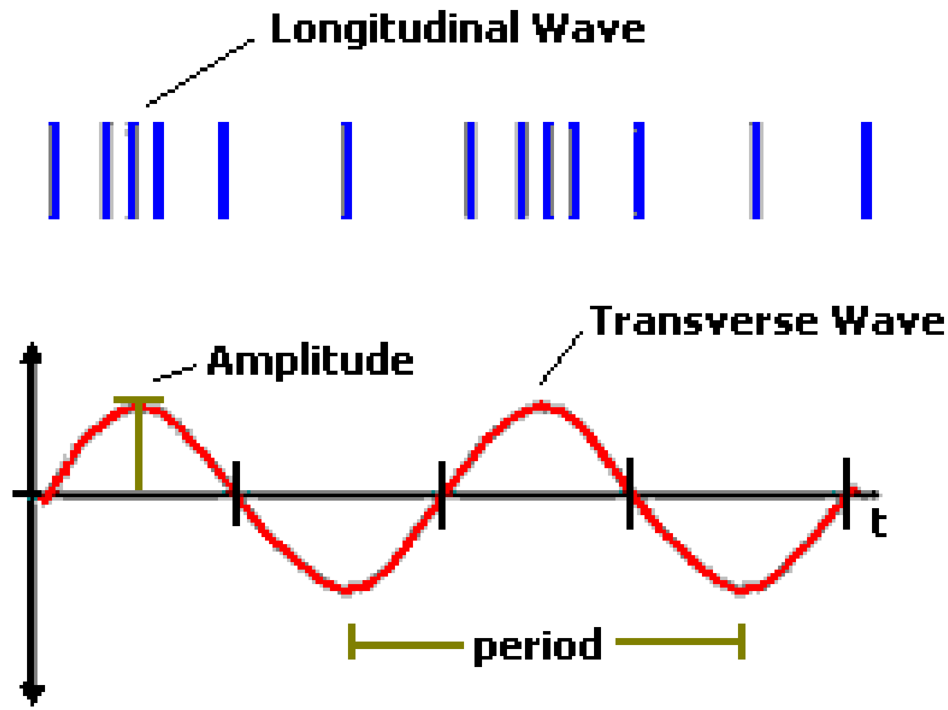
Auditory System

Slides adapted from
Rutgers University
(http://qneuro.rutgers.edu)
and
Imperial college
(http://www.doc.ic.ac.uk/~phwl/teaching/mm/Index.html)

The Nature of Sound (P. 149)

Sound as mechanical wave energy requires a medium such as air or water in which to move.



Sound: vibratory energy caused by movement of physical objects

- Rate of vibration is called **frequency**
  - What we hear is **pitch** (high or low)
  - We hear 20-20,000 Hz (cycles/sec)
- Size (intensity) of vibration is **amplitude**
  - What we experience is loudness
  - Measured in **decibels** (dB) (too loud too long = hearing loss)

Intensity

- **Doubling the ratio of signal intensities adds 3 dB as**

  log2 = 0.301

- **Halving the ratio of signal intensities subtracts 3 dB**
- **Multiplying the ratio by 10 adds 10 dB**

$$dB = 10 \log (Intensity_1/Intensity_2)$$

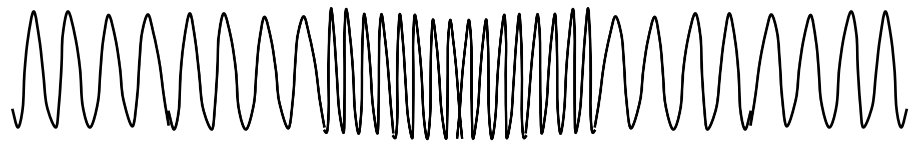
Frequency -

The number of sound pulses that travel past a fixed point within a second. A is a lower frequency sound than B. Unit is Hz.

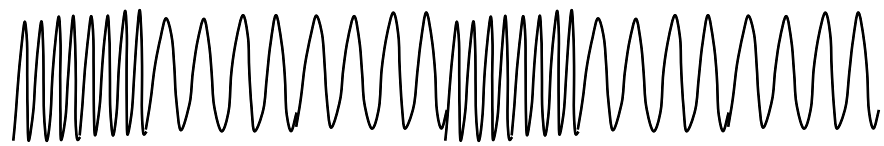
Speed of Sound -
How fast sound pulse travels. All sound travels at the same speed in a given medium
In air, the speed of sound is 344 m/S.

Pitch. This is **perception.** A high frequency sound is heard as a high pitch.

A

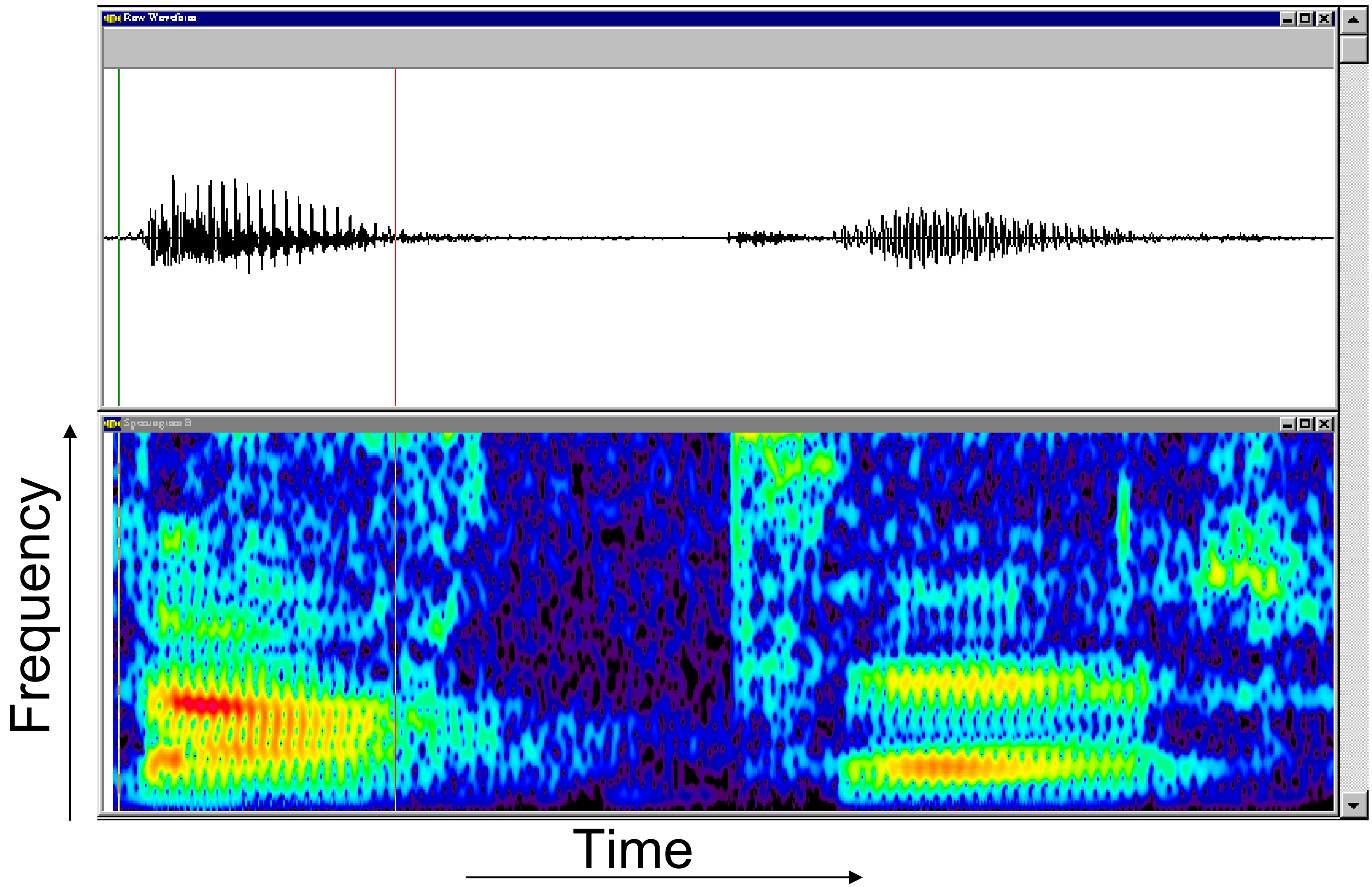


B



Species -	Frequency Range
Humans	20 - 20,000 Hz
Bats	100,000 Hz

Any sound can be broken down into component frequencies



The word “butter”

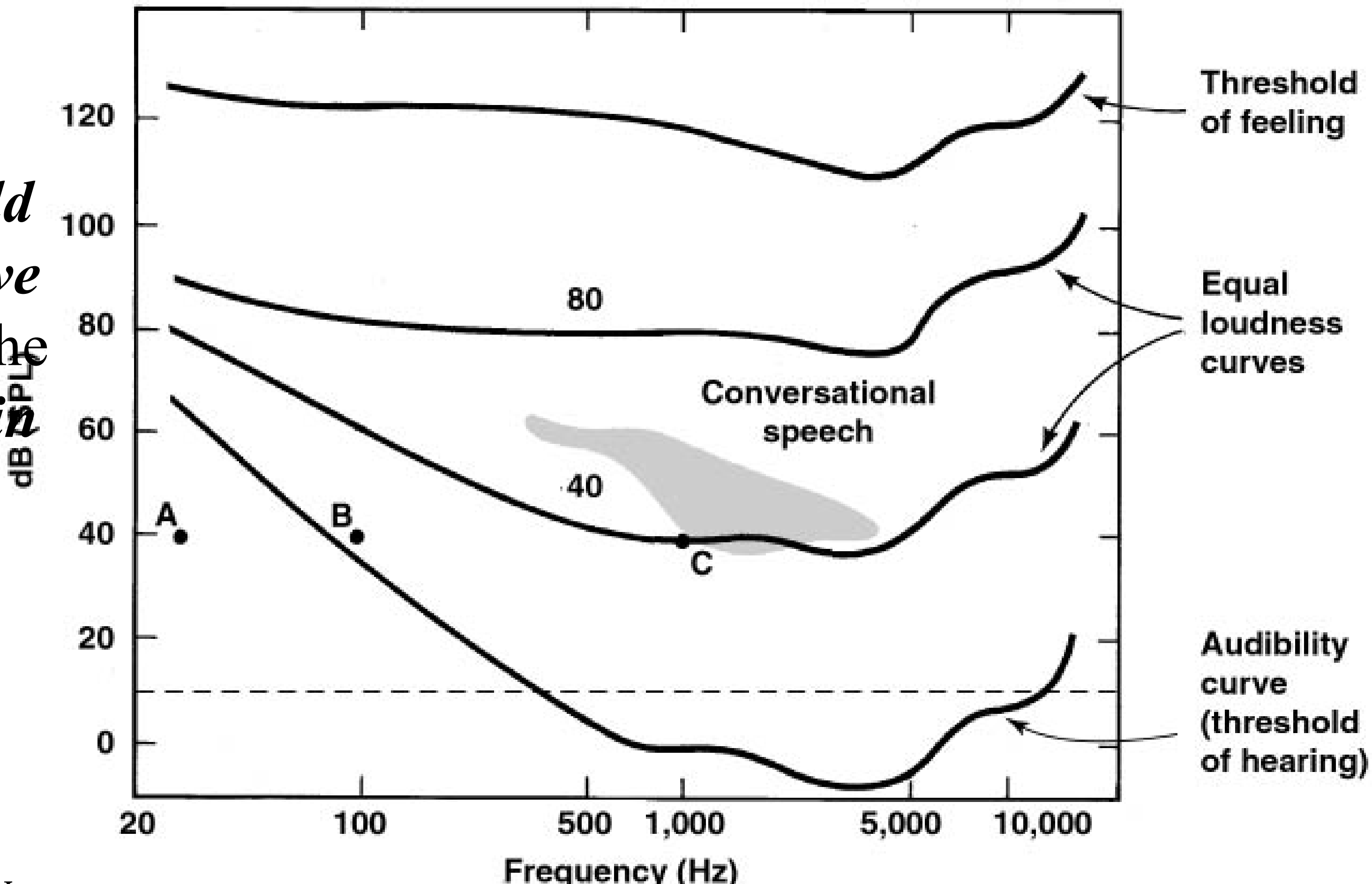
Auditory Response Area

Hearing occurs between the ***hearing threshold*** or ***audibility curve*** (at bottom) and the ***threshold for pain*** (at top).

Tones below the audibility curve cannot be heard.

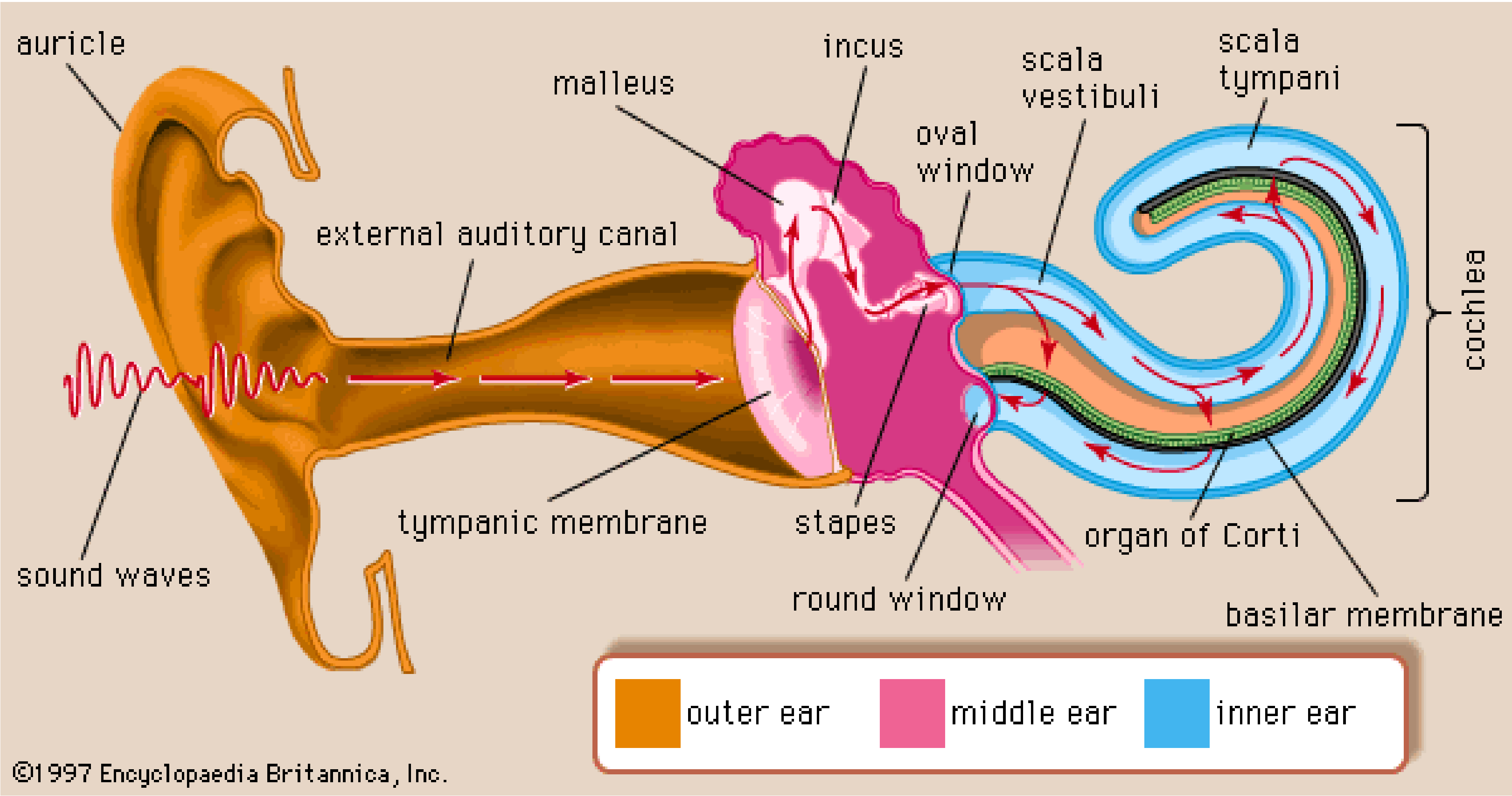
Note that a 10 dB tone of low or very high frequency cannot be heard.

intensity is not loudness



Equal Loudness curves indicate tones of different frequency that appear same in loudness to a 40 dB tone at 1000 Hz (see C)

The Ear


auricle
malleus
incus
scala vestibuli
scala tympani
oval window
external auditory canal
cochlea
tympanic membrane
stapes
organ of Corti
sound waves
round window
basilar membrane
outer ear
middle ear
inner ear
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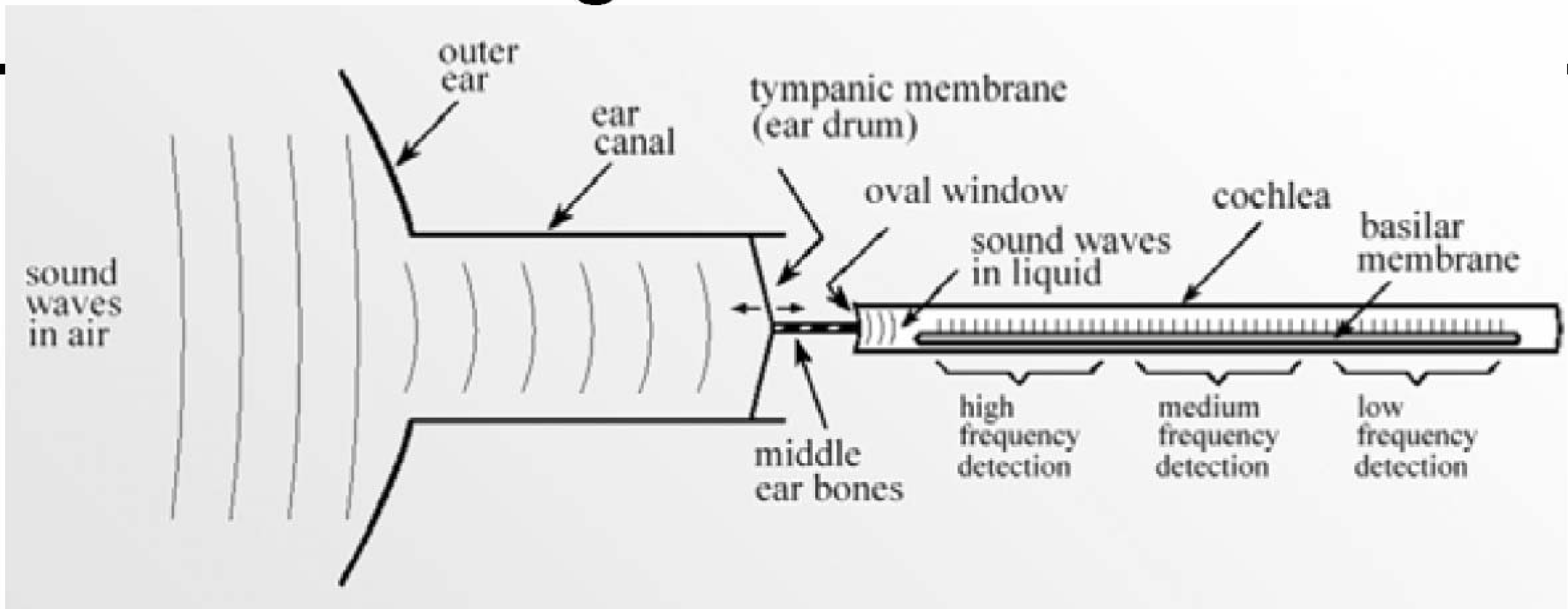
Human Hearing



The outer ear collects sound waves from the environment
⇒ ear drum => middle ear bones fluid filled cochlea
⇒ 12,000 nerve cells that form the cochlear nerve.
⇒ Each nerve cell only responds to a narrow range of audio frequencies, making the ear a frequency spectrum analyzer.

Structures of the ear

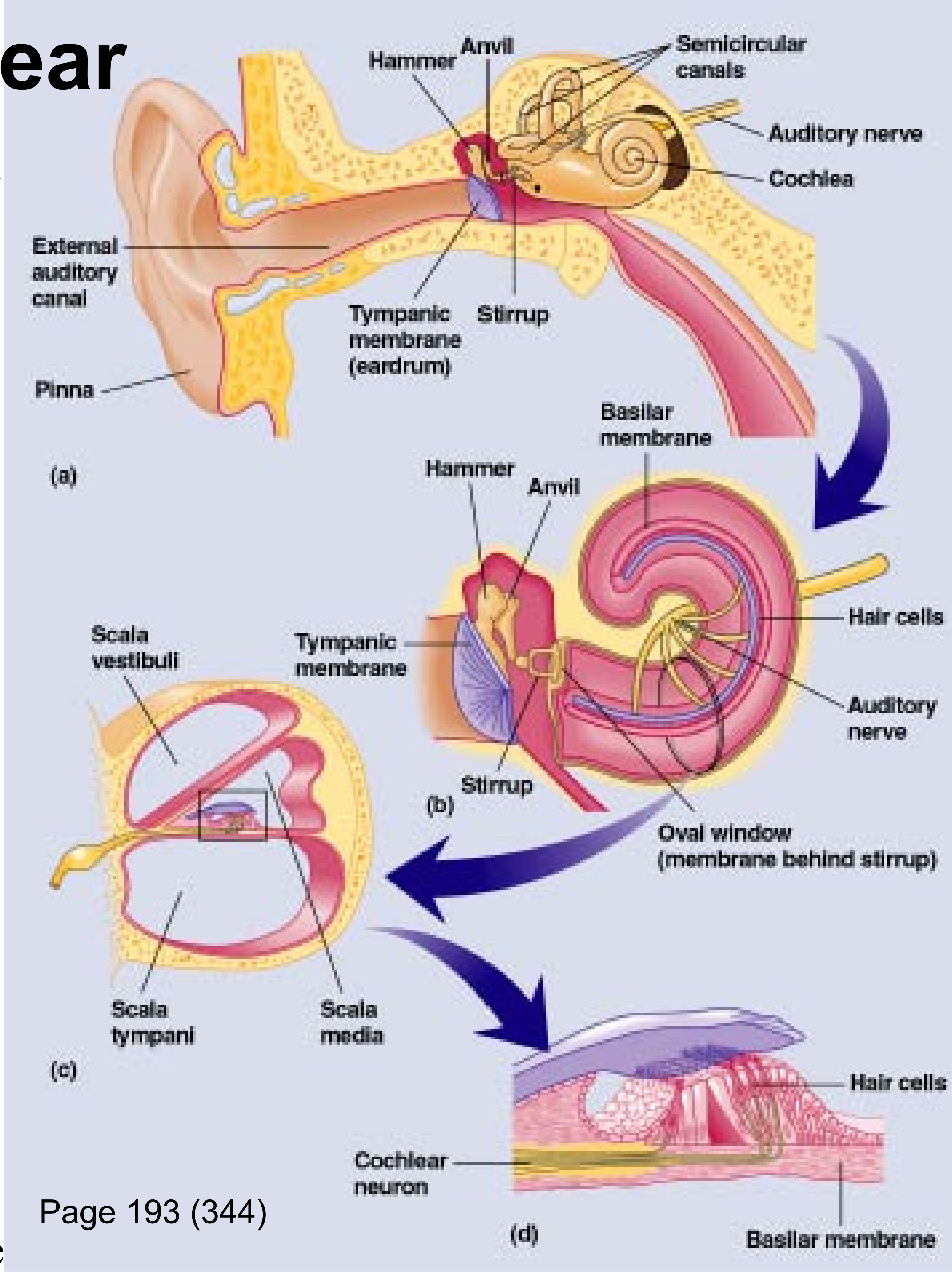
The ***pinnae*** help collect the sound, but are also somewhat directionally sensitive (much more so in dogs, bats and other animals)

The ear canal actually amplifies frequencies of 2000-5000 Hz due to ***resonance***.

The middle ear is filled with air through the ***Eustachian tubes*** which open in the throat.

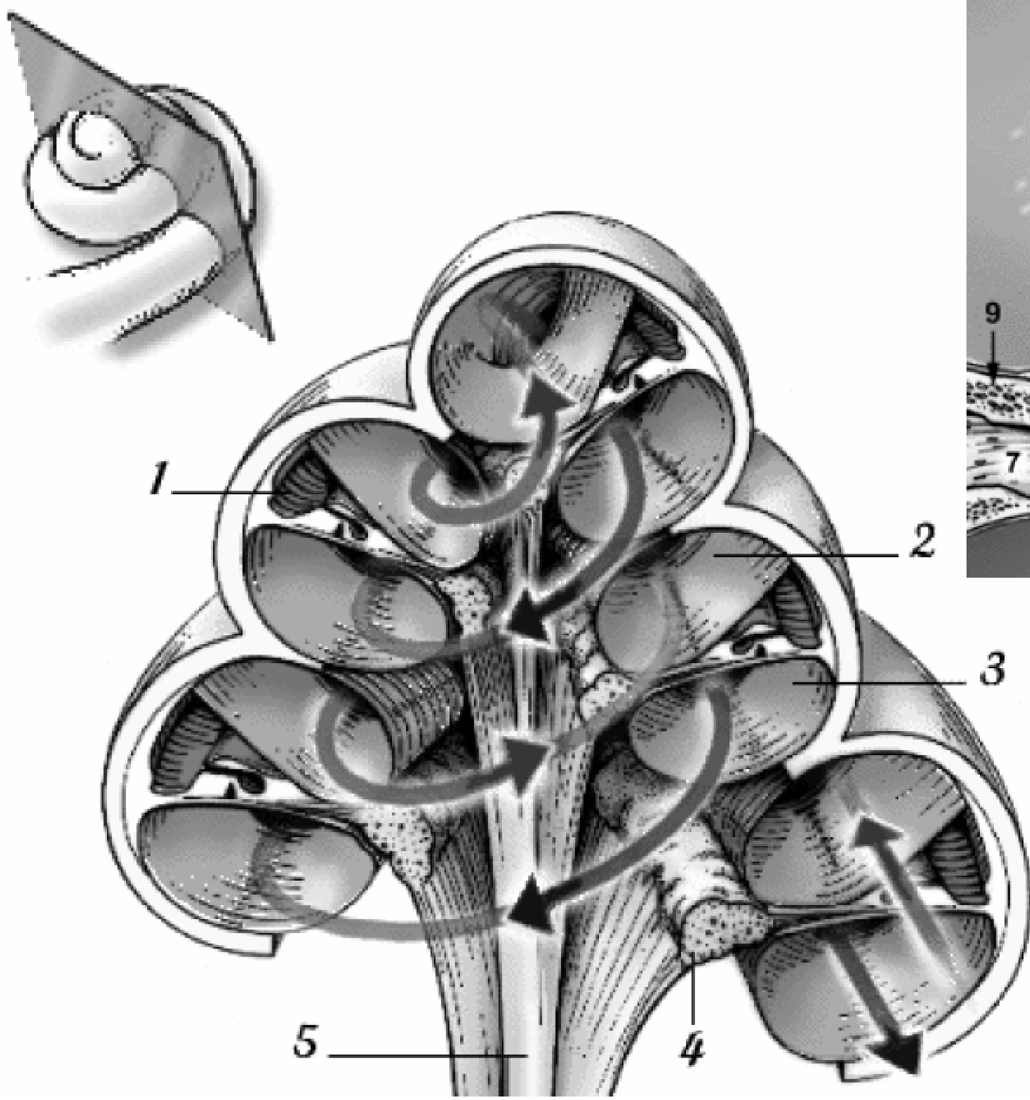
The ***ossicles*** of the middle ear amplify the pressure waves through lever action and by concentration (the oval window is 15x smaller than the eardrum.

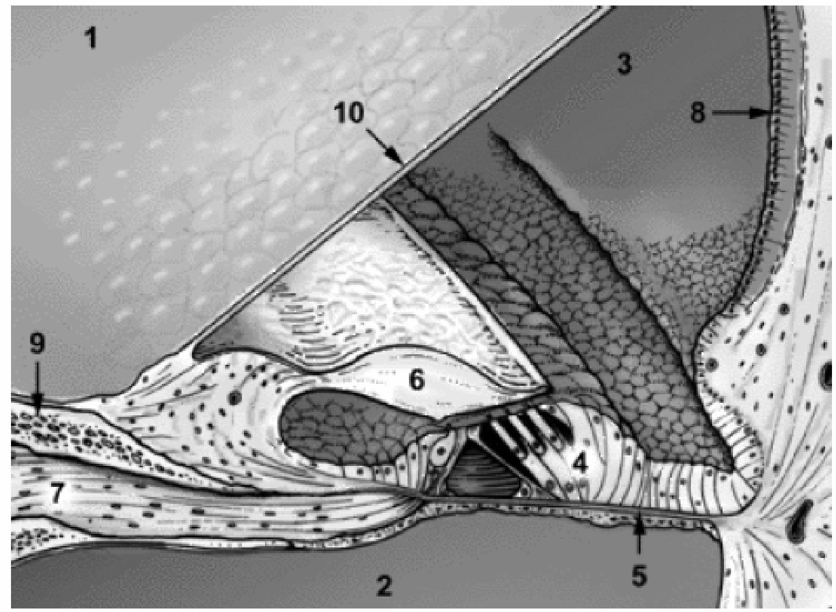
Tiny muscles on these bones reflex-ively contract in response to very high pressures, preventing cochlear damage



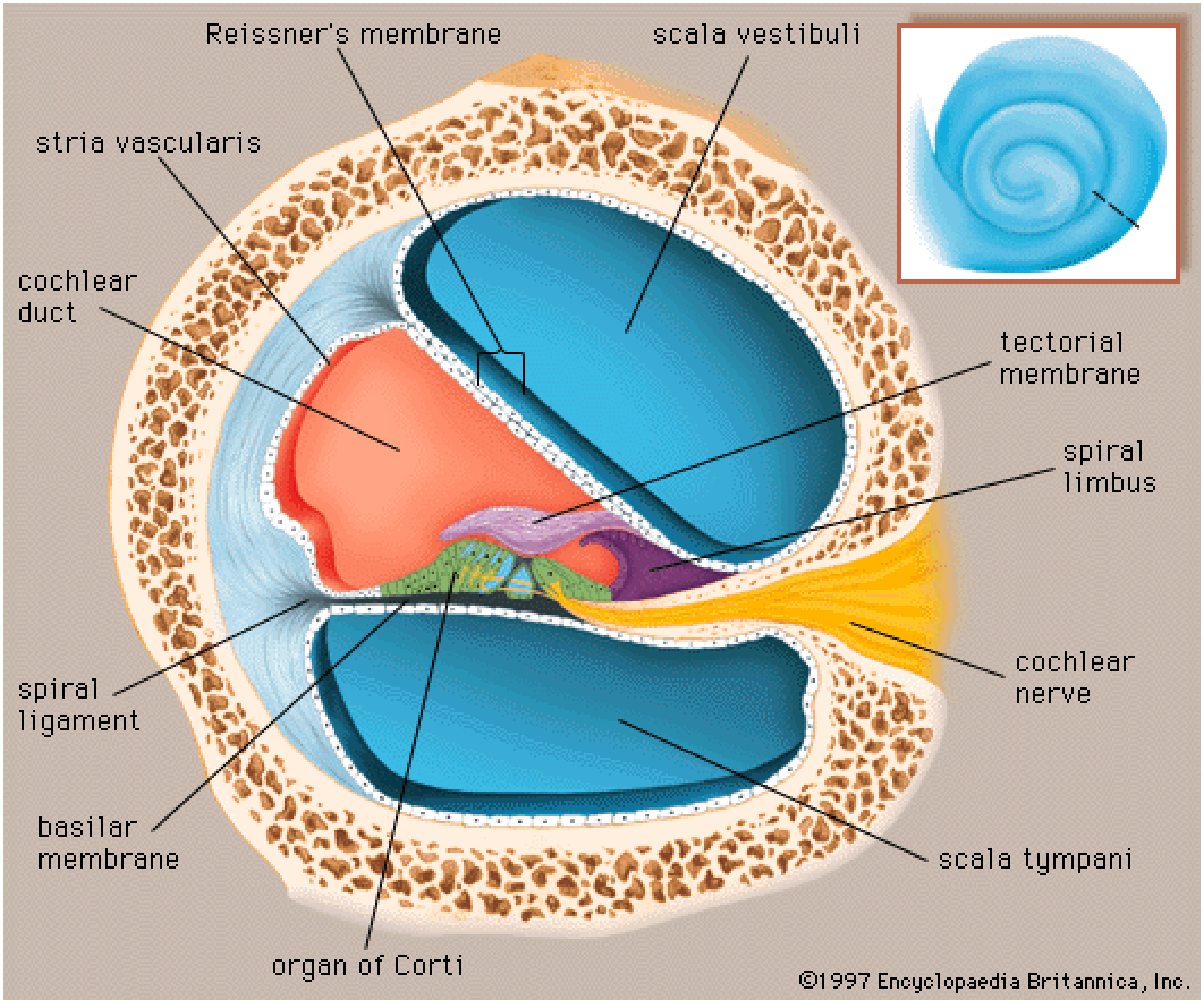
Page 193 (344)

Cochlea





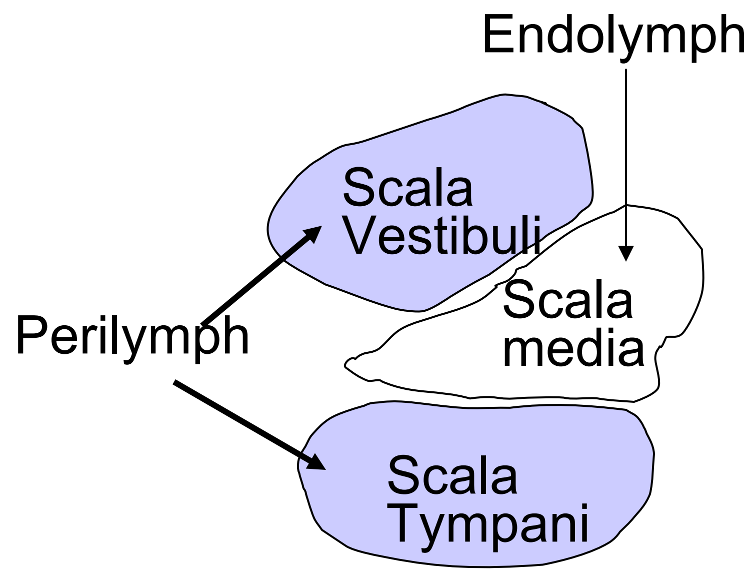
Inside the Cochlea



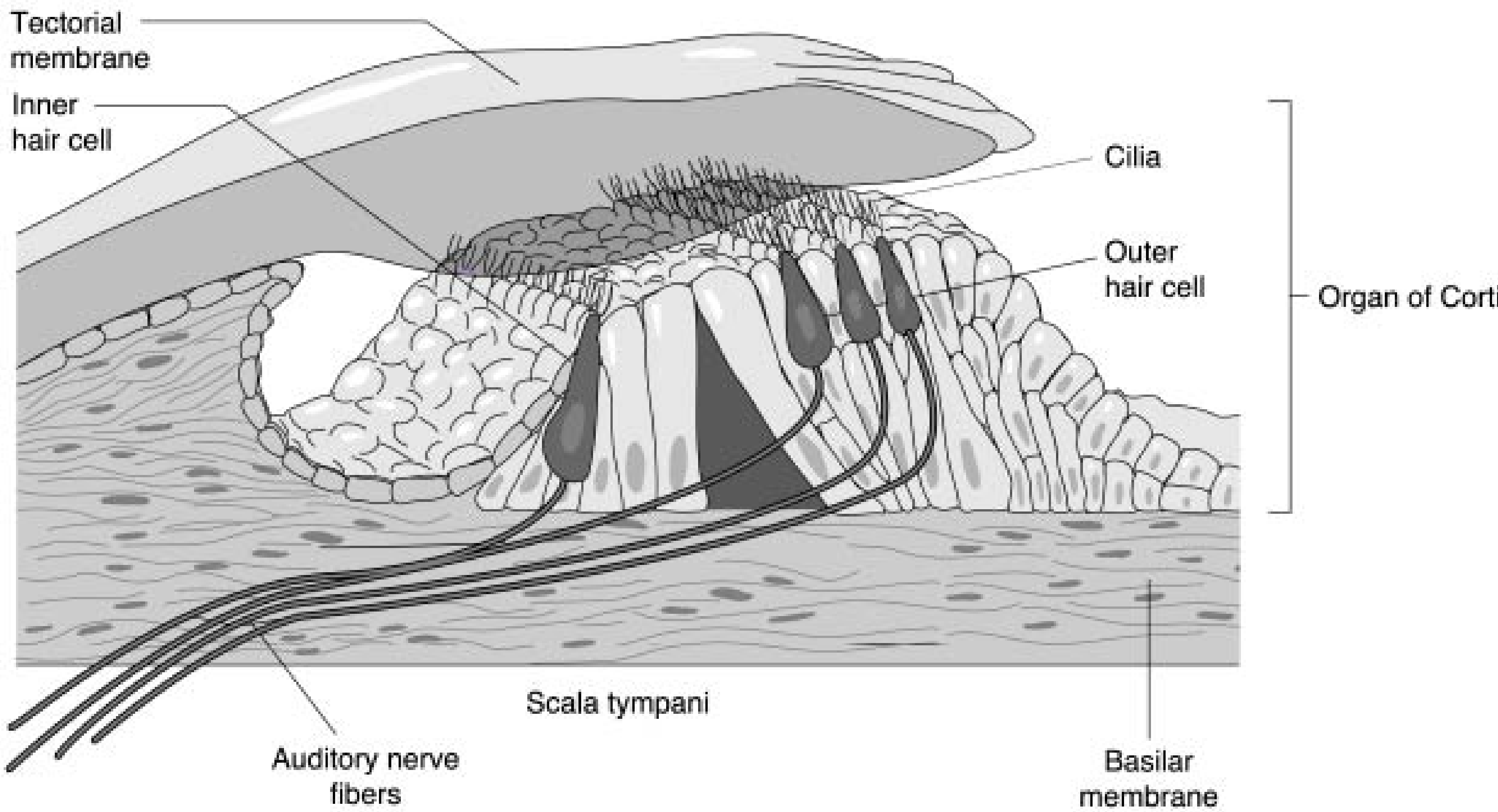
Fluid Constituents of Cochlear Chambers

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

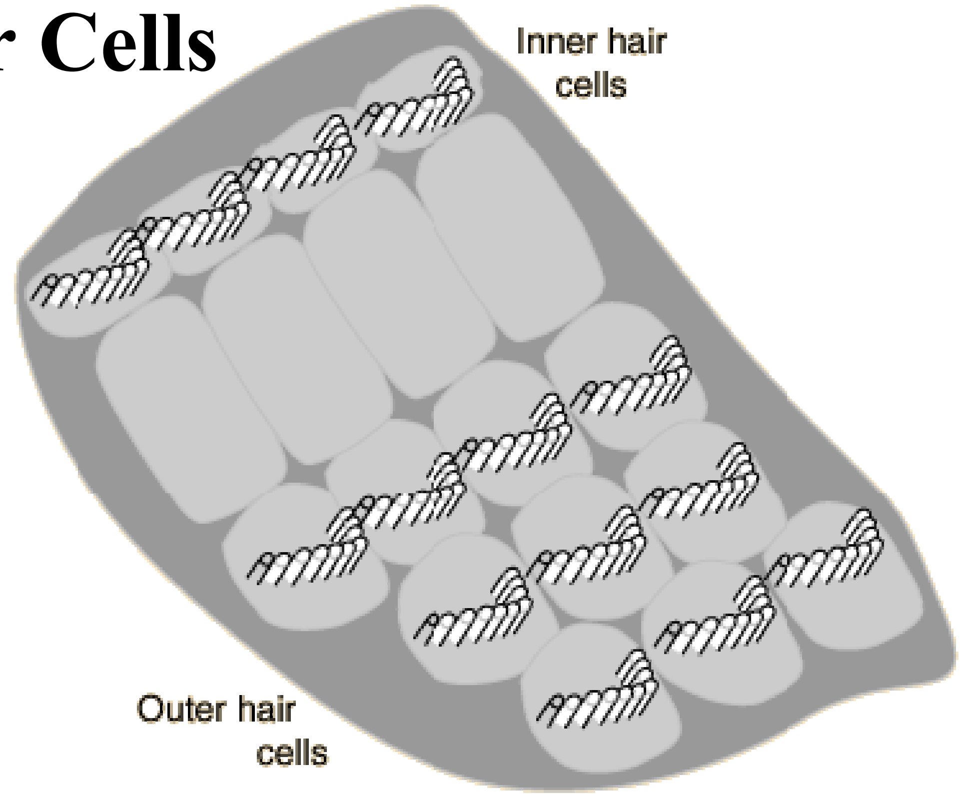
Endolymph has ionic concentrations similar to intracellular fluid. High concentrations of Potassium and Chloride.



Organ of corti



Arrays of Inner Ear Hair Cells



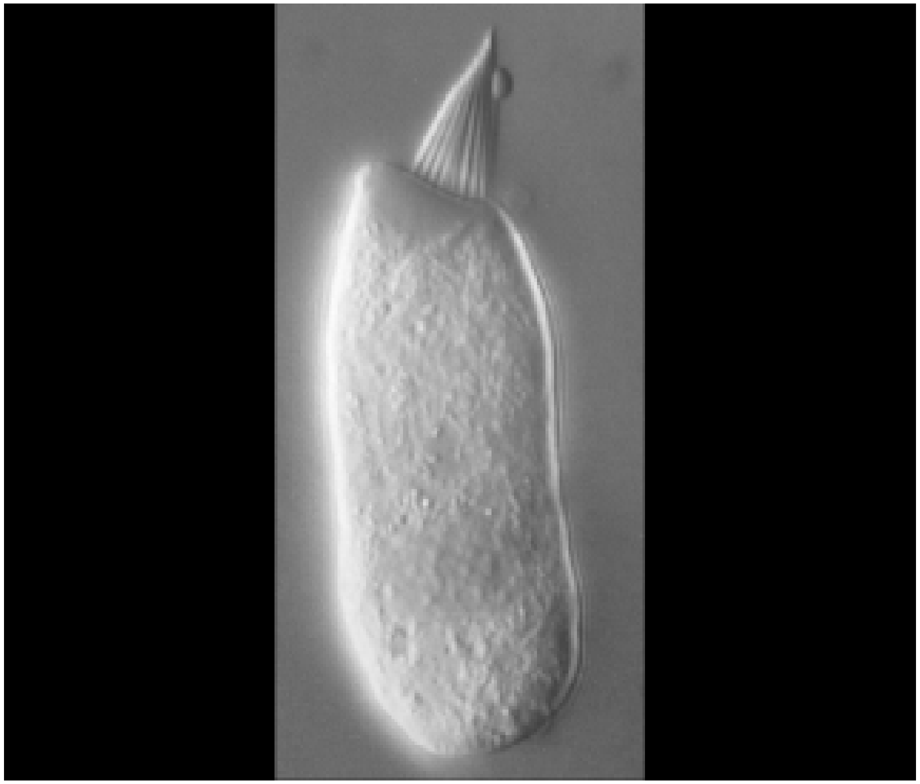
The hair cells of the organ of Corti are arranged in four rows along the length of the basilar membrane.

There may be 16,000 - 20,000 such cells (about 3000 inner hair cells, with 40-60 cilia each)

source: http://hyperphysics.phy-astr.gsu.edu/hbase/sound/corti.html#c3

- The outer hair cells are more numerous than inner hair cells, but they do not send a larger electrical response to the auditory cortex;
  - there are often 100-120 cilia per outer hair cell, arranges in rows of V-formations; only the tallest cilia extend into the tectorial membrane
- The function of the outer cells seems to be to amplify and sharpen basilar membrane vibration through an efferent-guided ***motile response*** that pushes and pulls against it

Hair cell



•This slide from (A.J. Hudspeth, *Science*, 230:745-752, 1985)

- A light microscopic image of a hair cell isolated from tissues normally surrounding it.
- This hair cell is about 30 μm long; the hair bundle is about 5 μm wide.
- Hair cells convert mechanical energy into an electrical energy through ion channels which open and close in sync with sound vibrations.

Tip Links

- Shorter cilia are attached to their longer neighbors by tip links
  - Made of actin, like cilia themselves
- Without bending, the ion gate “trapdoor” is open about 20% of the time.
  - inward flow of ions is matched by outward flow of ions, maintaining resting potential (no transmitter release)
- When cilia are bent (due to *endolymph* flow or membrane shearing), relatively more positively charged ions can enter, causing depolarization, which results in turn in neurotransmitter release

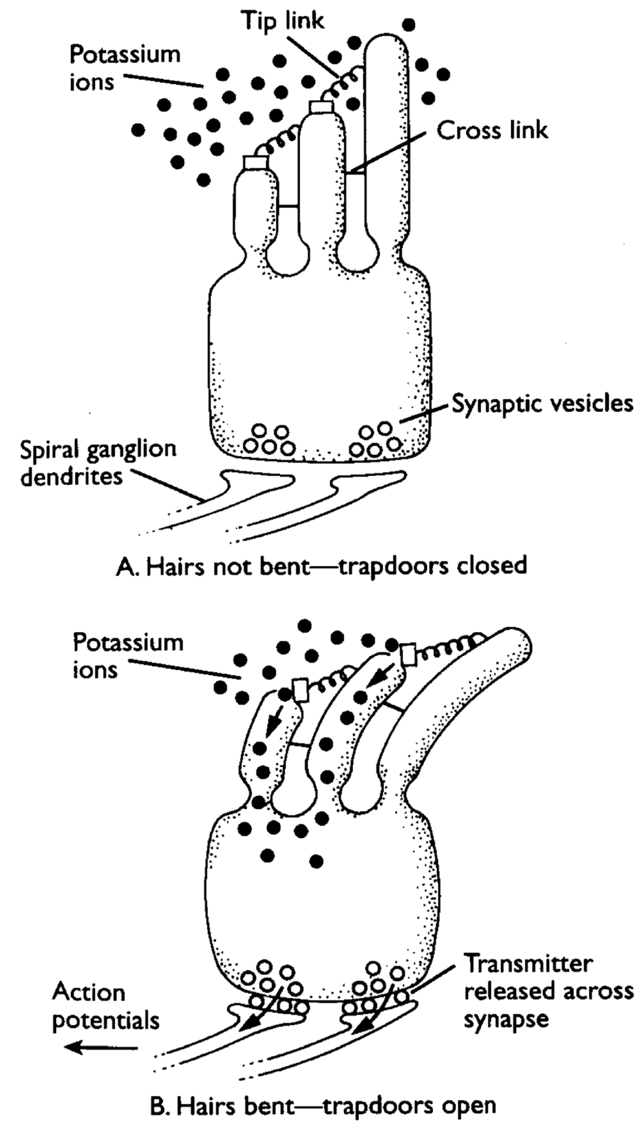
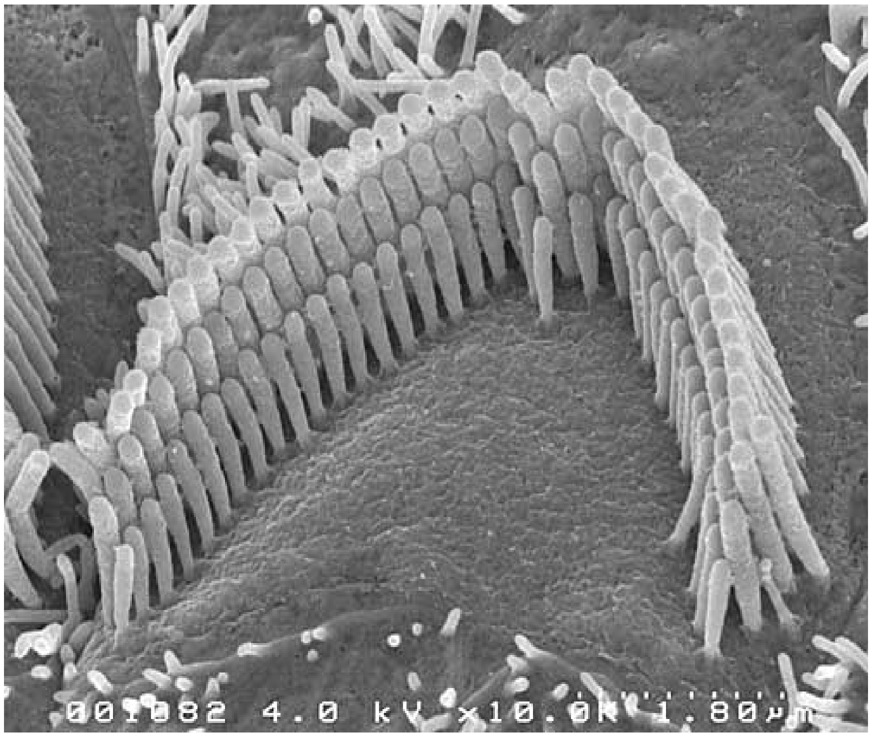


FIGURE 6-12 Model of transduction in hair cells. (A) No sound, hairs not bent, trapdoor closed, potassium ions excluded, no transmitter released, no action potentials; (B) sound present, hairs bent, trapdoor open, potassium ions enter, transmitter released, action potentials in auditory nerve.

Transducing Protein for Hearing

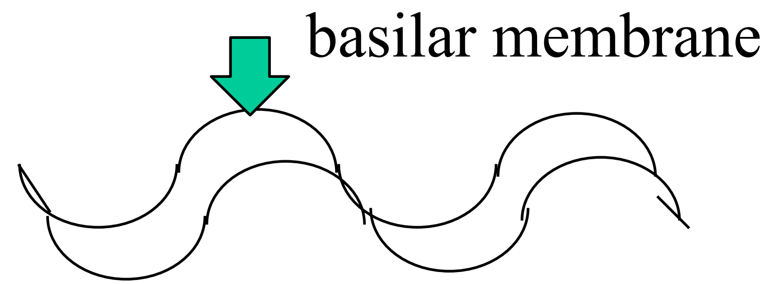


- TRPA1 (transient receptor potential), a mechanically-gated protein channel for ions, responds 1,000 times faster than the opening of similar channels in the eye in response to light.
- The same protein was known to be involved in pungent odor transduction (mustard, cinnamon, wasabi) and for painful cold.

•D. Corey et al, *Nature*, Dec 2004

Cochlear Representation of Sound

- **Frequency Theory**

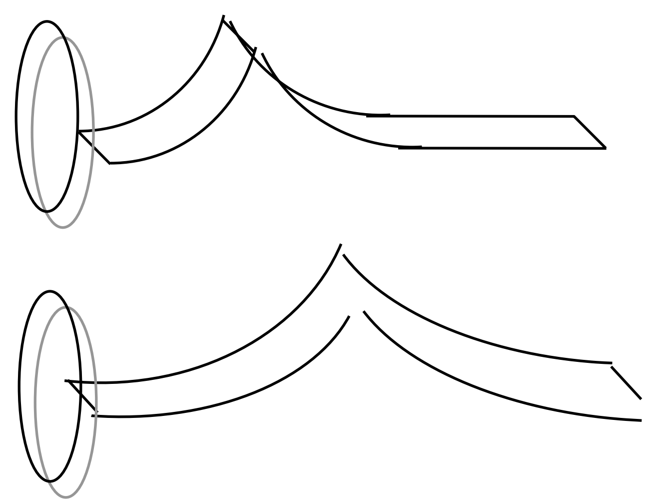


Membrane vibrates at frequency of Sound source

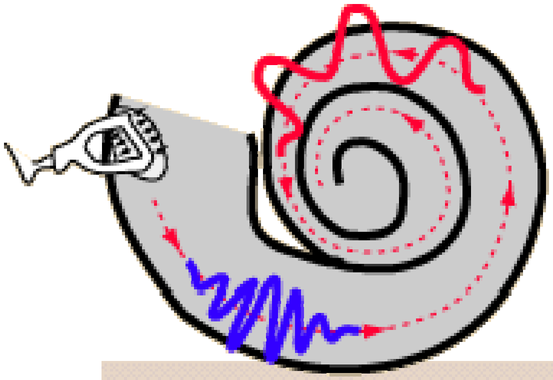
- **Place Theory**

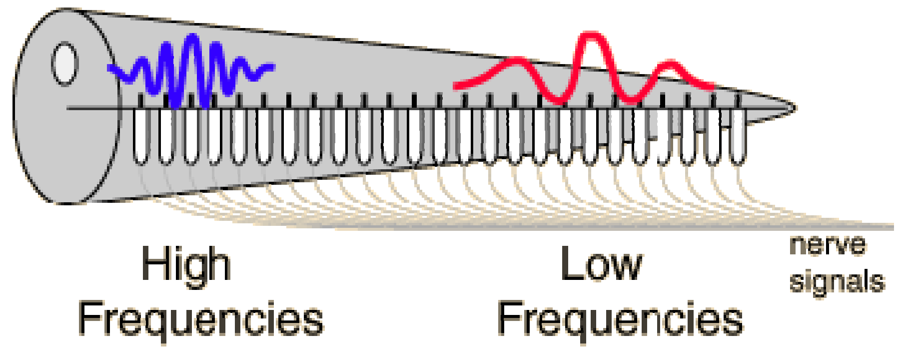
High Frequency sounds cause vibration near oval window

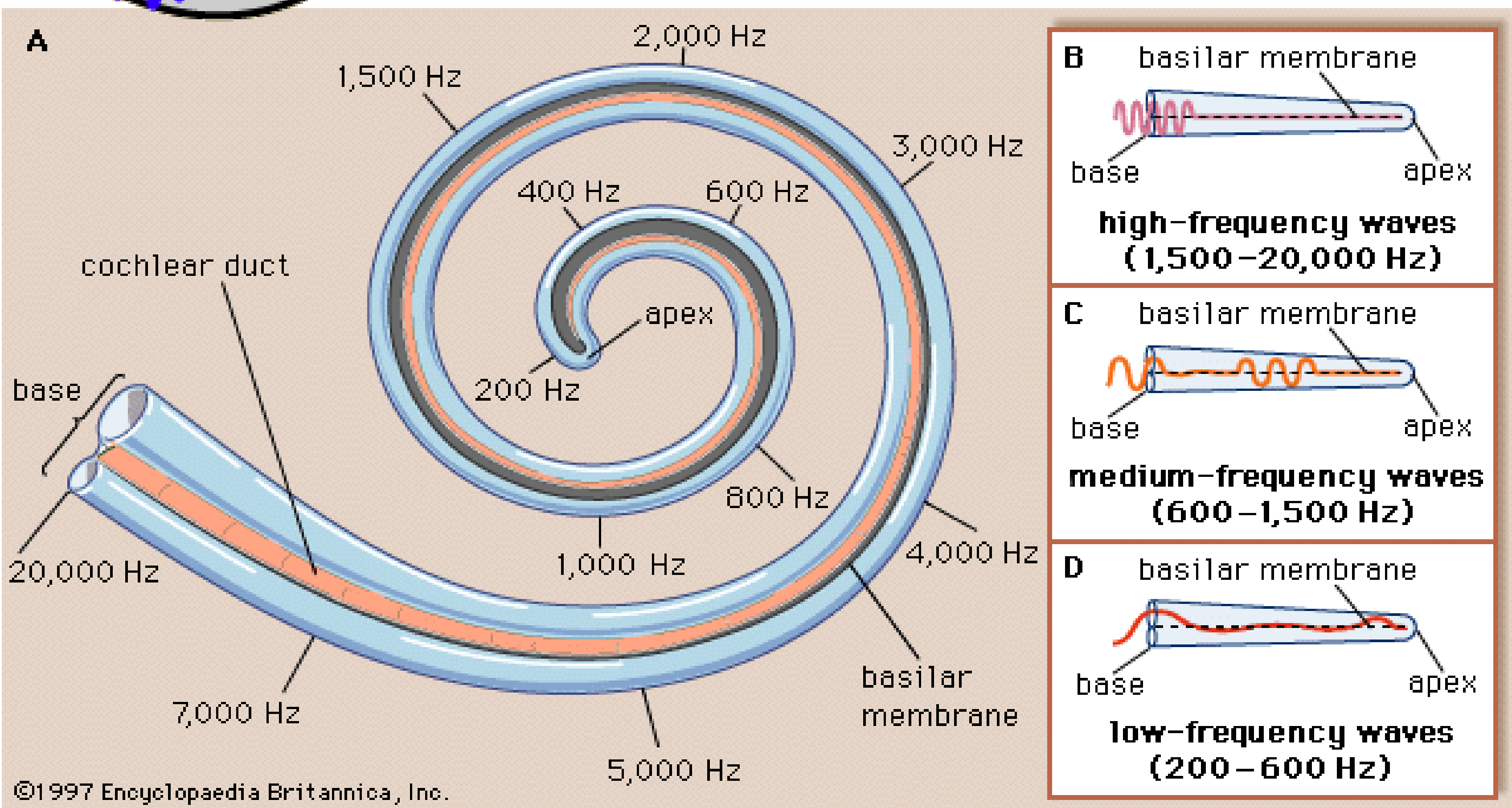
Low frequency sounds cause vibration near helicotrema



Place Theory







Different parts of the basilar membrane respond most to different frequencies: high frequency at base; low frequency at apex.

Cochlea and Frequency

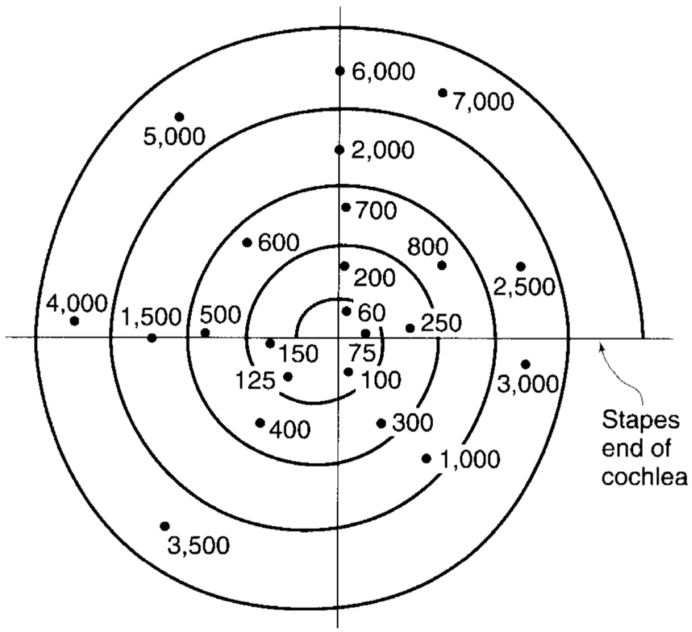
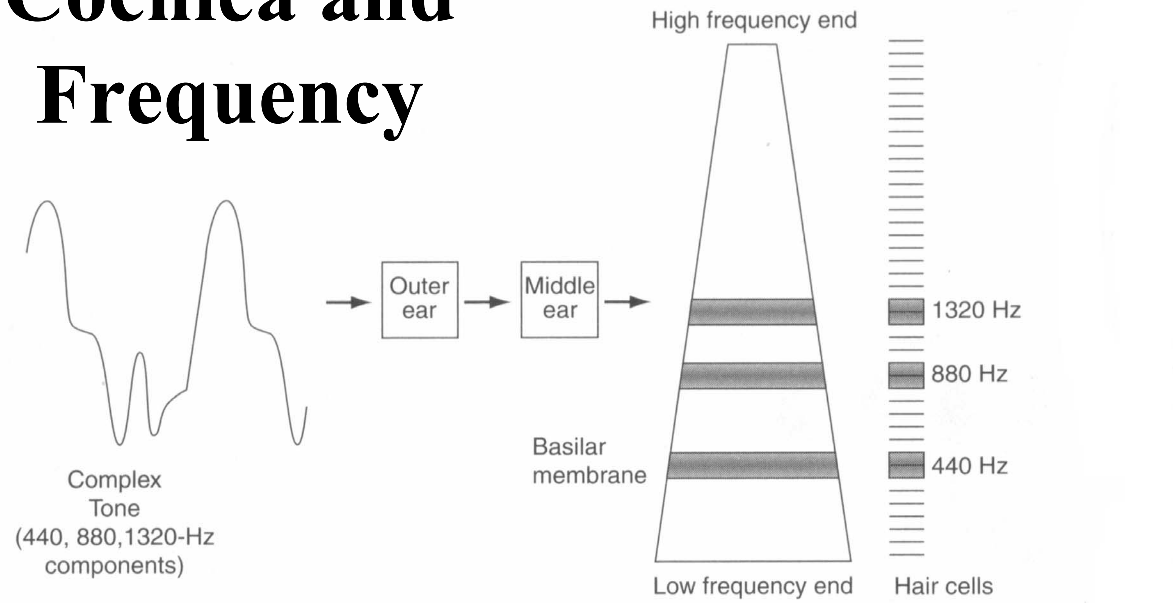


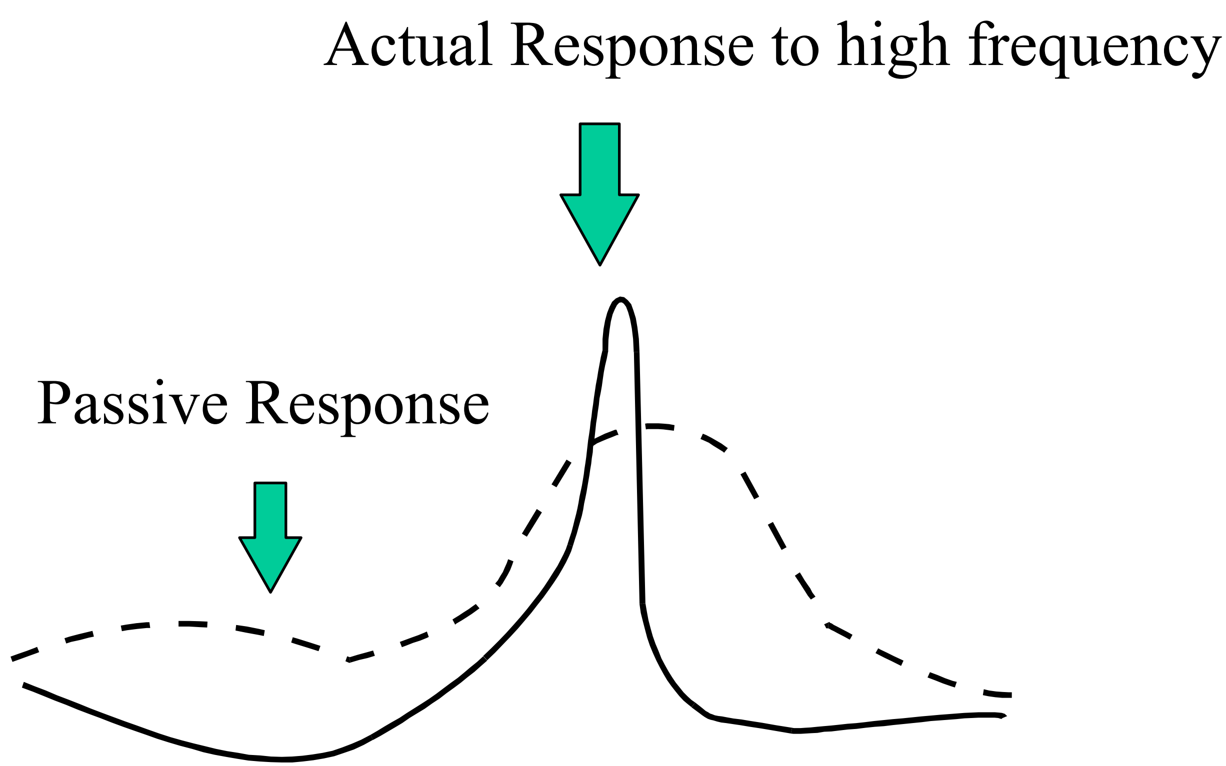
Figure 10.30
Tonotopic map of the cochlea. Numbers indicate the location of the maximum electrical response for each frequency. Low frequencies cause the largest response near the apex end of the spiral, and high frequencies cause the largest response at the base, at the stapes end of the cochlea. (From Culler et al., 1943.)



:alled a frequency analyzer because it analyzes incoming sound into its frequency components and translates : into separated areas of excitation along its length. In this example, the complex tone from Figure 10.7, which iency components at 440, 880, and 1,320 Hz, enters the outer ear. The shaded areas on the basilar membrane : of peak vibration for the tone's three components, and the darkened hair cells represent the hair cells that will n response to this tone.

- There is a ***tonotopic*** map of frequencies to different locations in the cochlea. This tonotopic mapping continues in the auditory cortex
- The basilar membrane responds to complex tones by responding to the individual composite tones of which it is composed.
  - The complex wave (middle) is composed of three frequencies, each of which has its own reaction in the basilar membrane

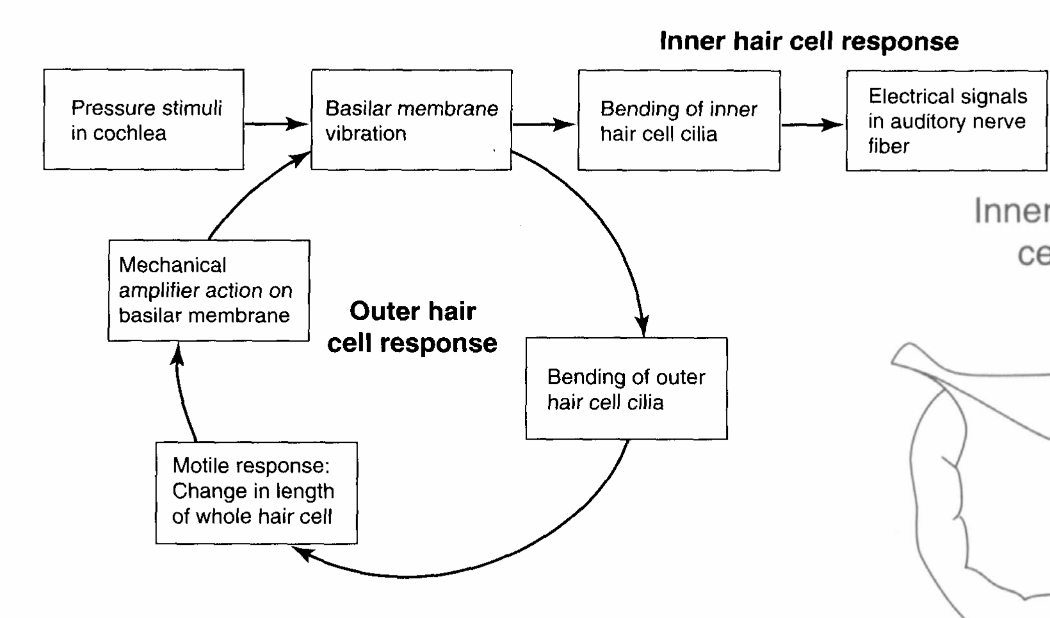
Cochlear Mechanics

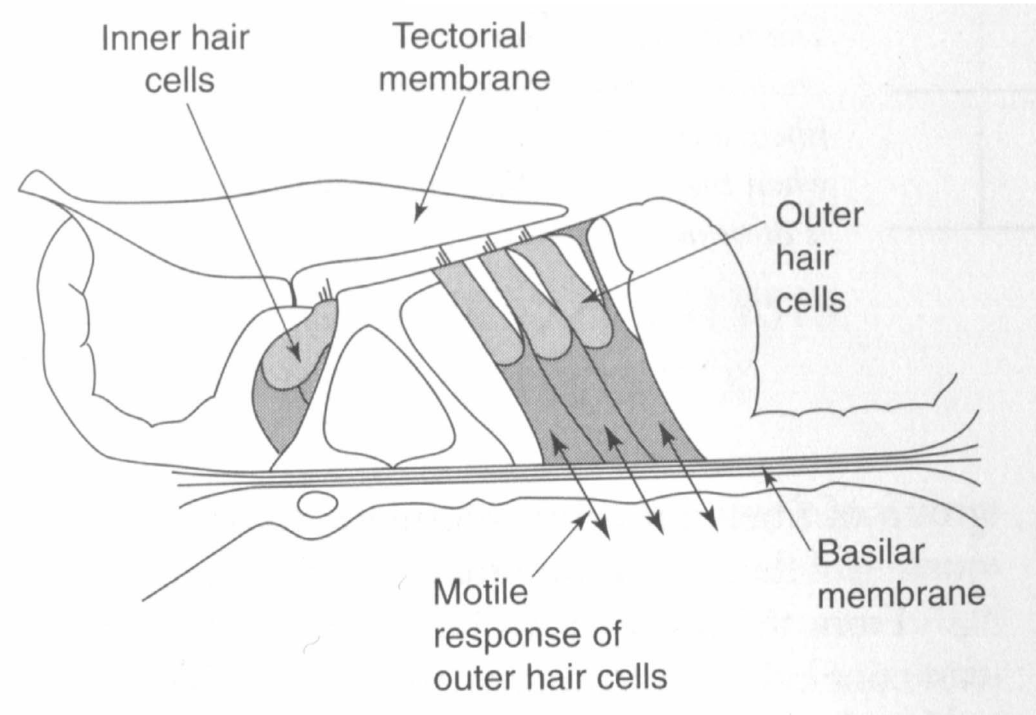


Passive response caused by mechanical properties of membranes (e.g. width)

Active Response is caused by outer hair cells, which inject energy back into vibration of cochlear membranes

Motile Response





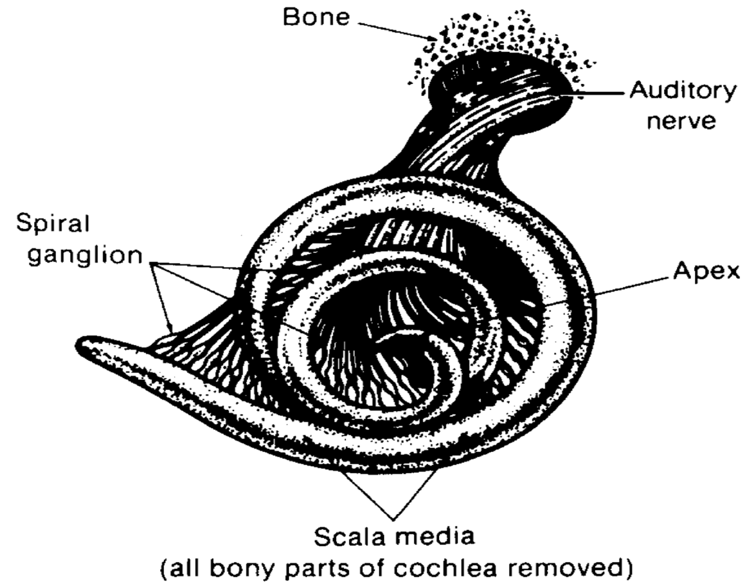
- Basilar membrane movement is cadavers is less than in living organisms. Why?
  - Also, destroying outer cells reduces response of inner cells
- Outer hair cells move (tilt slightly and change length) in response to sound (frequency specific).
- The movement pushes on the basilar membrane which amplifies and sharpens its response a given location along the membrane.

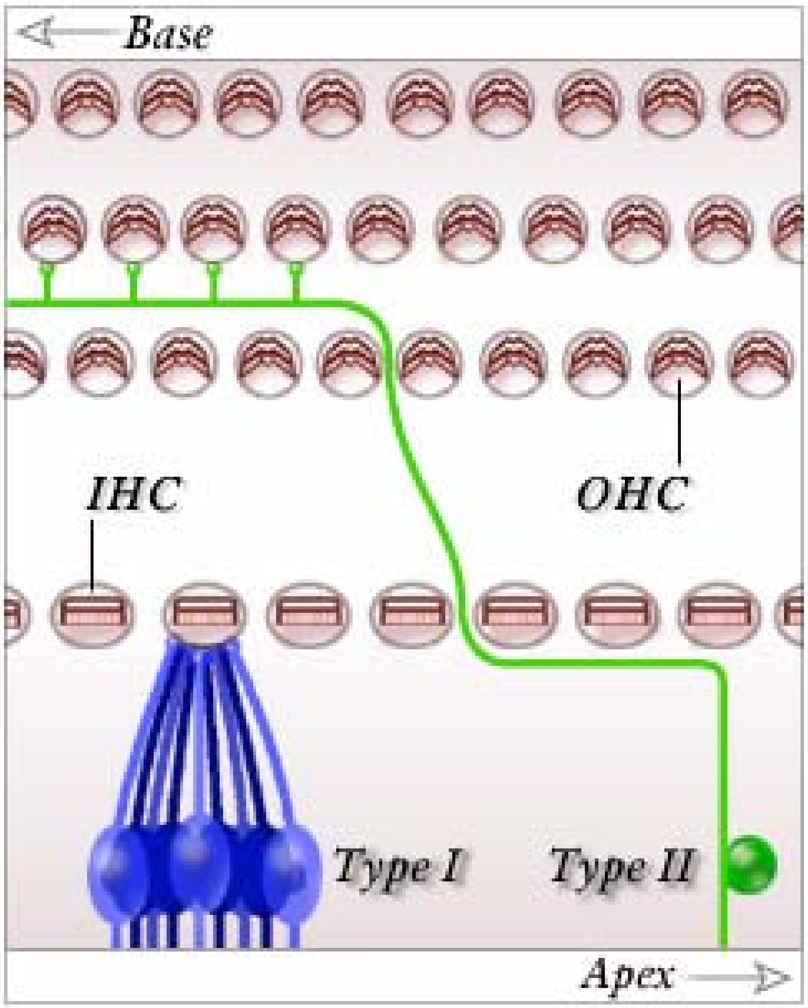
Variations in length and thickness of basilar membrane are insufficient to account for precise frequency tuning. Response is ***active*,** increasing size of wave motion in membrane.

Efferent inputs into cochlea actually produce sound: ***otoacoustic emissions*** (some over 20 dB)

Some sounds spontaneous; others contralateral

Spiral Ganglion



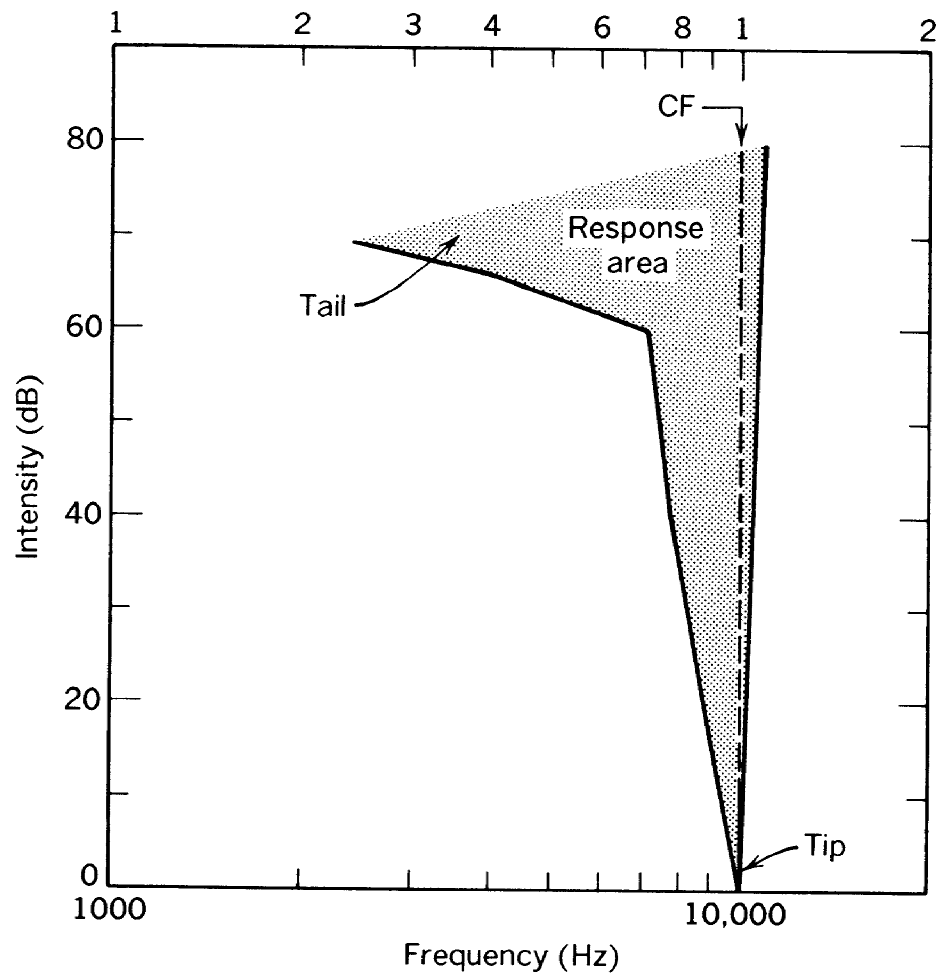


Type I spiral ganglion neurons (95% of the ganglion neurons) contact a single inner hair cells (each hair cell may contact 5 to 100 separate axons). As a result.

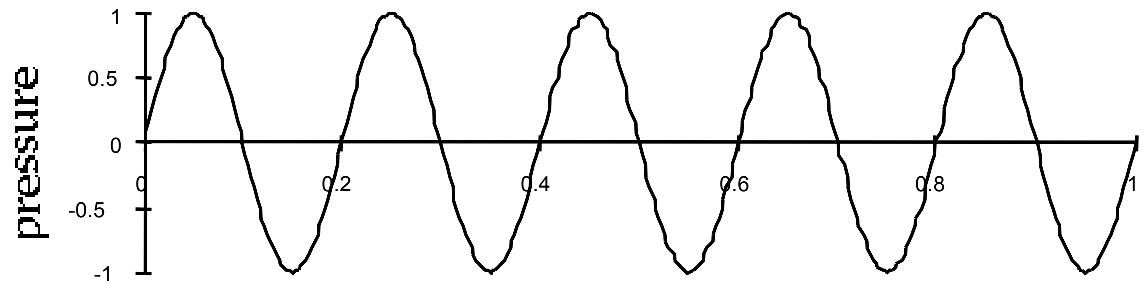
Type II small, unmyelinated spiral neurons branch to connect about ten outer hair cells, generally in the same row.

Single Fiber Tuning Curve

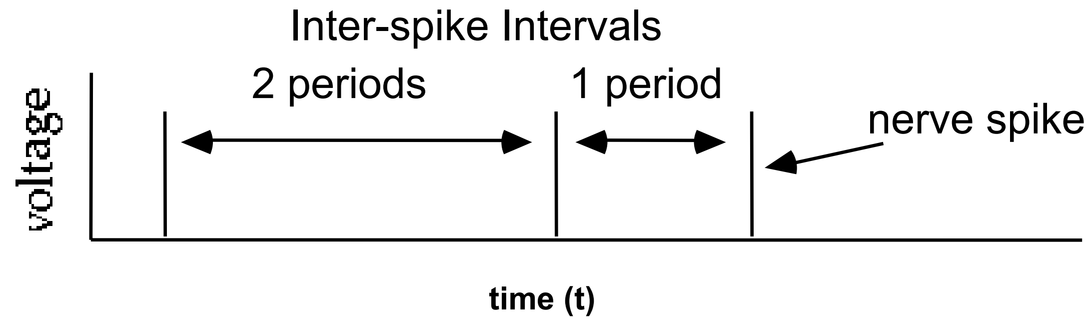
- Characteristic frequency (tip)
- Tail
- Difference in slope between the low frequency and high frequency sides
- Shaded area is the response area



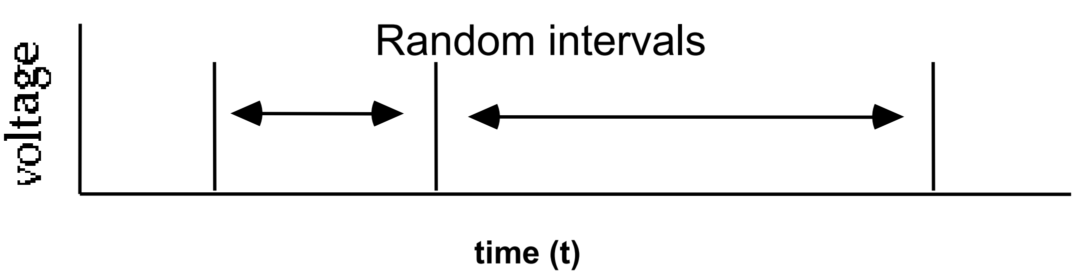
Phase-locking



Response to Low Frequency tones



Response to High Frequency tones > 5kHz



Summary

- Cochlea: frequency analysis
- Converts it to current that goes into the brain