Neurophysiolog

Hearing

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Sound waves

- Sound waves are alternating high- and low-pressure regions traveling in the same direction through a medium. They originate from a vibrating object.

- The higher the **frequency** of vibration, the higher is the pitch.

Sound waves

- The larger the **intensity (or amplitude**) of the vibration, the louder is the sound. Sound intensity is measured in decibels (dB).

- An increase of one decibel represents a tenfold increase in sound intensity.

Sound waves

- Most sounds are mixtures of pure tones. The human ear is sensitive to tones with frequencies between 20 and 20,000 Hz (a cycle/sec) and is most sensitive between 2000 and 5000 Hz.

- The usual range of frequencies in human speech is between 300 and 3500 Hz, and the sound intensity is about 65 dB.

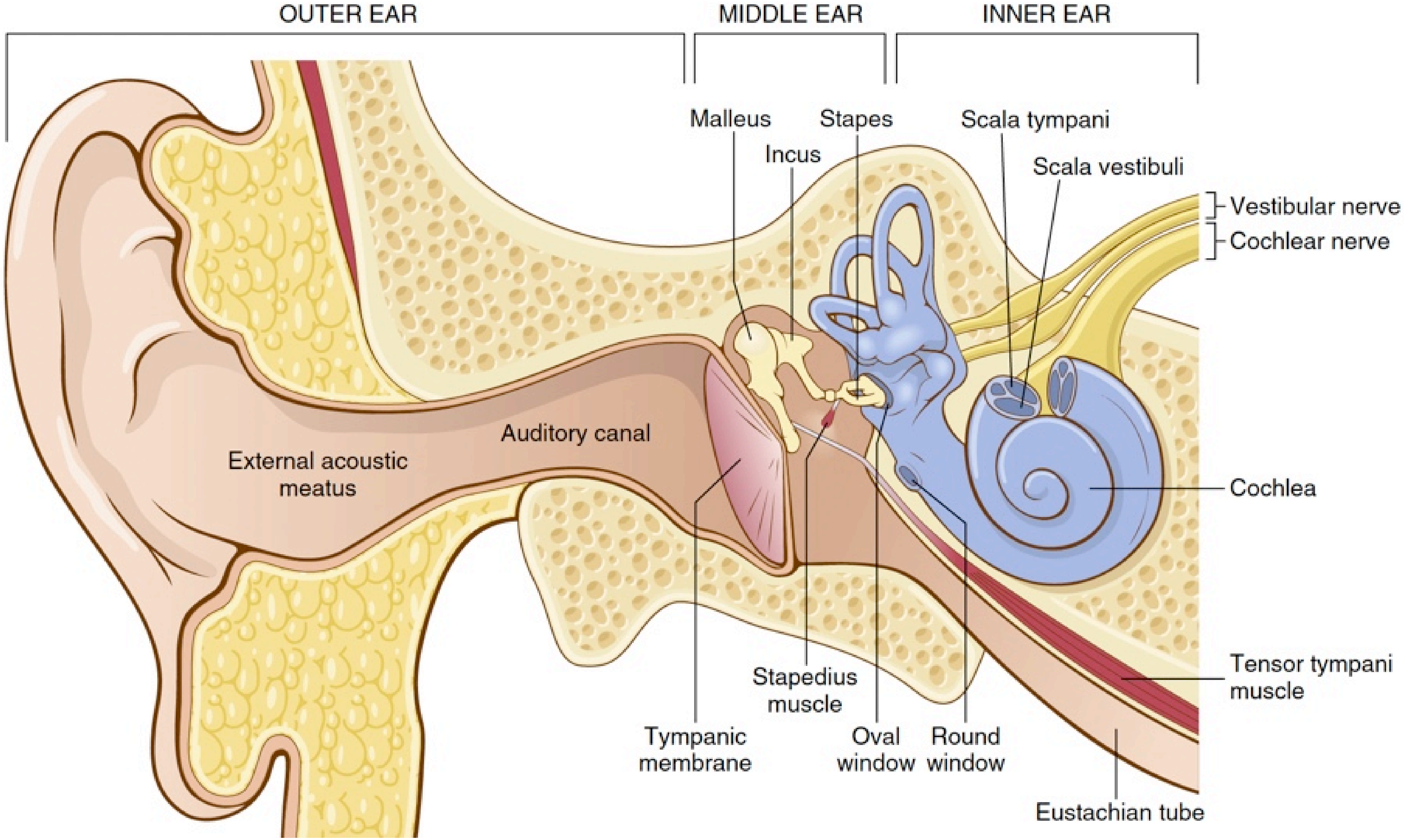
- Sound intensities greater than 100 dB can damage the auditory apparatus, and those greater than 120 dB can cause pain.

Sound	Loudness in Decibels (dB)	Comparison to Faintest Audible Sound (Hearing Threshold)
Rustle of leaves	10 dB	10 times louder
Ticking of watch	20 dB	100 times louder
Whispering	30 dB	1 thousand times louder
Normal conversation	60 dB	1 million times louder
Food blender, lawn mower, hair dryer	90 dB	1 billion times louder
Loud rock concert, ambulance siren	120 dB	1 trillion times louder
Takeoff of jet plane	150 dB	1 quadrillion times louder

Hearing

- Hearing is the ability to perceive sounds.

- The ear is divided into three main regions:
- (1) the external ear, which collects sound waves and channels them inward.
- (2) the middle ear, which conveys sound vibrations to the oval window.
- (3) the internal ear, which houses the receptors for hearing and equilibrium.


OUTER EAR
MIDDLE EAR
INNER EAR
Malleus
Stapes
Incus
Scala tympani
Scala vestibuli
Vestibular nerve
Cochlear nerve
Auditory canal
External acoustic meatus
Cochlea
Stapedius muscle
Tympanic membrane
Oval window
Round window
Tensor tympani muscle
Eustachian tube

Middle ear

- The middle ear is a small, air-filled cavity in the petrous portion of the temporal bone. It is separated from the external ear by the tympanic membrane and from the internal ear by a thin bony partition that contains two small openings: the oval window and the round window.

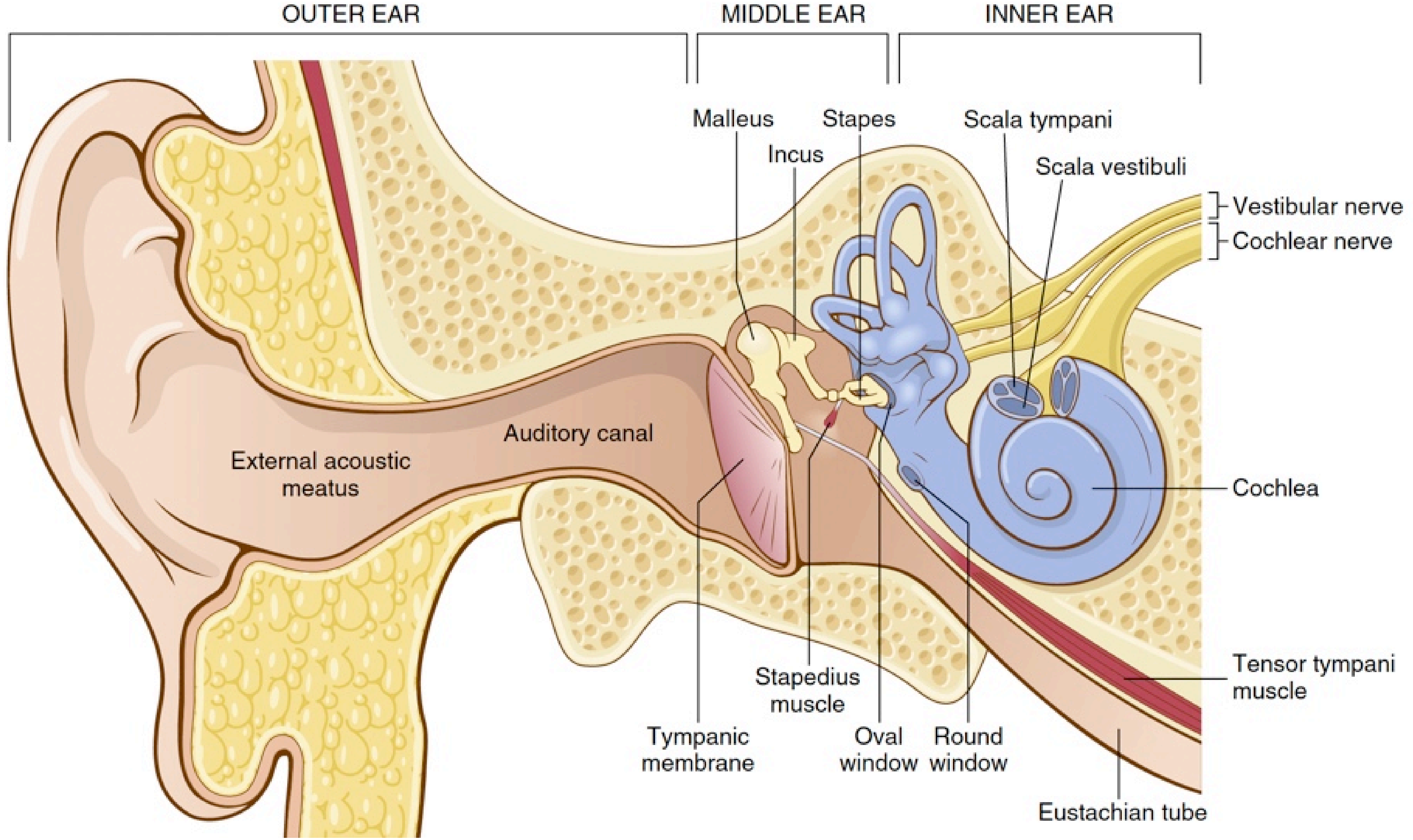
- Extending across the middle ear and attached to it by ligaments are the three smallest bones in the body, the auditory ossicles. The bones are the malleus, incus, and stapes.

Auditory transduction

- The external and middle ears are air filled, and the inner ear, which contains the organ of Corti, is fluid filled.

- Thus before transduction can occur, sound waves traveling through air must be converted into pressure waves in fluid.

- The acoustic impedance of fluid is much greater than that of air.
- The combination of the tympanic membrane and the ossicles serves as an **impedance-matching device** that makes this conversion.


OUTER EAR
MIDDLE EAR
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Malleus
Stapes
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Scala tympani
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Vestibular nerve
Cochlear nerve
Auditory canal
External acoustic meatus
Cochlea
Stapedius muscle
Tympanic membrane
Oval window
Round window
Tensor tympani muscle
Eustachian tube

Middle ear

- Besides the ligaments, two tiny skeletal muscles also attach to the ossicles.
- The **tensor tympani muscle**, which is supplied by the mandibular branch of the trigeminal (V) nerve, limits movement and increases tension on the eardrum to prevent damage to the inner ear from loud noises.
- keeps the tympanic membrane tensed. This tension allows sound vibrations on any portion of the tympanic membrane to be transmitted to the ossicles.
- The **stapedius muscle**, which is supplied by the facial (VII) nerve, is the smallest skeletal muscle in the human body. By dampening large vibrations of the stapes due to loud noises, it protects the oval window.

Middle ear

- When loud sounds are transmitted through the ossicular system and from there into the central nervous system, a reflex occurs after a latent period of only 40 to 80 milliseconds to cause contraction of the stapedius muscle and, to a lesser extent, the tensor tympani muscle.
- The tensor tympani muscle pulls the handle of the malleus inward while the stapedius muscle pulls the stapes outward.
- These two forces cause the entire ossicular system to develop increased rigidity, thus greatly reducing the ossicular conduction of low-frequency sound.

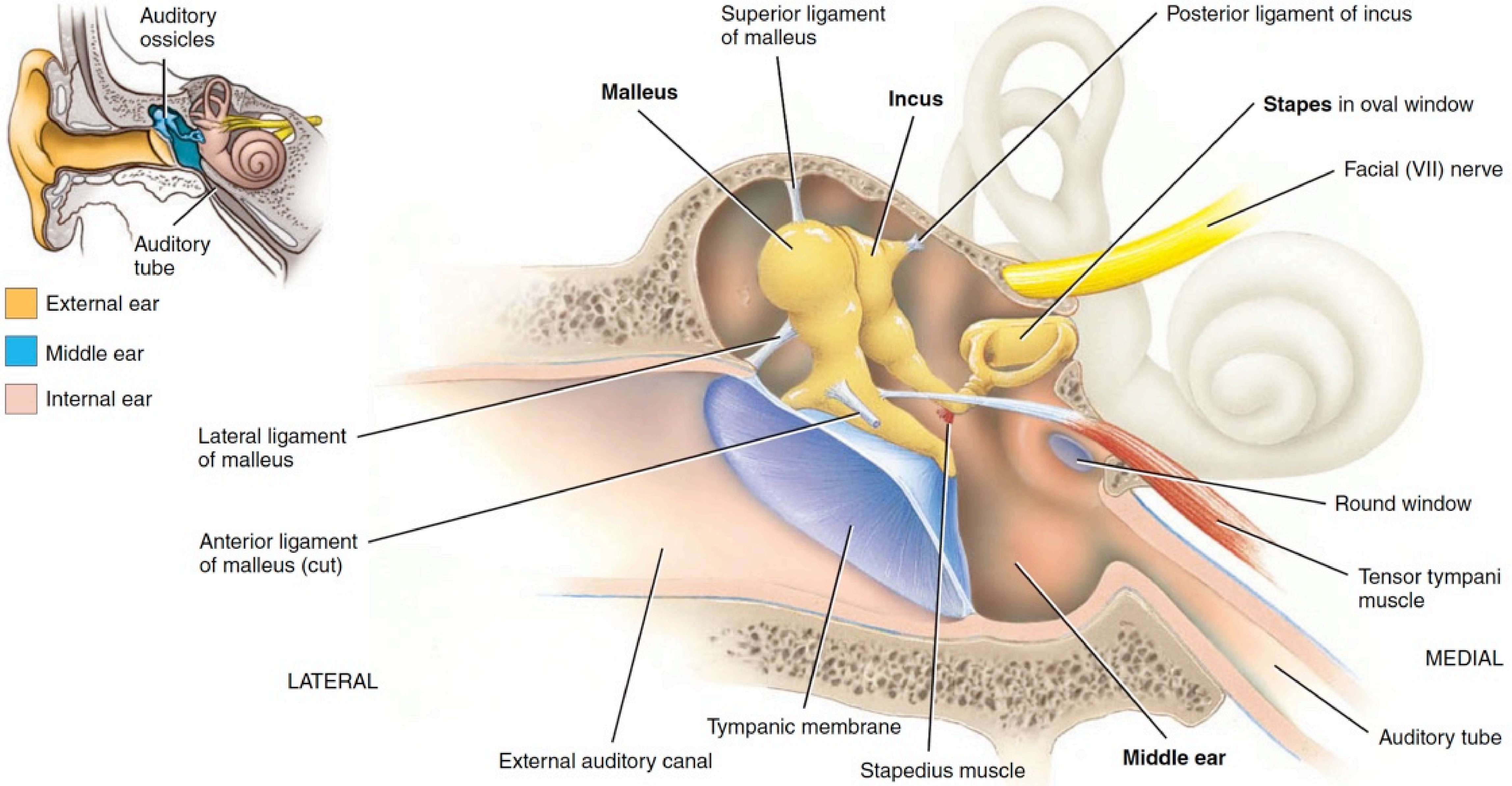
Attenuation reflex

- This reflex can reduce the intensity of lower frequency sound transmission by 30 to 40 decibels, which is about the same difference as that between a loud voice and a whisper.
- The function of this mechanism is:
- 1.to protect the cochlea from damaging vibrations caused by excessively loud sound and to mask low-frequency sounds in loud environments, and allows a person to concentrate on sounds above 1000 cycles/sec, where most of the pertinent information in voice communication is transmitted.
- 2.to decrease a person’s hearing sensitivity to his or her own speech.

Bone conductance

- Because the inner ear, the cochlea, is embedded in a bony cavity in the temporal bone, called the bony labyrinth, vibrations of the entire skull can cause fluid vibrations in the cochlea.

- Therefore, under appropriate conditions, a tuning fork or an electronic vibrator placed on any bony protuberance of the skull, but especially on the mastoid process near the ear, causes the person to hear the sound.

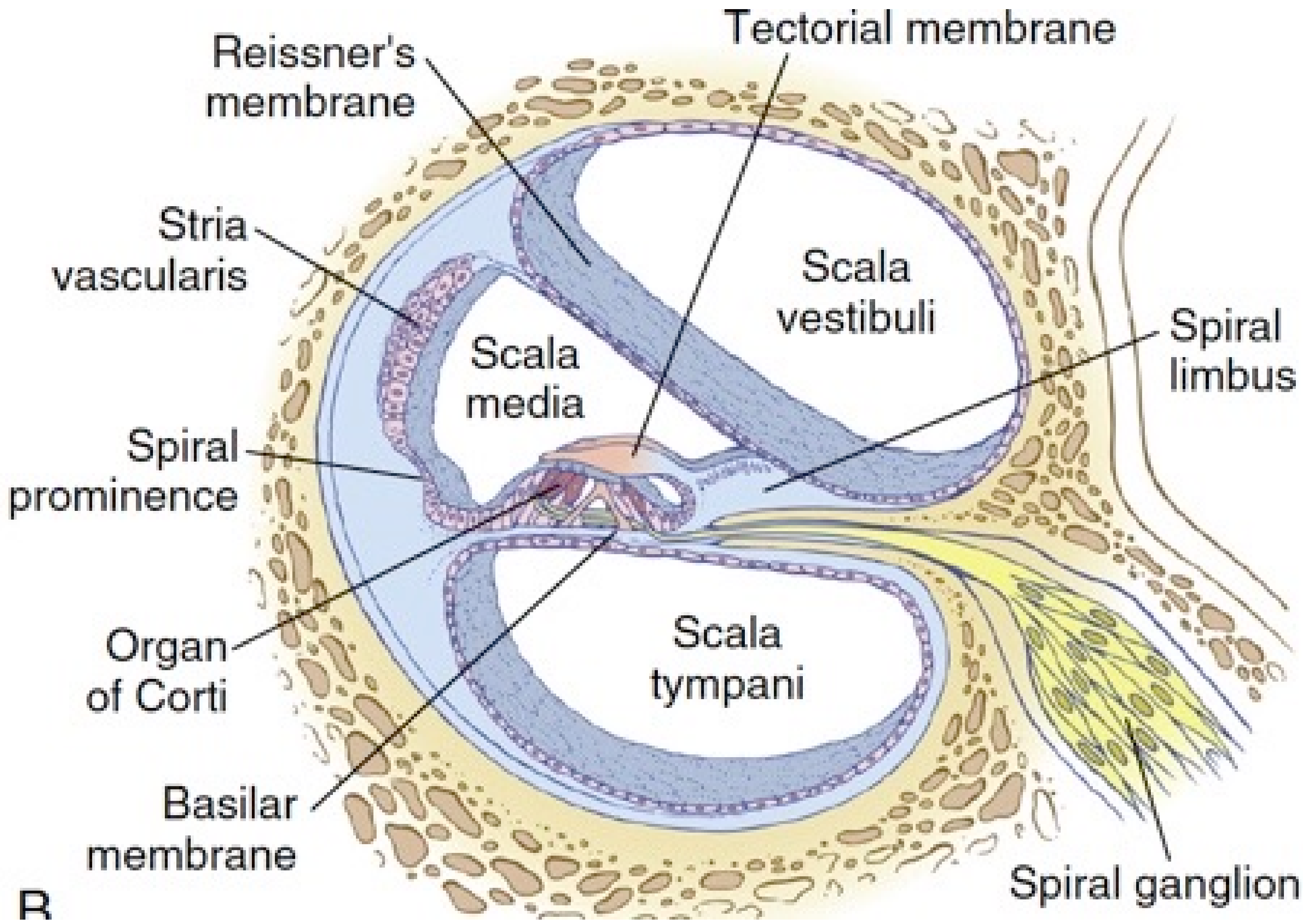

Auditory ossicles
Auditory tube
External ear
Middle ear
Internal ear
Superior ligament of malleus
Posterior ligament of incus
Malleus
Incus
Stapes in oval window
Facial (VII) nerve
Lateral ligament of malleus
Anterior ligament of malleus (cut)
Round window
Tensor tympani muscle
MEDIAL
LATERAL
Tympanic membrane
Auditory tube
External auditory canal
Stapedius muscle
Middle ear

Inner ear

- The inner ear is also called the labyrinth. Structurally, it consists of two main divisions: an outer bony labyrinth that encloses an inner membranous labyrinth.

- The **bony labyrinth** is a series of cavities in the petrous portion of the temporal bone divided into three areas: (1) the semicircular canals, (2) the vestibule, and (3) the cochlea.

- The **membranous labyrinth**, a series of epithelial sacs and tubes inside the bony labyrinth that have the same general form as the bony labyrinth and house the receptors for hearing and equilibrium.


Tectorial membrane
Reissner's membrane
Stria vascularis
Scala vestibuli
Scala media
Spiral limbus
Spiral prominence
Organ of Corti
Scala tympani
Basilar membrane
Spiral ganglion
B

Inner ear

- The **cochlea**, which is a spiral-shaped structure composed of three tubular canals or ducts, contains the organ of Corti.

- The **organ of Corti contains the receptor cells** and is the site of auditory transduction.

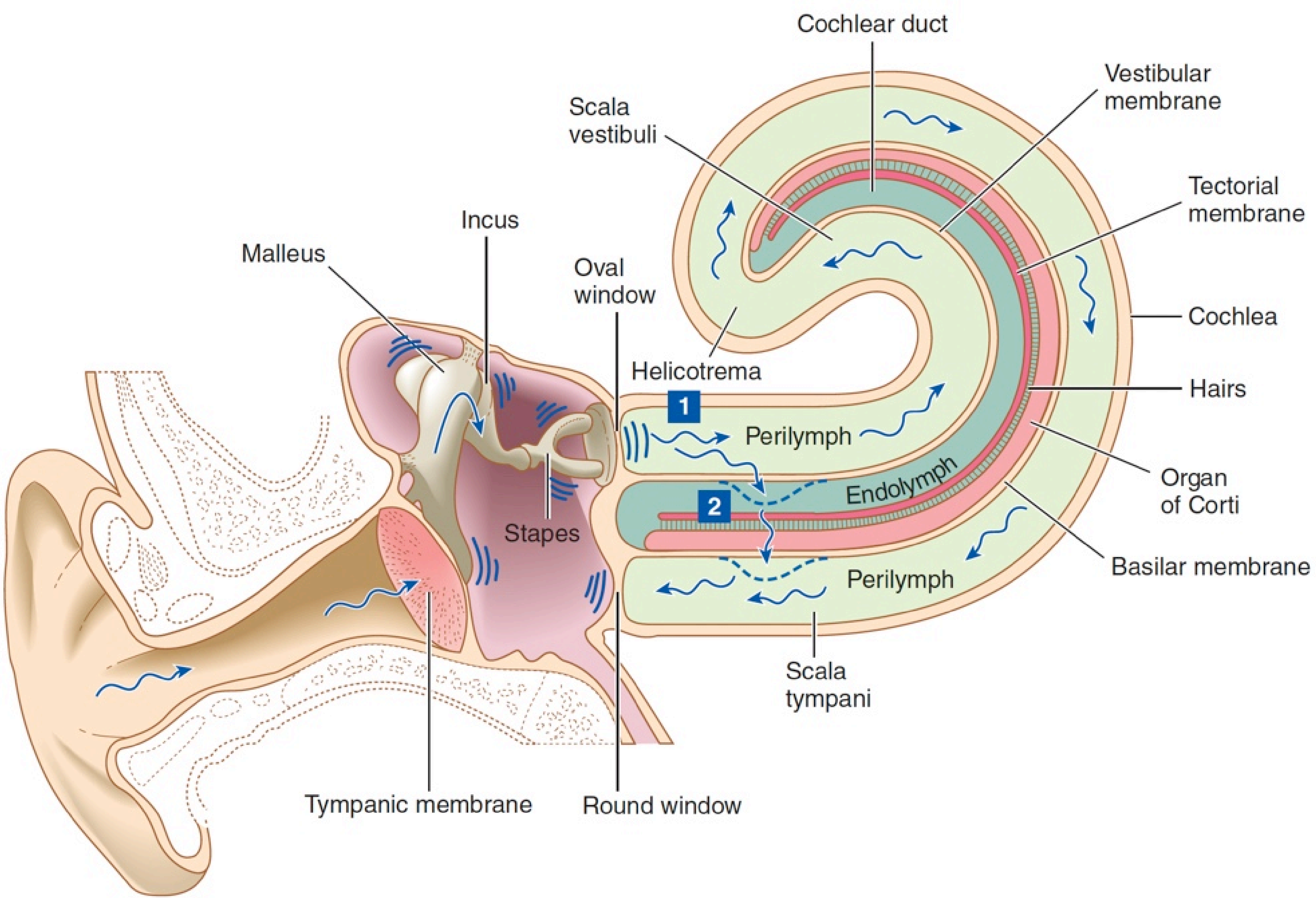
- The inner ear is **fluid filled**, and the fluid in each duct has a different composition.

Inner ear

- The fluid in the scala vestibuli and scala tympani is called **perilymph**, which is similar to extracellular fluid (CSF).

- The fluid in the scala media is called **endolymph**, which has a high potassium (K+) concentration.

- Thus endolymph is unusual in that its composition is similar to that of intracellular fluid, even though, technically, it is extracellular fluid.


Cochlear duct
Vestibular membrane
Scala vestibuli
Tectorial membrane
Incus
Malleus
Oval window
Cochlea
Helicotrema
Hairs
1
Perilymph
Endolymph
Organ of Corti
2
Stapes
Basilar membrane
Perilymph
Scala tympani
Tympanic membrane
Round window

Inner ear

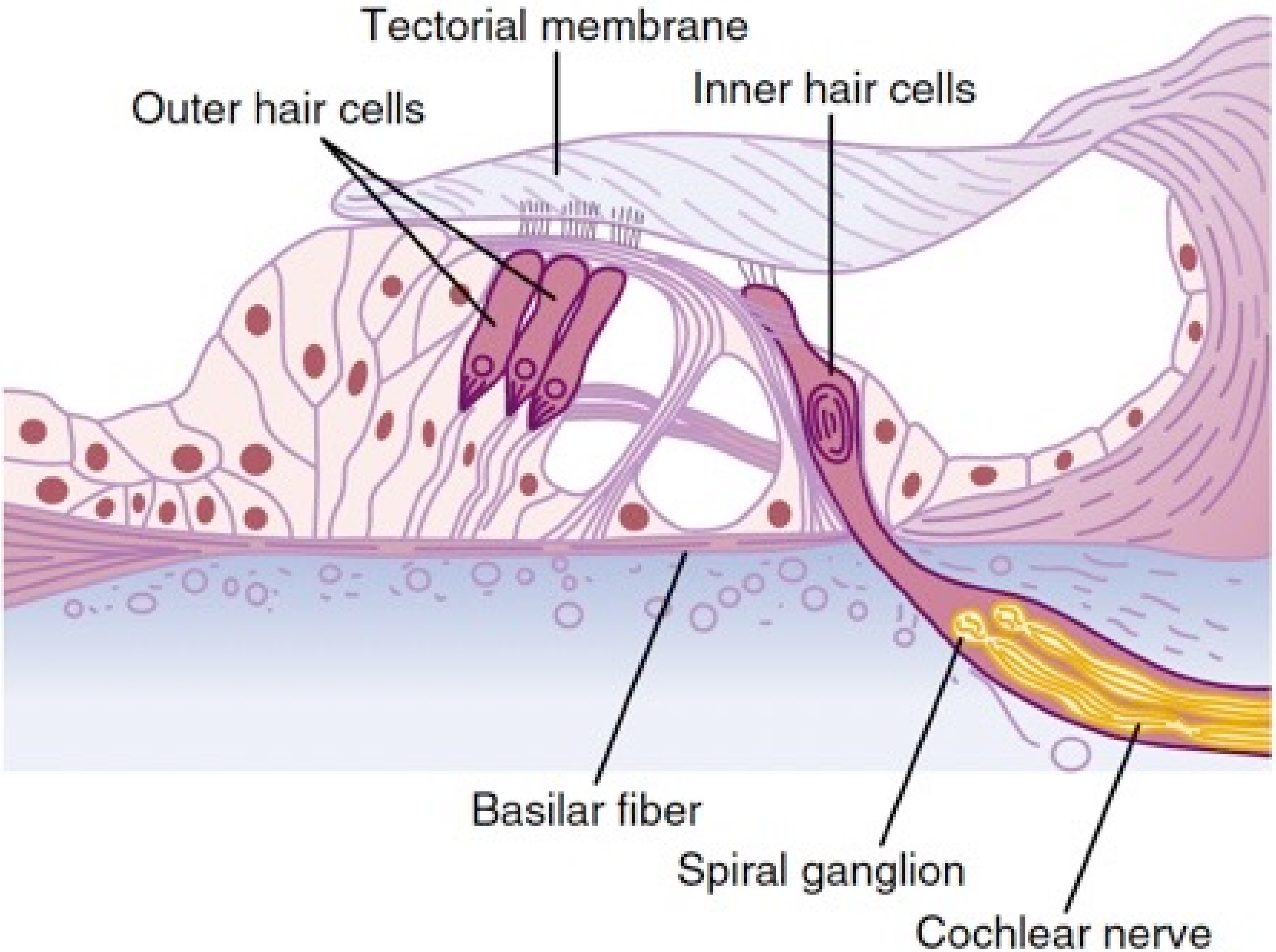
- The lengths of the basilar fibers increase progressively, beginning at the oval window and going from the base of the cochlea to the apex.

- The diameter of the fibers, however, decrease from the oval window to the helicotrema, so their overall stiffness decreases more than 100-fold.

- As a result, the stiff, short fibers near the oval window of the cochlea vibrate best at a very high frequency, whereas the long, limber fibers near the tip of the cochlea vibrate best at a low frequency.

Organ of Corti

- The organ of Corti lies on the basilar membrane of the cochlea and is bathed in the endolymph contained in the scala media.
- Auditory hair cells in the organ of Corti are the sites of auditory transduction.
- The organ of Corti contains two types of receptor cells: **inner hair cells and outer hair cells.**
- There are fewer inner hair cells, which are arranged in single rows. Outer hair cells are arranged in parallel rows and are more numerous.

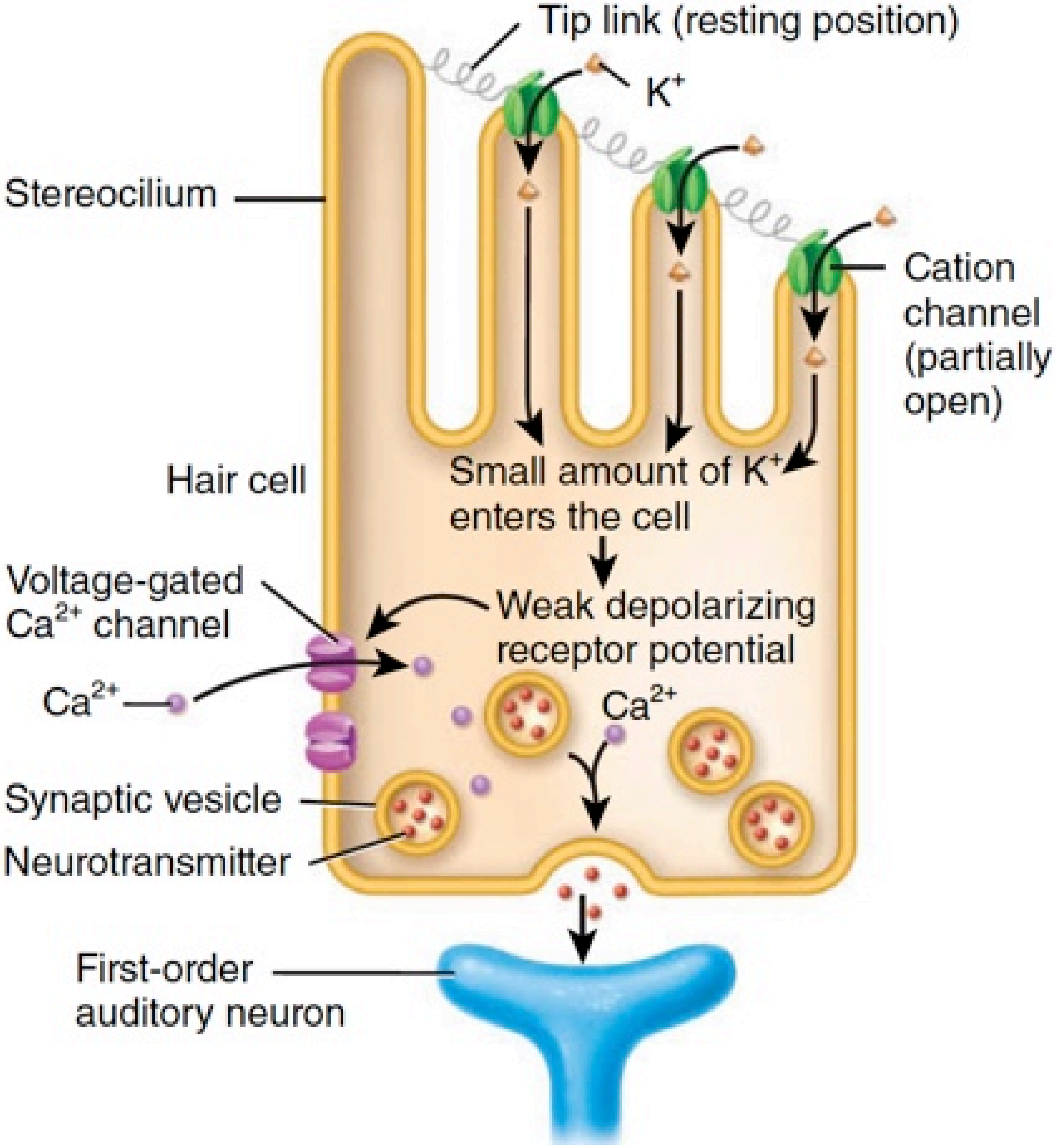

Tectorial membrane
Outer hair cells
Inner hair cells
Basilar fiber
Spiral ganglion
Cochlear nerve

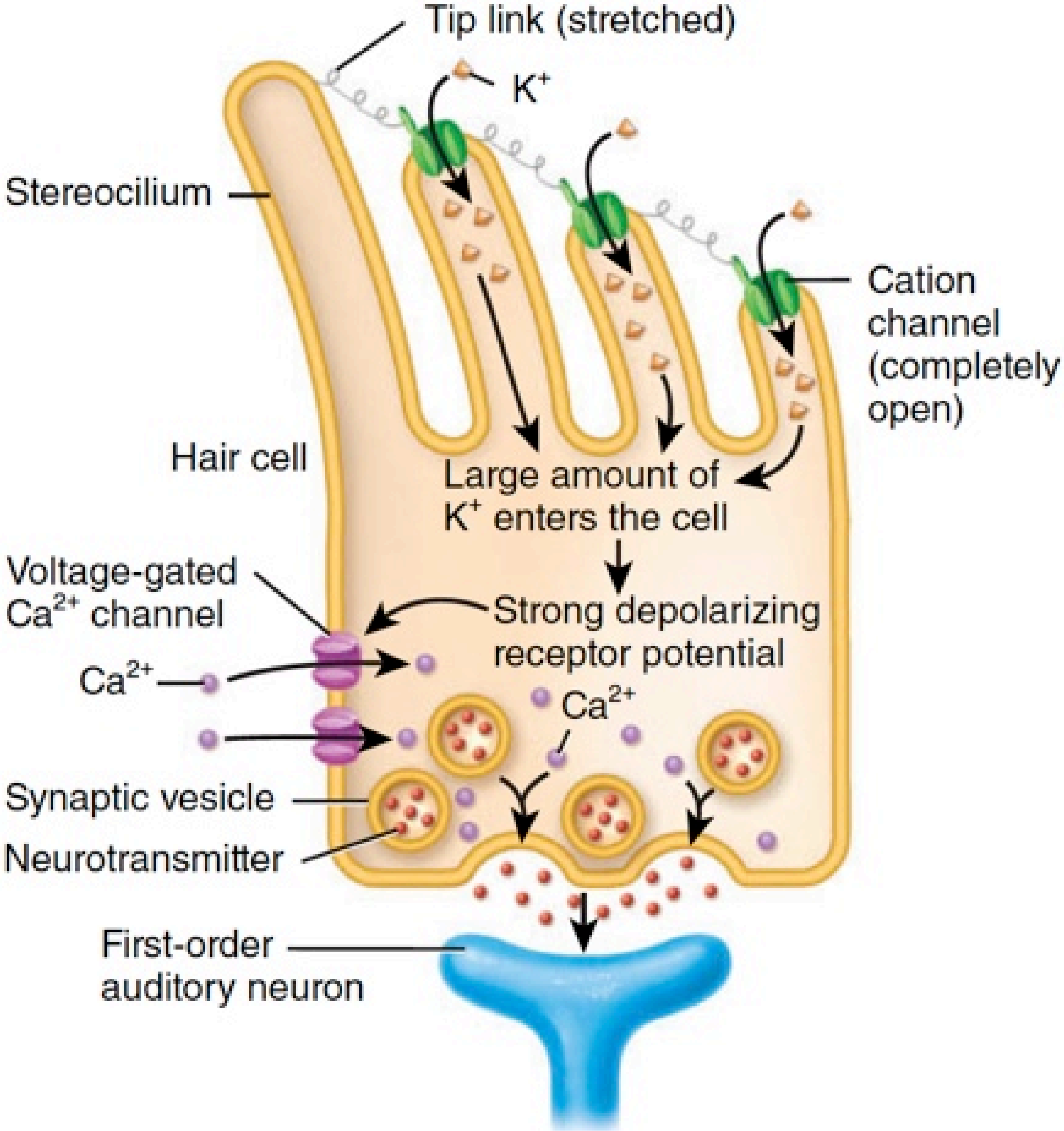
Organ of Corti

- Cilia, protruding from the hair cells, are touching/embedded in the tectorial membrane.

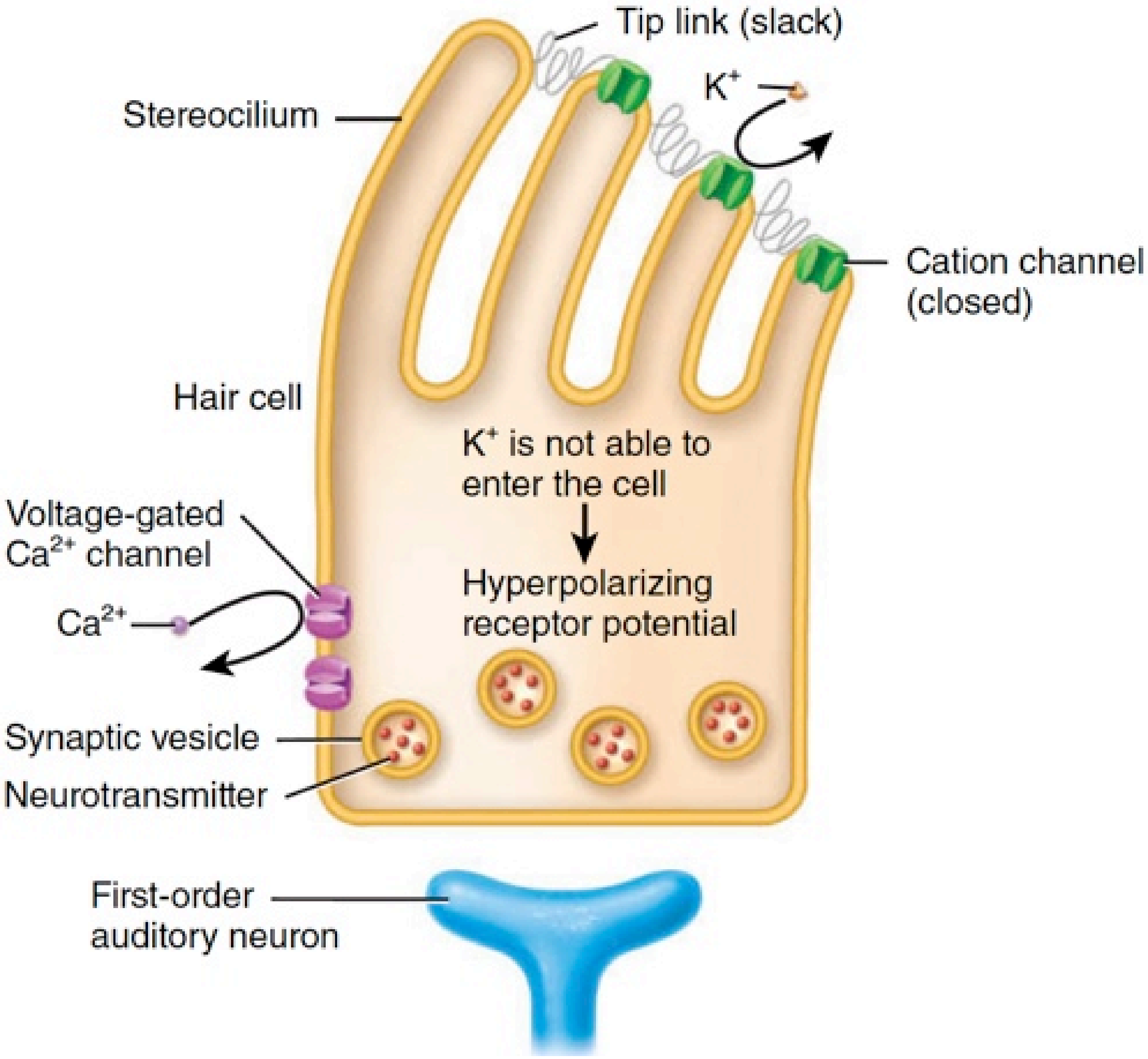
- Thus the bodies of the hair cells are in contact with the basilar membrane, and the cilia of the hair cells are in contact with the tectorial membrane.

- The nerves that serve the organ of Corti are contained in the vestibulocochlear nerve (CN VIII). The cell bodies of these nerves are located in spiral ganglia, and their axons synapse at the base of the hair cells.


Tip link (resting position)
K+
Stereocilium
Cation channel (partially open)
Small amount of K+ enters the cell
Hair cell
Voltage-gated Ca2+ channel
Weak depolarizing receptor potential
Ca2+
Ca2+
Synaptic vesicle
Neurotransmitter
First-order auditory neuron



Tip link (stretched)
K+
Stereocilium
Cation channel (completely open)
Hair cell
Large amount of K+ enters the cell
Voltage-gated Ca2+ channel
Strong depolarizing receptor potential
Ca2+
Ca2+
Synaptic vesicle
Neurotransmitter
First-order auditory neuron


Tip link (slack)
Stereocilium
K+
Cation channel
(closed)
Hair cell
K+ is not able to
enter the cell
Hyperpolarizing
receptor potential
Voltage-gated
Ca2+ channel
Ca2+
Synaptic vesicle
Neurotransmitter
First-order
auditory neuron

Encoding of frequency

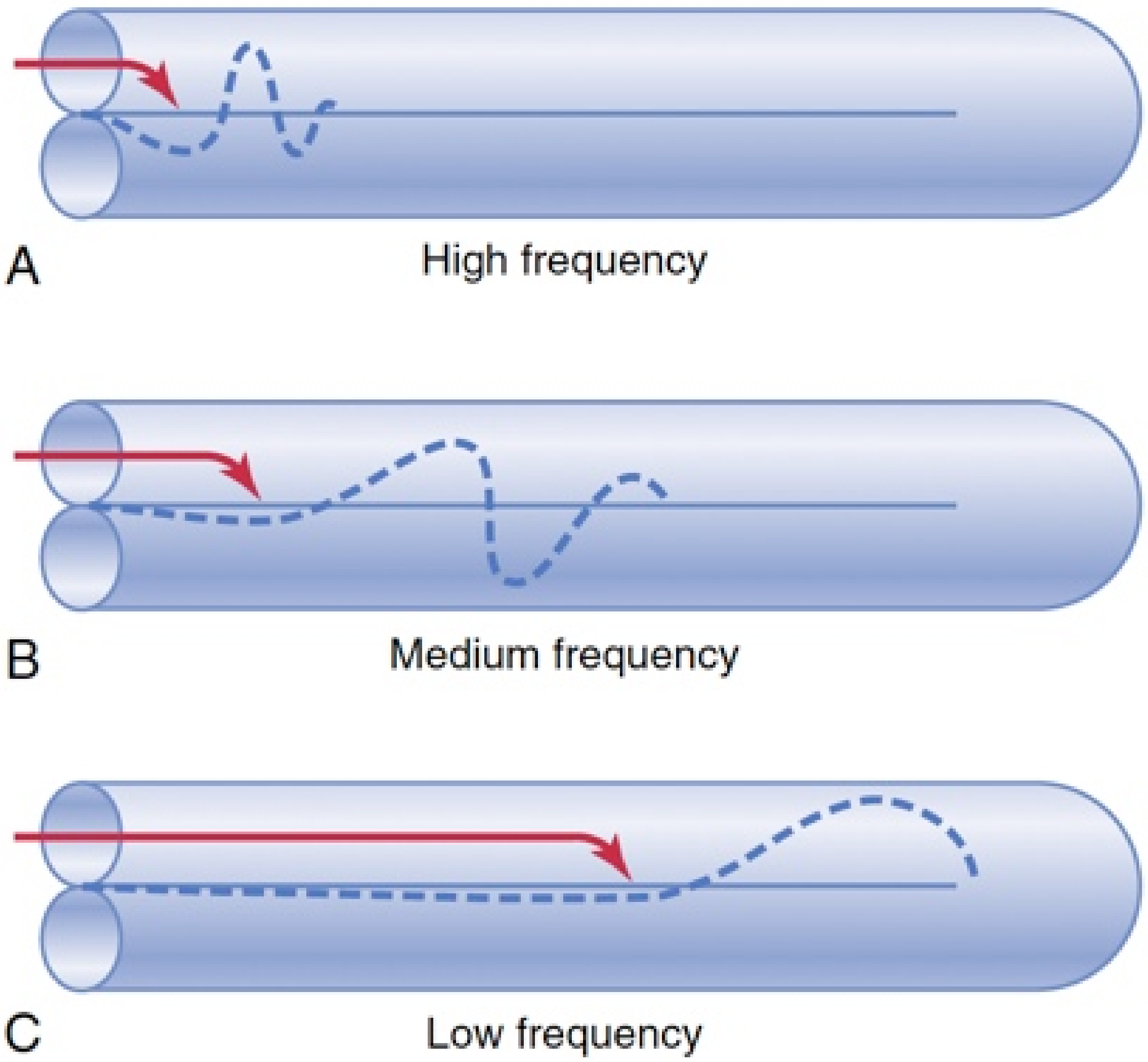
- Encoding of sound frequencies occurs because different auditory hair cells are activated by different frequencies.
- The frequency that activates a particular hair cell depends on the position of that hair cell along the basilar membrane.
- The base of the basilar membrane is nearest the stapes and is narrow and stiff. Hair cells located at the base respond best to high frequencies.

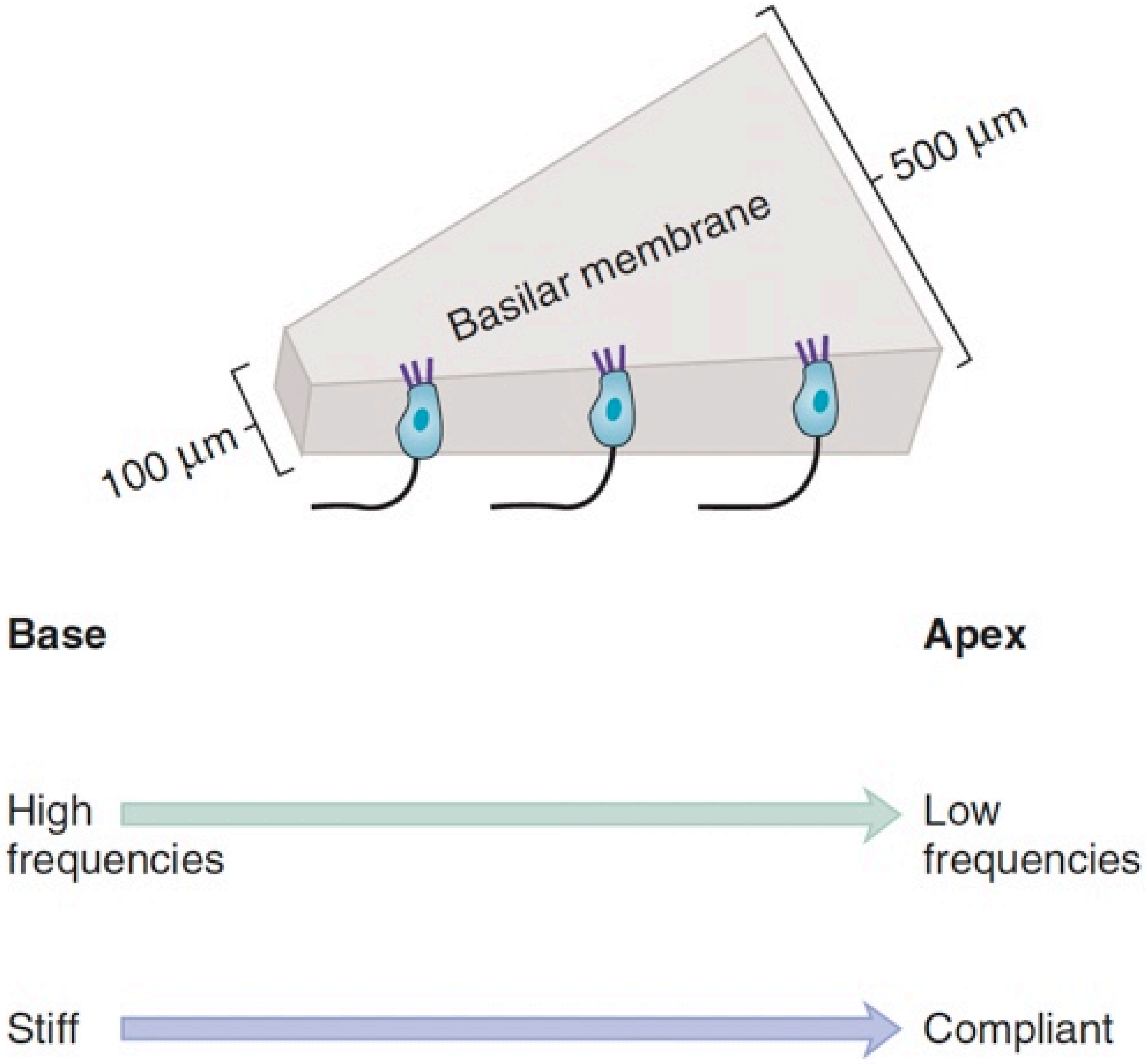
Encoding of frequency

- The **apex of the basilar membrane is wide and compliant**. Hair cells located at the apex respond best to low frequencies.

- Thus the **basilar membrane acts as a sound frequency analyzer**, with hair cells positioned along the basilar membrane responding to different frequencies.

- This **spatial mapping of frequencies generates a tonotopic map**, which then is transmitted to higher levels of the auditory system.


A
High frequency
B
Medium frequency
C
Low frequency


Basilar membrane
500 µm
100 µm
Base
Apex
High frequencies
Low frequencies
Stiff
Compliant

encoding of loudness

- First, as the sound becomes louder, the amplitude of vibration of the basilar membrane and hair cells also increases so that the hair cells excite the nerve endings at more rapid rates.

- Second, as the amplitude of vibration increases, it causes more and more of the hair cells on the fringes of the resonating portion of the basilar membrane to become stimulated, thus causing spatial summation of impulses.

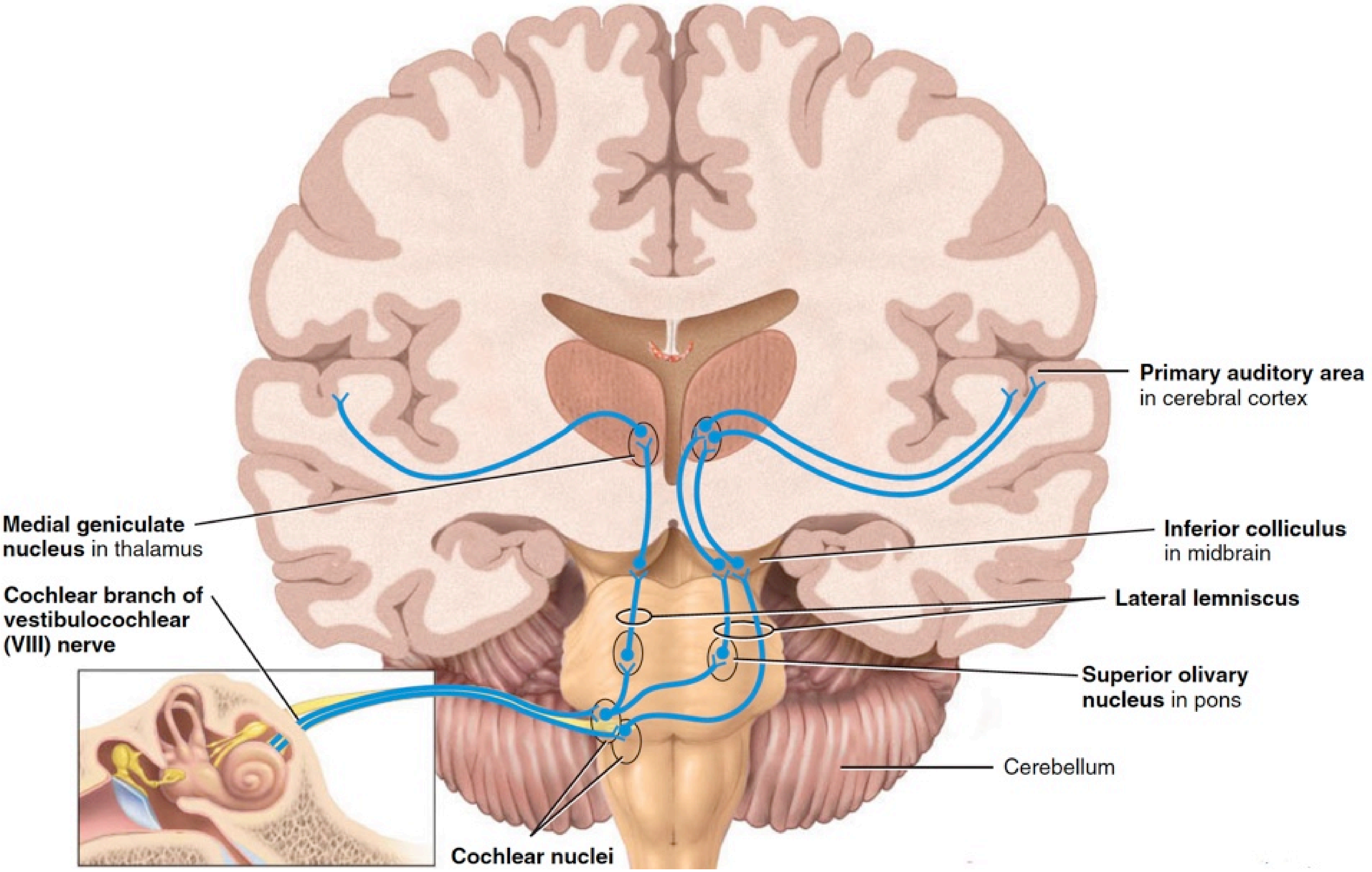
- Third, the outer hair cells do not become stimulated significantly until vibration of the basilar membrane reaches high intensity, and stimulation of these cells presumably apprises the nervous system that the sound is loud.

Auditory pathway

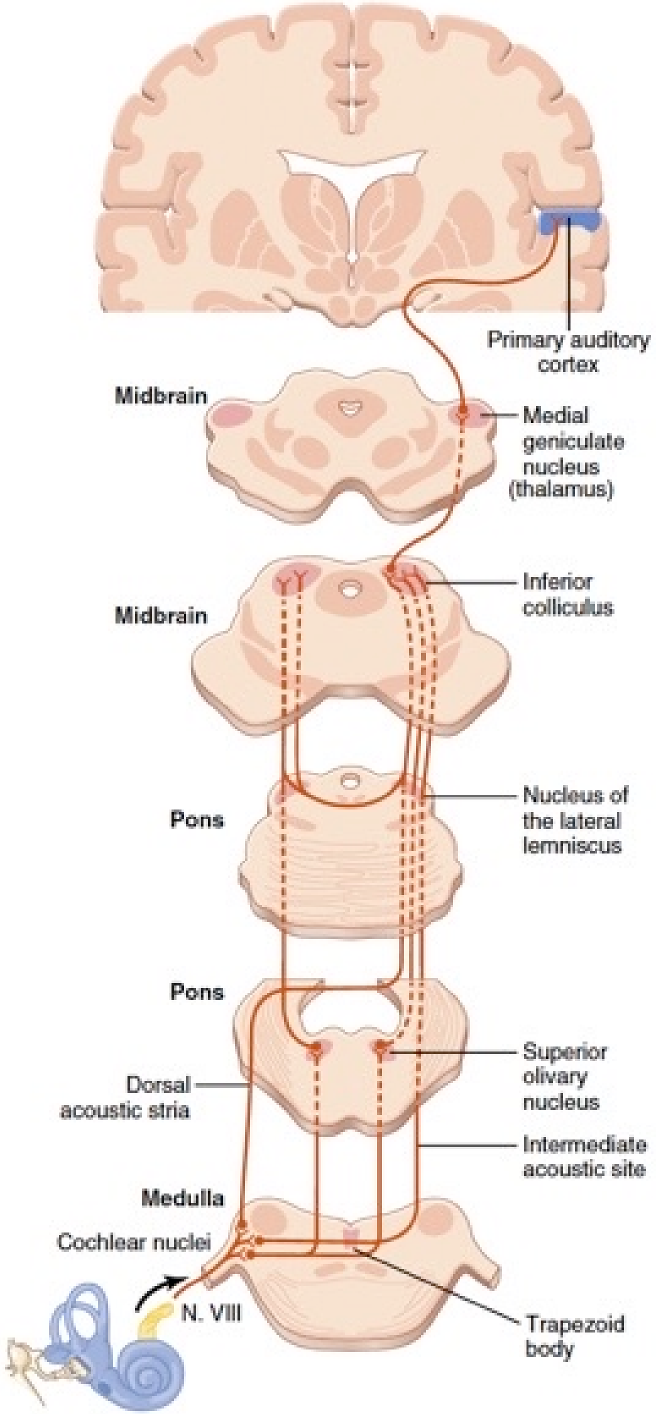
- Nerve fibers from the spiral ganglion of Corti enter the **dorsal and ventral cochlear nuclei** located in the medulla.

- At this point, all the fibers synapse, and second-order neurons pass mainly to the opposite side of the brain stem to terminate in the **superior olivary nucleus**.

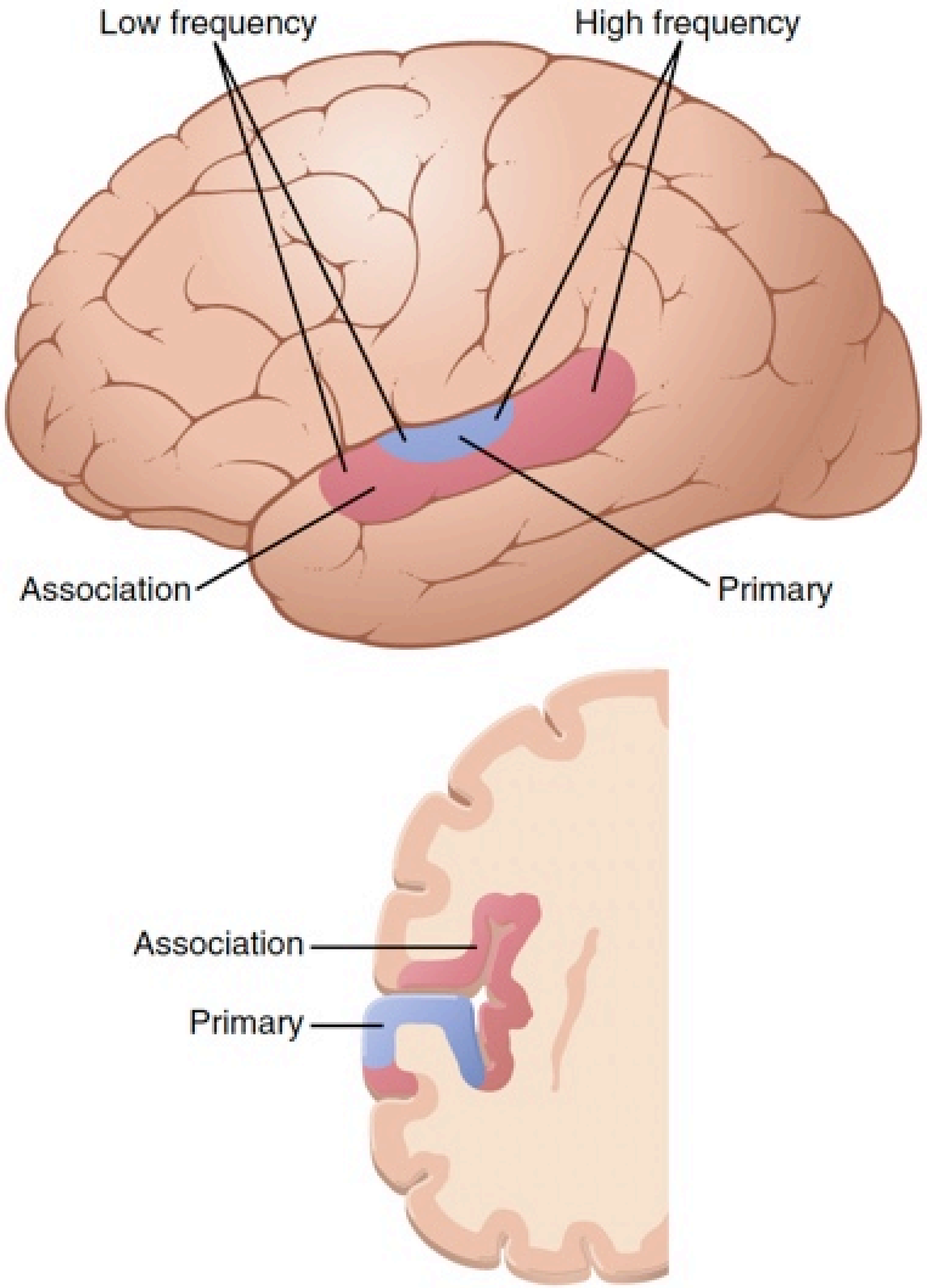
- A few second-order fibers also pass to the superior olivary nucleus on the same side.



Primary auditory area
in cerebral cortex
Medial geniculate
nucleus in thalamus
Inferior colliculus
in midbrain
Cochlear branch of
vestibulocochlear
(VIII) nerve
Lateral lemniscus
Superior olivary
nucleus in pons
Cerebellum
Cochlear nuclei



Primary auditory cortex
Midbrain
Medial geniculate nucleus (thalamus)
Inferior colliculus
Midbrain
Nucleus of the lateral lemniscus
Pons
Pons
Superior olivary nucleus
Dorsal acoustic stria
Intermediate acoustic site
Medulla
Cochlear nuclei
N. VIII
Trapezoid body


Low frequency
High frequency
Association
Primary
Association
Primary

- **Signals from both ears are transmitted through the pathways of both sides of the brain**, with a preponderance of transmission in the contralateral pathway.

- Many **collateral fibers** from the auditory tracts pass directly into the **reticular activating system** of the brain stem. This system projects diffusely upward in the brain stem and downward into the spinal cord and activates the entire nervous system in response to loud sounds.

- Other **collaterals** go to the vermis of the c**erebellum**, which is also activated instantaneously in the event of a sudden noise.

- A high degree of spatial orientation is maintained in the fiber tracts from the cochlea all the way to the cortex.

Auditory cortex

- **Destruction of both primary auditory cortices** in the human being greatly reduces one's sensitivity for hearing.
- **Destruction of one side** only slightly reduces hearing in the opposite ear; it does not cause deafness in the ear because of many crossover connections from side to side in the auditory neural pathway.
- However, it does affect one's ability to localize the source of a sound because comparative signals in both cortices are required for sound localization.

- **Lesions that affect the auditory association are**as but not the primary auditory cortex do not decrease a person's ability to hear and differentiate sound tones.

- However, the person is often unable to interpret the meaning of the sound heard (ex. Wernicke's area).

Determination of the direction of sound

- A person determines the horizontal direction from which sound comes by two principal means:

- (1) the **time lag** between the entry of sound into one ear and its entry into the opposite ear.

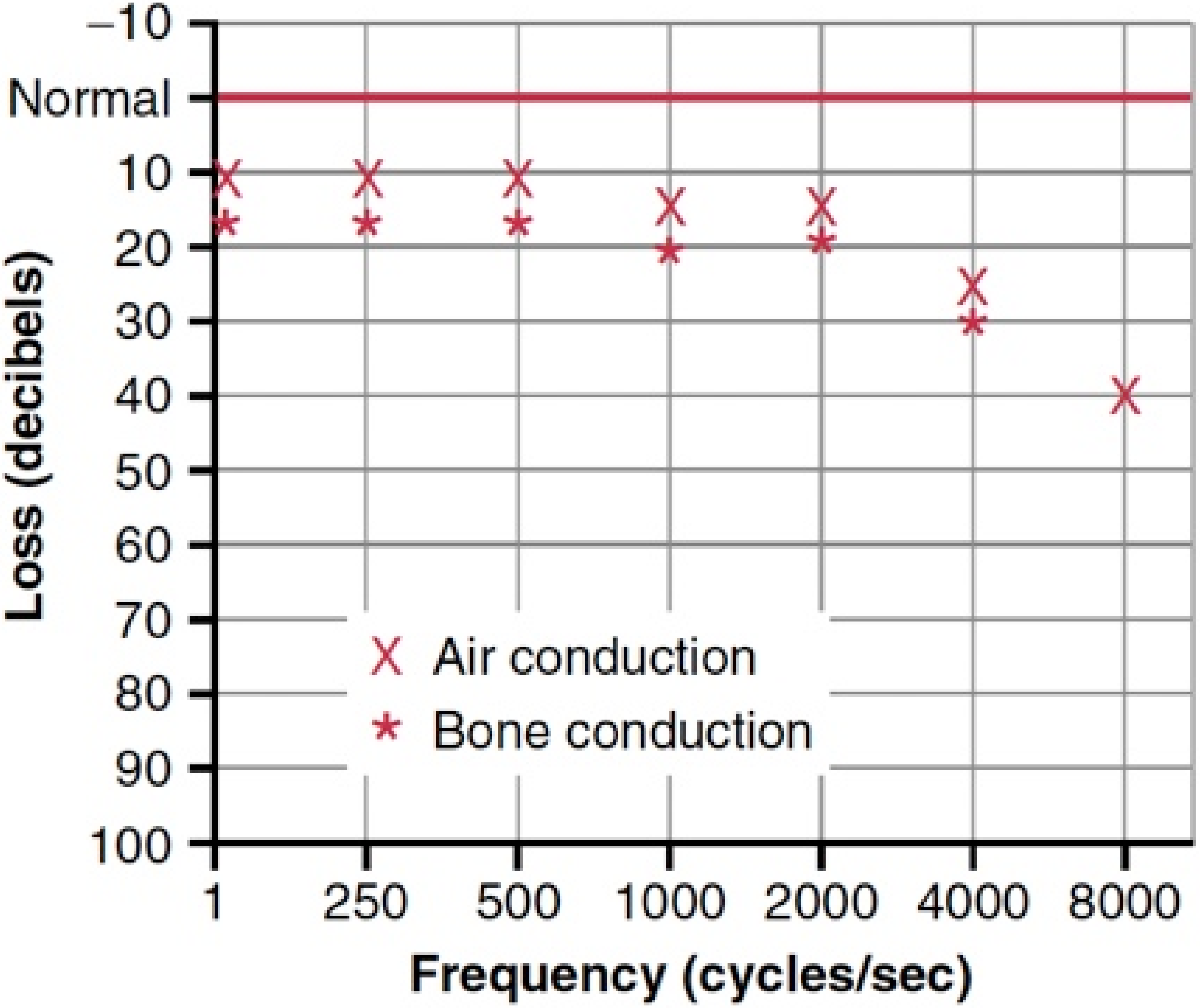
- (2) the difference between the **intensities** of the sounds in the two ears.

Determination of the direction of sound

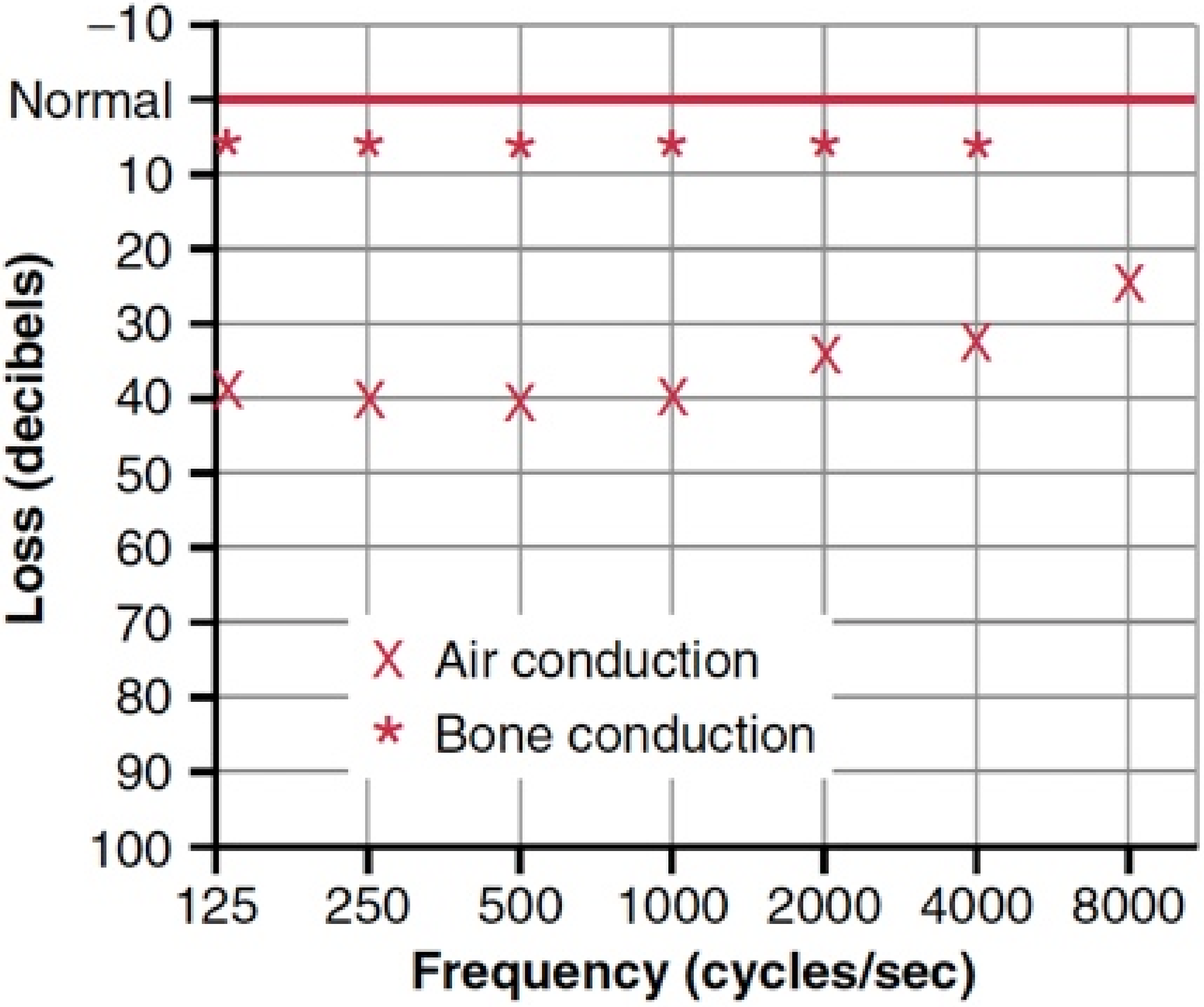
- These two mechanisms cannot tell whether the sound is emanating from in front of or behind the person or from above or below.
- This discrimination is achieved mainly by the **pinnae**, which act as funnels to direct the sound into the two ears.
- The shape of the pinna changes the quality of the sound entering the ear, depending on the direction from which the sound comes.

Determination of the direction of sound

- The neural analyses for the direction detection process begin in the **superior olivary nuclei** in the brain stem, even though the neural pathways all the way from these nuclei to the cortex are required for interpretation of the signals.

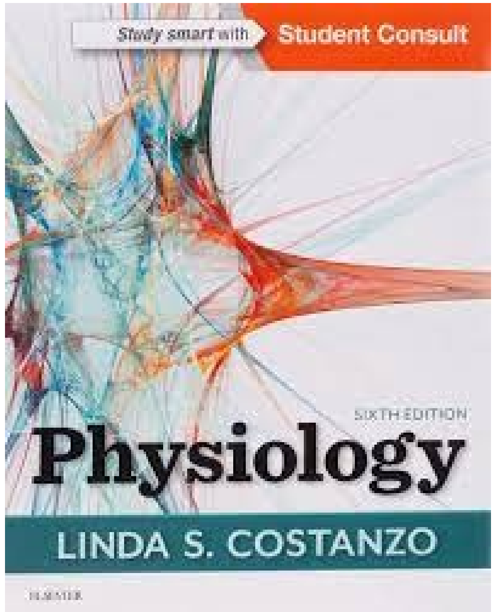


–10
Normal
10
20
30
40
50
60
70
80
90
100
Loss (decibels)
1
250
500
1000
2000
4000
8000
Frequency (cycles/sec)
Air conduction
Bone conduction



−10
Normal
10
20
30
40
50
60
70
80
90
100
Loss (decibels)
Air conduction
Bone conduction
125
250
500
1000
2000
4000
8000
Frequency (cycles/sec)

References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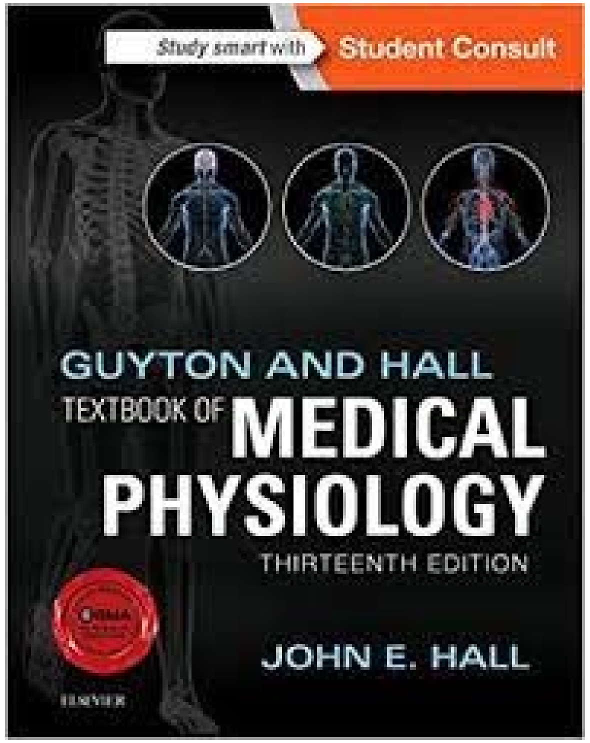
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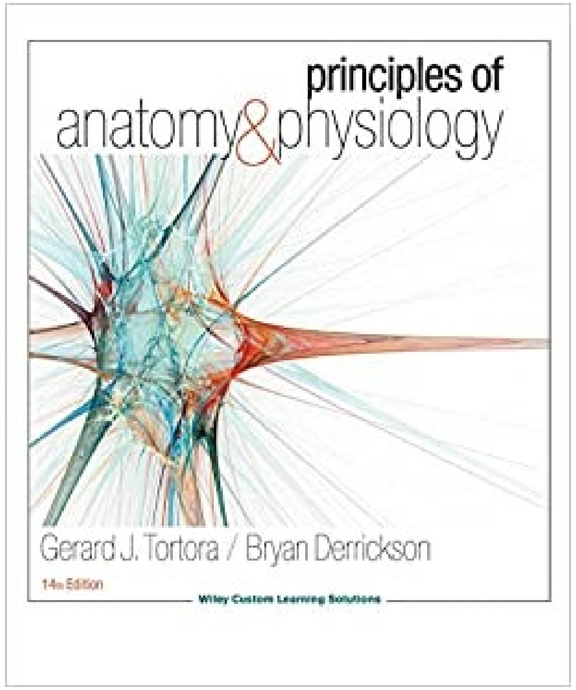
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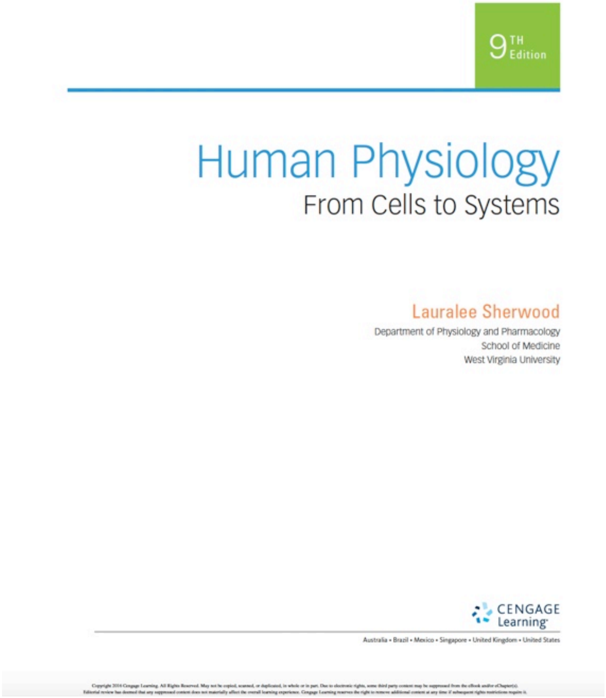
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