Fisiologi Pendengaran dan Keseimbangan

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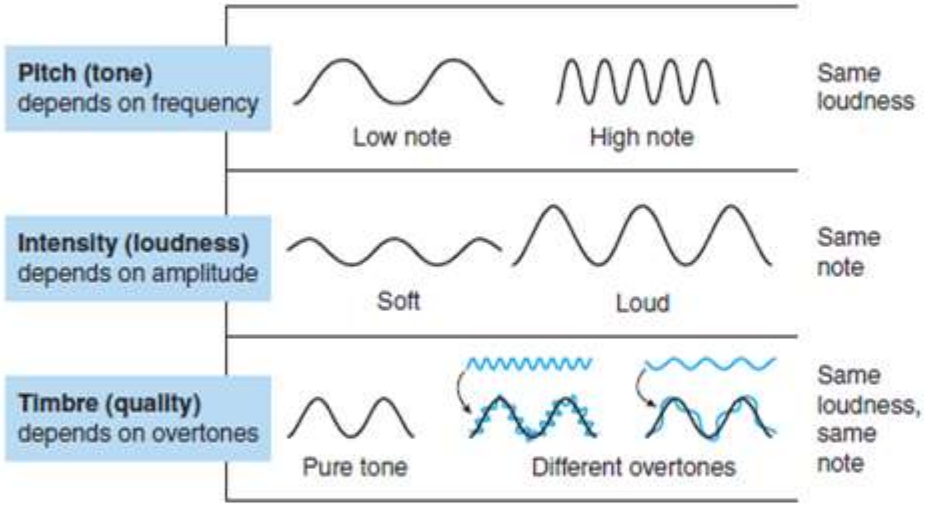


● **FIGURE 6-34** Properties of sound waves.

TABLE 6-5 Relative Magnitude of Common Sounds

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

ORGAN PENDENGARAN

Telinga

- Telinga luar
- Telinga tengah
- Telinga dalam

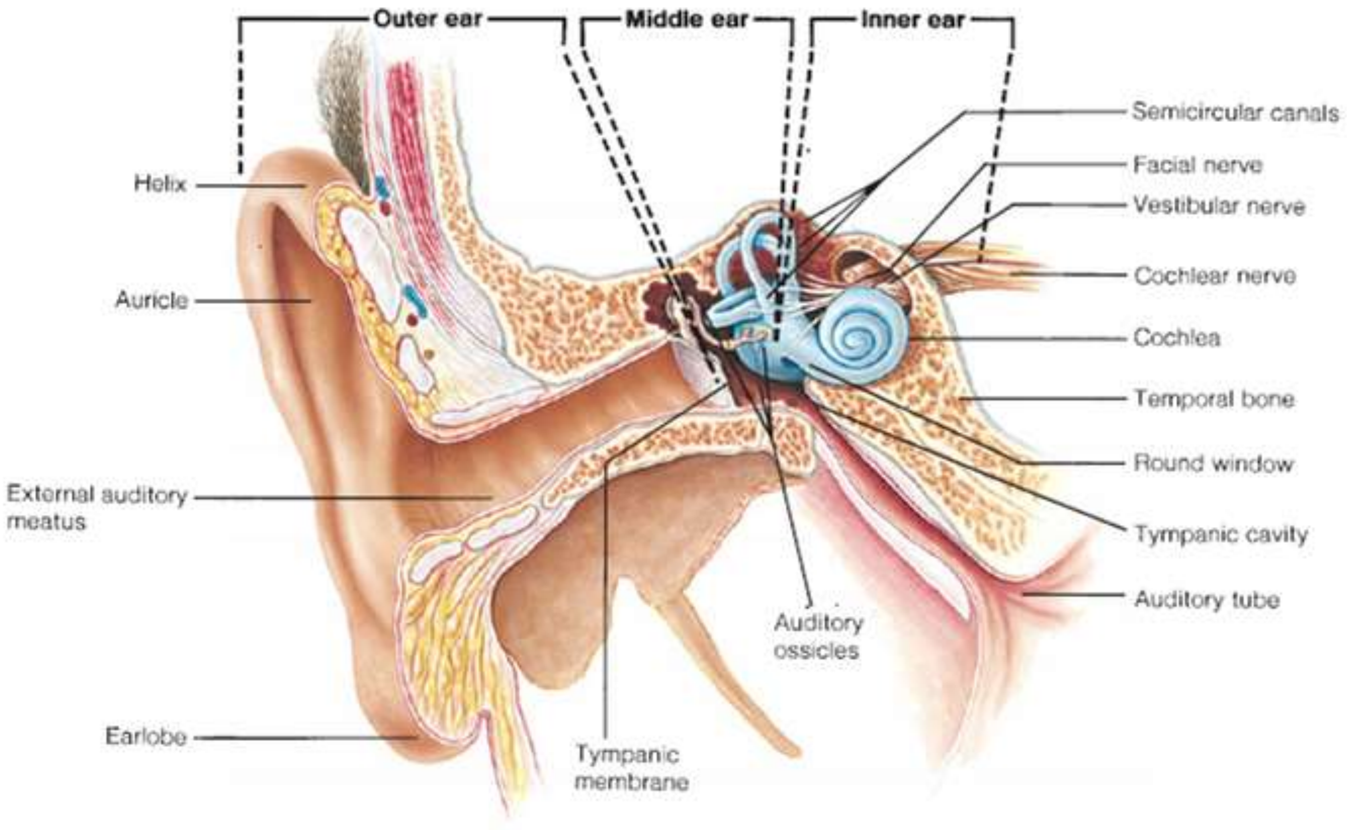


FIGURE 13–1 The structures of the outer, middle, and inner portions of the human ear. To make the relationships clear, the cochlea has been turned slightly and the middle ear muscles have been omitted. (From Fox SI, *Human Physiology*. McGraw-Hill, 2008.)

ORGAN PENDENGARAN TELINGA LUAR

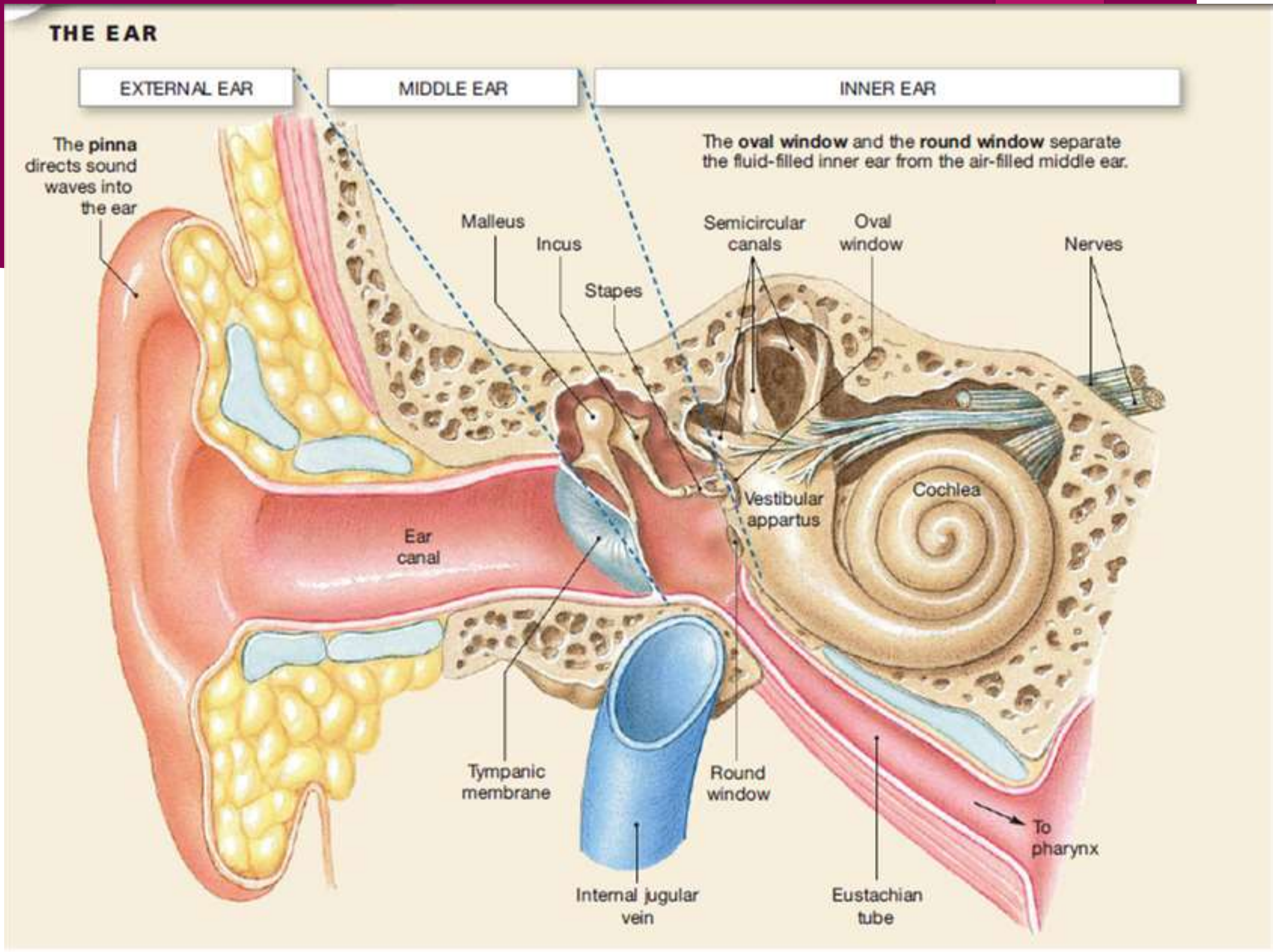
Pinna/auricle

- Mengumpulkan suara dari area yang luas

Kanal auditorik

- Tempat masuk ke bagian telinga yang lebih dalam
- Panjangnya ± 2,5 cm
- Berakhir di membran timpani/gendang telinga

Anatomi Telinga



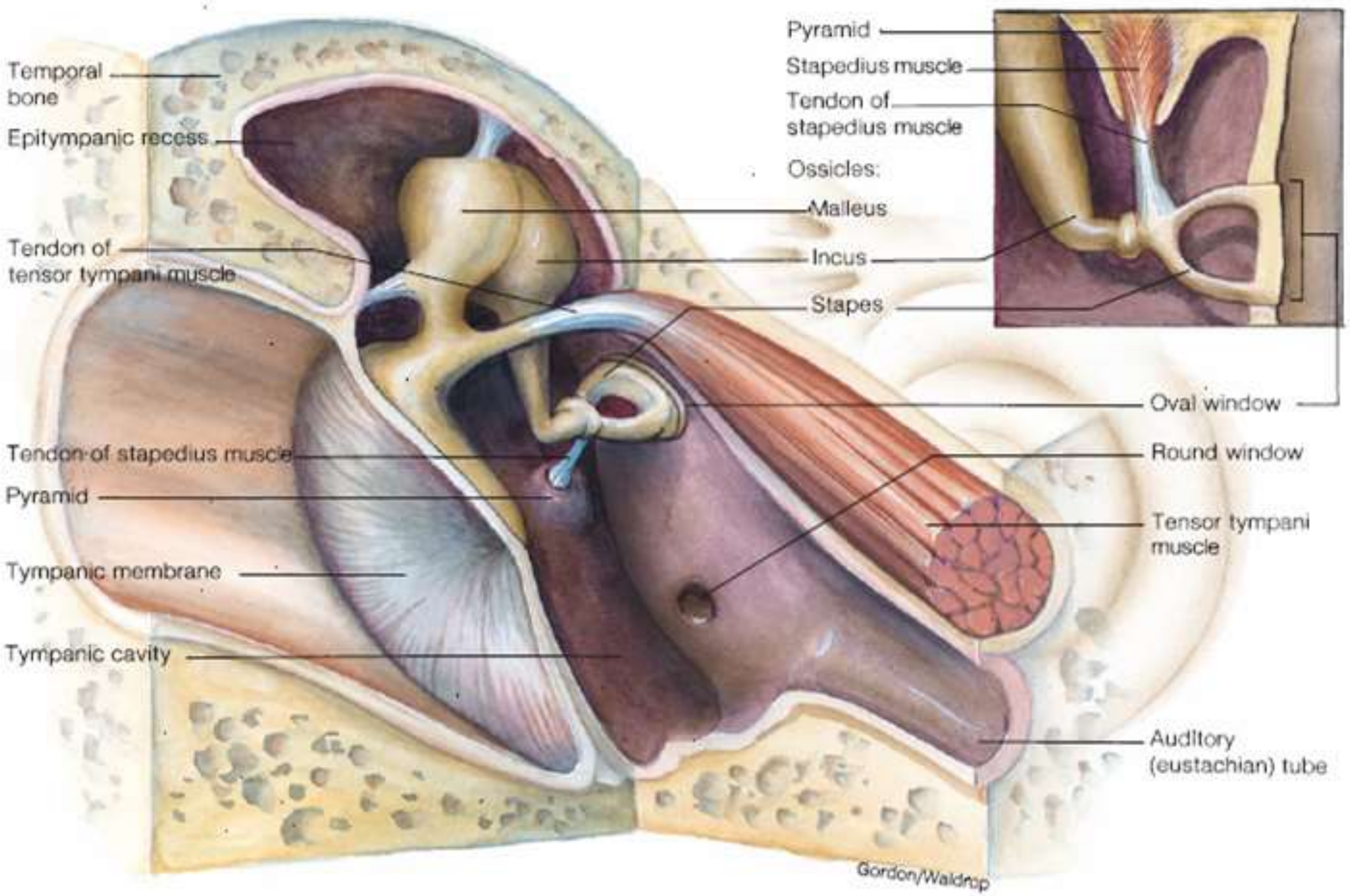


FIGURE 13–2 **The medial view of the middle ear.** The locations of auditory muscles attached to the middle-ear ossicles are indicated.
(From Fox SI, *Human Physiology*. McGraw-Hill, 2008.)

ORGAN PENDENGARAN TELINGA TENGAH

Tulang-tulang pendengaran (ossicles)

- Maleus
- Inkus
- Stapes, bagian bawahnya yang datar (*footplate*) bergerak maju mundur seperti piston di jendela oval meneruskan getaran suara ke cairan di koklea
- Berfungsi untuk **amplifikasi suara**

Otot pada ossicles

- Otot tensor timpani pada maleus
- Otot stapedius pada stapes
- Berfungsi untuk **refleks atenuasi**

- Telinga tengah berhubungan dengan rongga hidung **tuba Eustachia**

AMPLIFIKASI SUARA OLEH *OSSICLES*

- Bila tidak terjadi amplifikasi suara oleh *ossicles* membran jendela oval tidak akan bergerak & 99,9% suara akan dipantulkan tekanan di koklea > di belakang jendela oval

$$\text{Tekanan} = \frac{\text{kekuatan tekanan}}{\text{luas permukaan}}$$

 Tekanan di jendela oval akan > bila:

- Kekuatan tekanan di membran jendela oval > membran timpani amplifikasi oleh *ossicles* (seperti pengungkit)
- Luas permukaan jendela oval < membran timpani

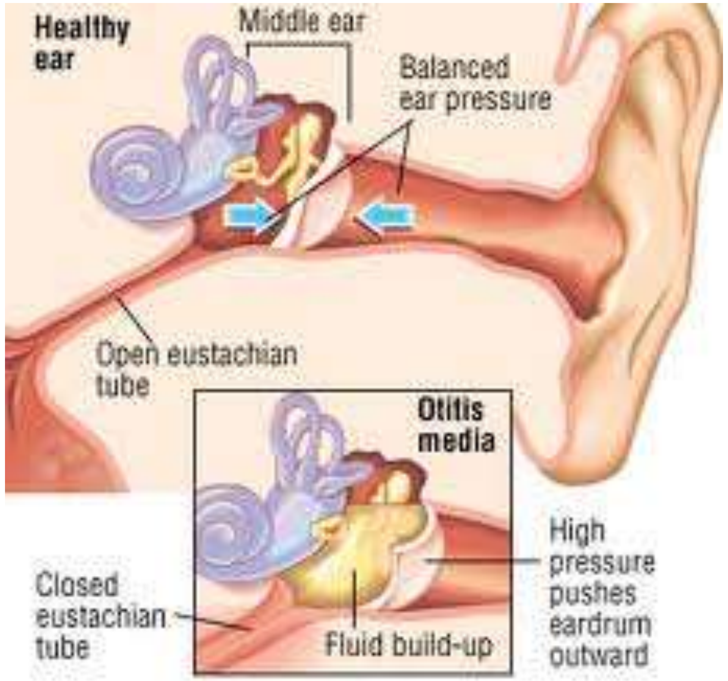
 Amplifikasi 20x lipat

REFLEKS ATENUASI (acoustic reflex)

- Dipicu oleh suara yang sangat keras kontraksi otot tensor timpani & stapedius kekakuan *ossicles* konduksi suara ↓↓
- Refleks atenuasi > baik pada frekuensi rendah membantu mendengar pembicaraan (*speech*) > baik pada lingkungan dengan banyak suara frekuensi rendah
- Keterbatasan: Terjadi keterlambatan refleks 50-100 msec dari saat suara mencapai telinga dapat terjadi kerusakan pada suara sangat keras yang tiba-tiba

Tuba Eustachius

- Normal tertutup
- Membuka : menguap, mengunyah, menelan tekanan udara di telinga tengah = tekanan atm shg tekanan di kedua sisi membran timpani setara



ORGAN PENDENGARAN TELINGA DALAM

Koklea untuk pendengaran

- Bentuknya spiral, ø 2 mm, panjang tergelung 9 mm, tidak tergelung 32 mm
- Pilar sentral modiouls

Labirin untuk keseimbangan

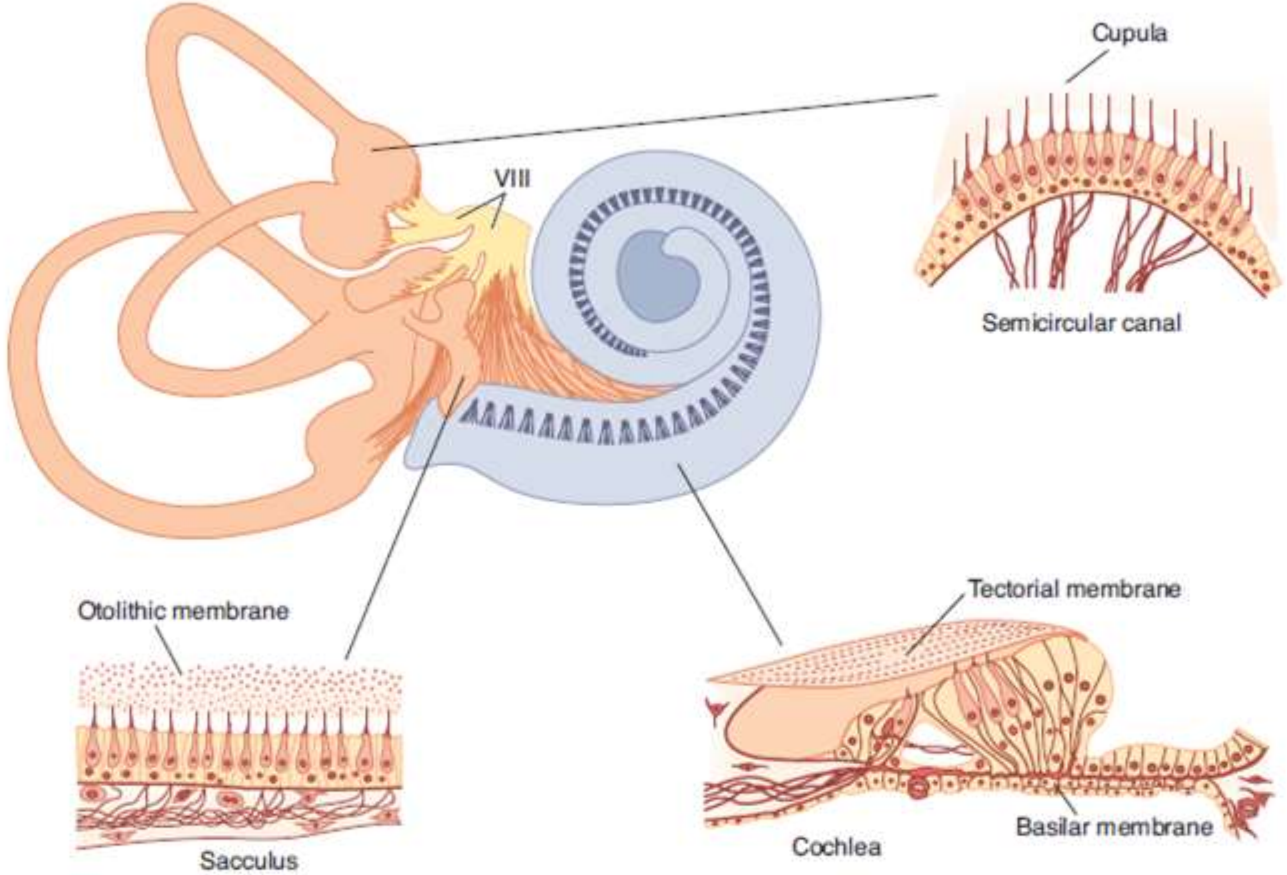
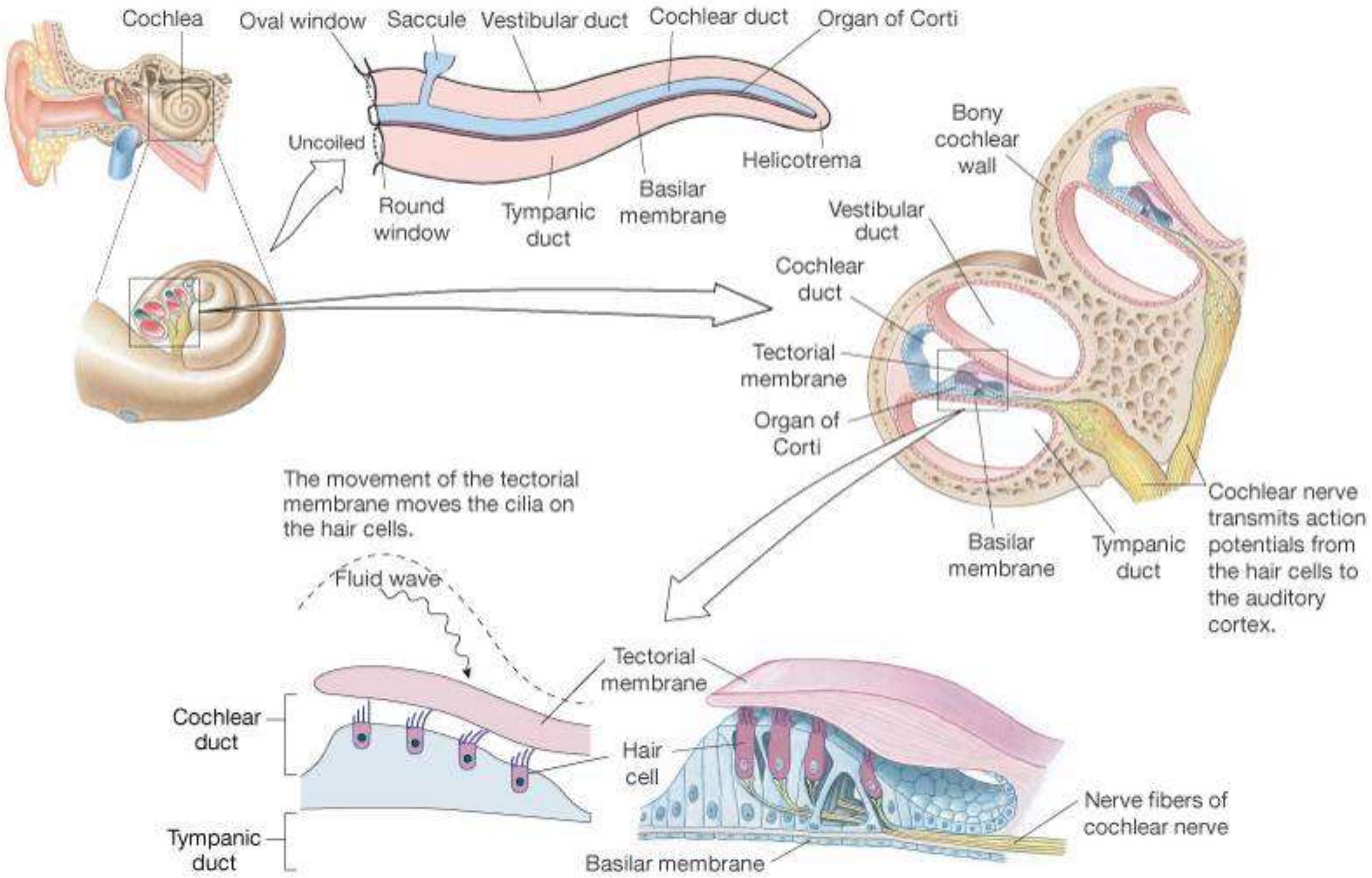


FIGURE 13–3 Schematic of the human inner ear showing the membranous labyrinth with enlargements of the structures in which hair cells are embedded. The membranous labyrinth is suspended in perilymph and filled with K^+-rich endolymph which bathes the receptors. Hair cells (darkened for emphasis) occur in different arrays characteristic of the receptor organs. The three semicircular canals are sensitive to angular accelerations which deflect the gelatinous cupula and associated hair cells. In the cochlea, hair cells spiral along the basilar membrane in the organ of Corti. Airborne sounds set the eardrum in motion, which is conveyed to the cochlea by bones of the middle ear. This flexes the membrane up and down. Hair cells in the organ of Corti are stimulated by shearing motion. The otolithic organs (saccule and utricle) are sensitive to linear acceleration in vertical and horizontal planes. Hair cells are attached to the otolithic membrane. VIII, eighth cranial nerve, with auditory and vestibular divisions. (Reproduced with permission from Hudspeth AJ: How the ear's works work. Nature 1989;341:397. Copyright © 1989 by Macmillan Magazines.)

ORGAN PENDENGARAN TELINGA DALAM

Koklea potong lintang

- Skala vestibuli dasar: jendala oval; cairan: perilimfe
- Skala timpani cairan: endolimfe ($[K^+]$ ↑, $[Na^+]$ ↓) (transport aktif oleh stria vaskularis) potensial endokoklear > positif $\pm$ 80mV daripada perilimfe
- Skala media dasar: jendela bulat; cairan: perilimfe
- Membran Reissner memisahkan skala vestibuli dari skala media
- Membran basilar memisahkan skala timpani dari skala media; terdapat organ Corti
- Skala vestibuli & timpani bertemu di *helicotrema* di apeks koklea



Cochlea
Oval window
Saccule
Vestibular duct
Cochlear duct
Organ of Corti
Uncoiled
Round window
Tympanic duct
Basilar membrane
Helicotrema
Bony cochlear wall
Vestibular duct
Cochlear duct
Tectorial membrane
Organ of Corti
Basilar membrane
Tympanic duct
Cochlear nerve transmits action potentials from the hair cells to the auditory cortex.
The movement of the tectorial membrane moves the cilia on the hair cells.
Fluid wave
Cochlear duct
Tympanic duct
Tectorial membrane
Hair cell
Basilar membrane
Nerve fibers of cochlear nerve

TELINGA DALAM

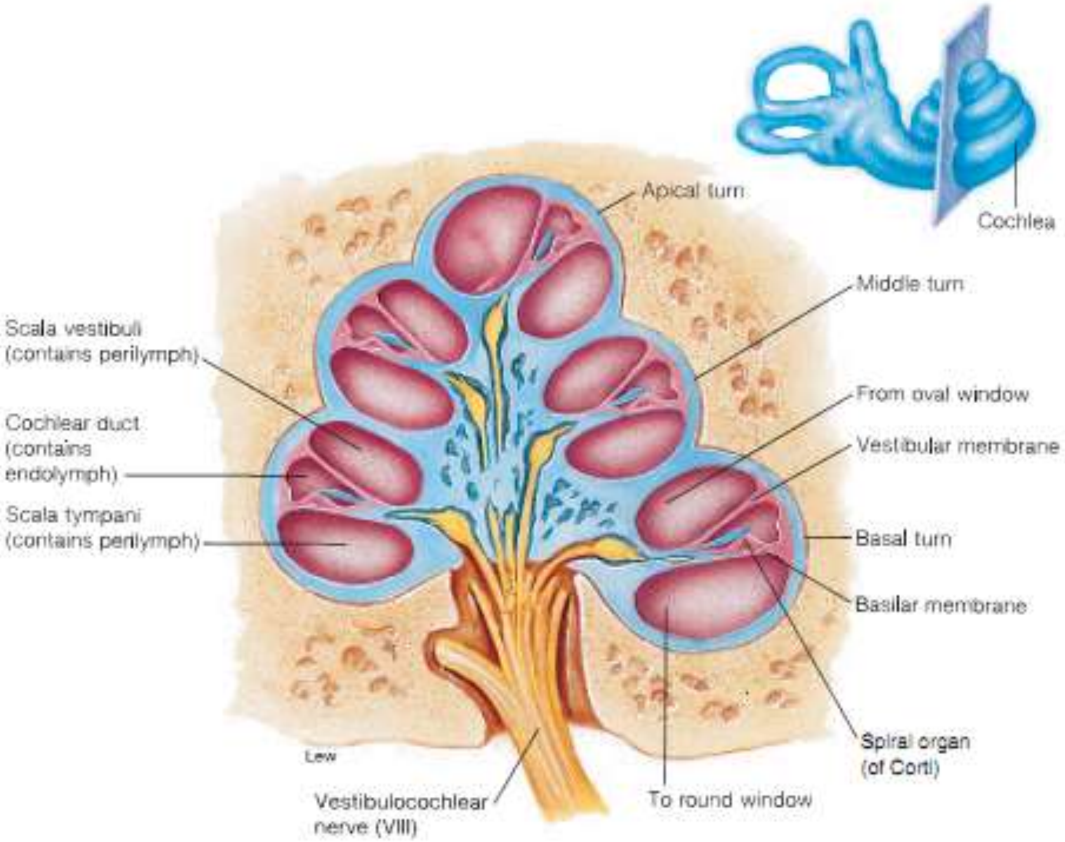
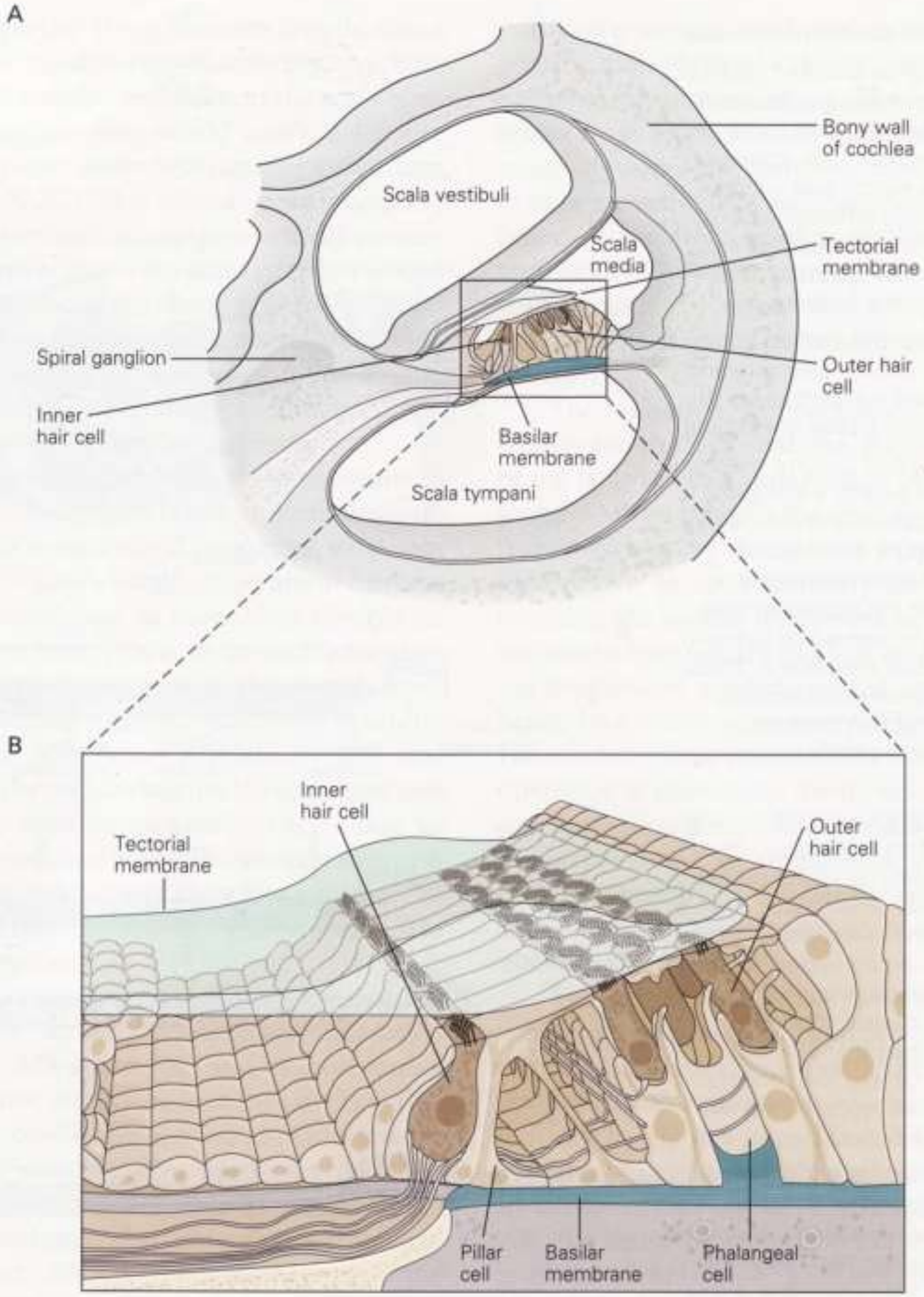


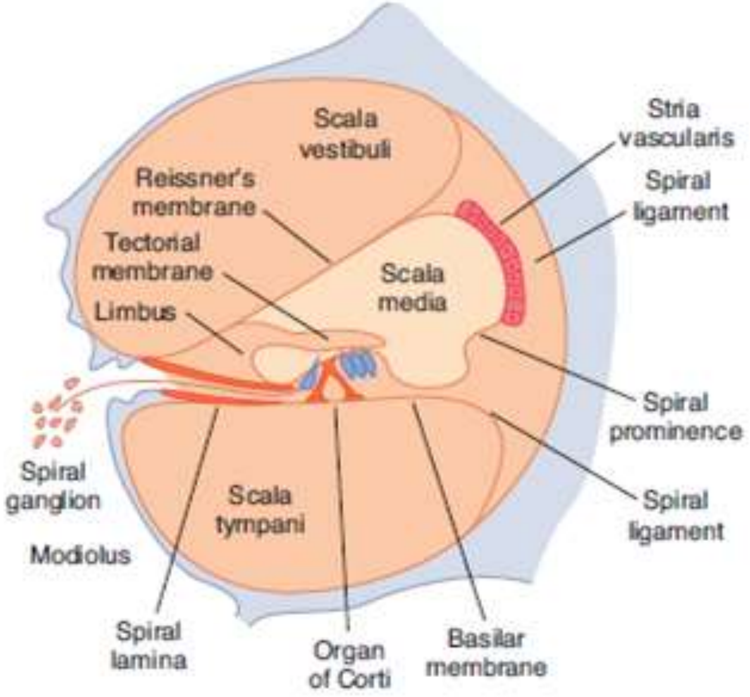
Figure 10.19 **A cross section of the cochlea.** In this view, its three turns and its three compartments—the scala vestibuli, cochlear duct (scala media), and scala tympani—can be seen.


A
Bony wall of cochlea
Scala vestibuli
Scala media
Tectorial membrane
Spiral ganglion
Outer hair cell
Inner hair cell
Basilar membrane
Scala tympani
B
Inner hair cell
Tectorial membrane
Outer hair cell
Pillar cell
Basilar membrane
Phalangeal cell

ORGAN PENDENGARAN TELINGA DALAM

Organ Corti

- Sel-sel rambut memiliki *stereocilia*; terletak di antara membran tektorial & *reticular lamina*; ditunjang oleh batang Corti (*rods of Corti*)
    - Sel rambut dalam antara modiolus & *reticular lamina*
    - Sel rambut luar di luar *rods of Corti*
- Sel-sel rambut bersinaps ke neuron yang badan selnya terletak di ganglion spiral di modiouls



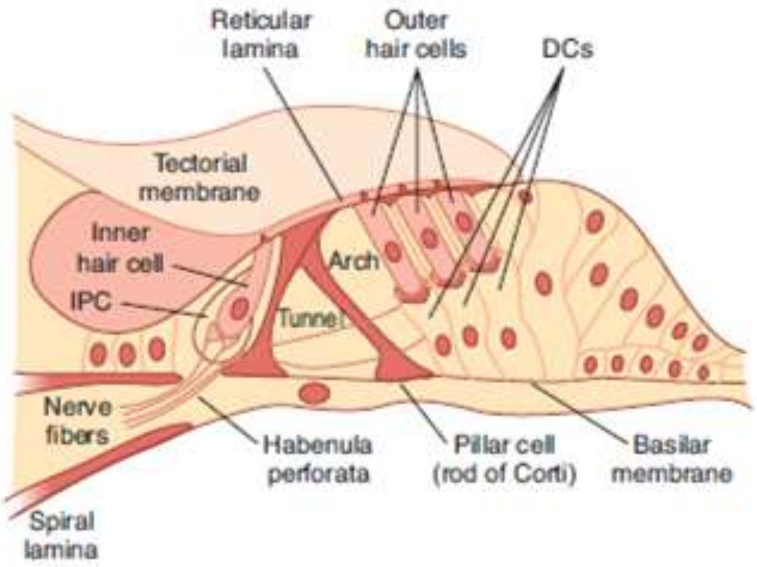
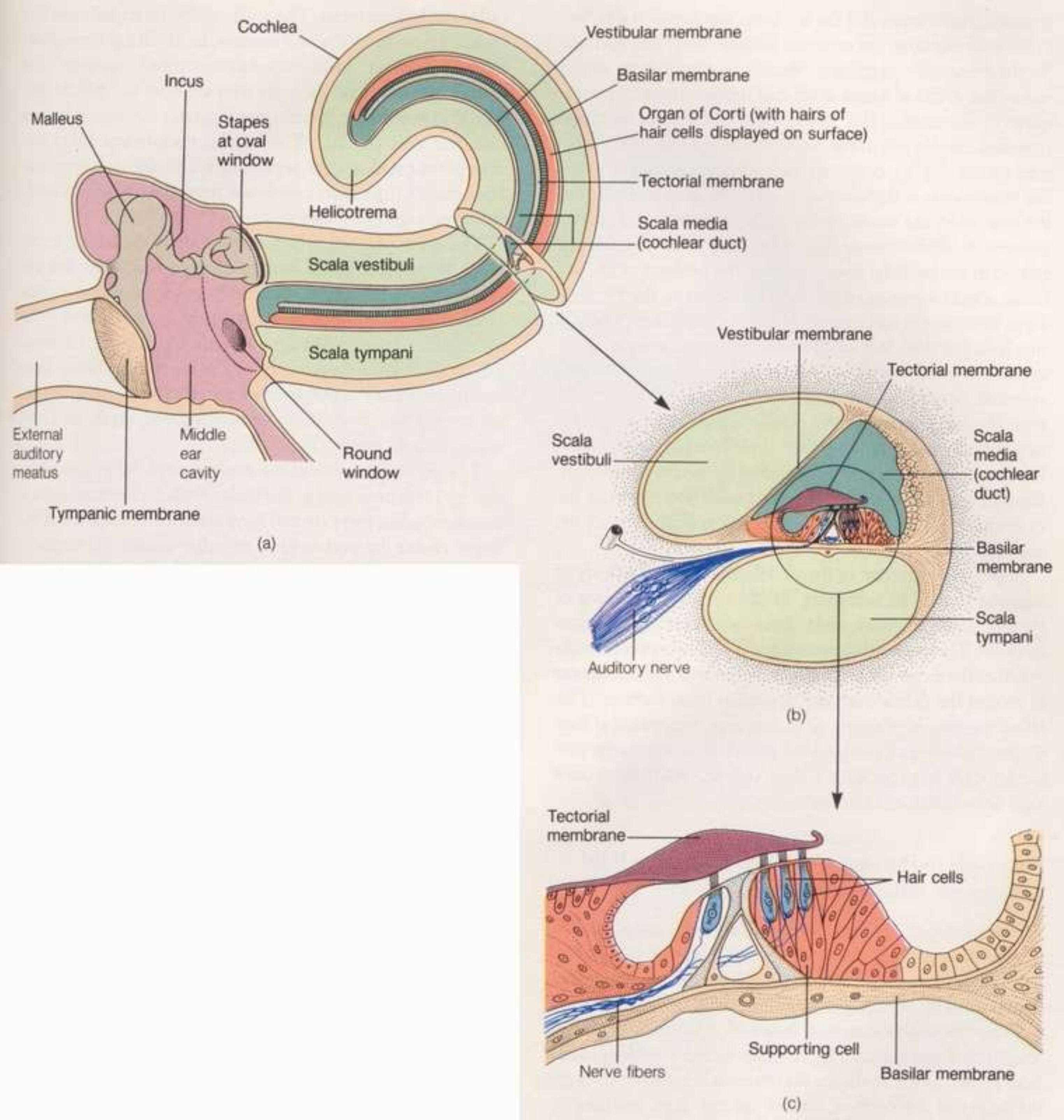


FIGURE 13–4 Top: Cross-section of the cochlea, showing the organ of Corti and the three scalae of the cochlea. Bottom: Structure of the organ of Corti, as it appears in the basal turn of the cochlea. DC, outer phalangeal cells (Deiters' cells) supporting outer hair cells; IPC, inner phalangeal cell supporting inner hair cell. (Reproduced with permission from Pickels JO: *An Introduction to the Physiology of Hearing*, 2nd ed. Academic Press, 1988.)



Cochlea
Vestibular membrane
Basilar membrane
Incus
Malleus
Stapes at oval window
Organ of Corti (with hairs of hair cells displayed on surface)
Tectorial membrane
Helicotrema
Scala media (cochlear duct)
Scala vestibuli
Scala tympani
External auditory meatus
Middle ear cavity
Round window
Tympanic membrane
(a)
Vestibular membrane
Tectorial membrane
Scala vestibuli
Scala media (cochlear duct)
Basilar membrane
Scala tympani
Auditory nerve
(b)
Tectorial membrane
Hair cells
Supporting cell
Nerve fibers
Basilar membrane
(c)

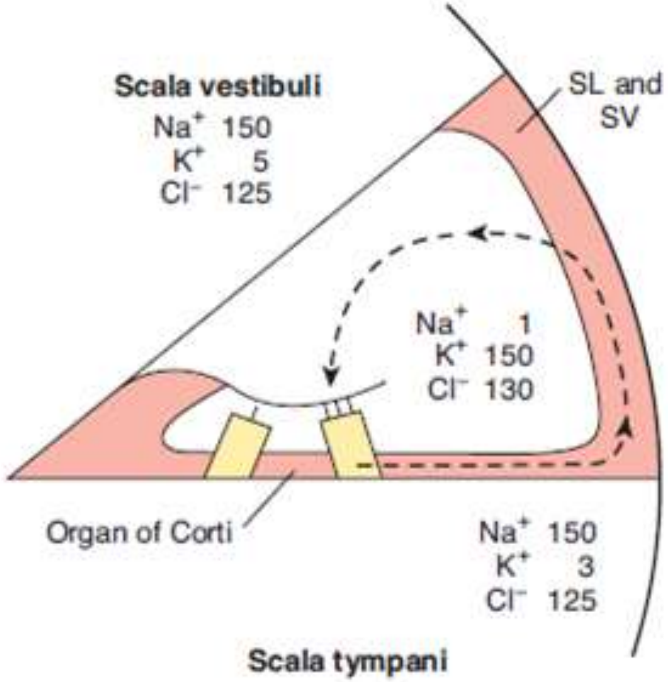


FIGURE 13–7 Ionic composition of perilymph in the scala vestibuli, endolymph in the scala media, and perilymph in the scala tympani. SL, spiral ligament. SV, stria vascularis. The dashed arrow indicates the path by which K^+ recycles from the hair cells to the supporting cells to the spiral ligament and is then secreted back into the endolymph by cells in the stria vascularis.

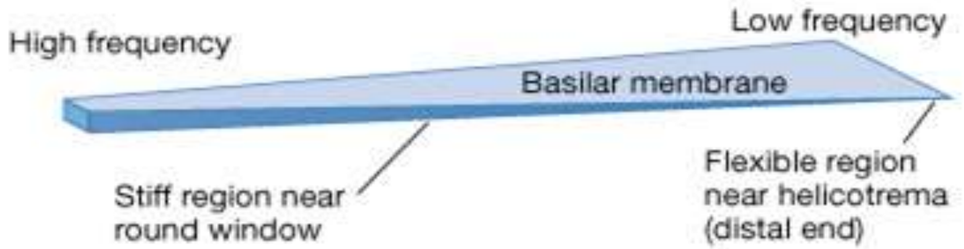
FISIOLOGI KOKLEA

- Respon membran basilar terhadap suara
- Transduksi suara
- Amplifikasi suara oleh sel rambut luar

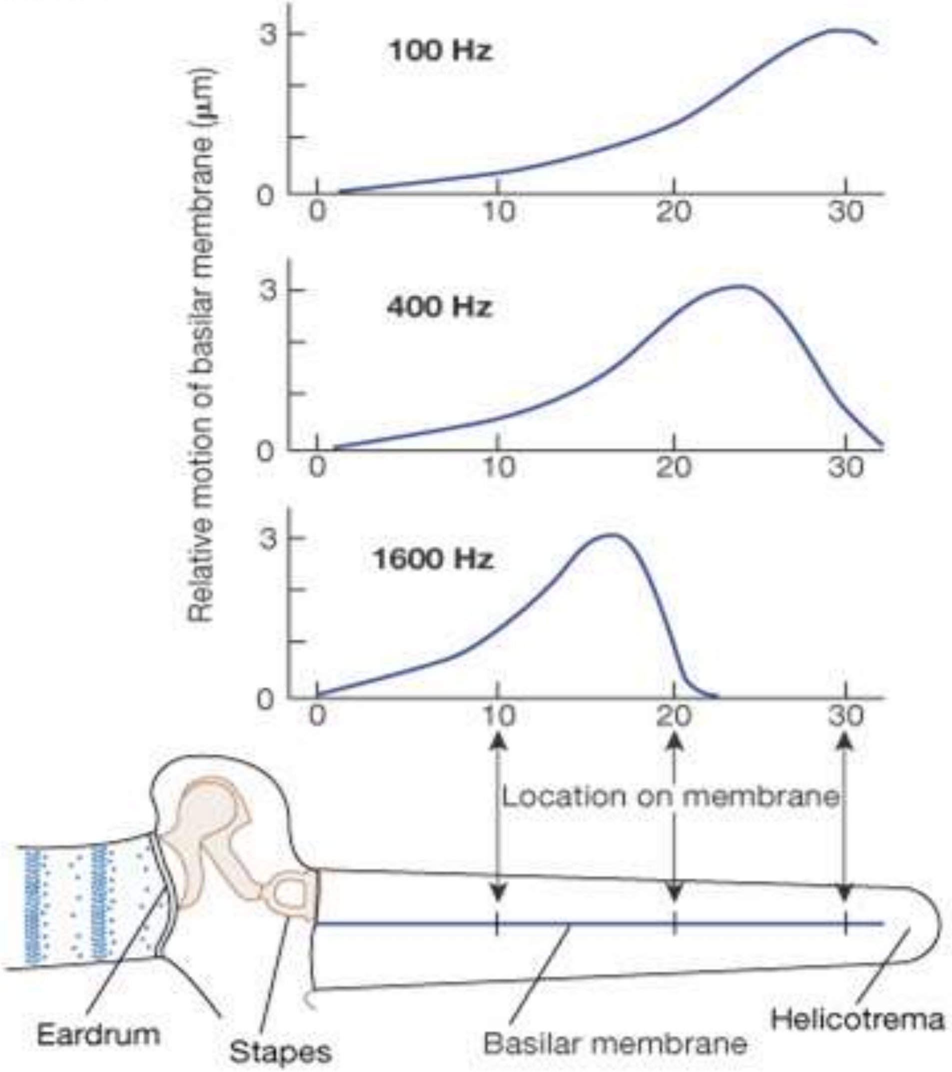
RESPON MEMBRAN BASILAR TERHADAP SUARA

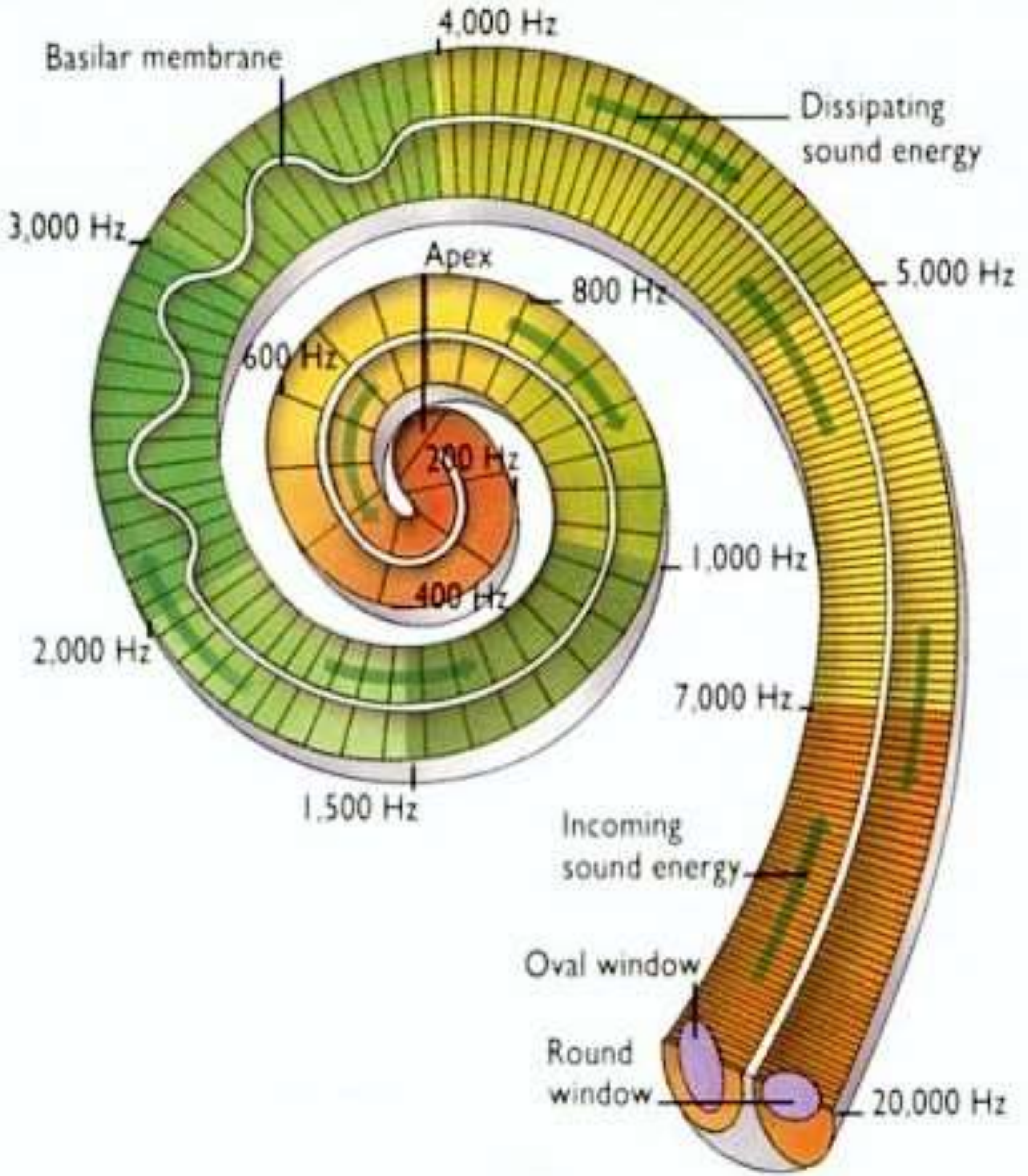
- Sifat struktural membran basilar:
  - 5x > lebar di apex daripada di basis
  - Kekakuan membran berkurang 100x dari basis ke apex
- Pada frekuensi ↑, membran paling bergetar di basis
  - 1/3 apex 20-200 Hz
  - 1/3 tengah 200 Hz-2 kHz
  - 1/3 basis 2-20 kHz
- Suara kompleks bergetar pada beberapa daerah membran basilar

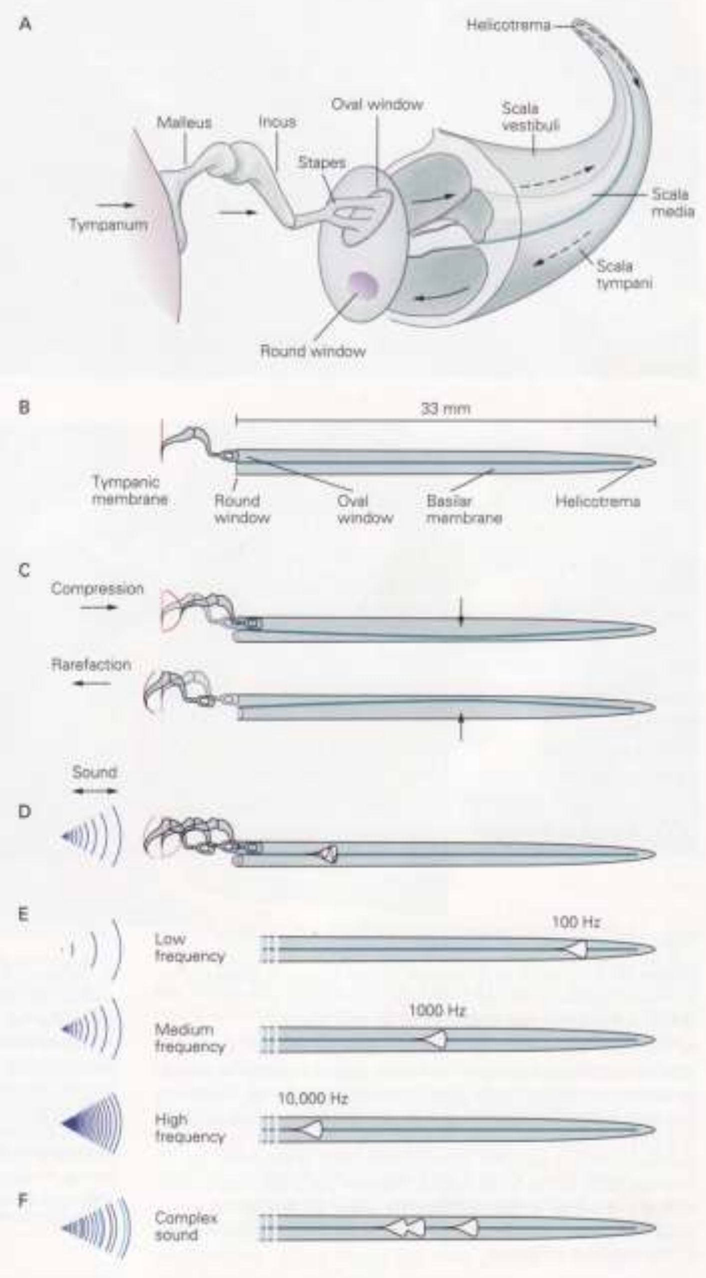
(a) The basilar membrane has variable sensitivity to sound wave frequency along its length.

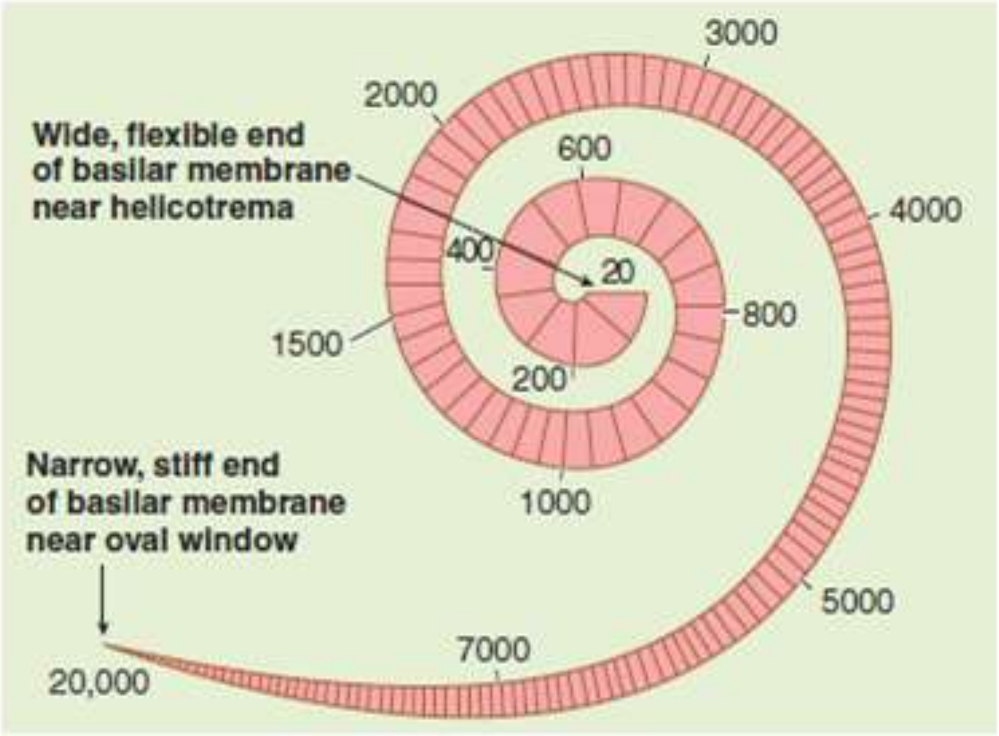


(b) The frequency of sound waves determines the displacement of the basilar membrane. The location of active hair cells creates a code that the brain translates as information about the pitch of sound.



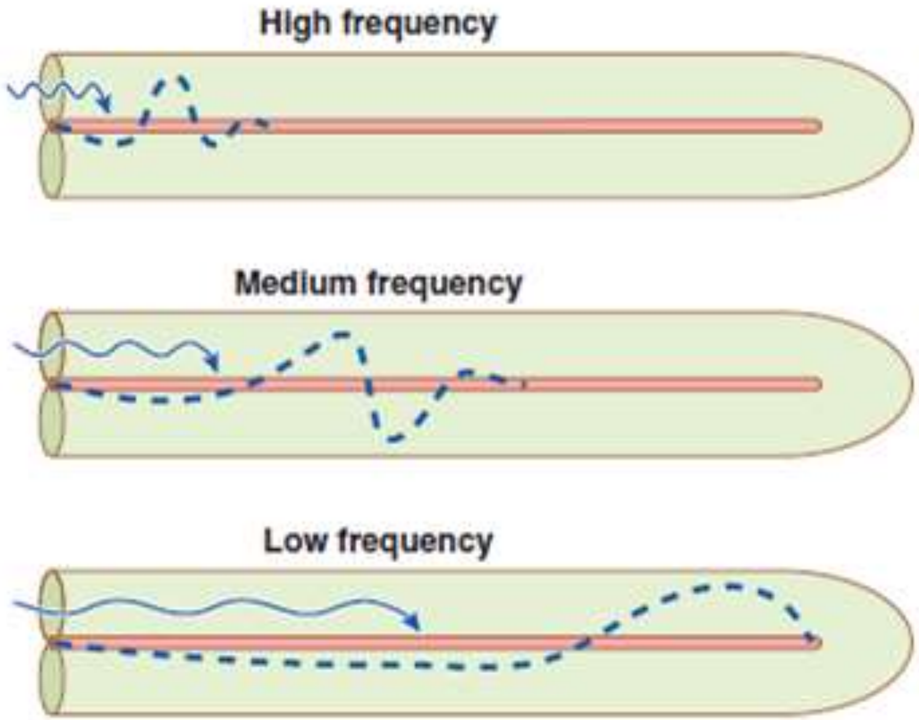

4,000 Hz
Basilar membrane
Dissipating
sound energy
3,000 Hz
Apex
800 Hz
5,000 Hz
600 Hz
200 Hz
1,000 Hz
400 Hz
2,000 Hz
7,000 Hz
1,500 Hz
Incoming
sound energy
Oval window
Round
window
20,000 Hz


A
Helicotrema
Malleus
Incus
Oval window
Scala
vestibuli
Stapes
Tympanum
Scala
media
Scala
tympani
Round window
B
33 mm
Tympanic
membrane
Round
window
Oval
window
Basilar
membrane
Helicotrema
C
Compression
Rarefaction
Sound
D
E
Low
frequency
100 Hz
Medium
frequency
1000 Hz
High
frequency
10,000 Hz
F
Complex
sound



The numbers indicate the frequencies of sound waves in cycles per second with which different regions of the basilar membrane maximally vibrate.

(b) Basilar membrane, partly uncoiled

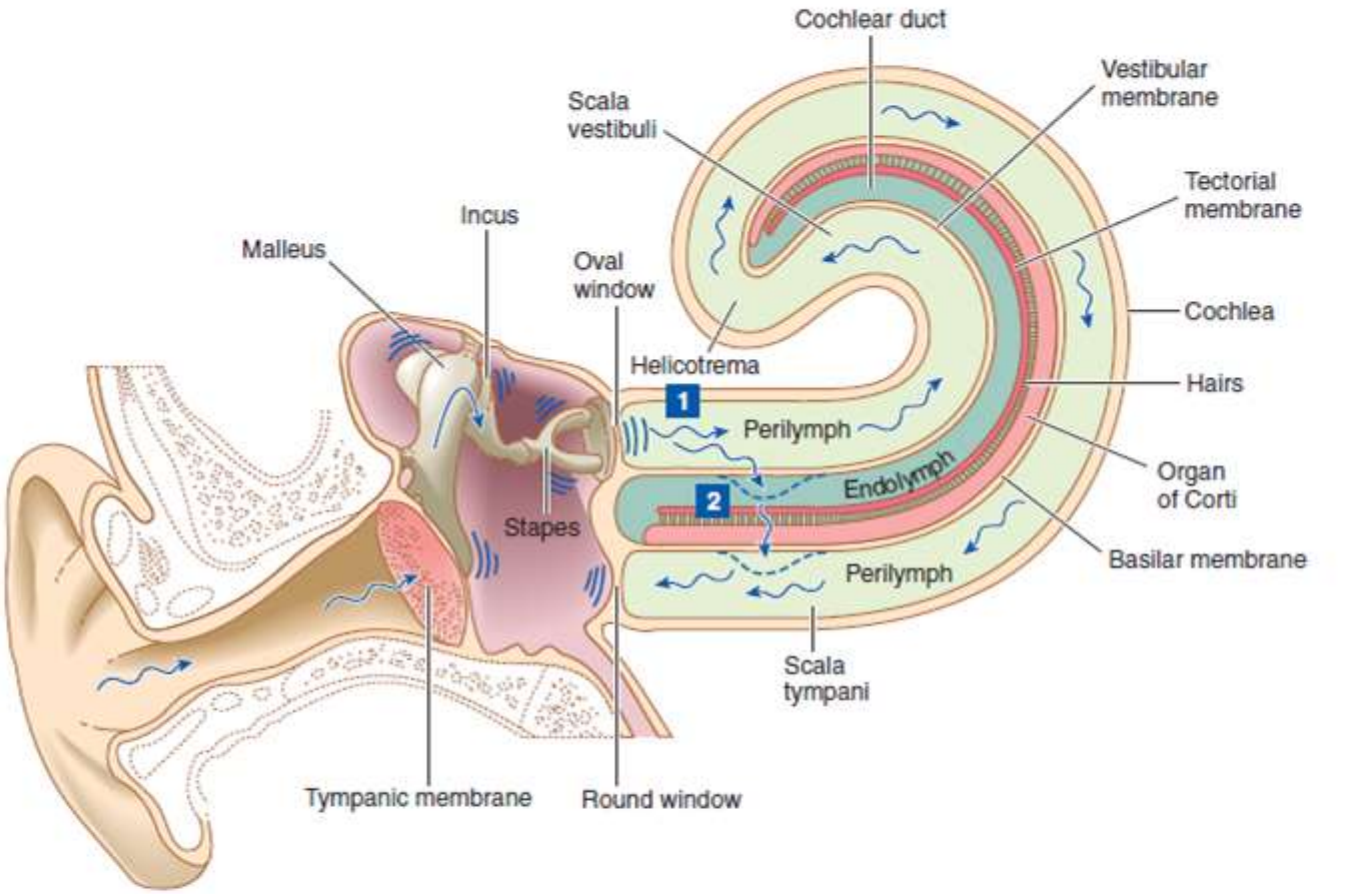


(c) Basilar membrane, completely uncoiled

● **FIGURE 6-36 Transmission of sound waves.** (a) Fluid movement within the cochlea set up by vibration of the oval window follows two pathways, one dissipating sound energy and the other initiating the receptor potential. (b) Different regions of the basilar membrane vibrate maximally at different frequencies. (c) The narrow, stiff end of the basilar membrane nearest the oval window vibrates best with high-frequency pitches. The wide, flexible end of the basilar membrane near the helicotrema vibrates best with low-frequency pitches.

TRANSDUKSI SUARA

Terjadi pada sel rambut (terletak pada membran basalis) getaran pada stapes membran basalis bergerak seluruh pondasi yang mendukung sel-sel rambut bergetar membran basalis, organ corti, lamina retikularis, & sel-sel rambut bergerak sebagai sebuah unit (namun poros insersi membran basilar & tektorial berbeda) berputar menuju atau menjauhi membran tektorial perubahan posisi/membengkoknya stereosilia

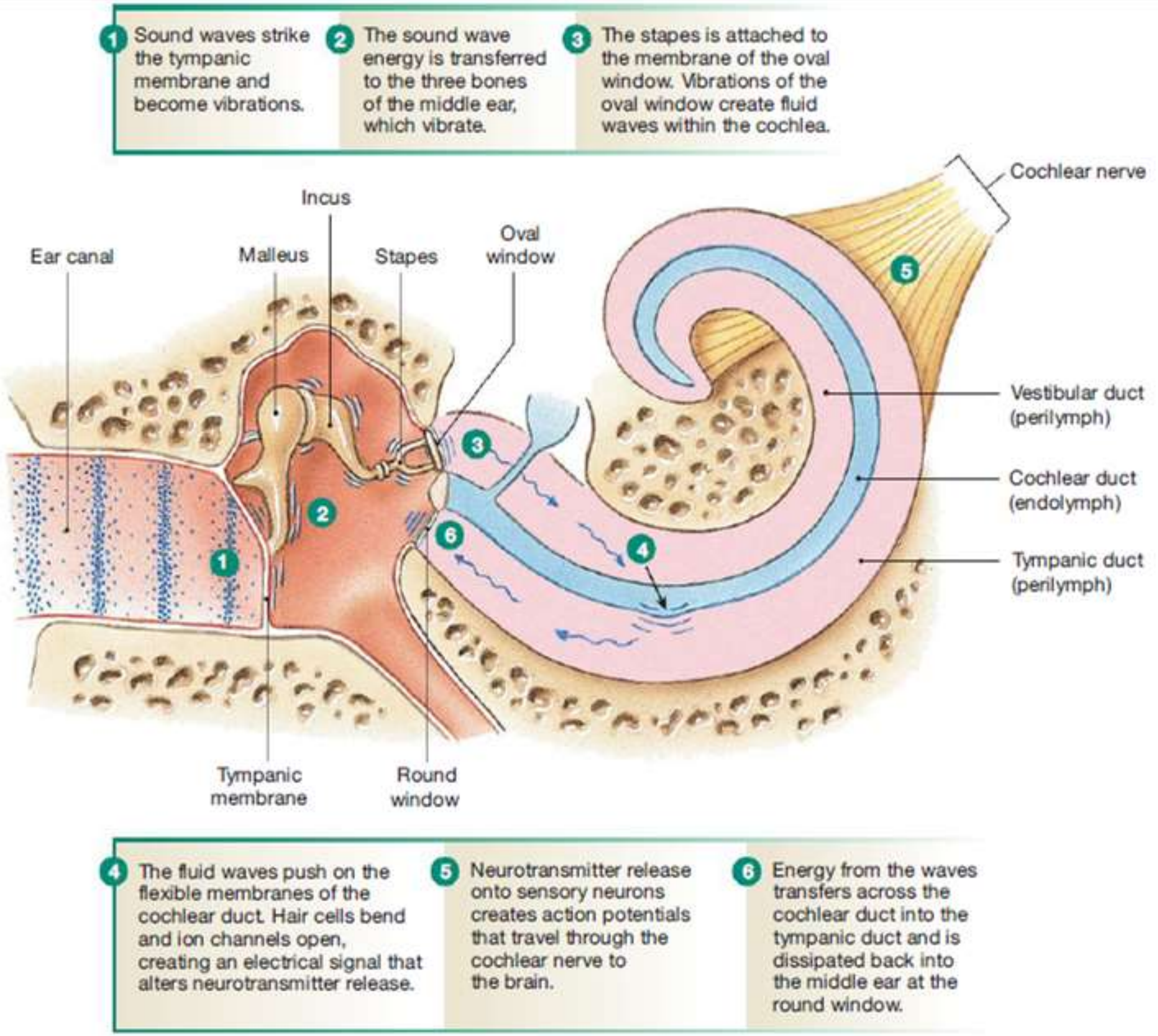


Fluid movement within the perilymph set up by vibration of the oval window follows two pathways:

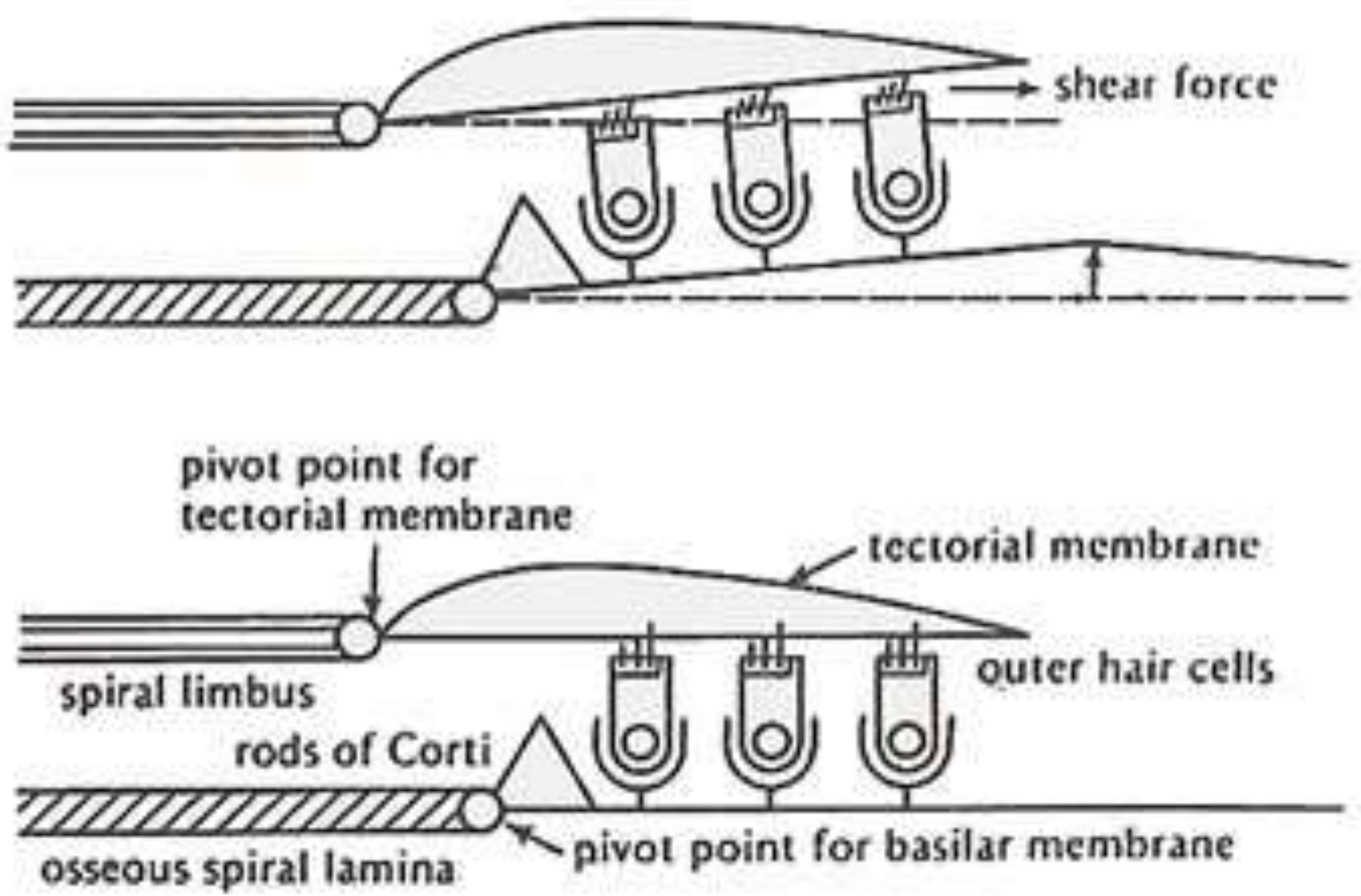
Pathway 1: Through the scala vestibuli, around the heliocotrema, and through the scala tympani, causing the round window to vibrate. This pathway just dissipates sound energy.

Pathway 2: A "shortcut" from the scala vestibuli through the basilar membrane to the scala tympani. This pathway triggers activation of the receptors for sound by bending the hairs of hair cells as the organ of Corti on top of the vibrating basilar membrane is displaced in relation to the overlying tectorial membrane.

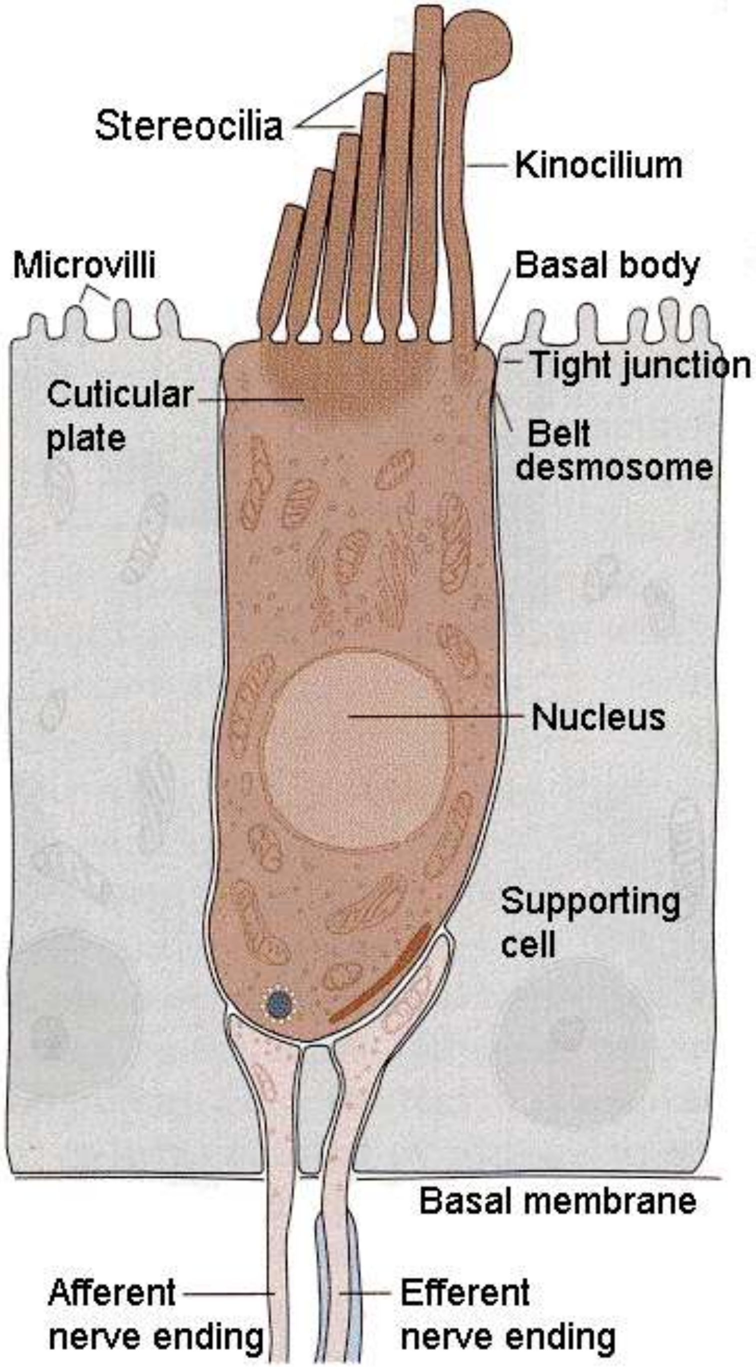
(a) Fluid movement in cochlea



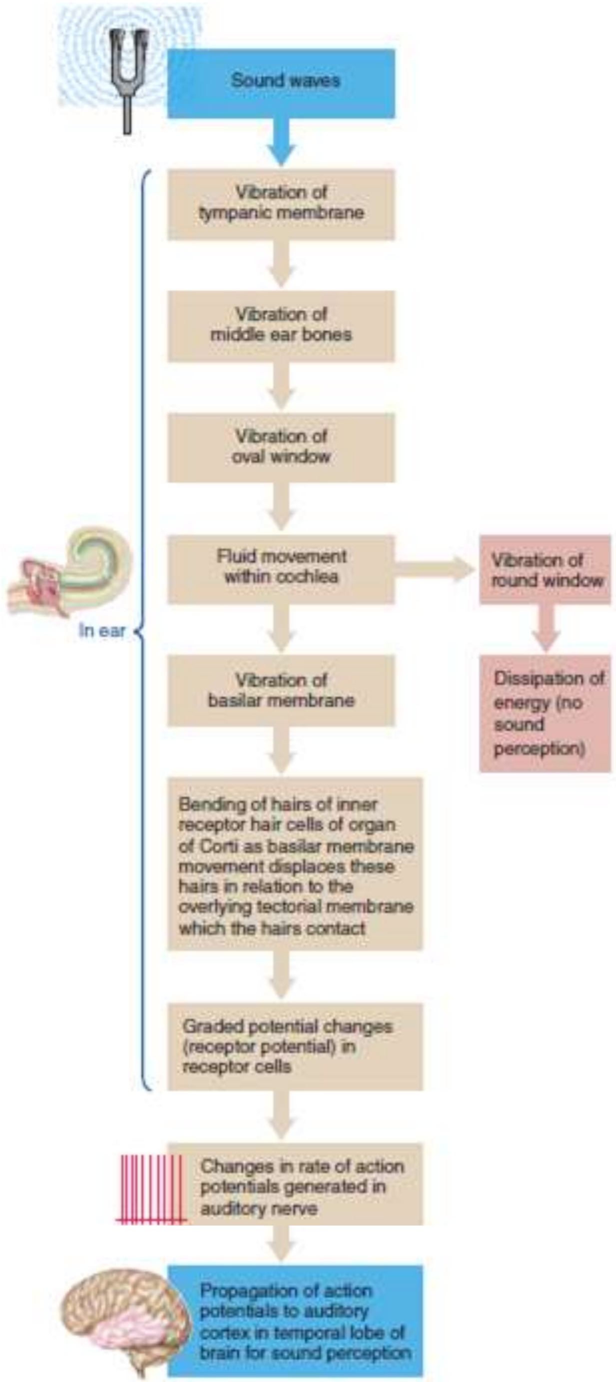
1 Sound waves strike the tympanic membrane and become vibrations.
2 The sound wave energy is transferred to the three bones of the middle ear, which vibrate.
3 The stapes is attached to the membrane of the oval window. Vibrations of the oval window create fluid waves within the cochlea.
Cochlear nerve
Incus
Ear canal
Malleus
Stapes
Oval window
Vestibular duct (perilymph)
Cochlear duct (endolymph)
Tympanic duct (perilymph)
Tympanic membrane
Round window
4 The fluid waves push on the flexible membranes of the cochlear duct. Hair cells bend and ion channels open, creating an electrical signal that alters neurotransmitter release.
5 Neurotransmitter release onto sensory neurons creates action potentials that travel through the cochlear nerve to the brain.
6 Energy from the waves transfers across the cochlear duct into the tympanic duct and is dissipated back into the middle ear at the round window.



shear force
pivot point for
tectorial membrane
tectorial membrane
outer hair cells
spiral limbus
rods of Corti
pivot point for basilar membrane
osseous spiral lamina


Stereocilia
Kinocilium
Microvilli
Basal body
Tight junction
Cuticular plate
Belt desmosome
Nucleus
Supporting cell
Basal membrane
Afferent nerve ending
Efferent nerve ending

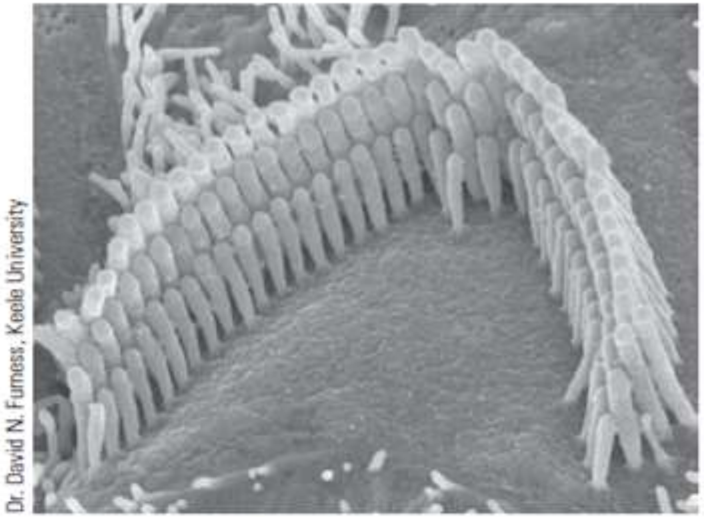
Jalur Transduksi Suara



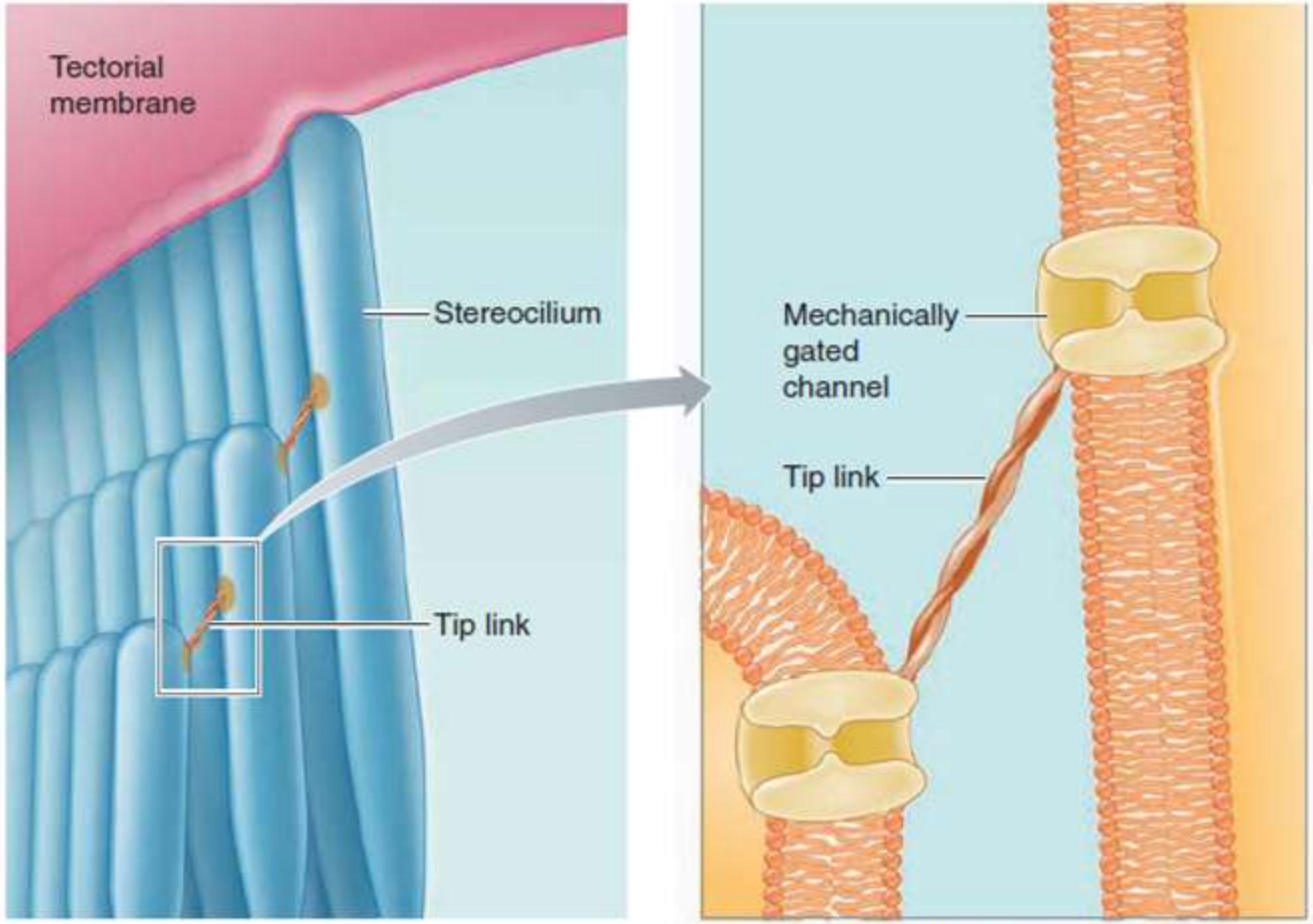
● FIGURE 6-39 Pathway for sound transduction.

TRANSDUKSI SUARA

- Membengkoknya stereocilia kanal TRPA1 (pada puncak stereocilia) membuka /menutup menciptakan perbedaan pada potensial reseptor sel-sel rambut
- Setiap kanal dihubungkan dengan dinding silia yang bersebelahan oleh filamen elastis *tip link*
  - Silia pada posisi lurus tegangan pada *tip link* menahan kanal pada keadaan terbuka sebagian terdapat sedikit kebocoran kalium dari endolimfe ke sel-sel rambut
  - Membengkoknya silia ke kinocilium me↑ tegangan pada *tip link* me↑ arus masuknya kalium ke sel-sel rambut
  - Membengkoknya silia ke arah yang berlawanan menghilangkan tegangan pada *tip link* kanal menutup seluruhnya mencegah masuknya kalium ke sel-sel rambut



(a) Bundle of stereocilia from a single receptor hair cell



(b) Tip link pulling open mechanically gated channel

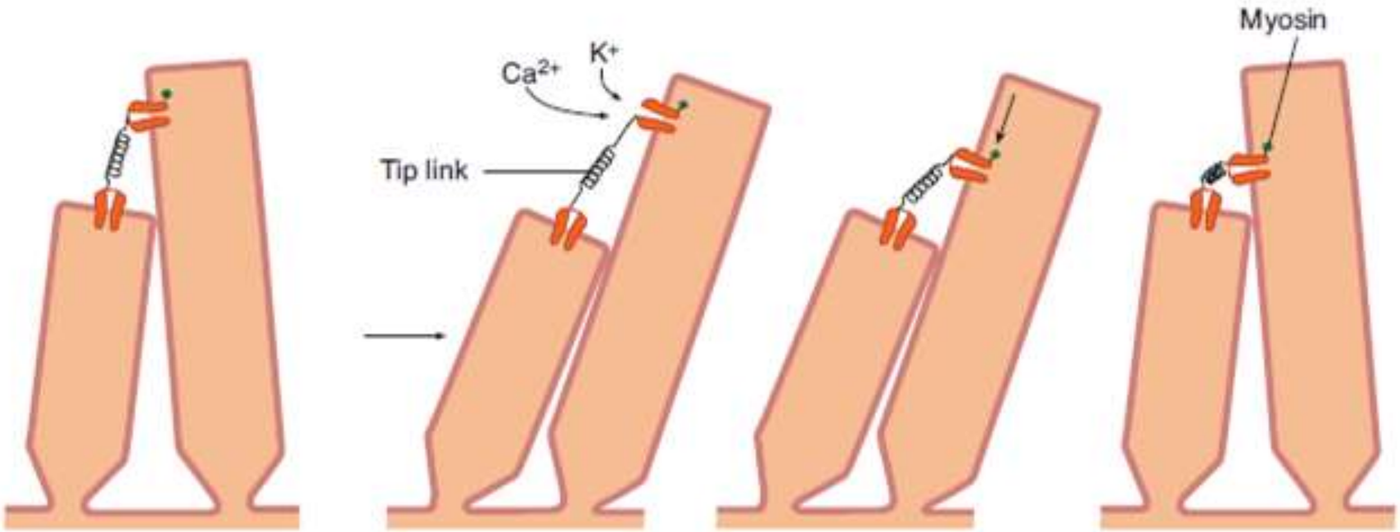
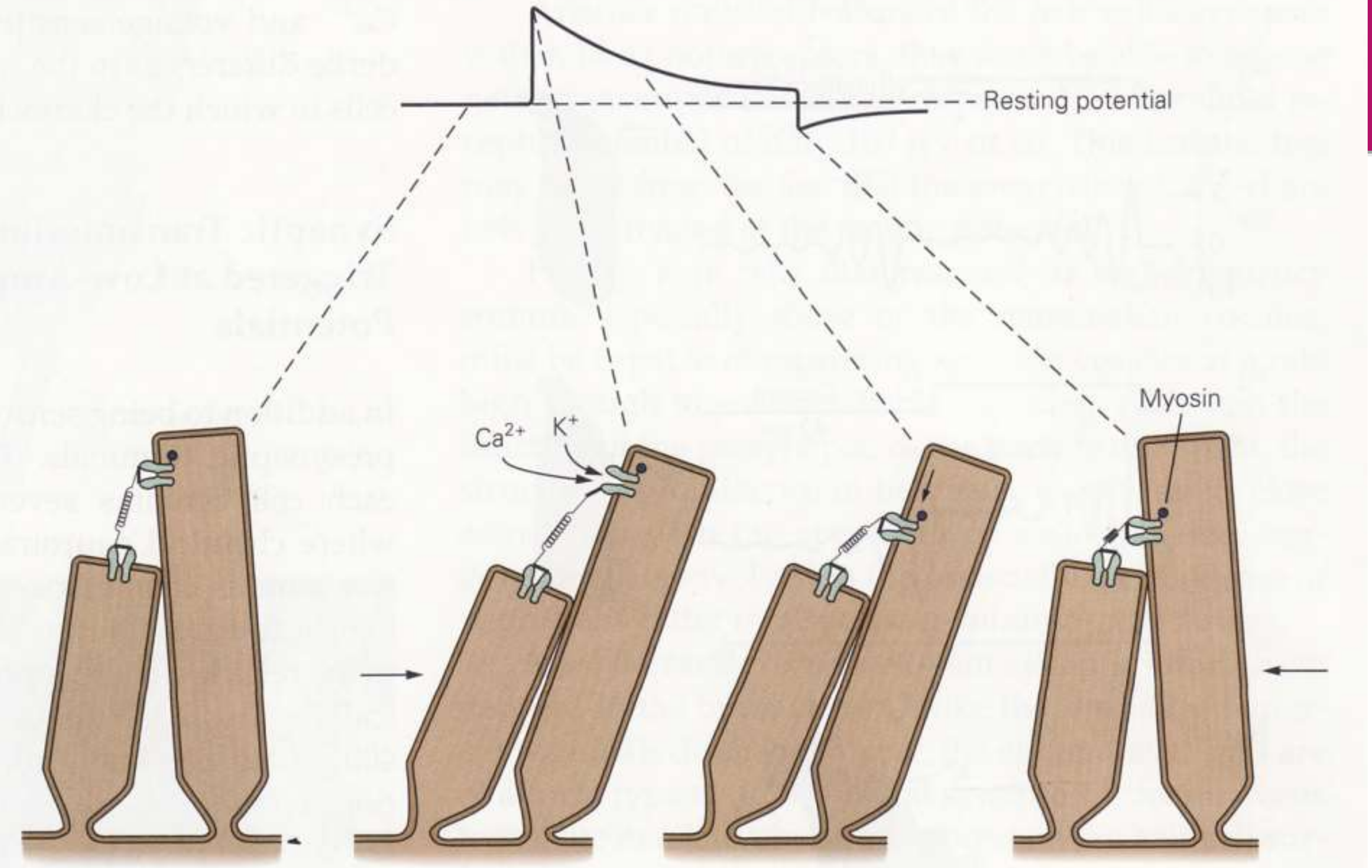
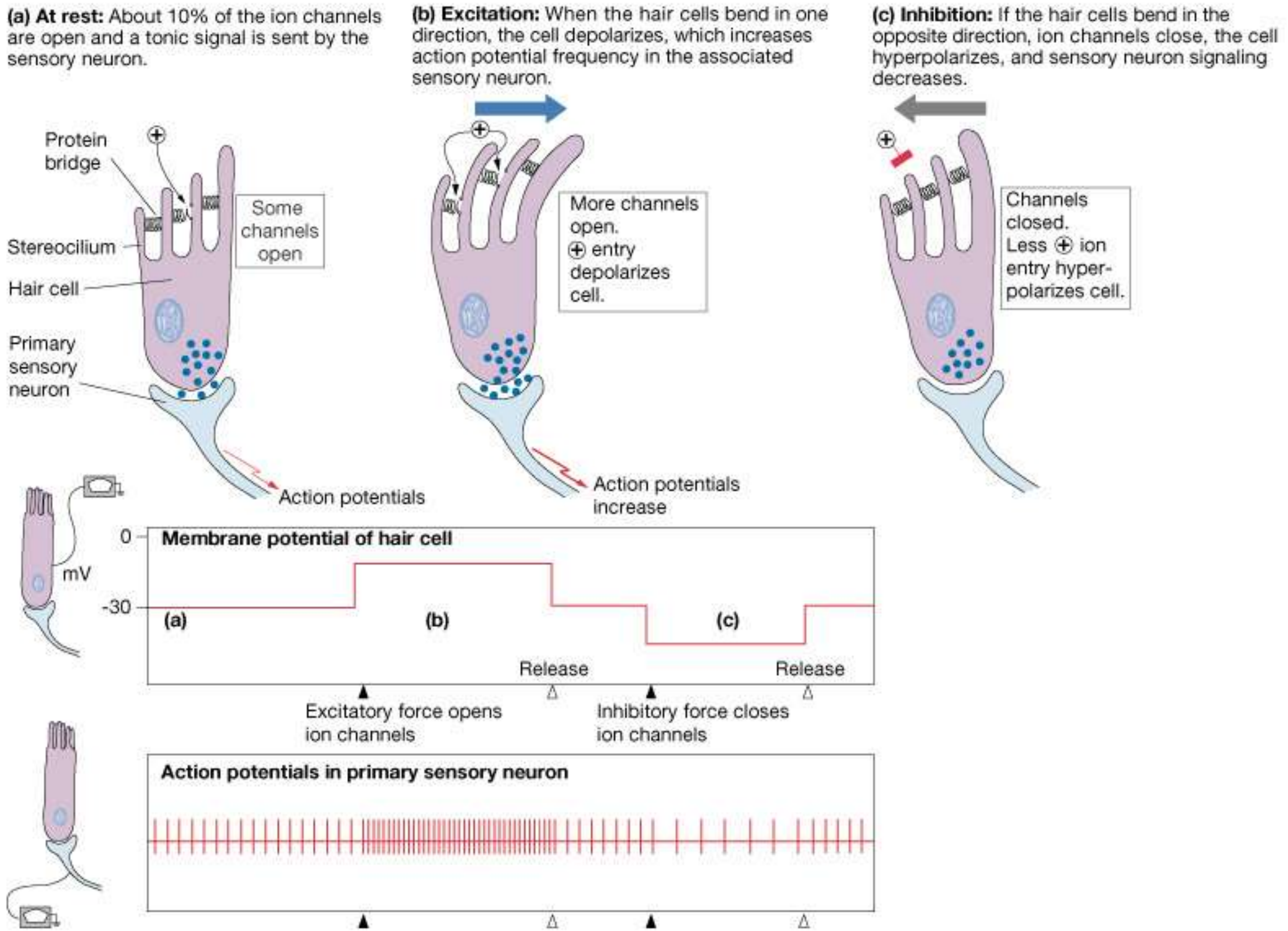


FIGURE 13–6 Schematic representation of the role of tip links in the responses of hair cells. When a stereocilium is pushed toward a taller stereocilium, the tip line is stretched and opens an ion channel in its taller neighbor. The channel next is presumably moved down the taller stereocilium by a molecular motor, so the tension on the tip link is released. When the hairs return to the resting position, the motor moves back up the stereocilium. (Modified from Kandel ER, Schwartz JH, Jessel TM [editors]: *Principles of Neuroscience*, 4th ed. McGraw-Hill, 2000.)

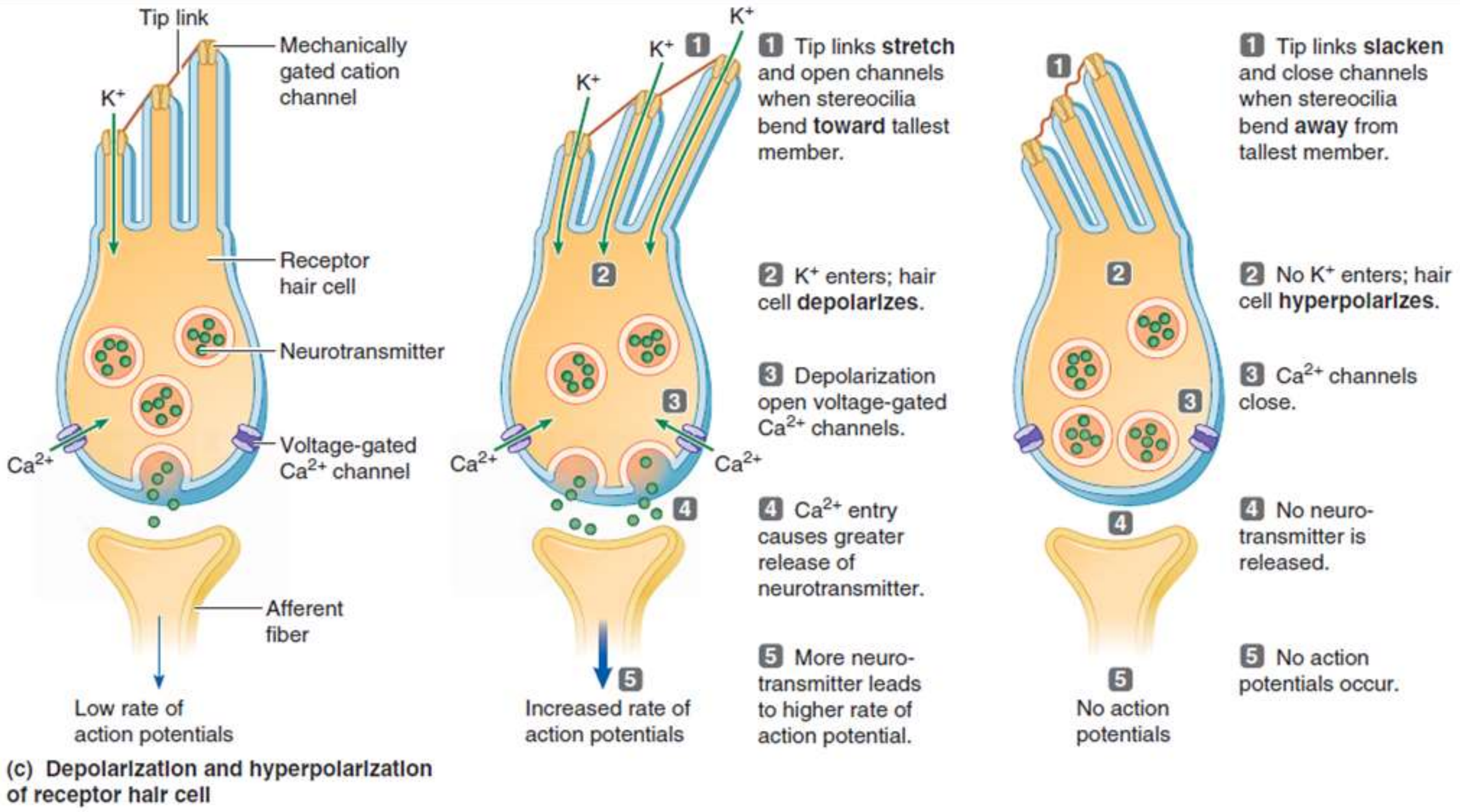

Resting potential
Ca2+
K+
Myosin

TRANSDUKSI SUARA

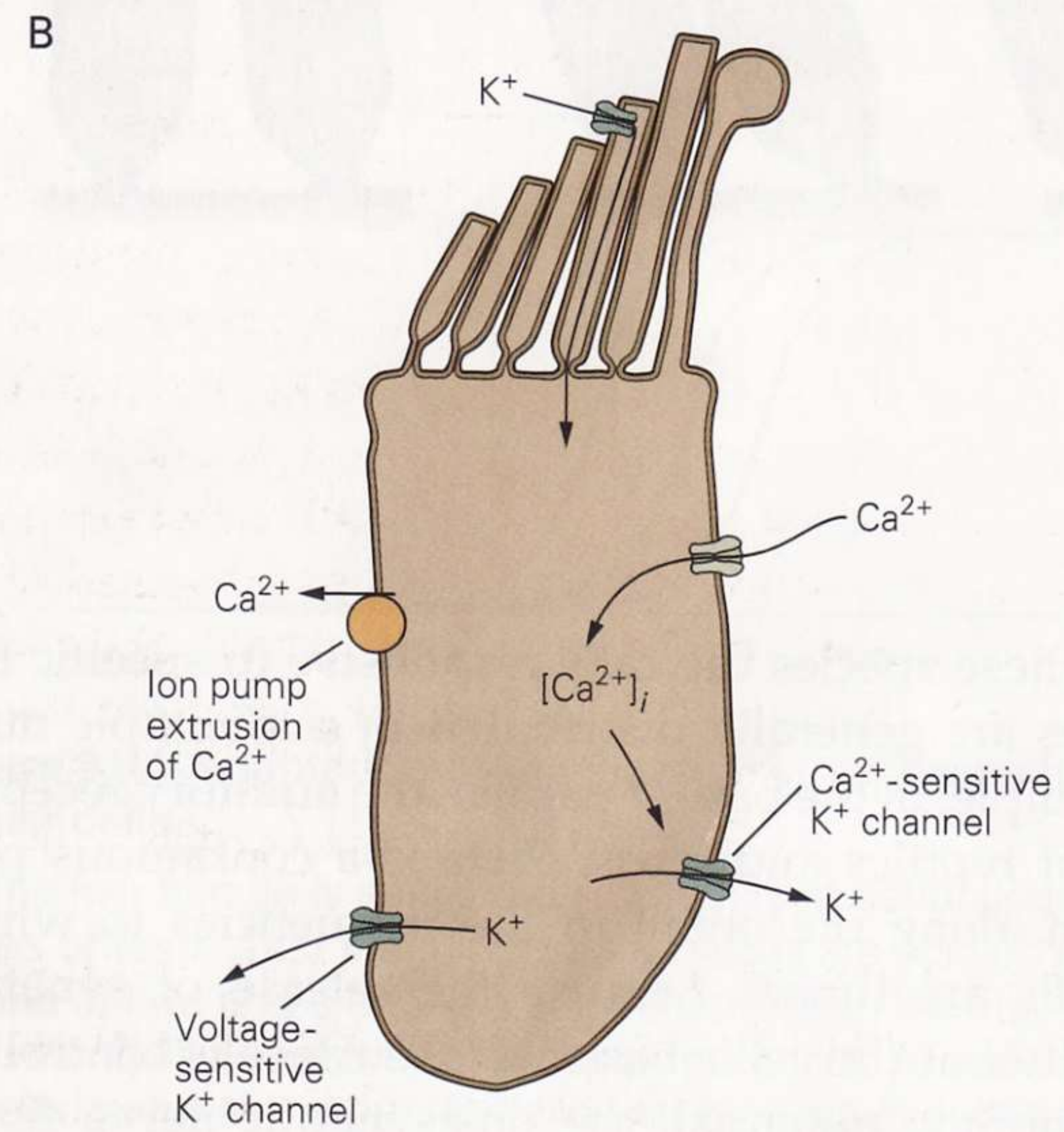
- Masuknya kalium ke sel-sel rambut depolarisasi mengaktivasi *voltage-gated calcium channels* masuknya kalsium ke dalam sel-sel rambut penglepasan neurotransmitter (glutamat) mengaktivasi serat ganglion spiralis pada post-sinaptik sel-sel rambut
- Pada sel-sel rambut: masuknya kalium depolarisasi tingginya konsentrasi kalium pada endolimfe



(a) At rest: About 10% of the ion channels are open and a tonic signal is sent by the sensory neuron.
(b) Excitation: When the hair cells bend in one direction, the cell depolarizes, which increases action potential frequency in the associated sensory neuron.
(c) Inhibition: If the hair cells bend in the opposite direction, ion channels close, the cell hyperpolarizes, and sensory neuron signaling decreases.
Protein bridge
Stereocilium
Hair cell
Primary sensory neuron
Some channels open
Action potentials
More channels open.
⊕ entry depolarizes cell.
Action potentials increase
Channels closed.
Less ⊕ ion entry hyper-polarizes cell.
mV
0
-30
Membrane potential of hair cell
(a)
(b)
(c)
Release
Release
Excitatory force opens ion channels
Inhibitory force closes ion channels
Action potentials in primary sensory neuron



● **FIGURE 6-38 The role of stereocilia in sound transduction.**


B
K+
Ca2+
Ca2+
Ion pump extrusion of Ca2+
[Ca2+]i
Ca2+-sensitive K+ channel
K+
K+
Voltage-sensitive K+ channel