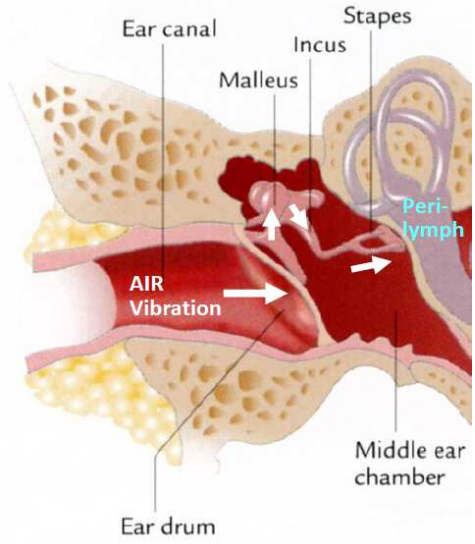
L9 Audition

A. Functions of the Auditory Periphery

1. External Ear

- **External ear** includes the auricles and the external auditory meatus
- Functions:
  - Collection of sound
  - Localization of sound
  - Modification of sound

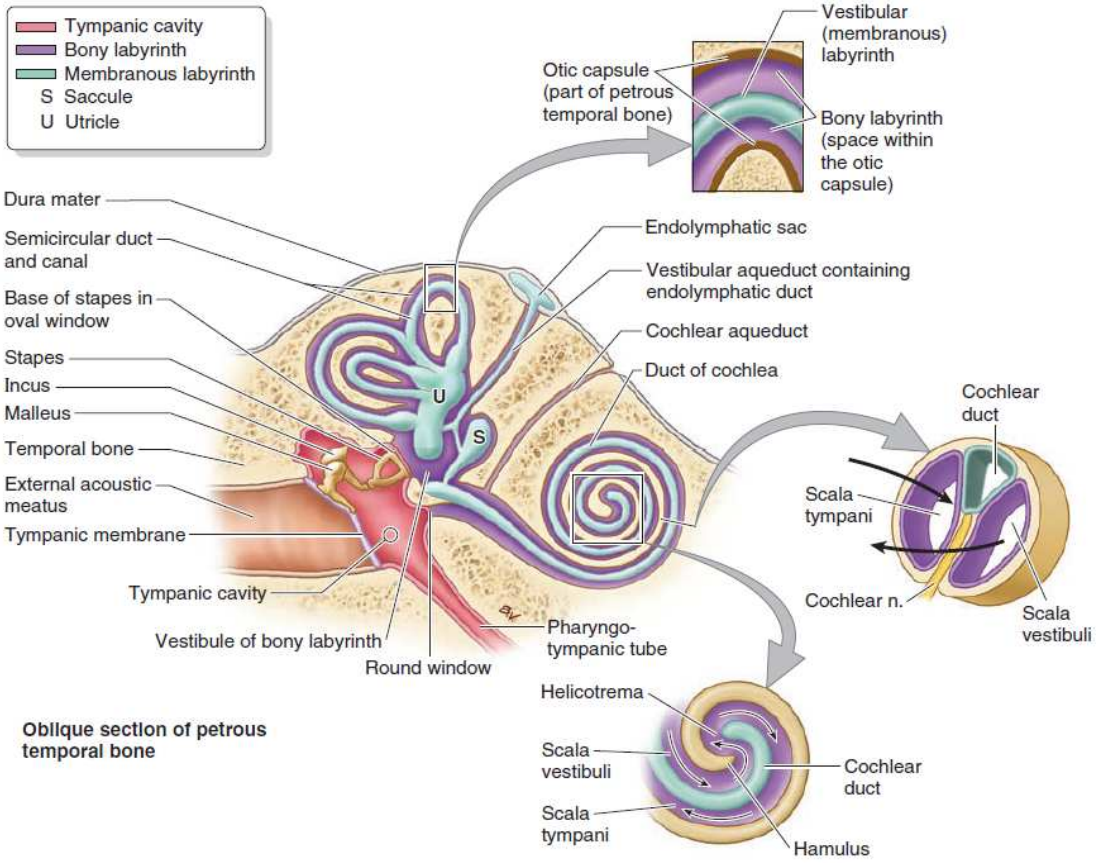


2. Middle Ear

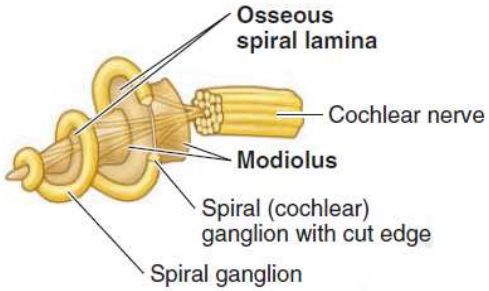
- Three **ossicles** transmit vibrations
  - Origin: air vibration at **tympanic membrane**
  - Target: fluid vibration at **fenestra vestibuli**
- Two important functions besides transmission:
  - **Impedance matching**
  - **Sound attenuation**
- **Impedance matching**:
  - **Impedance**: resistance posed by a medium to the transmission of wave
  - Sound waves will be reflected at medium boundaries if there is a large difference in impedance
    → impedance matching critical for efficient sound transmission
  - Fluid impedance >> air impedance
    → reflects need for impedance matching
  - Achieved by magnifying the vibration to match the impedance difference
    → Area ratio between large **tympanic membrane** and small **fenestra vestibuli**
    → Levering action of ossicles
- Sound attenuation by **middle ear muscle reflex**
  - **Stapedius** and **tensor tympani** contraction dampens vibration of ossicles
  - Activated during:
    → Exposure to loud sounds
    → Prior to vocalization (i.e. talking)
  - Importance:
    → Attenuates low frequency (selective)
    → Protects inner ear
    → Improves speech discrimination in noise

3. Inner Ear

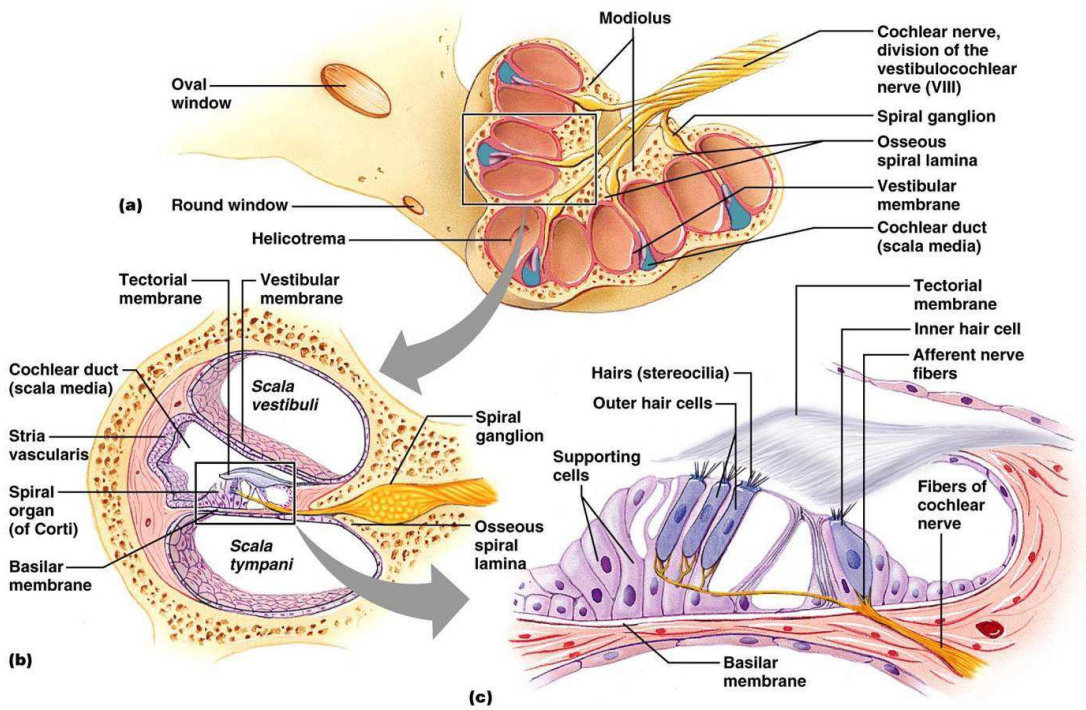
a. Relevant Anatomy of Inner Ear



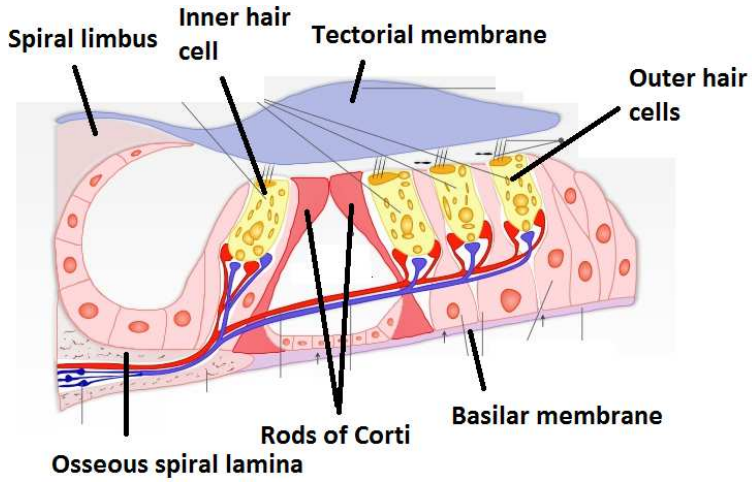
- **Inner ear** consists of:
  - **Bony labyrinth**: a series of cavities and bony canals in the petrous temporal bone
  - **Membranous labyrinth**: a series of **endolymph-filled** sacs and ducts suspended within the **perilymph-filled** bony labyrinth

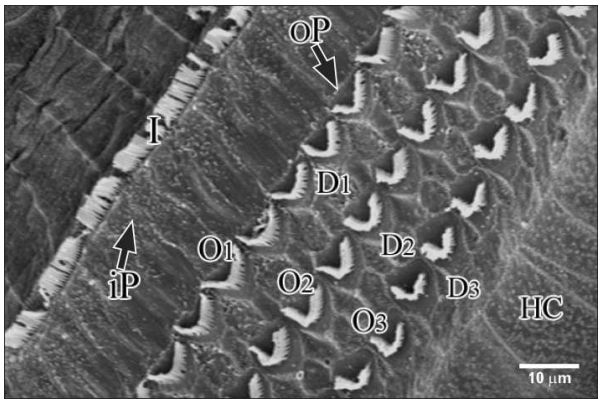


- **Cochlea**: shell-shaped cavity of bony labyrinth
  - **Spiral canal** makes 2.5 turns around **modiolus** (bony core)
  - **Modiolus** contains nerve fibres (**spiral ganglion**) and blood vessels
  - **Cochlear duct (scala media)**: endolymph-filled part of membranous labyrinth suspended in the middle of the **spiral canal** of cochlea
- **Spiral canal** of cochlea divided into:
  - **Scala vestibuli** (perilymph) connected to the **fenestra vestibuli**
  - **Scala media** containing the **spiral organ of Corti** for sound detection
  - **Scala tympani** (perilymph) connected to **fenestra cochleae**
- **Scala vestibuli** and **scala tympani** are connected at the apex of cochlea at **helicotrema**



- **Cochlear duct**:
  - Roof formed by <u>thin</u> **Reissner's (vestibular) membrane**
  - Floor formed by **spiral organ of Corti**
- **Spiral organ of Corti**:
  - Lies on the tough **basilar membrane**
  - Three rows of **outer hair cells** and one row of **inner hair cells** lie on basilar membrane
  - **Rods of Corti** separate the two types of hair cells
  - **Spiral limbus**: expanded periosteum of the upper plate of **osseous spiral lamina**
  - **Tectorial membrane**: gelatinous membrane attaching to the spiral limbus in which the tips of hairs of the hair cells are embedded in

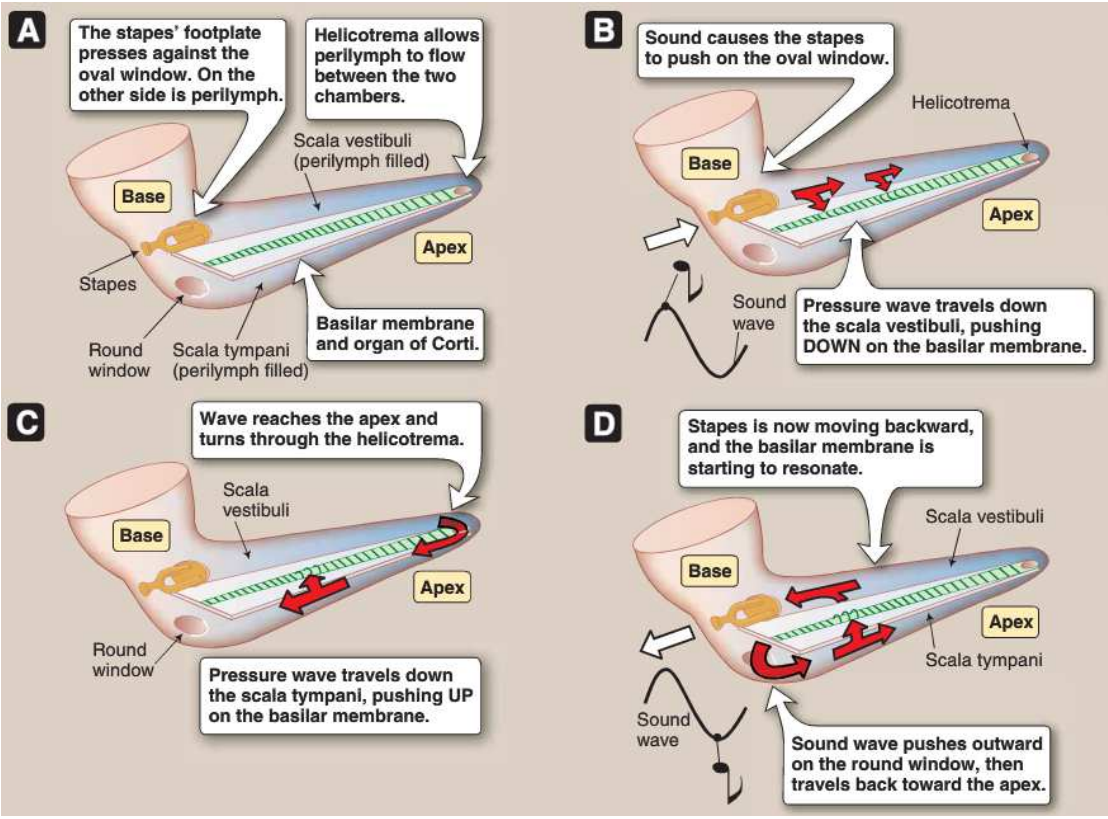




b. Sensory Transduction

- **Sensory transduction**: conversion of external sensory signal into electrical signal in nerves
  - Modality-specific

i. Mechanical Events



- Note that as the **Reissner's membrane** is thin, functionally the **scala vestibuli** and **scala media** acts as <u>one</u> canal
- Process:

(1) Sound wave pushes against the **oval window**
→ movement of perilymph in **scala vestibuli**;

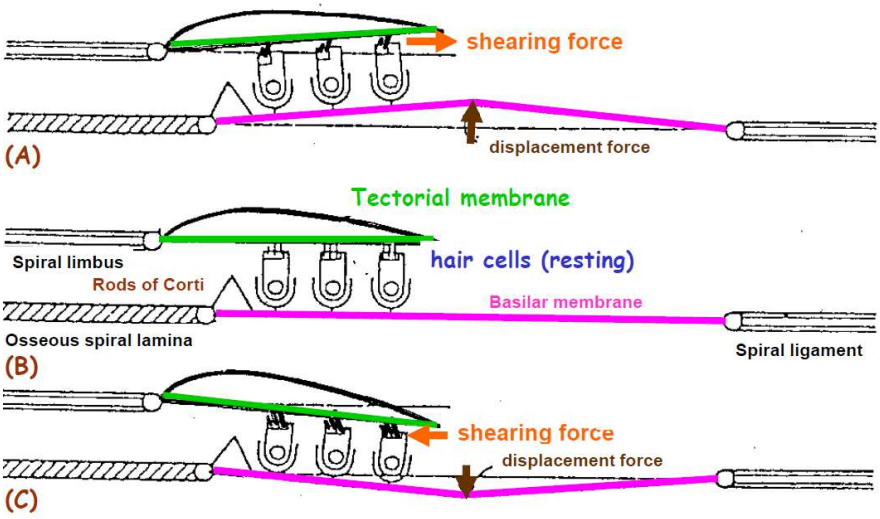
(2) High pressure in scala vestibuli perilymph (and thus endolymph) pushes the **basilar membrane** <u>down</u>;

(3) Perilymph movement propagated from **scala vestibuli** to **scala tympani** via the **helicotrema**;

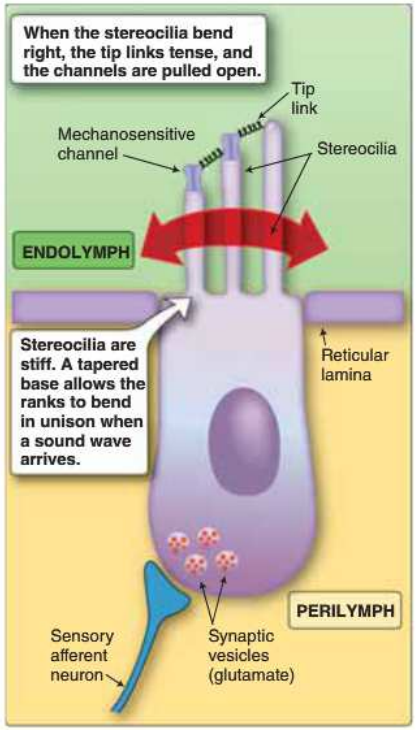
(4) High pressure in scala tympani perilymph pushes the **basilar membrane** <u>up</u>;

(5) Pressure wave reflected by round window and produces **resonance** in the **perilymph** of scala vestibuli and tympani;

(6) **Basilar membrane** <u>resonates</u> due to sound wave propagation in the perilymph.



- Note how the **stereocilia (hairs)** of **hair cells** are embedded in the gelatinous **tectorial membrane** overlying the hair cells
- Displacement of **basilar membrane** is converted into **shearing force** on stereocilia by this arrangement (see figure above)
  - □ Upward displacement
    → hair bundle pushed towards the tallest stereocilia

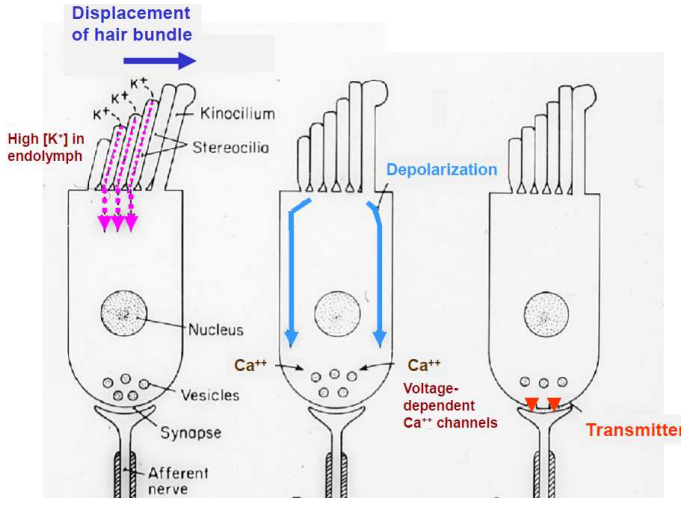


ii. Cellular Events

- **Mechanosensitive K^+ channel** located on the tip of stereocilia
- **Tip link**: fine elastic protein strands joining the channels
- When hair bundle displaced towards the tallest cilia, difference in lengths of stereocilia means that the **tip links** will tense
  → opening of **mechanosensitive K^+ channel**
- Note that **endolymph** is very high in K^+ (different to extracellular fluid elsewhere in body):

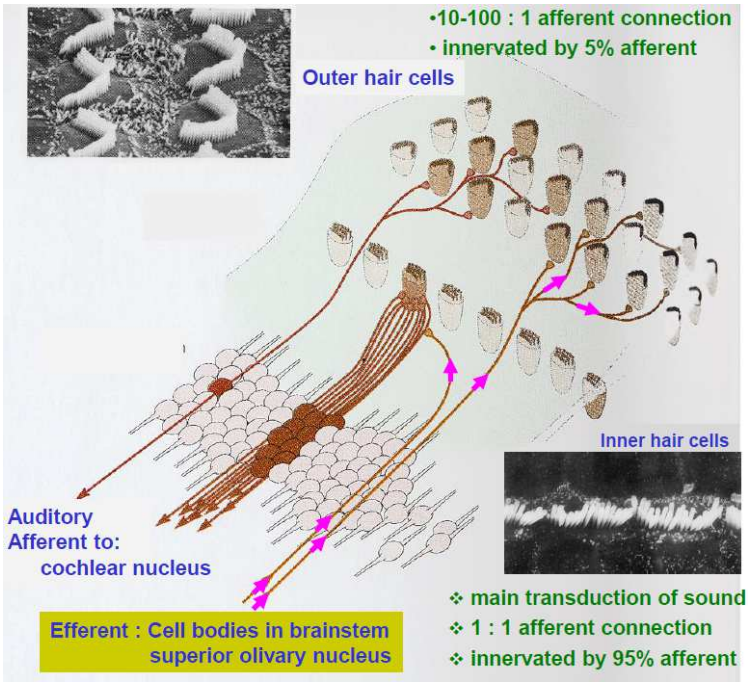
$$\text{Reversal potential } E_K = \frac{RT}{zF} \ln \frac{[K^+]_{out}}{[K^+]_{in}}$$

With $[K^+]_{out} >> [K^+]_{in}$,
This means that E_K is now positive.
$\uparrow K^+$ permeability tends to move the membrane potential towards E_K
i.e. depolarization ensues
Depolarization spreads (as **graded receptor potential**) to its base → voltage-dependent Ca^{2+} channels open → Ca^{2+} entry → signal transduction for the release of neurotransmitters.
Graded **generator potential** generated postsynaptically at afferent nerve ending
→ triggers **action potential** along its axon in the auditory nerve.



iii. Innervation of Hair Cells

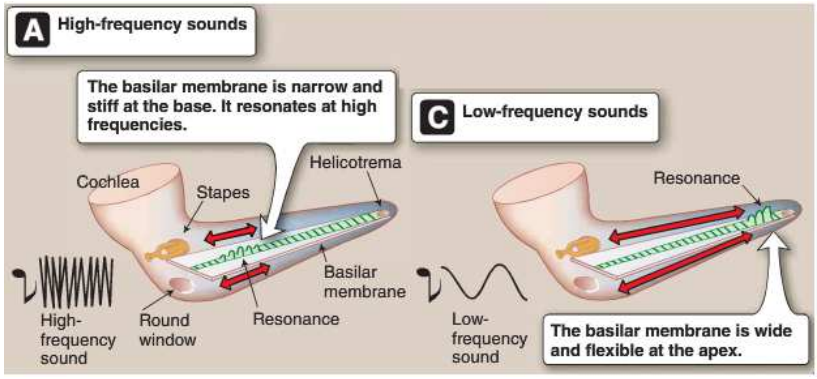
- **Outer hair cells**:
  - Modification of sound
  - 10-100:1 afferent connection
  - Innervated only by 5% of afferent fibres
- **Inner hair cells**:
  - Main transducer of sound
  - 1:1 afferent connection
  - Innervated by 95% of afferent fibres
- Central connections:
  - Afferent: **cochlear nucleus**
  - Efferent: **superior olivary nucleus**

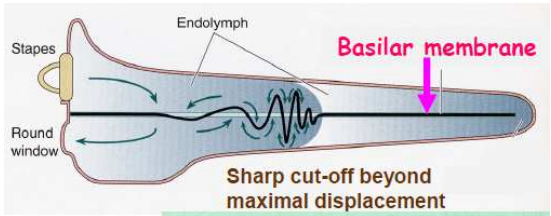


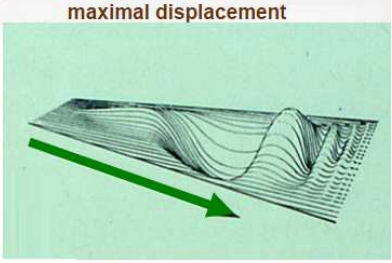
c. Sound Processing in Inner Ear

i. Processing of Sound Frequency

- **Tonotopic pattern (place-coding)**: linear array of inner hair cells along length of cochlea corresponds to a linear profile of frequencies
- Physical properties of **basilar membrane** varies along the length of cochlear duct
- At the base,
  - Basilar membrane narrow and stiff
  - Stereocilia short
  - Resonates at high frequencies
- At the apex,
  - Basilar membrane wide and floppy
  - Stereocilia long
  - Resonates at low frequencies
- Frequency of incoming tone determines the peak position of travelling wave along the basilar membrane
- Wave subsides rapidly beyond maximal displacement towards the apex,
  i.e. wave exhibits sharp cut-off towards apex (reason unknown)

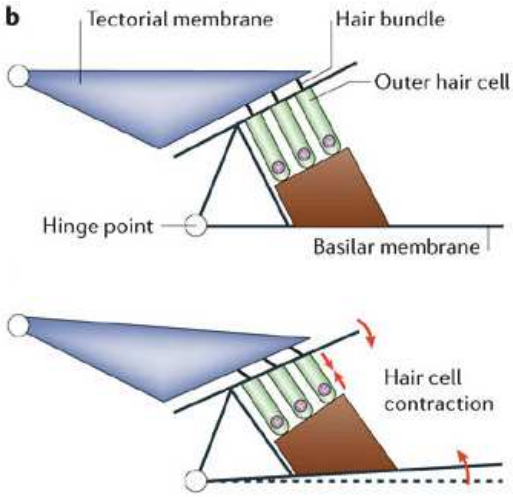




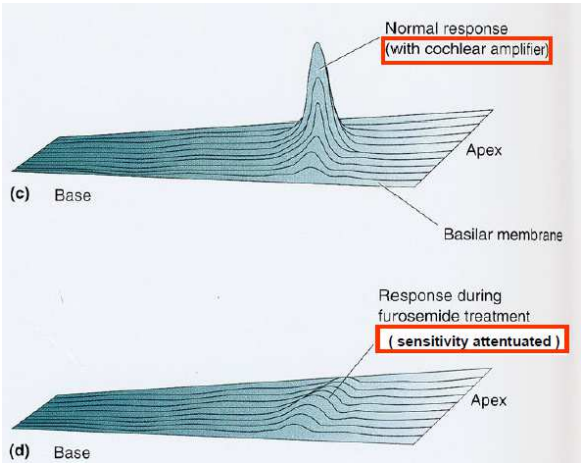


ii. Processing of Sound Intensity

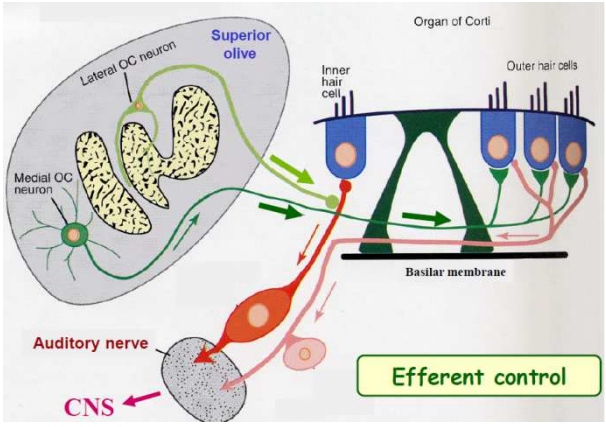
- Sound amplitude coded as amplitude of receptor potential and spike frequencies
- Loud sound
  → ↑basilar membrane displacement
  → prolonged opening of channels
  → ↑hair cell output
- This is aided by:
  - Mechanical layout of organ of Corti
    → amplifies small vibrations
  - **Cochlear amplifier** action by **outer hair cells**



- Action of **outer hair cells** as **cochlear amplifier**
  - Note that the OHCs also depolarize in response to sound waves that deflect the **basilar membrane** upwards
  - In addition to the sensory transduction to auditory nerve, it also results in contractions of motor proteins in the soma
    → shortening of OHCs
  - This draws the basilar membrane further upward → amplification of basilar membrane vibrations



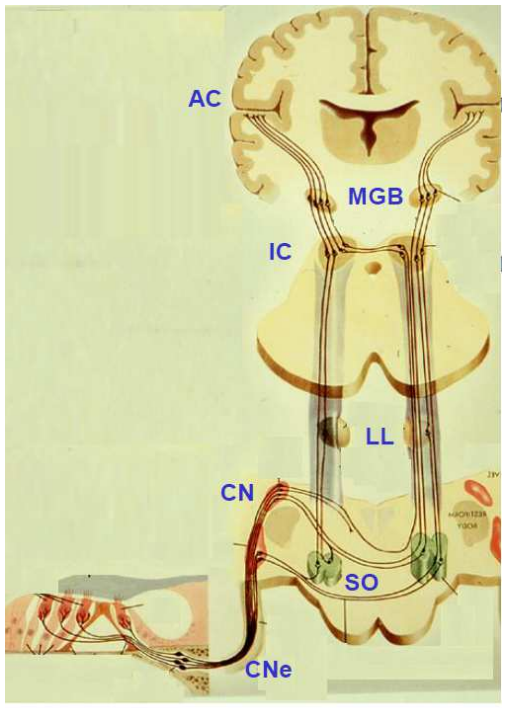
- Action of **cochlear amplifier** controlled by efferent innervation via **descending auditory pathway** from **superior olive**
  - Significance: alters sensitivity of IHC to different sounds
  - **Cocktail party phenomenon**: weak auditory signals can be detected against strong background noise (via selective filtering of noise)
  - Essential for sophisticated speech in humans



**Otoacoustic emissions*: *cochlear amplifier can actually function as a generator of sounds. Some studies have found that by electrically stimulating the auditory nerve, a sound can be heard just outside the external ear, presumably due to efferent action on OHCs.*

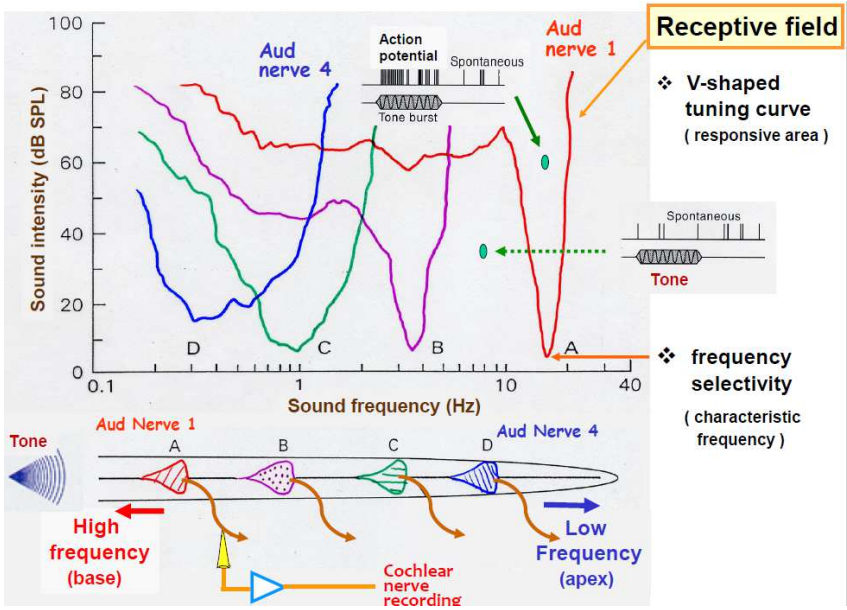
***Furosemide** treatment stops K^+ recycling into endolymph. This impairs the sensory transduction in OHCs and greatly reduces the action of cochlear amplifier. A drastic drop in basilar membrane vibration is seen, as shown in the above diagram.*

B. Functions of Central Auditory Pathways



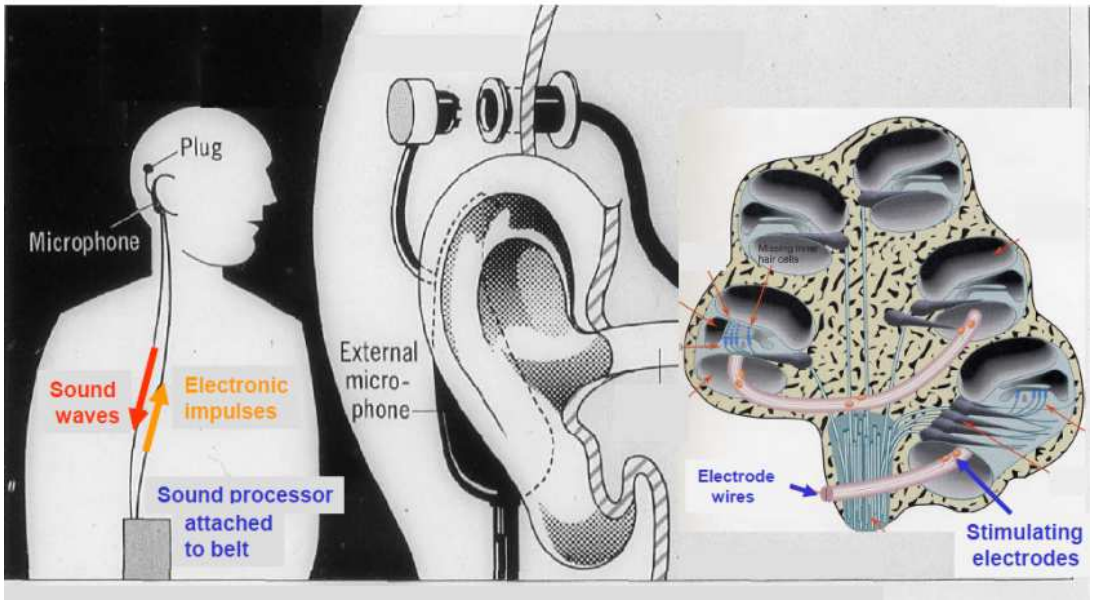
- Seven 'stops':
  - **Cochlear nerve** as part of CN VIII
  - **Cochlear nucleus** in pontomedullary junction
  - **Superior olive** in medulla
  - **Lateral lemniscus** in brainstem
  - **Inferior colliculi** in midbrain tectum
  - **Medial geniculate body** in posterior thalamus
  - **Auditory cortex** in superior temporal gyrus
- Anatomical characteristics:
  - **Tonotopic** projections
  - Bilateral networks with strong crossed connections
  - Expansion in cell population of inferior colliculus and cortex
  - Hierarchical organization

1. Functional Feature of Auditory Nerve

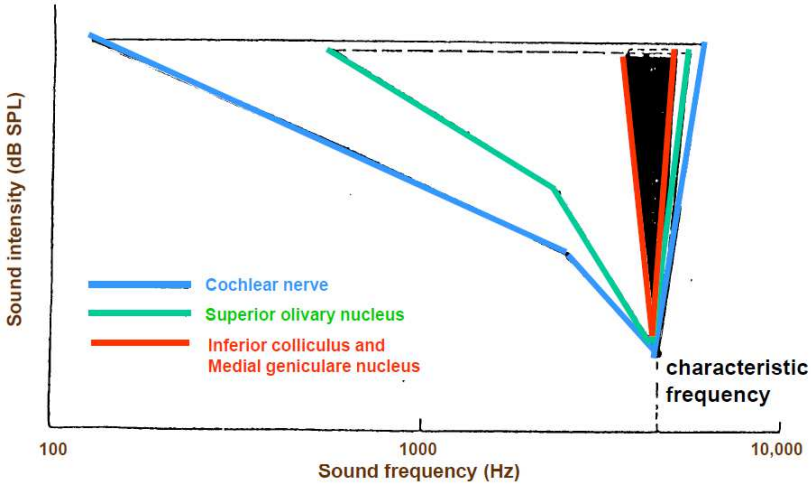


- **Receptive field** of single auditory nerve fibres described as the **V-shaped tuning curve**
  - Discrimination threshold plotted against frequency
  - Below curve
    → tonic activity only
  - Above curve
    → action potential
- Tip of curve: **characteristic frequency (CF)**
  - Signifies the locus of hair cell on basilar membrane with which auditory nerve innervates
- Nerves sharply tuned to exclude frequencies above characteristic frequency
- Significance: permits discrimination of very soft (near threshold) tones with slightly different frequencies
- **Presbycusis** (age-related hearing loss) has larger effect on high-frequency ranges
  - Loss of high frequency hair cells → **sensory loss**
  - Loss of cochlear neurones → **neural loss**

**Note that there are some tonic tension in the tip-links between stereocilia → resting basilar membrane will give spontaneous tonic activities.*

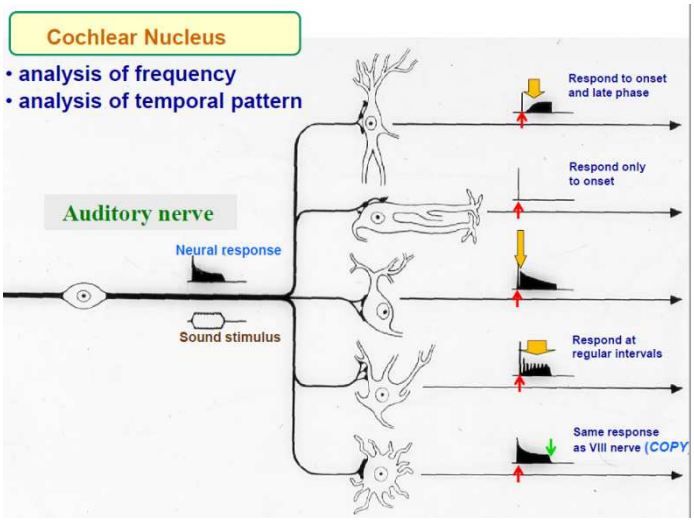


- Clinical relevance: **bionic ear**
  - Sensory transduction converts sound signals into electrical signals on the cochlear nerve
  - Cochlear problems (especially specific frequency defects) amenable by **bionic ear** installation
  - Can process sound signals into electrical signals
    → stimulation of cochlear nerve in accordance to sound signal pattern
  - Practically replaces the role of the spiral organ of Corti in sensory transduction
  - Problem: cost
- Note that the **V-shaped tuning curve** sharpens progressively along the ascending auditory pathway
  - ↑frequency discrimination up ascending pathway
  - Probably a result of **lateral inhibition**



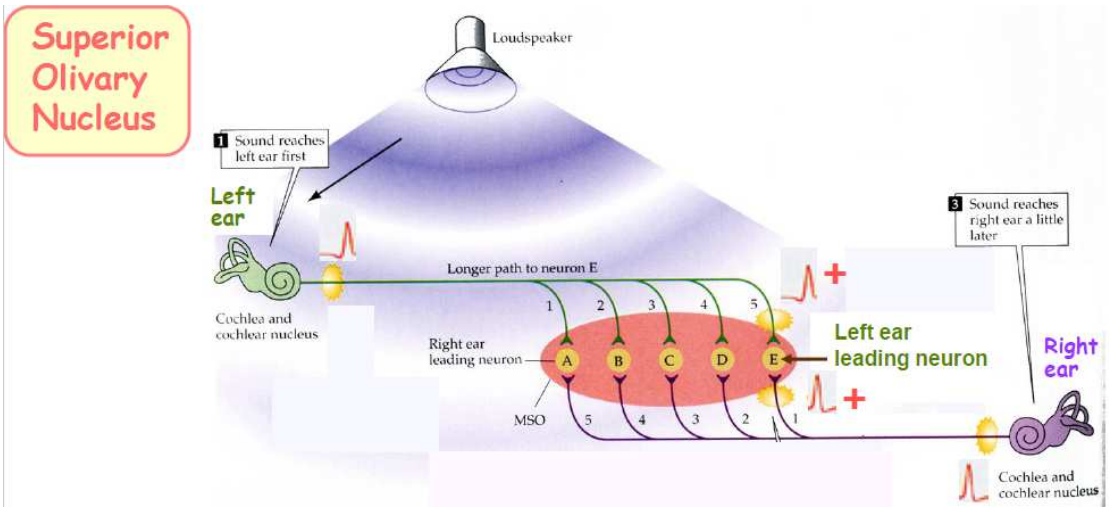
2. Functional Features of Lower Brainstem Centres

a. Cochlear Nucleus



- Function: analysis of frequency and intensity
- Many different types of cells inside cochlear nucleus
  - Each with specific functions
  - Arises from different patterns of synaptic connections with afferent fibres
  - Provides division of labour between different cells
  - Some produce the <u>same</u> response as CN VIII
    → act as 'backup' for comparison of signals

b. Superior Olive



- Function: gross differentiation of sound direction
  - Accurate localization of sound still relies on higher cortical centre
- Performs **basic binaural sound processing**
  - Compares <u>time</u> and <u>intensity</u> differences from two ears
  - Example: a sound source closer to left ear
    → Left ear receive a <u>stronger</u> and <u>earlier</u> signal
    → **Left ear leading neurone** with long path to left ear compared to right ear receives signals of equal intensities from left and right ear at the same time
    → Brain can therefore deduce that the sound source is closer to left ear

3. Functional Features of Midbrain Centre

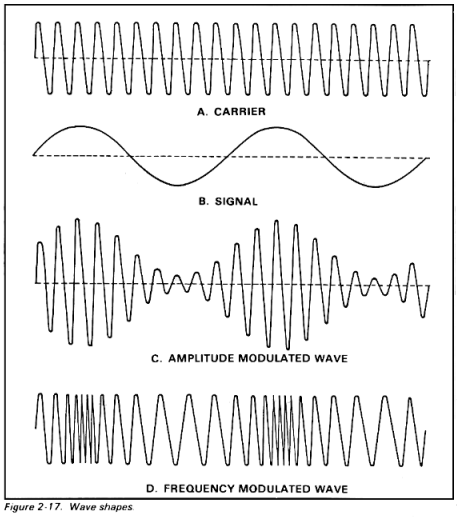


Figure 2-17. Wave shapes.

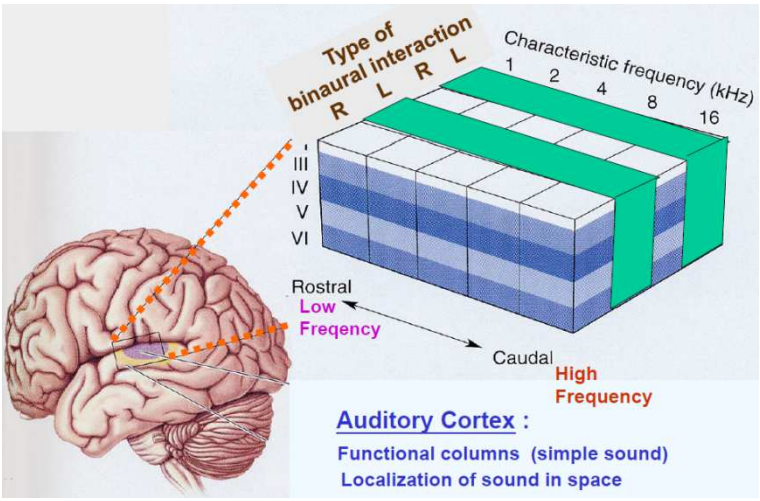
- Midbrain centre: **inferior colliculus**
- Detects in speech:
  - **Frequency modulation (FM)**: changes in frequency
  - **Amplitude modulation (AM)**: changes in amplitude
- Reflex centre for:
  - **Sound-orienting response** to <u>novel</u> sound
  - **Startle response** to <u>loud</u> sound
- Receives descending projection from auditory cortex
  → modulate ascending signals

4. Functional Features of Thalamic Centre

- Thalamic centre: **medial geniculate body**
- Functions:
  - Ascending relay to auditory cortex
  - Receives descending projection from auditory cortex
    → modulate ascending signals

5. Cortical Centres

- **Primary auditory cortex** in areas 41 and 42
  - Simple sounds: <u>functional columns</u> organized as a matrix of **isofrequency bands** and **binaural bands**
  - Accurate localization of sounds in space

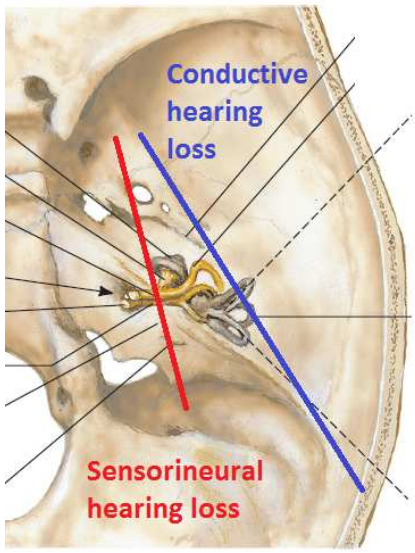


- Processing of complex sounds especially language:
  - **Wernicke's area**: area 22 in temporal lobe of dominant hemisphere
    → For <u>comprehension</u> of language
  - **Broca's area**: areas 44, 45 in frontal lobe of dominant hemisphere
    → For <u>production</u> of language

C. Clinical Relevance of Audition

1. Common Disability Associated with Hearing

- **Tinnitus**: ringing of ear
- **Hearing loss** divided into:
  - **Conductive hearing loss** caused by problems in auditory periphery
  - **Sensorineural hearing loss** caused by problems along central auditory pathway
  - Causes of hearing loss:
    - → Hereditary
    - → Ototoxicity
    - → Infection or tumour
    - → Extreme noise exposure
    - → **Temporal bone fracture** (from head trauma)



2. Auditory Tests

- Pure tone **audiometry**: measures hearing threshold of a conscious subject in terms of
  - **Intensity** as in decibel sound pressure level (dBSPL)
  - **Frequency** as in Hertz (Hz)
- **Brainstem auditory evoked response**:
  - Neural activity along auditory pathway evoked by a click sound
  - Assess hearing ability of subjects esp infants