media-endolymph*
- ✓ *scala vestibuli-perilymph*

The organ of Corti contains the auditory receptors; it sits upon the basilar membrane and is covered by the tectorial membrane.



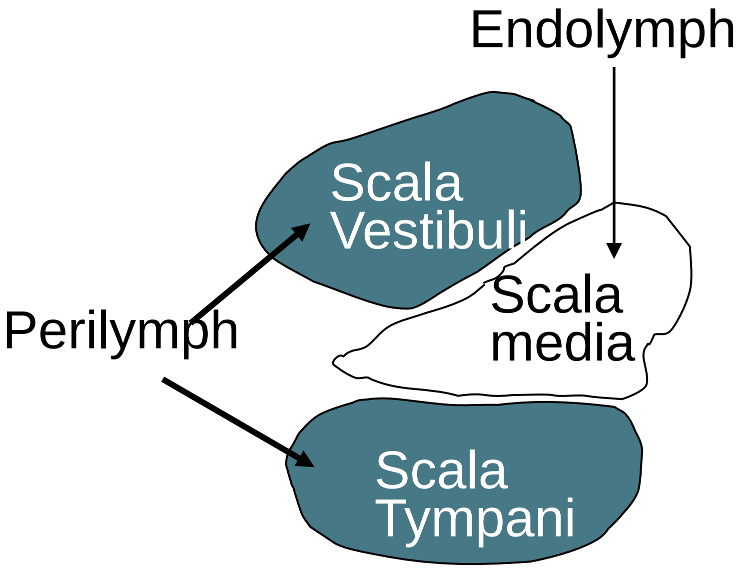
Inside the Cochlea



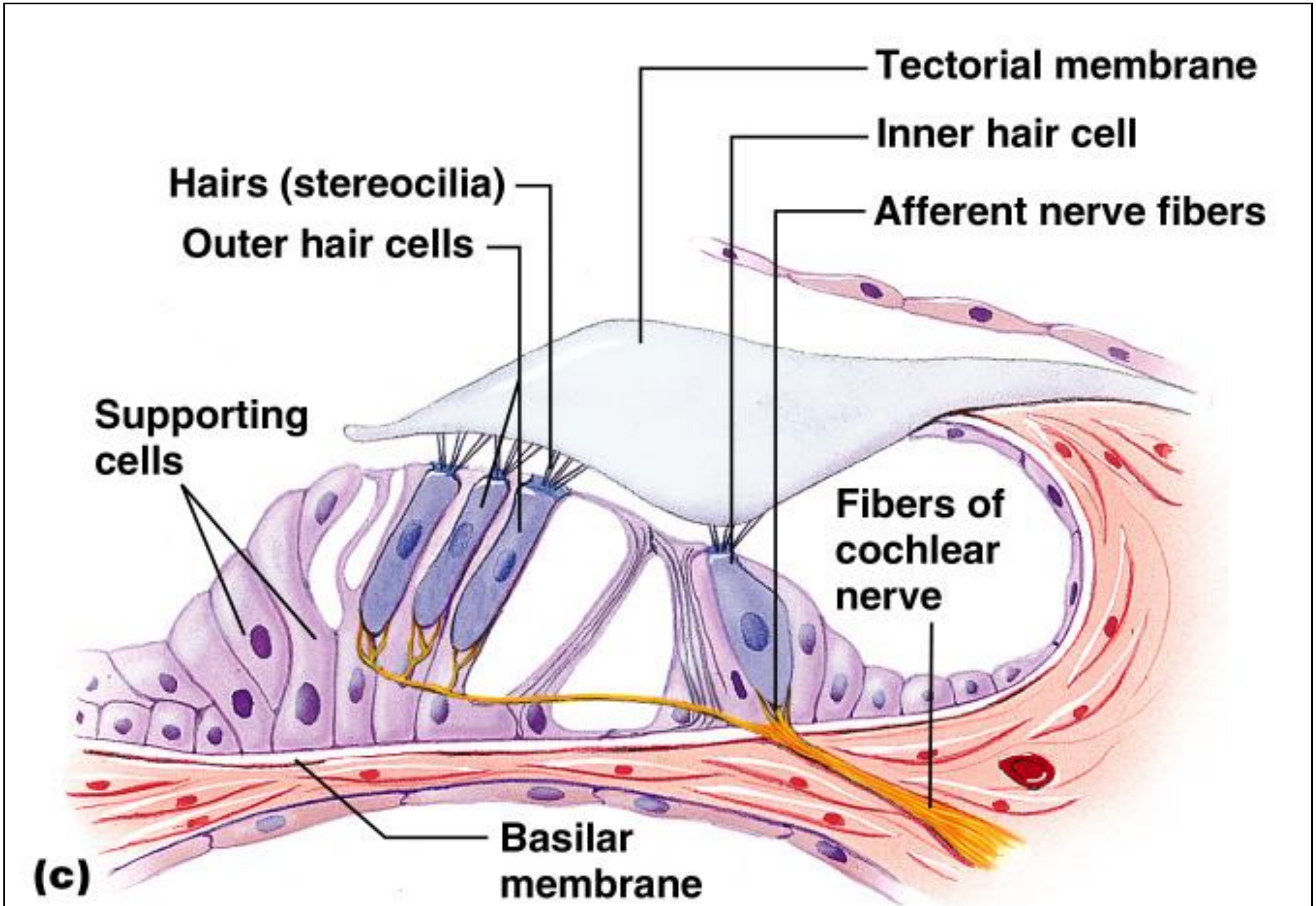
Fluid Constituents of Cochlear Chambers

Perilymph has a similar ionic constituents to the extracellular fluid. High concentration of sodium and low concentrations of Potassium.

Endolymph has ionic concentrations similar to intracellular fluid. High concentrations of Potassium, and low concentration of sodium.

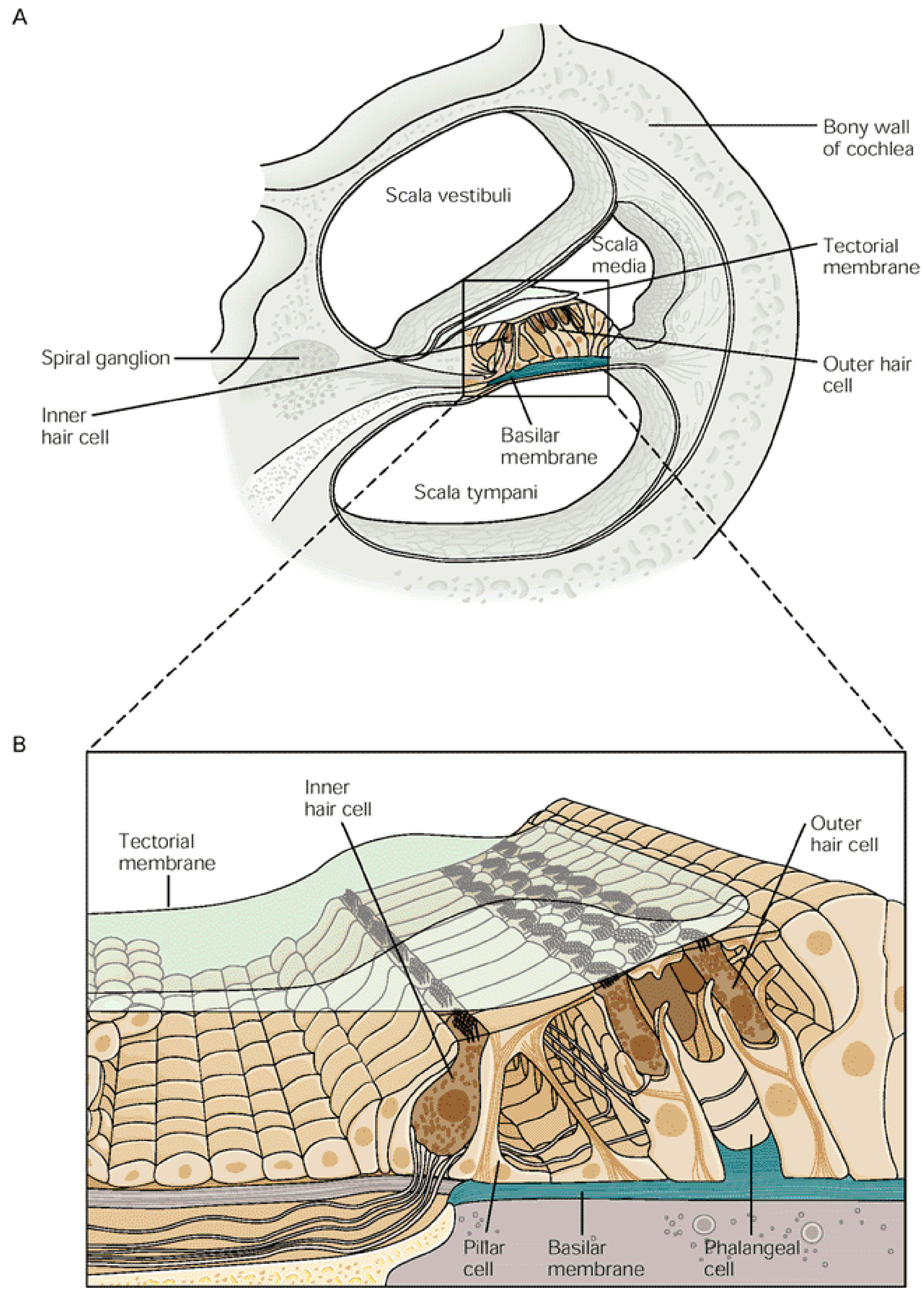


The Organ of Corti



Hair cells arranged in 4 rows: A single row of inner hair cells and 3 of outer hair cells.

Outer hair cells tips (V shaped) are embeded in the lower surface of the tectorial membrane. (?).



Supporting cells: Phalangeal cells,

Pillar cells.

Afferent, and efferent fibers. !!

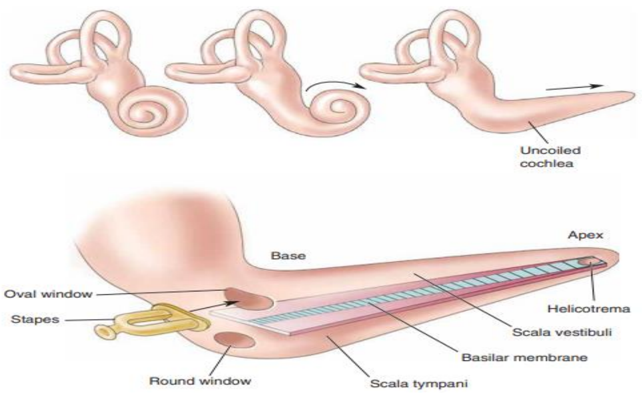
Organ of Corti

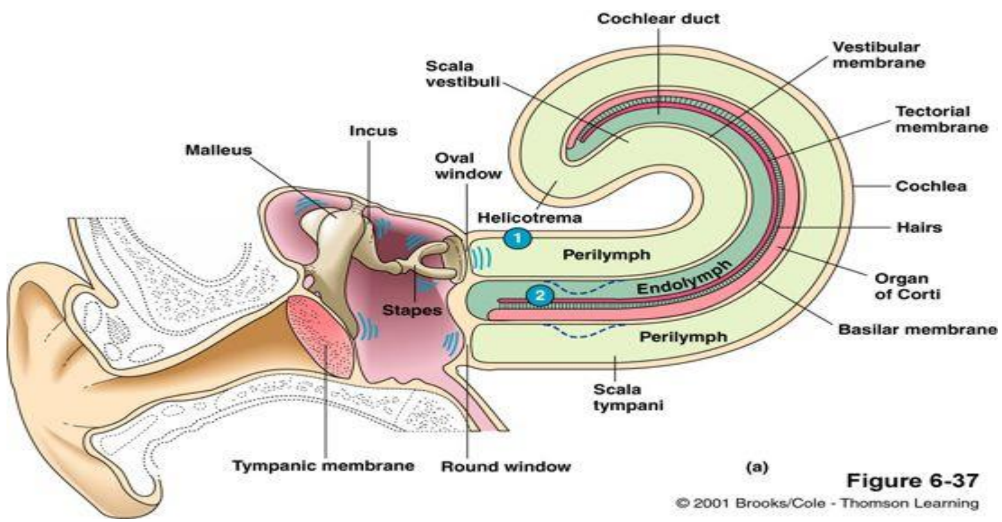
- The organ of Corti, located on the basilar membrane
- Receptor organ that generates nerve impulses.
- Contains rows of hair cells that have ***stereocilia***.
- **Hair cells :**.
- The hair cells are sandwiched between the basilar membrane and a thin sheet of tissue called the reticular lamina
- Hair cells between the modiolus and the rods of Corti are called inner hair cells ,
- Cells farther out than the rods of Corti are called outer hair cells
- Inner hair cells :auditory receptors l
- Hair cells synapse with **cochlear nerve (CN VIII) endings- cell bodies located in spiral ganglia**
- The tectorial membrane lies above the stereocilia of the hair cells.
- Movement of the basilar membrane causes the stereocilia of the hair cells to shear back and forth against the tectorial membrane.

Although the cochlea narrows from base to apex, the basilar membrane widens toward the apex. and scala tympani

.

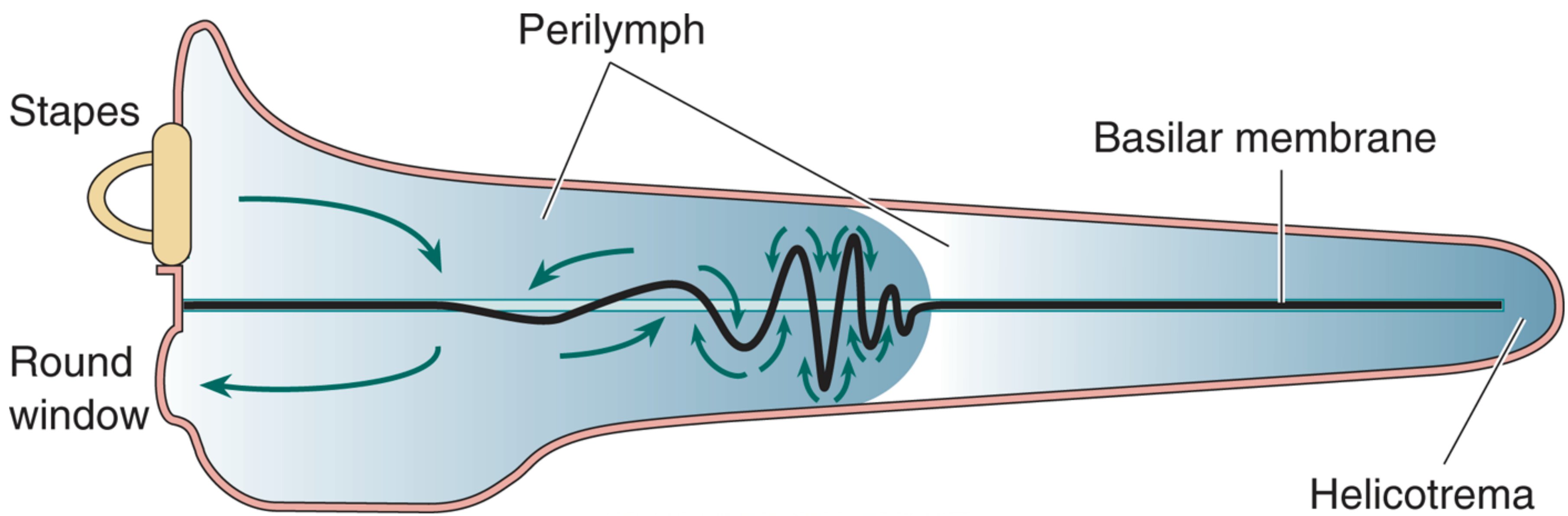
The helicotrema is a hole at the apex of the basilar membrane, which connects the scala vestibuli he part of the cochlear labyrinth where the scala tympani and the scala vestibuli





The Inner Ear

- Travelling wave in the Basilar Membrane



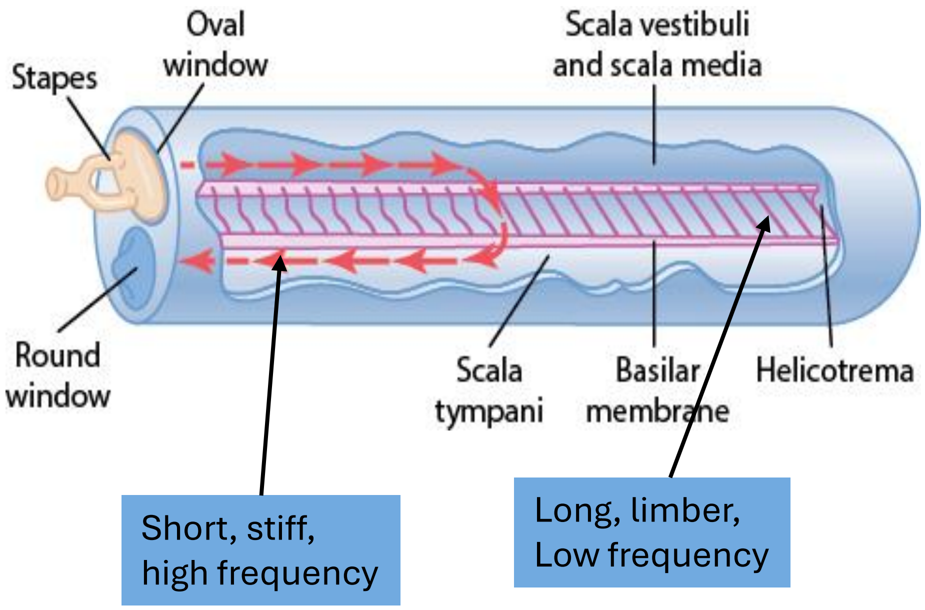
Basilar Membrane

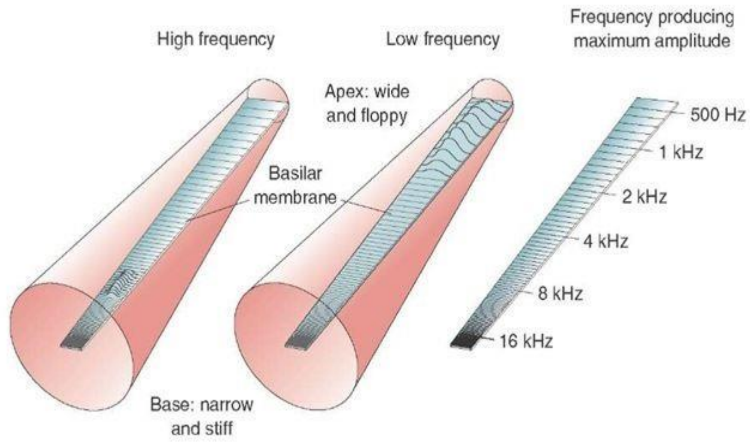
- Contains about basilar fibers

<u>**Characteristics of basilar fibers**</u>

- Different size and shape along cochlea
- ***Elastic membrane***
- ***(near the Stapes Base of cochlea):***
- Narrow and stiff, short, thick & stiff→ high freq. sounds
- Best responds to high frequencies
- ***Basilar Membrane near the Apex of cochlea :***
- Wide and flexible long, thin & soft. sounds
- Best responds to low frequencies

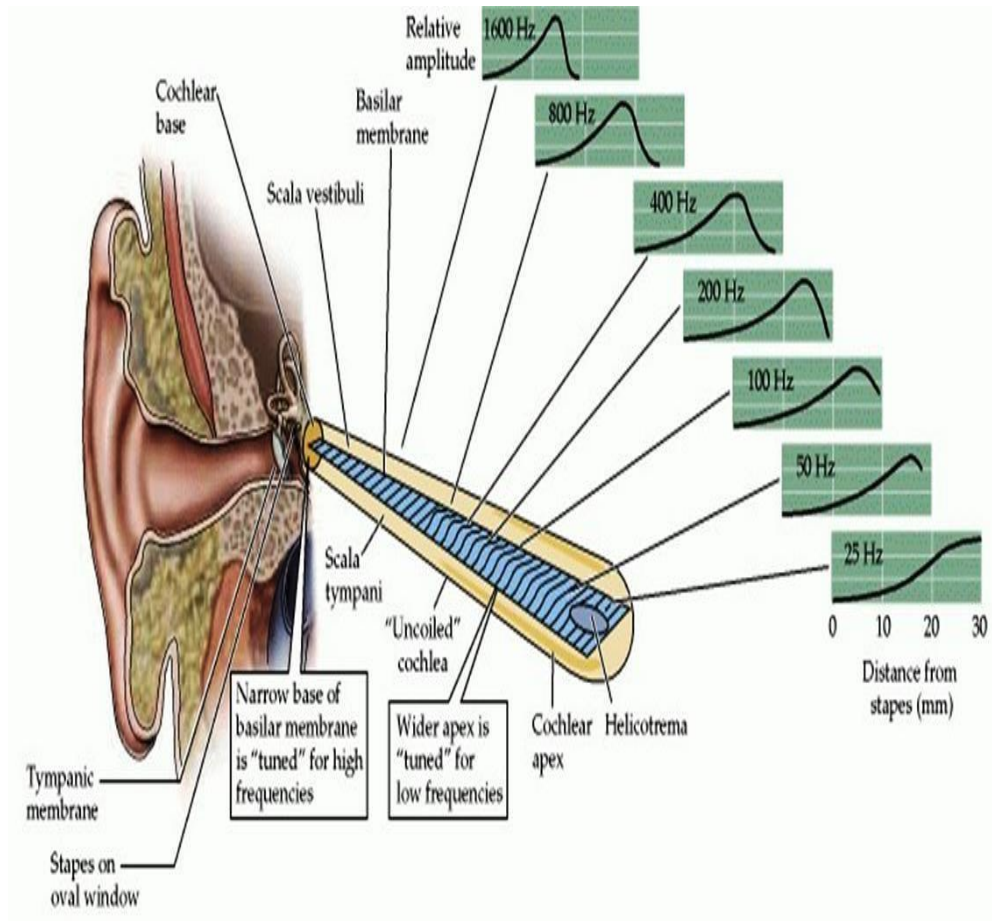
Although the cochlea narrows from base to apex, the basilar membrane widens toward the apex. and scala tympani



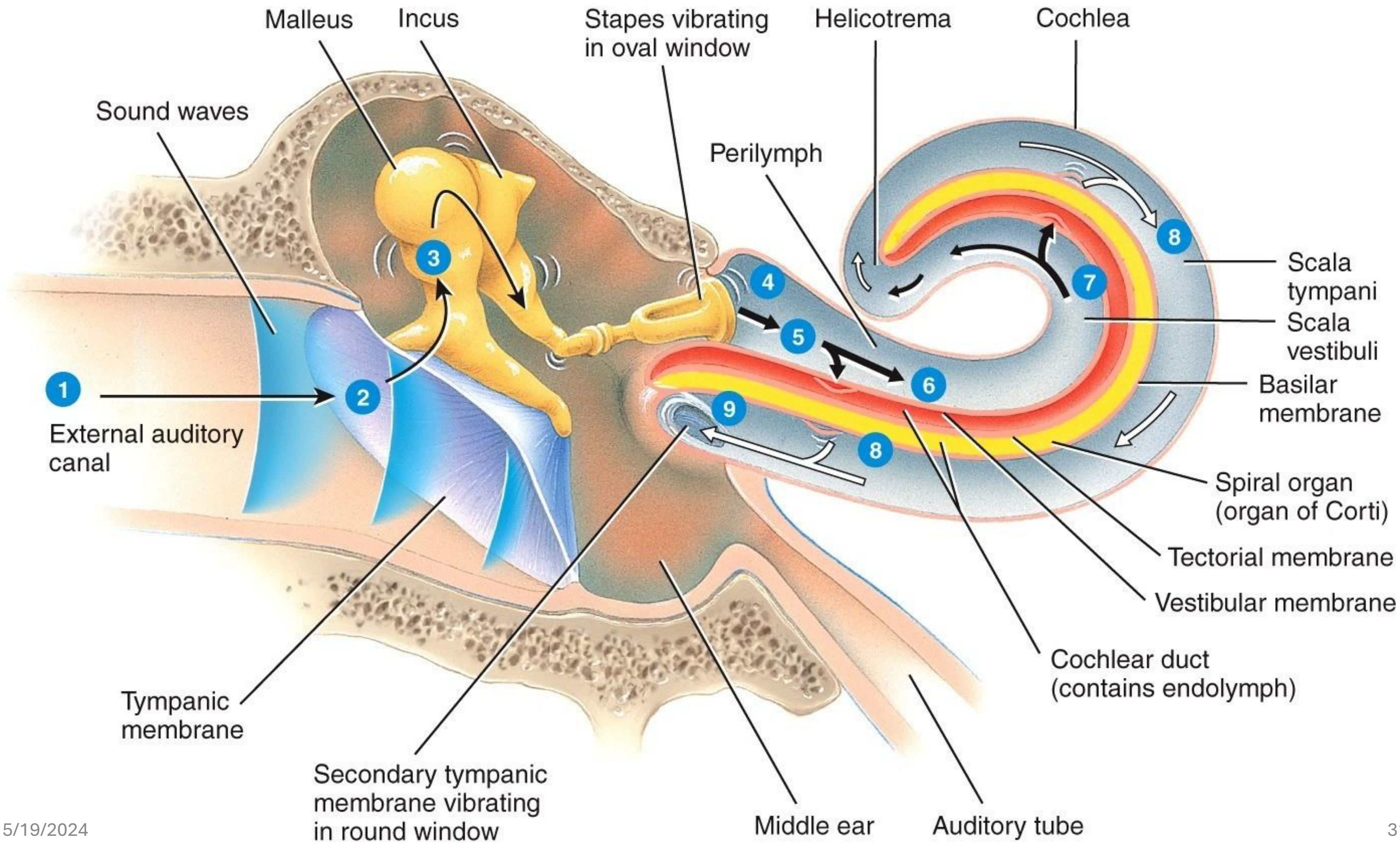


Traveling waves along the cochlea. A traveling wave is shown at a given instant along the cochlea, which has been uncoiled for clarity

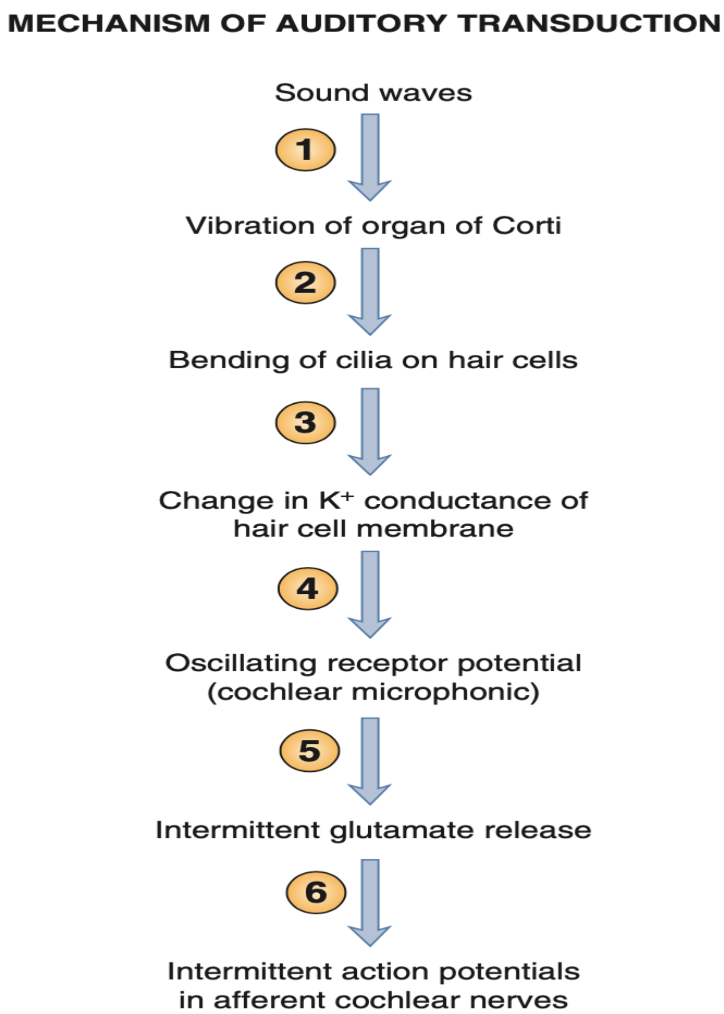
- The principal method whereby sound frequencies are discriminated from one another is based on the "place" of maximum stimulation of the nerve fibers from the organ of Corti lying on the basilar membrane
- There is a place code on the basilar membrane for the frequency that produces the maximum amplitude deflection



Summary of Steps of transmission of sound waves through the ear



Mechanism of auditory transduction



Ionic basis of receptor potential in cochlear hair cells

- Resting potential -45 to -60 mV
- Depolarization when hairs bend towards the tallest stereocilia and resulted in opening of mechanically gated K channels.
- Depolarization leads into opening of voltage-gated Ca and consequently NT release
- The neurotransmitter glutamate is released and cause excitation of cochlear nerve cells

Hair cells excitation in the organ of Corti

Bending of the hairs in one direction depolarizes the hair cells, and bending in the opposite direction hyperpolarizes them.

Depolarization in turn excites the auditory nerve fibers synapsing with their bases

Mechanoelectrical Transduction:

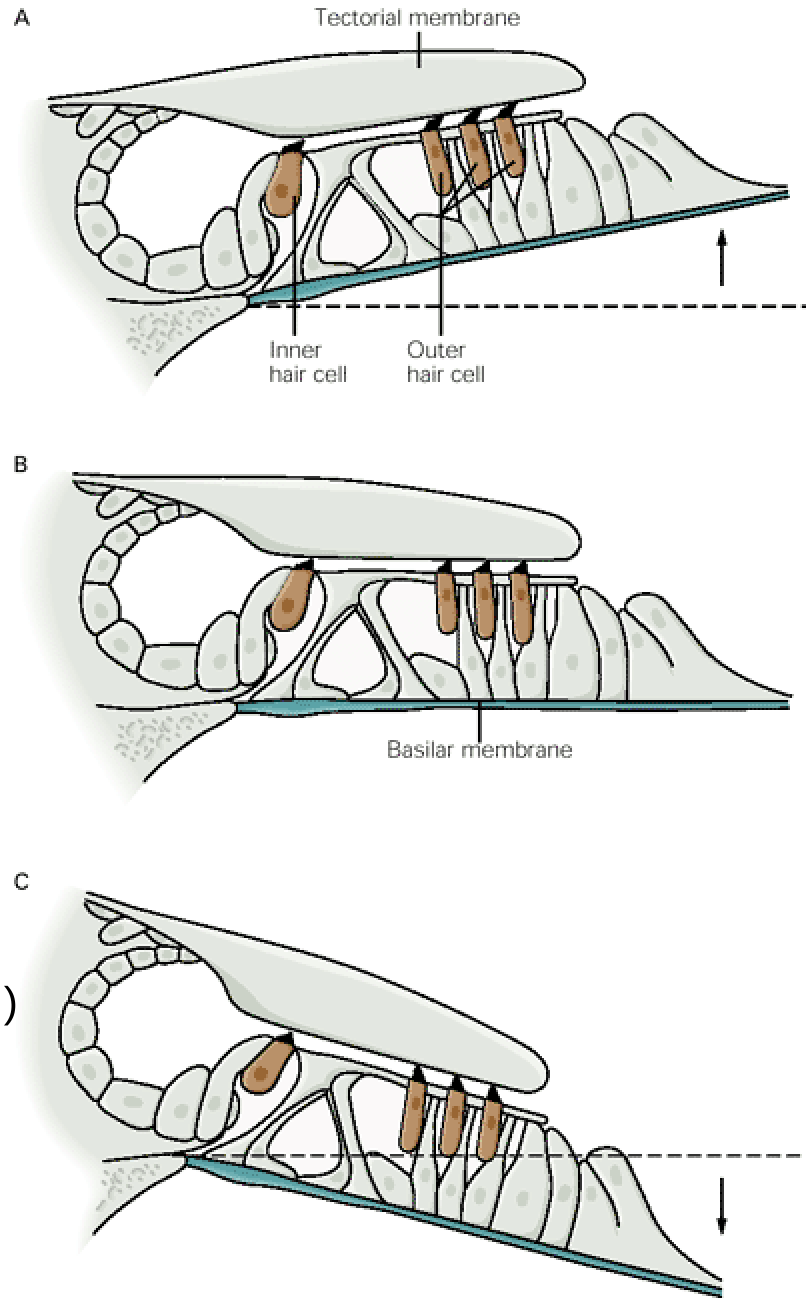
Upward mov: Depolarization.

Mid position:

Resting state

Down ward :

Inhibition(Hyperpol.)



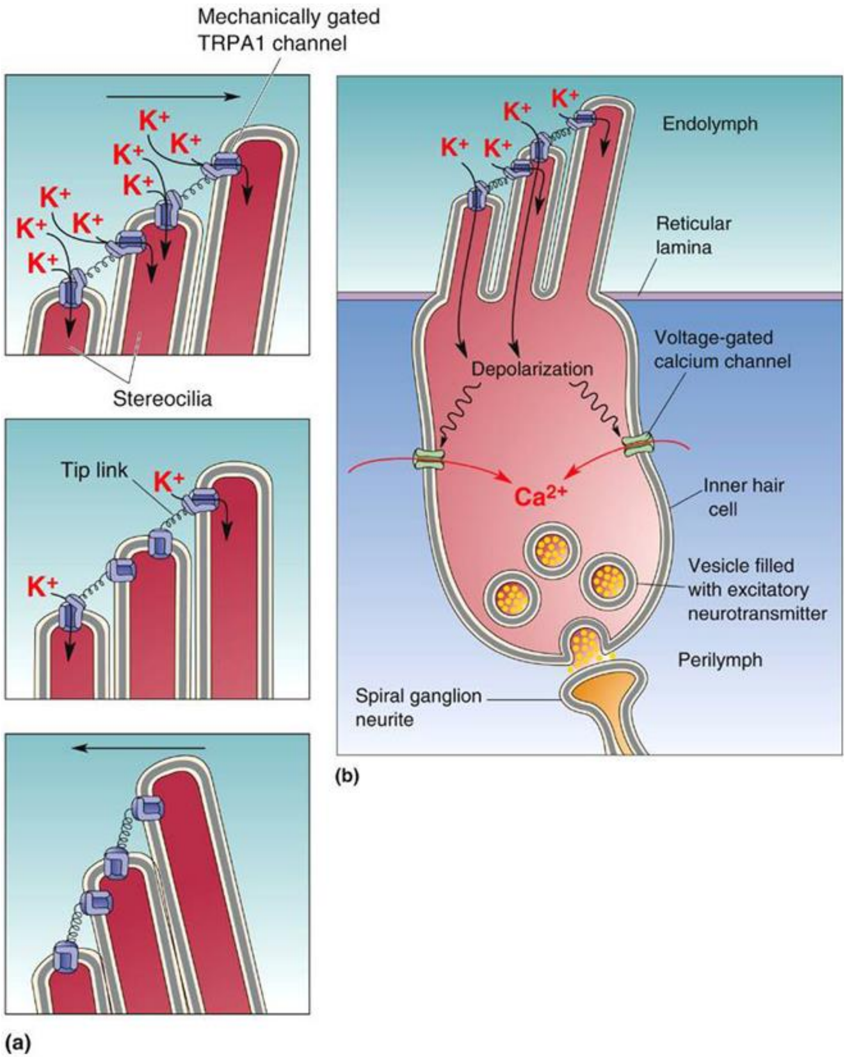
Cochlear amplification: (outer HC)

Depolarizing current= Cell shorten

Hyperpolarizing current= Cell lengthen.

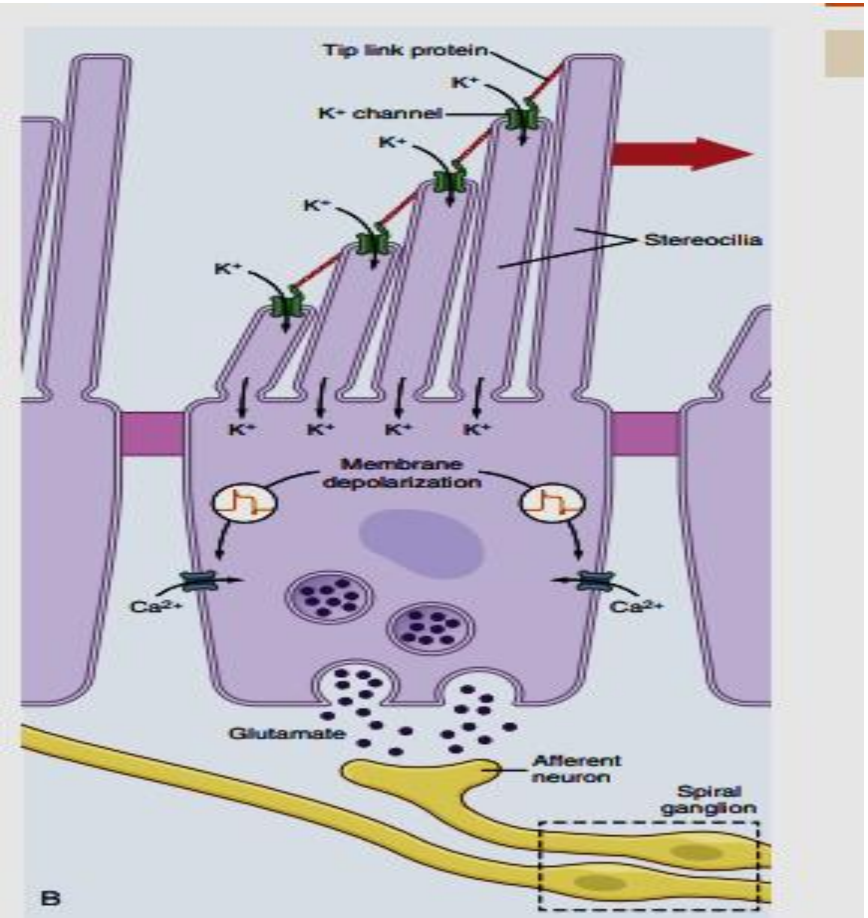
The Inner Ear

- Transduction by Hair Cells
  - Sound: Basilar membrane movement causes stereocilia to bends and K channels to open



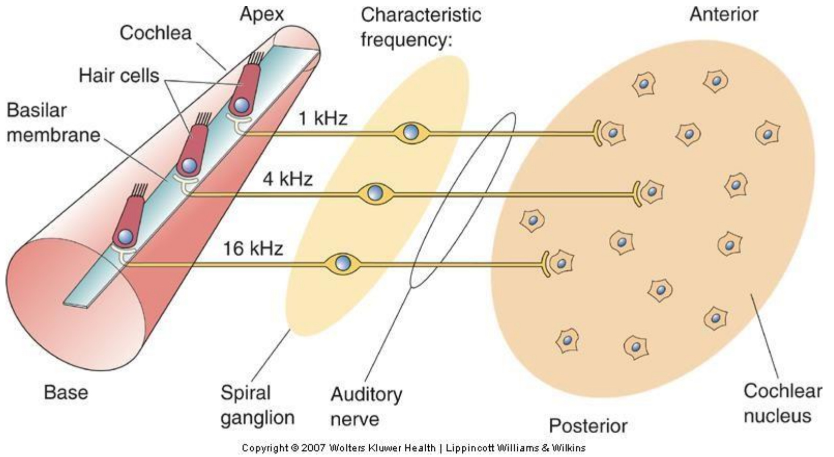
Transduction by Hair Cells(Mechanoelectrical coupling in inner hair cells)

- B, Transduction of mechanical energy into neural signals by the hair cells. When the stereocilia are bent in the direction of the longer ones, K+ channels are opened, causing depolarization, which in turn opens voltage-gated Ca2+ channels. The influx of Ca2+ augments the depolarization and elicits release of the excitatory transmitter glutamate, which depolarizes the sensory nerve.



Encoding of sound frequency in auditory system

- *Place principle* determines the frequency of sound perceived.
  - different frequencies of sound will cause the basilar membrane to oscillate at different positions.
  - position along the basilar membrane where hair cells are being stimulated determines the pitch of the sound being perceived
- Tonotopy : systematic organization of sound frequency within an auditory structure is called tonotopy.



Tonotopic maps exist on the basilar membrane and within each of the auditory relay nuclei, the MGN, and auditory cortex

Encoding Sound Intensity

- Encoding Information about Sound Intensity
  - Firing rates of neurons
  - Number of active neurons (Special summation)
  - Displacement amplitude of basilar membrane Outer cell stimulation **Cochlear amplification: (outer HC)**

    Depolarizing current shortens cells

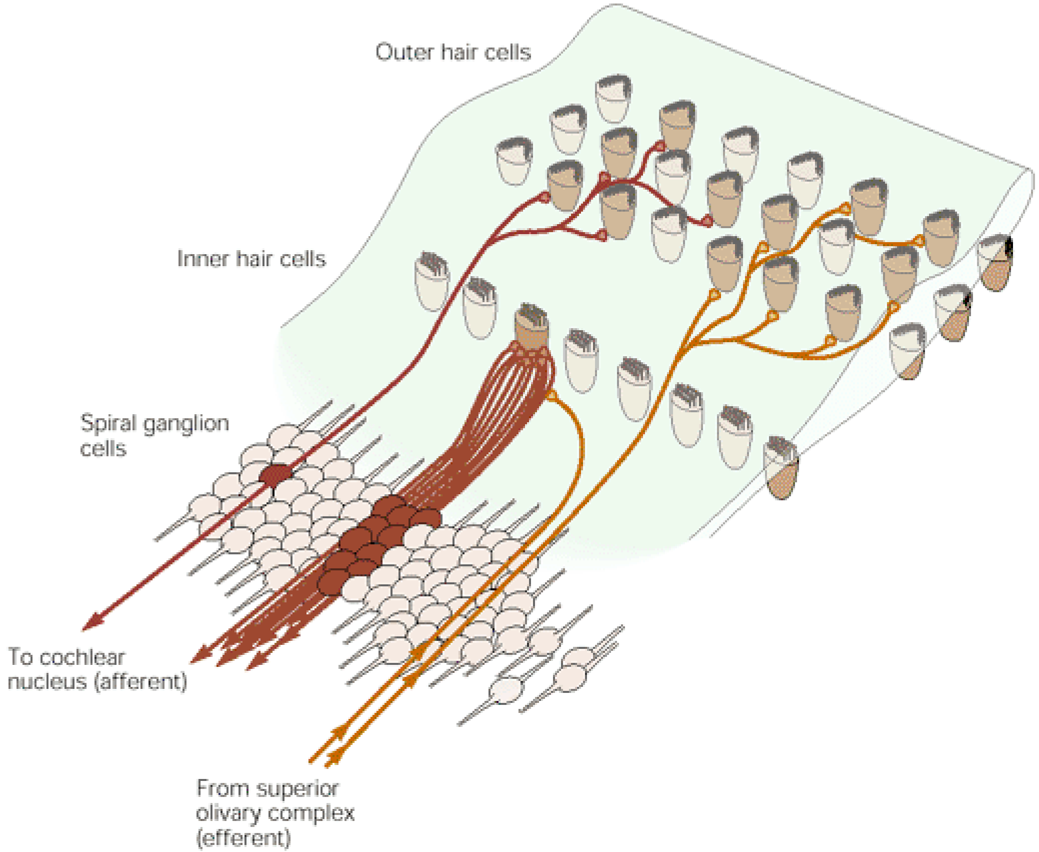
    Hyperpolarizing current= Cell lengthen

15000 hair cells

3500 inner hair cells.

30000 afferent nerve fibers

(about 1 inner HC gives information to 10 ganglion cells)



Innervation of the organ of Corti:

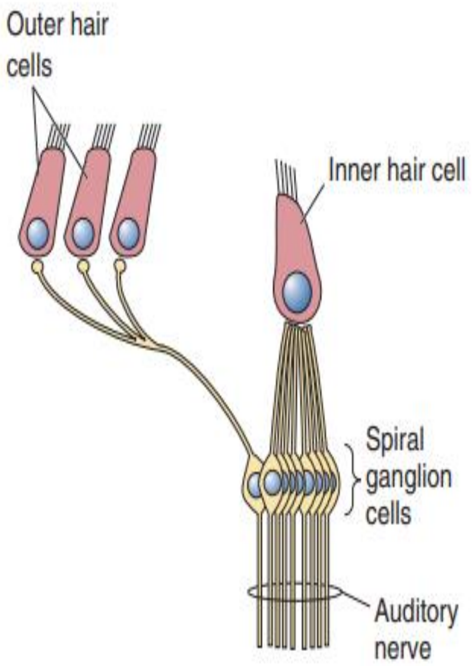
1- Majority of afferents are from the inner hair cells (90-95% of the cochlear ganglion cells).

2- Very few afferents from the outer hair cells.

3- Most of the efferents (from superior oliv. Complex) are to the outer hair cell (direct synapses). Few also to the inner hair cells.

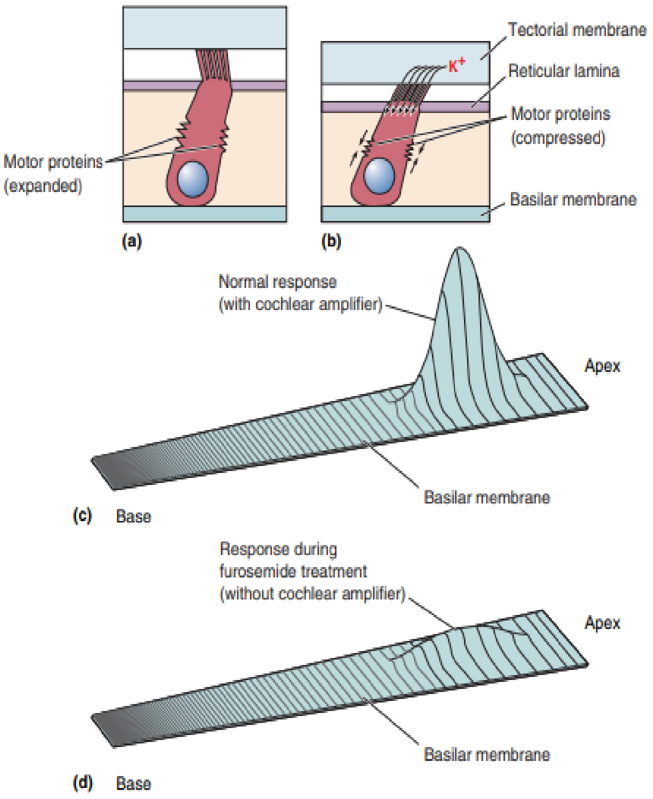
The innervation of hair cells by neurons from the spiral ganglion

- 90 -95% of cochlear nerve endings on **inner** hair, auditory signals are transmitted by the inner hair cells
- Auditory nerve fibers are excited mainly by inputs from inner hair cells
- Outer hair cells 3-4 times more than inner hair cells outer hair cells.
- Outer hair cells receive extensive innervation from the brain stem
- outer hair cells may control the sensitivity of the inner hair cells for different sound pitches.
- Outer hair cells seem to act like tiny motors that amplify the movement of the basilar membrane during low-intensity sound stimuli.
- This action of the outer hair cells on the basilar membrane is called the cochlear amplifier
- The efferent out flow by olivocochlear bundle cause changes in the activity of outer hair cells



Function of outer hair cells (cochlear amplifier)

- Amplification by outer hair cells.
- (a) Motor proteins in the membranes of outer hair cells.
- (b) Bending of the stereocilia causes potassium to enter the hair cell, depolarizing it, and triggering motor proteins to activate and shorten the hair cell.
- (c) The shortening and lengthening of the hair cell increase the flexing of the basilar membrane.



Olivocochlear bundle

- is a prominent bundle of efferent fibers in each auditory nerve that arises from both ipsilateral and contralateral superior olivary complexes
- Ends primarily around the bases of the outer hair cells of the organ of Corti.
- The activity in this nerve bundle modulates the sensitivity of the outerhair cells via the release of acetylcholine.
- The effect is inhibitory, and it may function to block background noise while allowing other sounds to be heard.

Depolarization and repolarization of outer hair cells by olivocochlear fibers

- There is a protein molecule in the outer hair cells know as Prestin, a contractile protein .
- Depolarization of these hair cells will cause relaxation of this protein and thus elongation of the outer hair cells.
- This cause decrease vibration of basilar membrane
- This may occur during for example when the cochlea is exposed to high noise or when you are listening to different musical instruments

Auditory Pathway

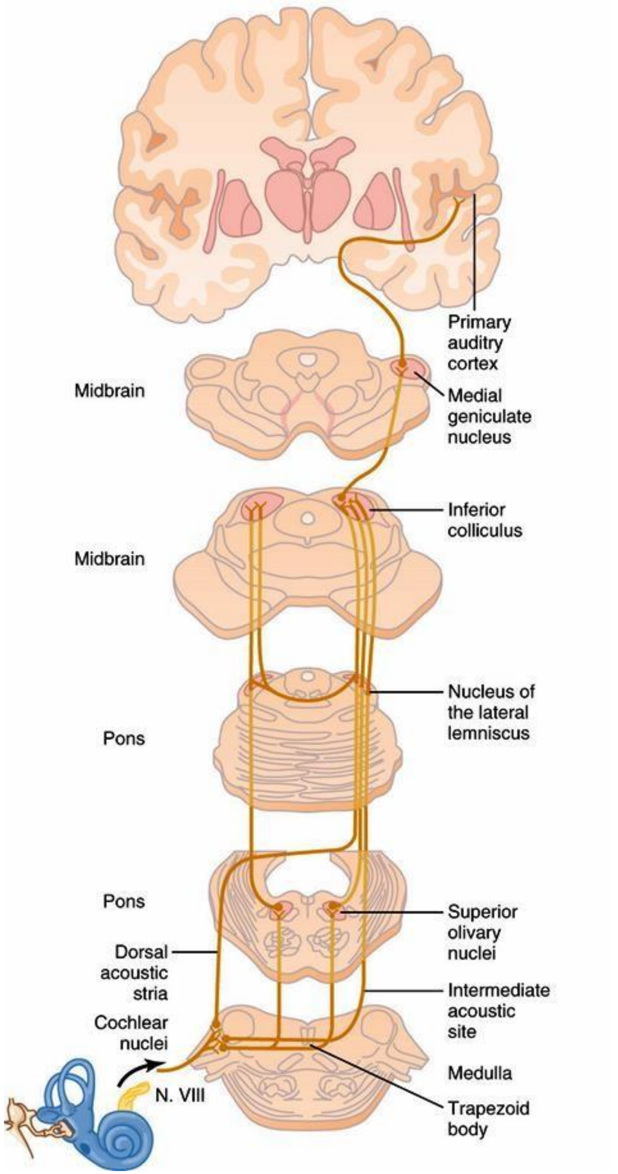


Figure 52-10

Auditory Cortex and Association Areas

- arranged by tonotopic maps.
- high frequency sounds at one end of map.
- low frequency sounds at other end.
- discrimination of sound patterns.

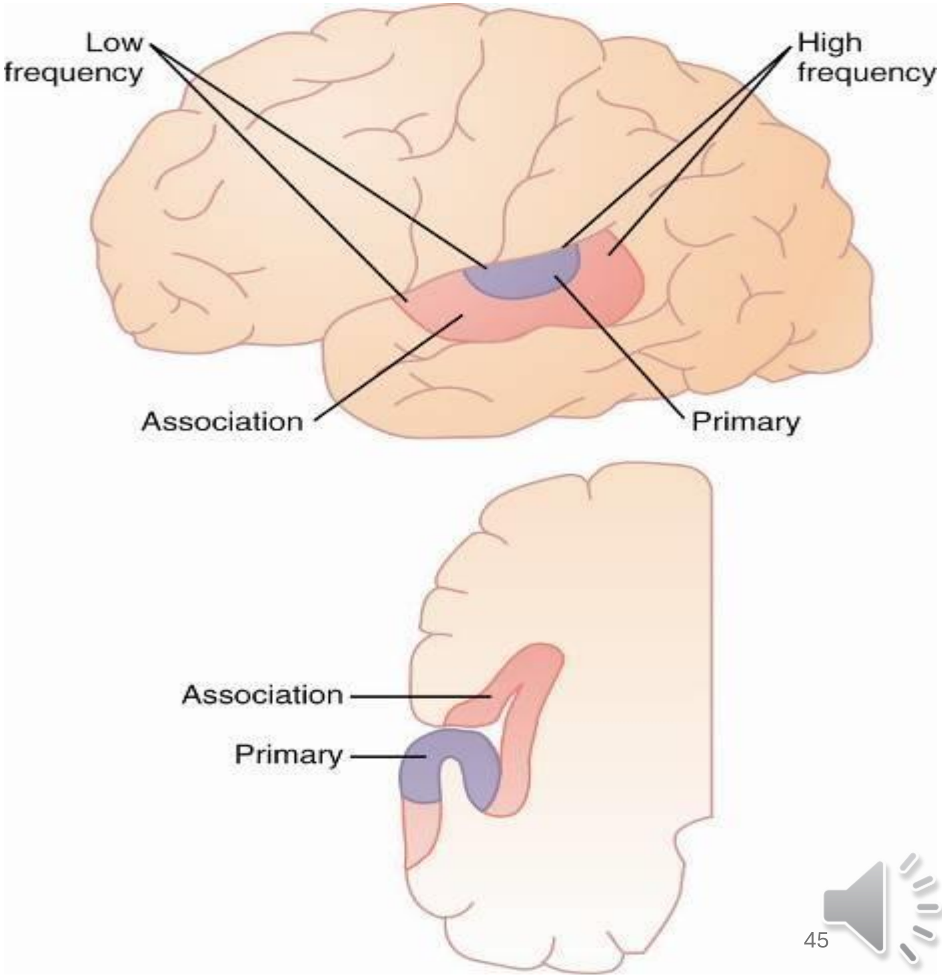
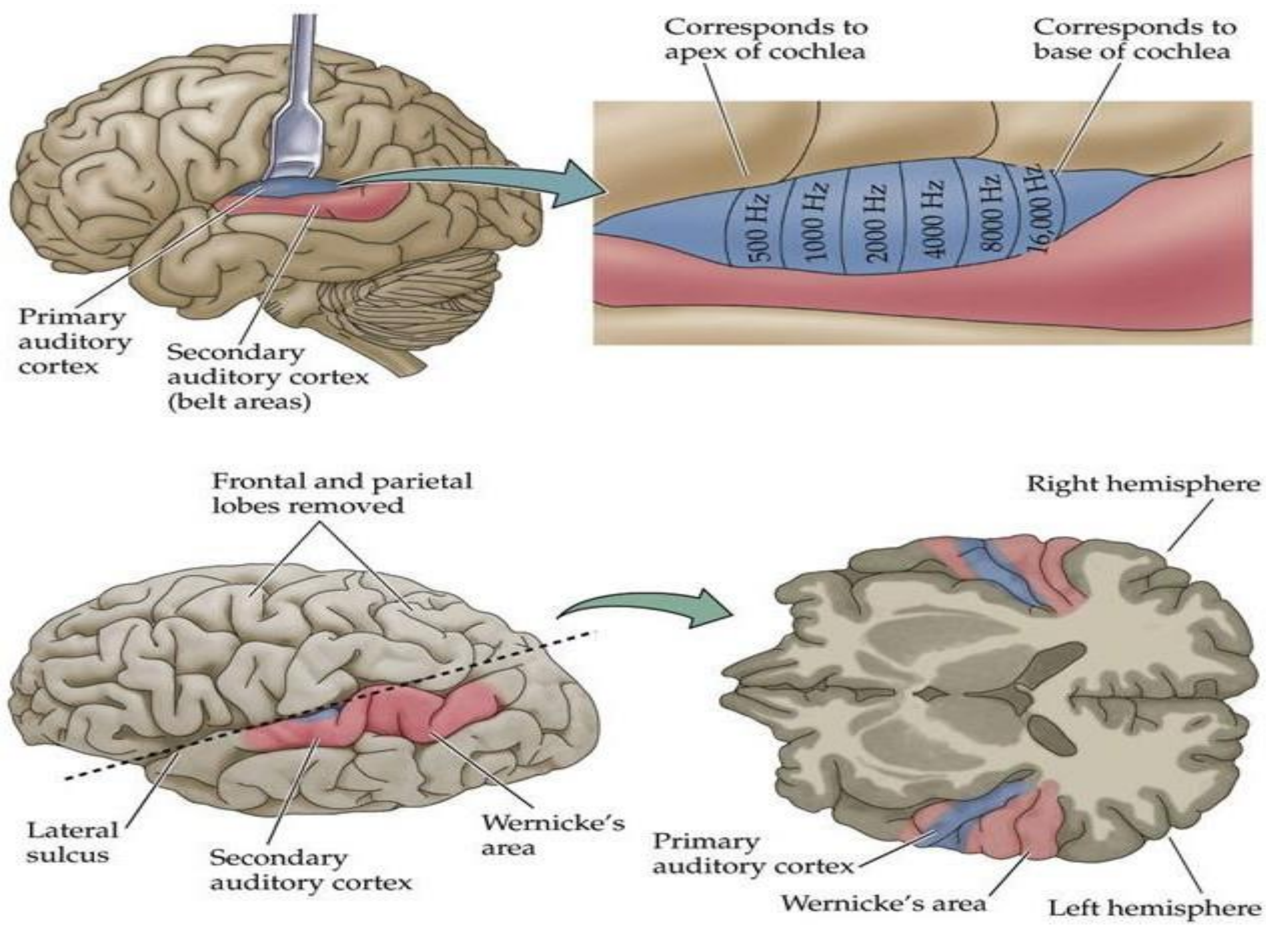


Figure 52-11


Corresponds to apex of cochlea
Corresponds to base of cochlea
500 Hz
1000 Hz
2000 Hz
4000 Hz
8000 Hz
16,000 Hz
Primary auditory cortex
Secondary auditory cortex (belt areas)
Frontal and parietal lobes removed
Right hemisphere
Lateral sulcus
Secondary auditory cortex
Wernicke's area
Primary auditory cortex
Wernicke's area
Left hemisphere

Function of auditory cortex

- The primary auditory cortex is organized tonotopically and are important for
- frequency discrimination and sound localization
- discrimination of tonal and sequential sound patterns
- plays an important role in processing of intraspecific communication sounds and speech
- detect special qualities such as the sudden onset of sounds, or perhaps special modulations, such as noise versus pure frequency sounds
- responses to vocalization-related auditory feedback,
- suggestive of a predictive sensorimotor mechanism

Mechanisms of Sound Localization

- Techniques for Sound Localization
  - Horizontal: Left-right, Vertical: Up-down
- Localization of Sound in Horizontal Plane
  - Interaural time delay: Time taken for sound to reach from ear to ear
  - Interaural intensity difference: Sound at high frequency from one side of ear
  - Duplex theory of sound localization:
    - Interaural time delay: 20-2000 Hz
    - Interaural intensity difference: 2000-20000 Hz
- These two mechanisms cannot tell whether the sound is emanating from in front of or behind the person or from above or below.
- This discrimination is achieved mainly by the pinnae (the visible outer part), which act as funnels to direct the sound into the two ears

Neural Mechanisms for Detecting Sound Direction

- Auditory cortex Destruction of the auditory cortex on both sides of the brain causes loss of almost all ability to detect the direction from which sound comes
- superior olivary nuclei in the brain stem,
- lateral nuclei detects direction by the difference in sound intensities between the 2 ears. (interaural *intensity)* by simply comparing the difference in intensities of the sound reaching the two ears and sending an appropriate signal to the auditory cortex to estimate the direction
- medial nuclei detects direction by the time lag between acoustic signals entering the ears. (interaural *time).*

Function of Ear Pinnae in sound localization

- The mechanism of superior olive can't determine whether the sound is coming from in front of or behind the person or from above or below.
- This discrimination is achieved mainly by the *pinnae* of the two ears.
- The shape of the pinna changes the *quality* of the sound entering the ear, depending on the direction from which the sound comes.
- It changes the quality by emphasizing specific sound frequencies from the different directions
- Passive resonance.

Deafness

Conduction deafness – something prevents sound conduction to the fluids of the inner ear (*e.g.*, impacted earwax, perforated eardrum, otitis media, otosclerosis of the ossicles)

Sensorineural deafness – results from damage to the neural structures at any point from the cochlear hair cells to the auditory cortical cells

Tinnitus – ringing or clicking sound in the ears in the absence of auditory stimuli

Deafness

High degree of bilateral connectivity. Almost never have Monaural hearing loss.

Unilateral hearing loss strongly implicates unilateral peripheral damage, either to middle or inner ear, or to auditory nerve

Hearing tests

- Rinne test
- Weber test,
- **Audiometry**
- **Brain stem evoked potential**