

2.1 The auditory system

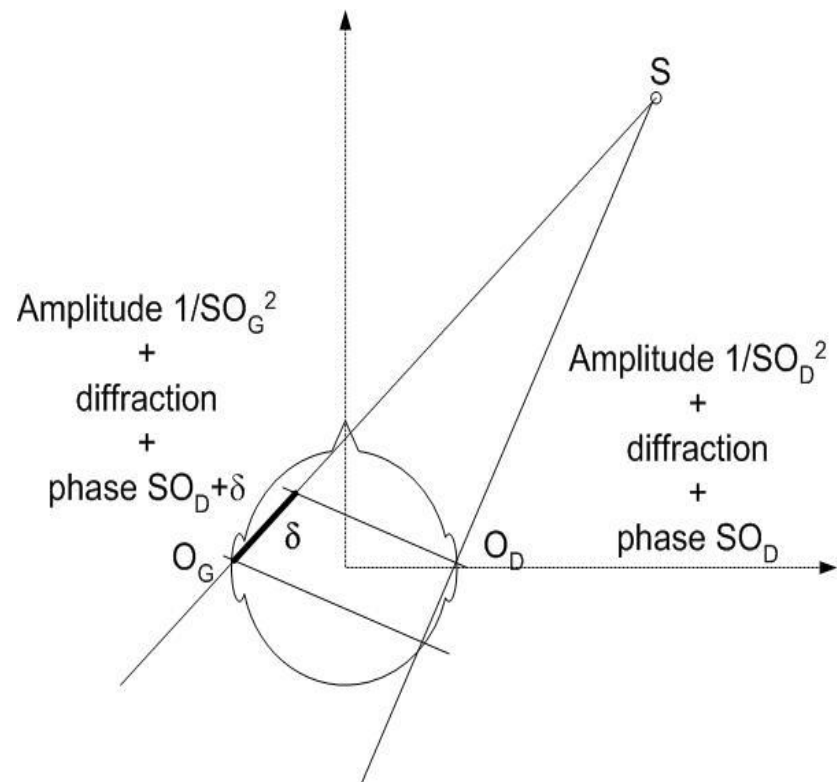


Introduction

The **auditive system** and the "**audition**" **function** are complex and certain mechanisms are far from being clearly understood

This chapter presents, in a very concise way, the **morphology** and the **behavior** of the human auditive system

Source localization



👂 **Interaural Intensity Difference (IID'S)**
A sound source is perceived closest to the ear with highest pressure magnitude

👂 **Interaural Time Difference (ITD'S)**
A sound source is perceived closest to the ear where sound wave arrives first

👂 **Diffraction by the body/head**
Helps to localize source

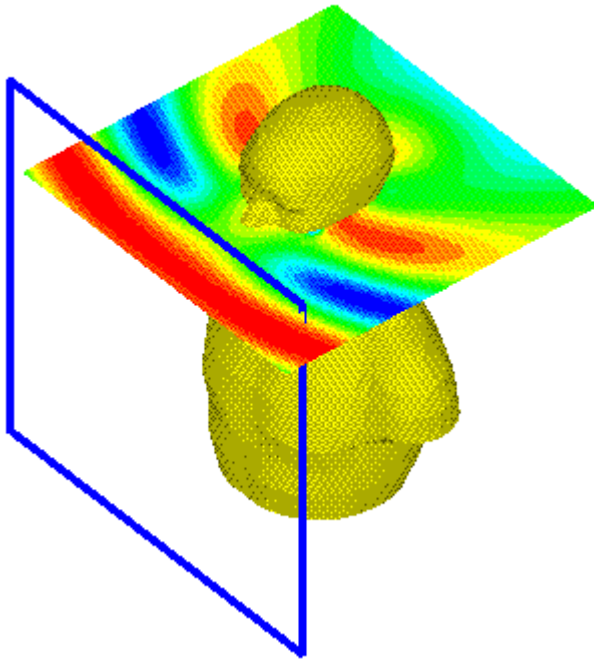
Diffraction by head and body

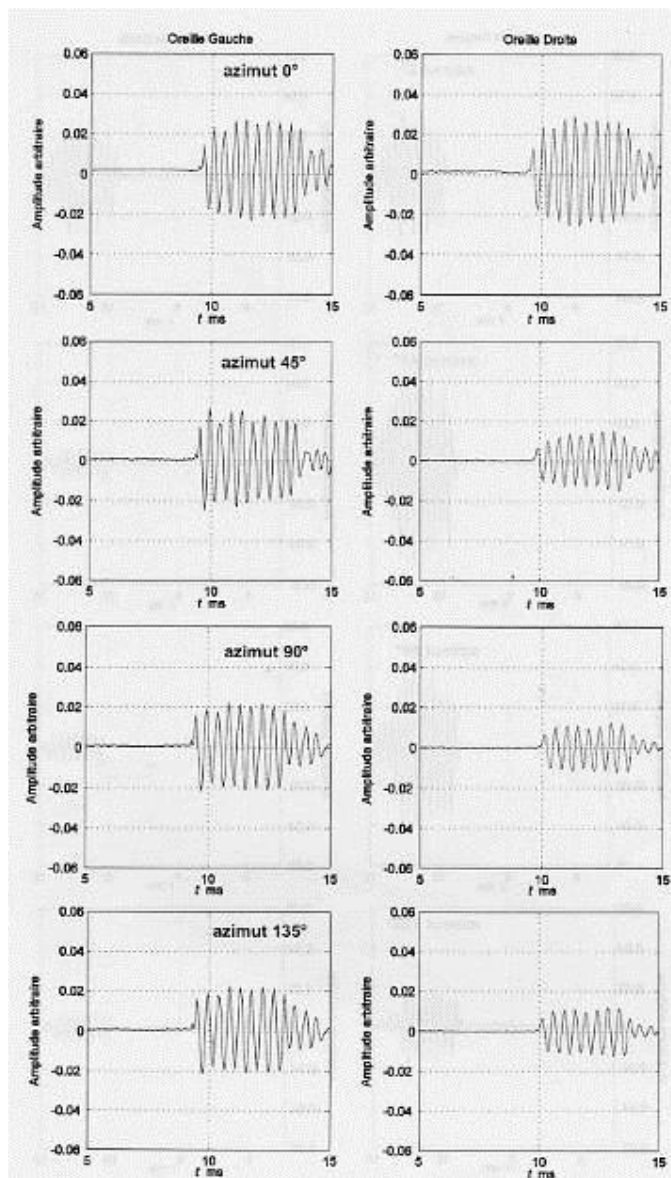
- 👂 The body constitutes an obstacle against propagation of sound
 - Head, shoulders and torso are diffracting
 - The acoustic pressures at the "inputs" of the ears are different than the ones without the presence of the listener
- 👂 These effects depend on the incidence of the wave and frequency
 - Diffraction depends on the size of obstacles with respect to wavelengths

These phenomena are the basis of our ability to spatially localize sound sources

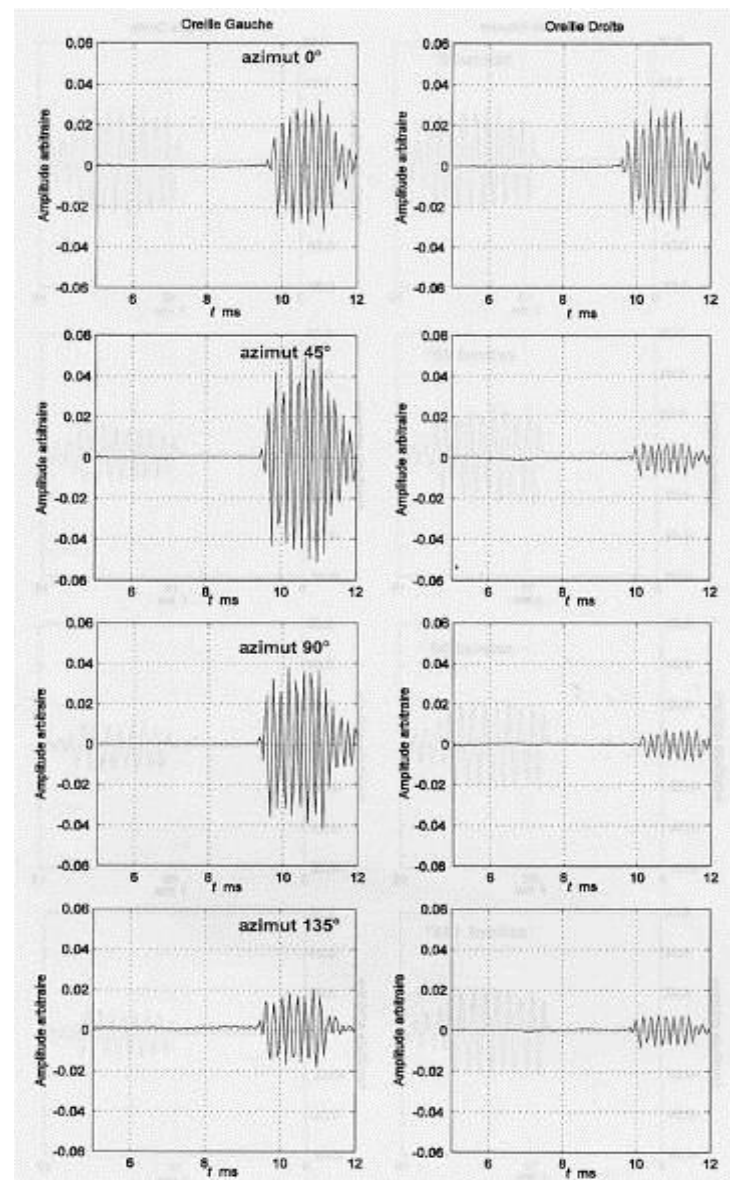
Diffraction by head and body

- 👂 Evidence of these phenomena is obtained by the help of manikins, simulating head and torso, comprising artificial ears





Burst at 2160 Hz



Burst at 4860 Hz

HRTF: functions of diffraction by the head

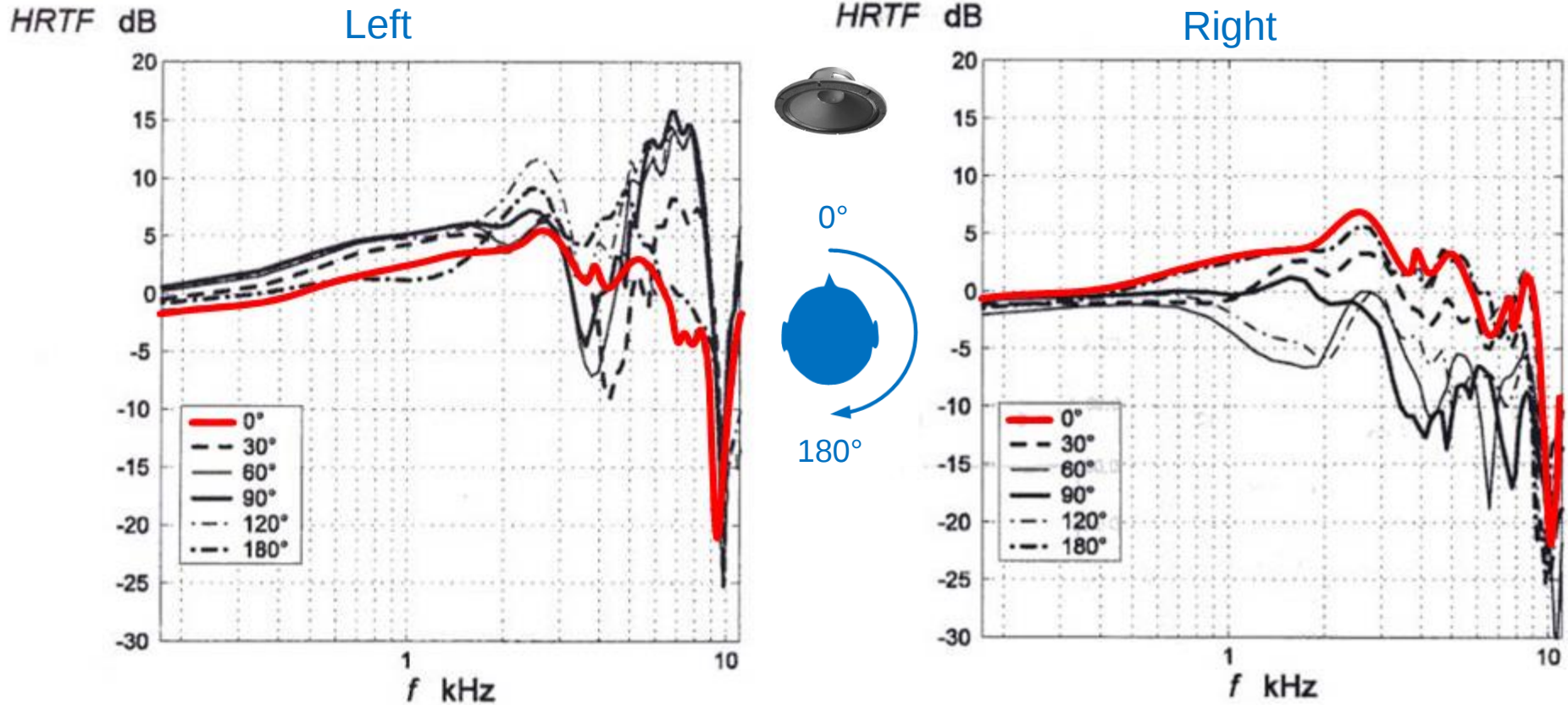
HRTF (Head Related Transfer Functions)

- characterizes diffraction effects
- *Formulations* : p_g/p_i and p_d/p_i

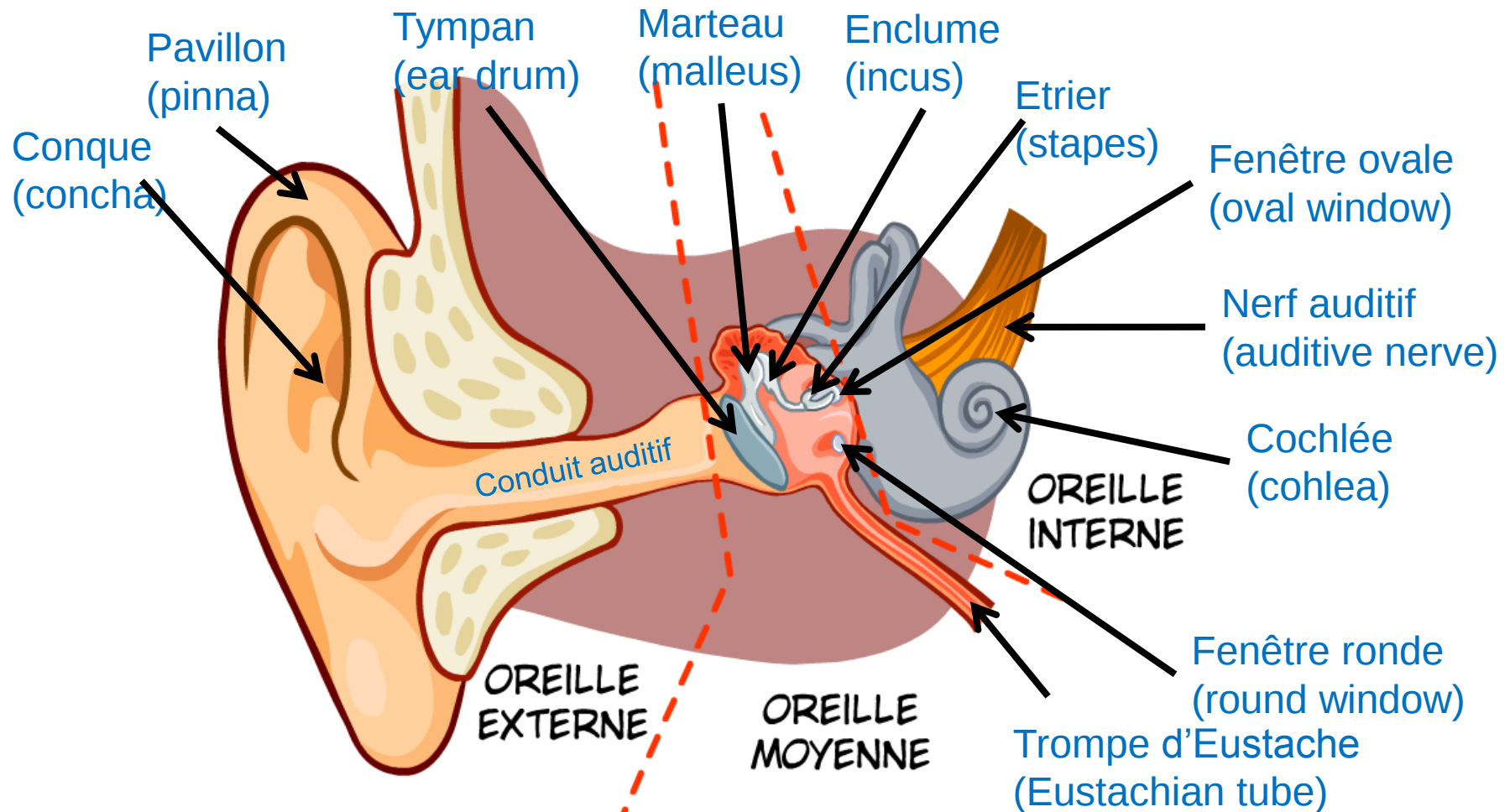
Definition

- p_g and p_d represent the pressures measured at the ears entrance (in case ears are closed)
- p_i represents the pressure measured without the listener (obstacle)
- Measurements are performed in steady state

One example of HRTF

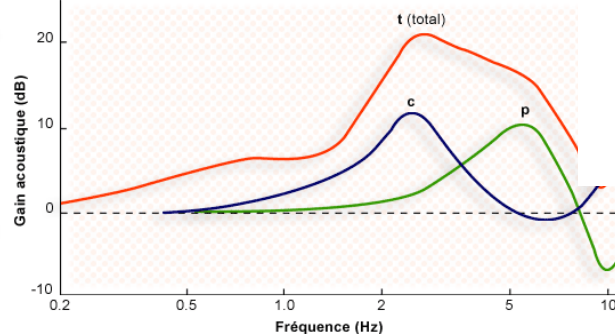
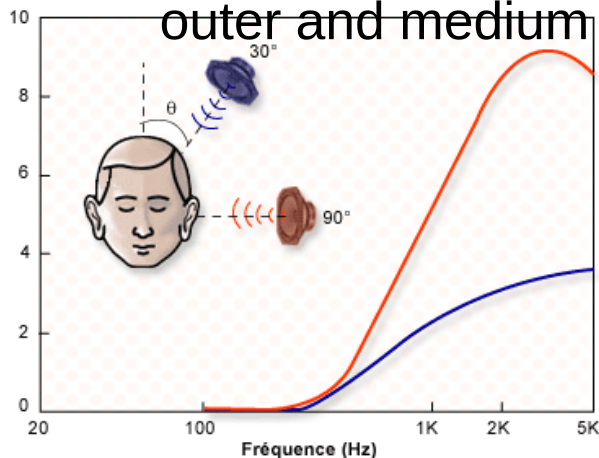
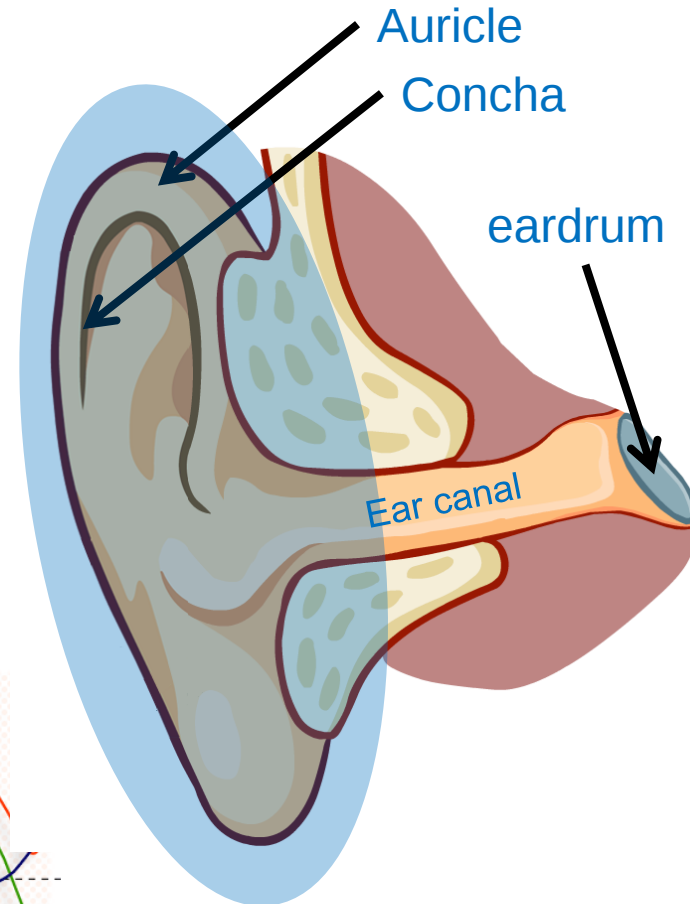


The human ear



The external ear

- 👂 Senses airborne sound
- 👂 Diffraction on **the auricle (pavillon)** allows localization (mainly in elevation)
- 👂 **The concha** resonates around 5 kHz and **the ear canal** around 3 kHz
- 👂 **The auricle (pinna)** and **concha** allows an impedance matching between **external medium** and **the ear canal**
- 👂 **The eardrum** is the interface between **outer and medium ear**



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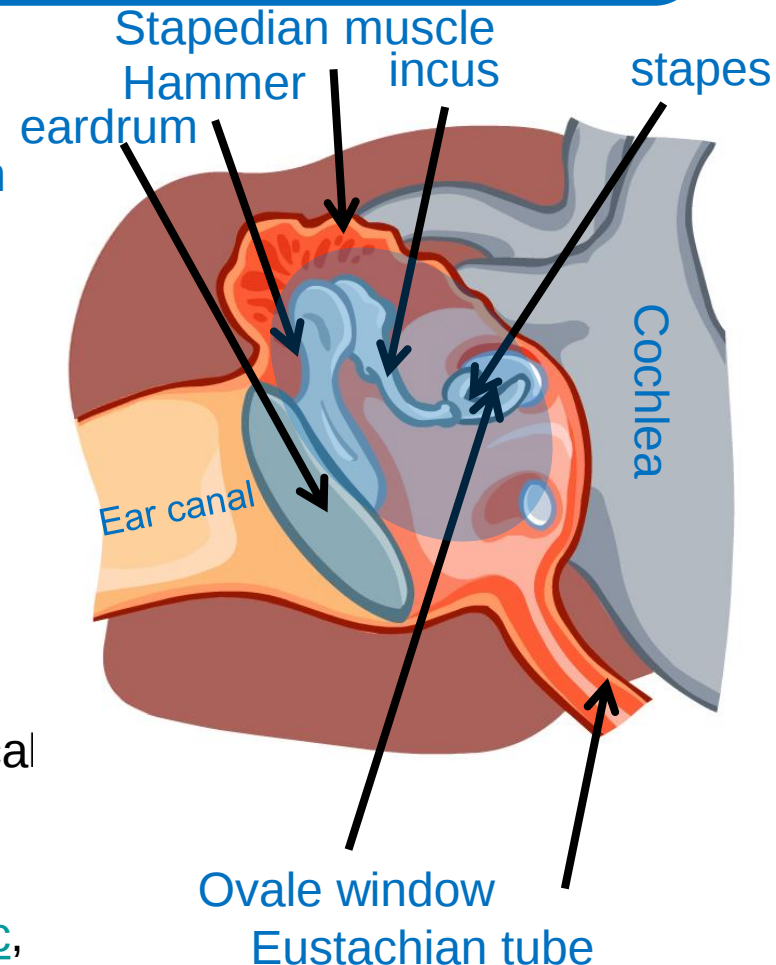
The eardrum

- Animation

(<http://www.youtube.com/watch?v=PeTriGTENoc>,
bpletsch@thomasdirect.com)

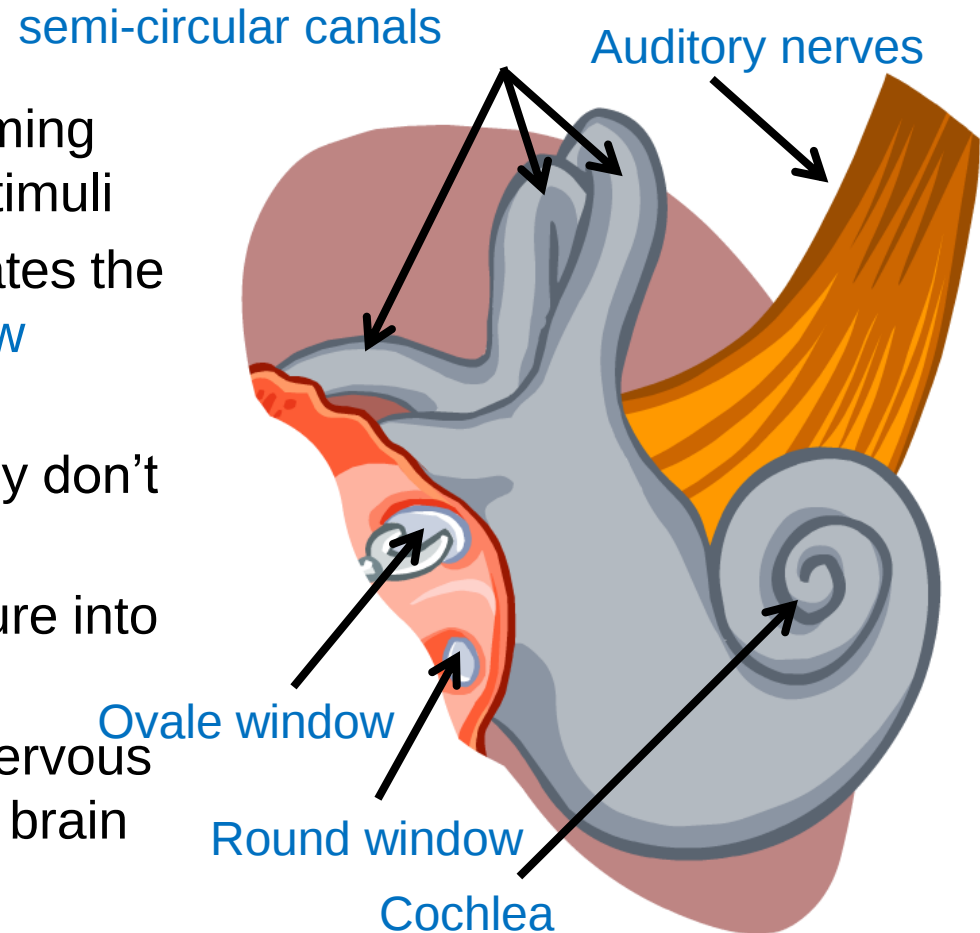
Middle ear

- Allows the impedance matching between the auditory canal ($Z_c=420 \text{ kg.s.m}^{-2}$) and the cochlea ($Z_c=1,6 \cdot 10^6 \text{ kg.s.m}^{-2}$) : surface ratio between eardrum and the elliptical window
- The malleus (marteau), incus (enclume) and stapes (étrier) are the ossicles
- The stapedius protects the ear
- Ossicles and ligaments are a mechanical chain (mass-spring-losses system)
- The Eustachian tube allows the equalization of static pressures (inner / outer ear)
- Ensures a mechanical transmission to the elliptical window
- Animation
(<http://www.youtube.com/watch?v=PeTriGTENoc>,
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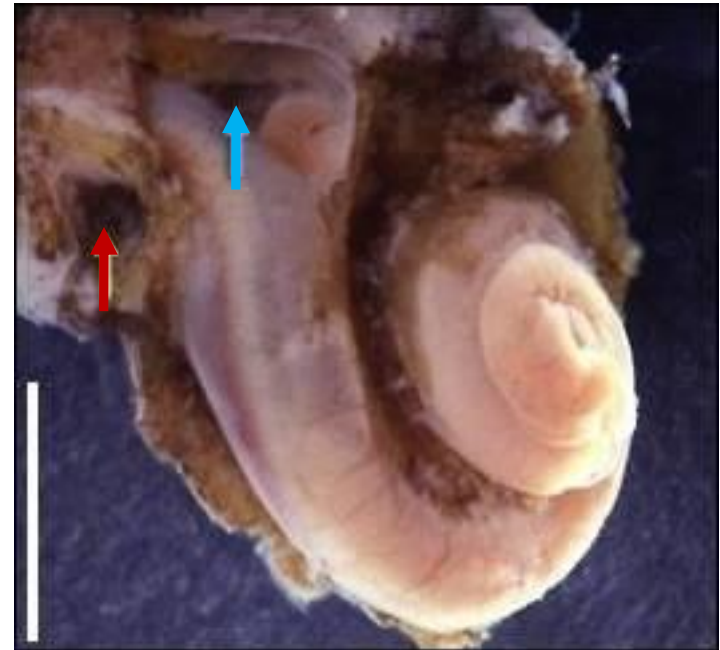


Inner ear

- Transforms the information coming from middle ear into nervous stimuli
- The **circular window** compensates the pressure at the **elliptical window**
- The **semi-circular canals** are responsible of our balance. They don't have any auditory function
- Cochlea** codes acoustic pressure into nervous information
- The **auditory nerve** transmits nervous signals from **the cochlea** to the brain



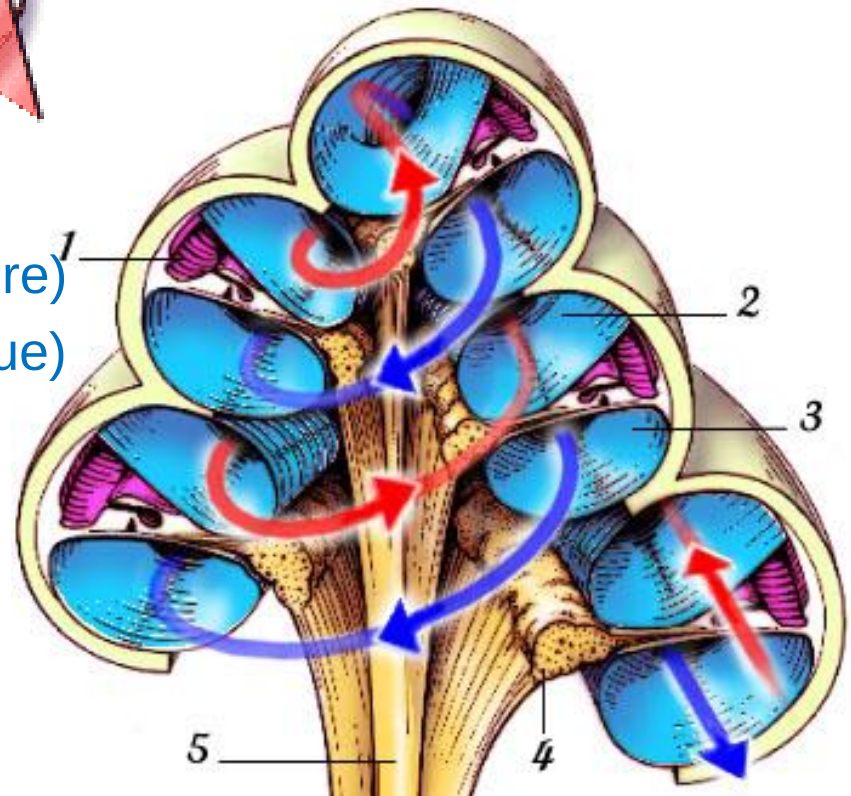
The cochlea



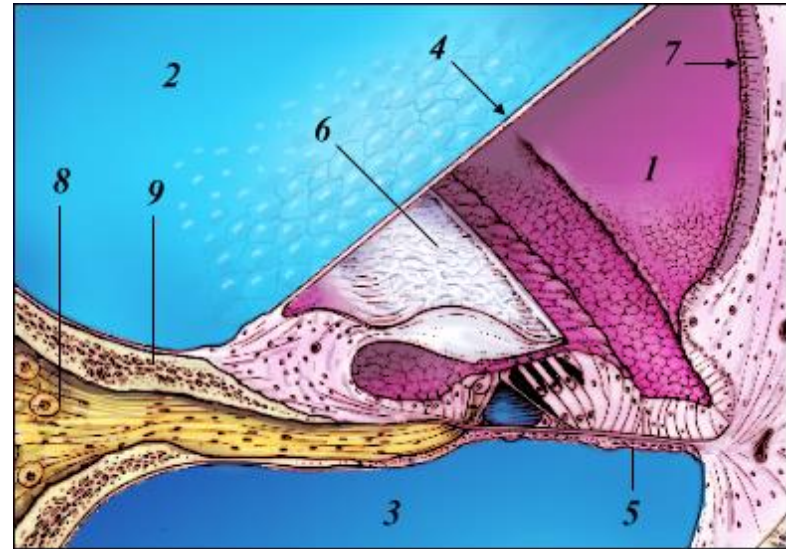
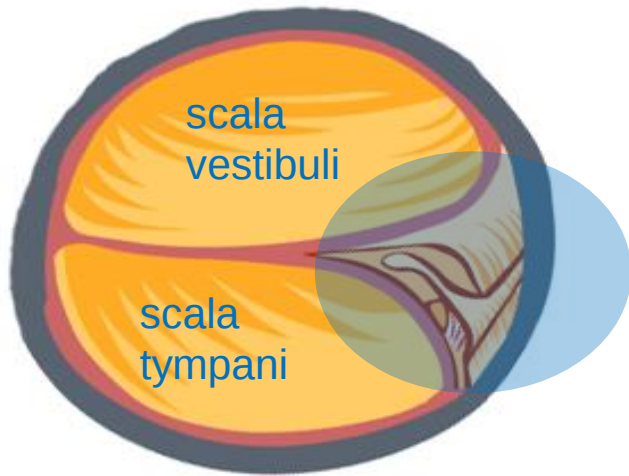
A cut of the cochlea



1. Scala media (Rampe cochléaire)
2. Scala vestibuli (Rampe vestibulaire)
3. Scala tympani (Rampe tympanique)
4. Organ of Corti
5. Cochlear nerve



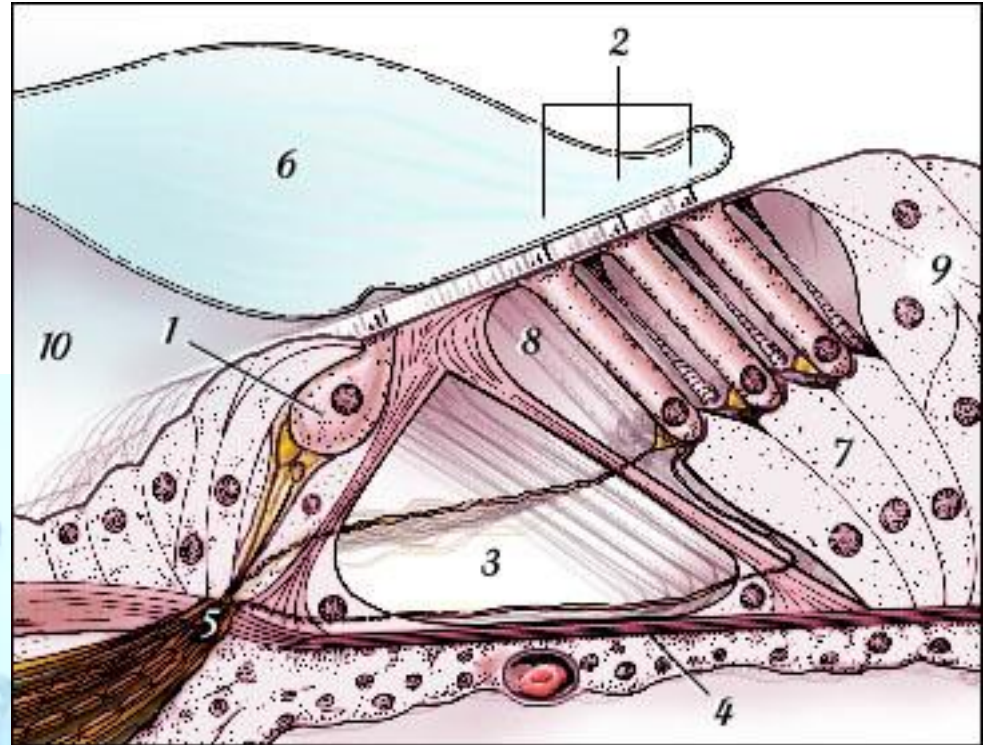
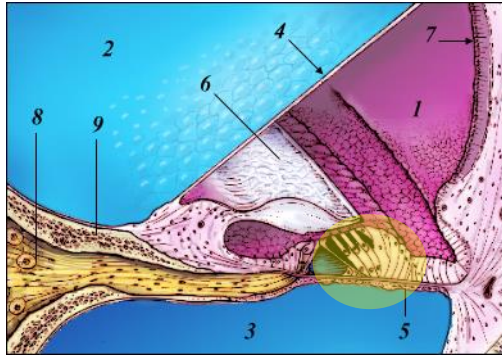
A cut of the cochlea



1. Scala media
2. Scala vestibuli
3. Scala tympani
4. Reissner's membrane
5. Basilar membrane
6. Tectorial membrane
7. Stria vascularis
8. Ganglion
9. Lamina spiralis

 Hydro-mechanical transmission
at the basilar membrane

Organ of Corti



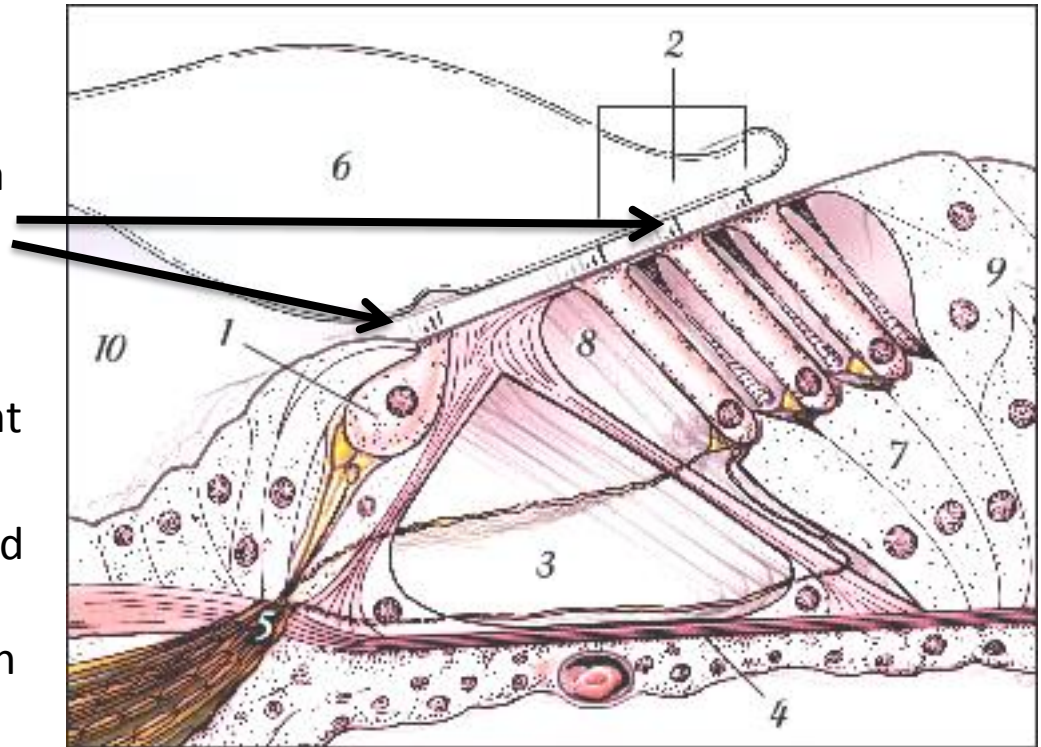
1. Inner hair cells
2. Outer hair cells
3. Tunnel
4. Basilar membrane
5. Habenula perforata
6. Membrana tectoria
7. Cells of Deiters
8. Espaces de Nuel
9. Cells of Hensen
10. Sillon spiral interne



Electro-chemical transmission at the hair cells

Organ of Corti – hair cells

- cochlear/vestibular sensory cells are called hair cells
- they are characterised by having a cuticular plate with a tuft of stereocilia bathing in the surrounding endolymph,
- the cell body itself is localised in the perilymph compartment
- Schematically, both types of cells, inner hair cells (IHCs) and outer hair cells (OHCs), differ by their shape and the pattern of their stereocilia.



Electro-chemical transmission at the hair cells

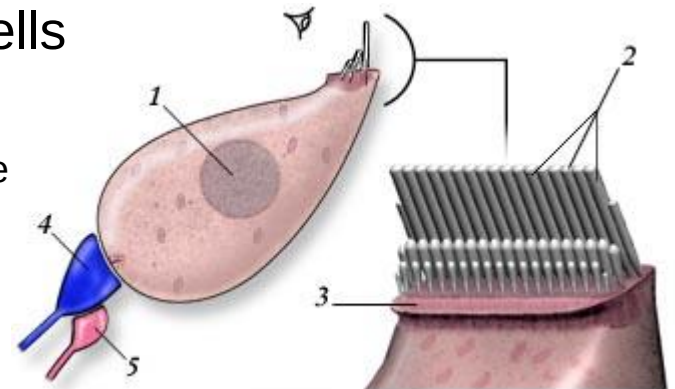
Hair cells

Electro-chemical transmission at the hair cells

3,500 inner hair cells (IHCs)

The IHC and its innervation are represented here. Note, unlike in OHCs, the medial location of the nucleus, and a "normal" lateral plasma membrane.

Only a single synaptic complex is represented: i.e. a radial afferent bouton (blue) and a lateral efferent ending (pink). On average, one IHC is innervated by ten of these complexes.

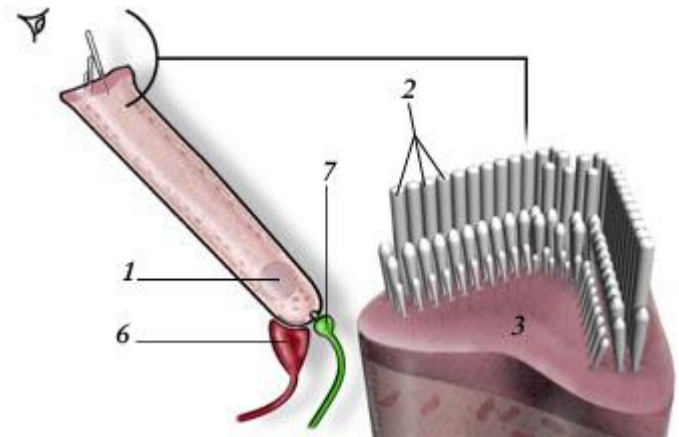


12,000 outer hair cells (OHCs)

At the apical pole, the stereocilia of the OHC are embedded in the cuticular plate. Lateral cisterns and mitochondria are typically aligned along the lateral membrane.

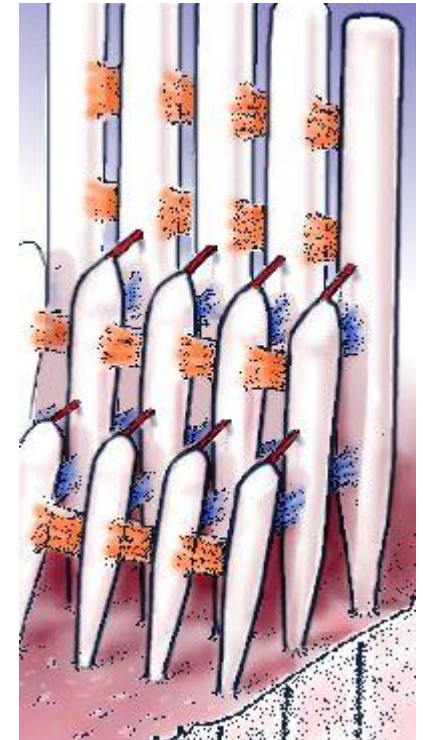
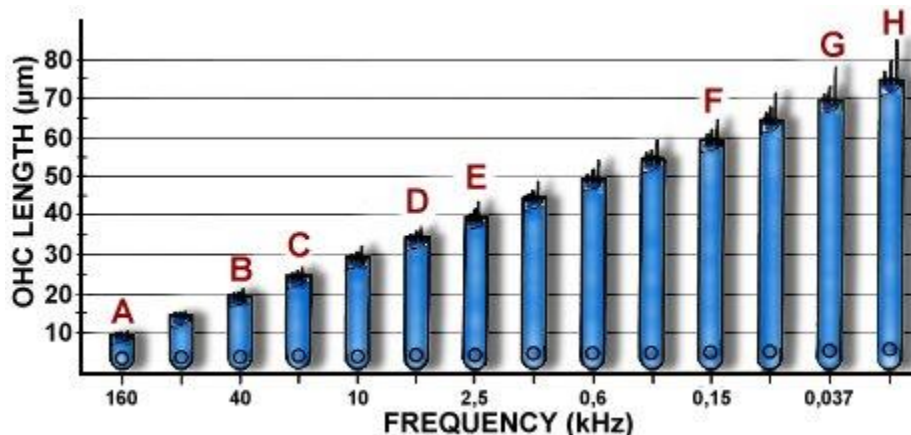
Below an inferiorly located nucleus the synaptic compartment contains mitochondria.

An afferent bouton (green) from a type II ganglion neuron and a medial efferent ending (red) are represented at the synaptic pole of the OHC.

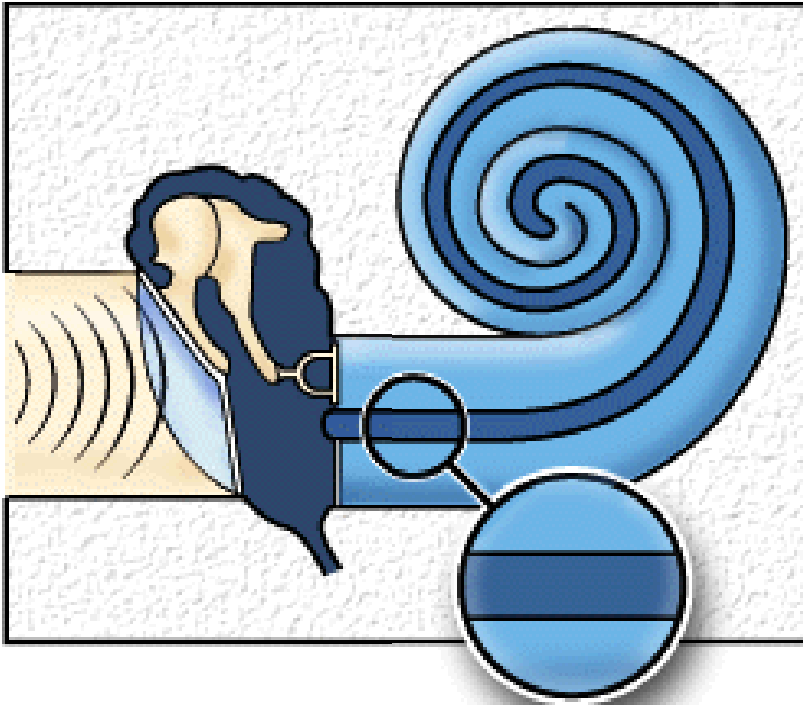


Outer hair cells

- Pattern of arrangement of stereocilia in an adult mammalian cochlear hair cell.
- Stereocilia (around a hundred) are generally arranged in three rows of graded lengths. In addition to thin tip links (shown here in red) which are involved in the mechano-transduction process, stereocilia are attached by transverse (lateral) links, both in the same row and from row to row.



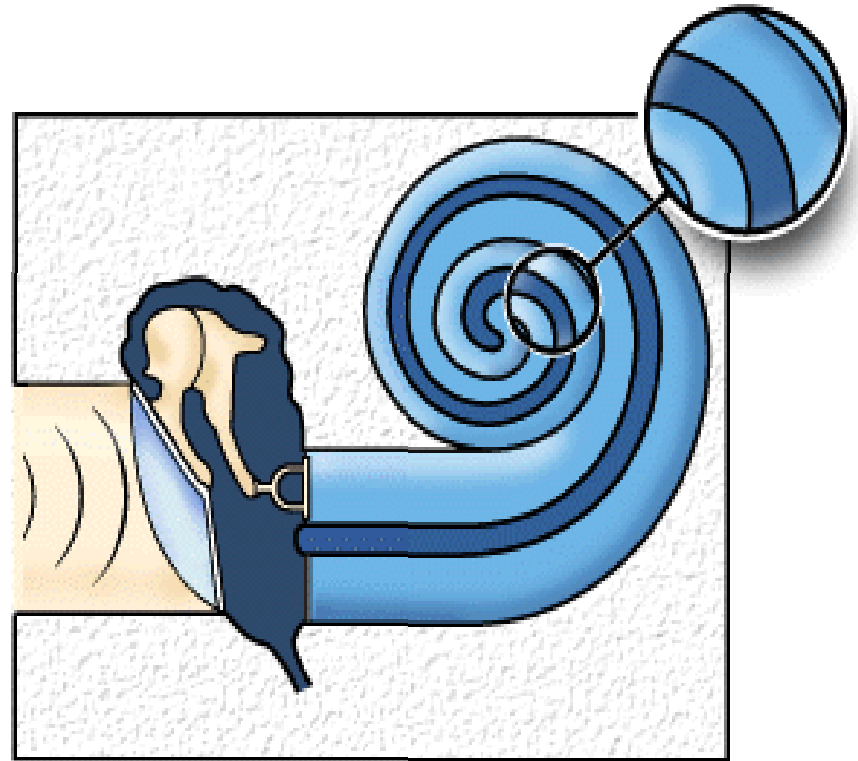
Basilar membrane function



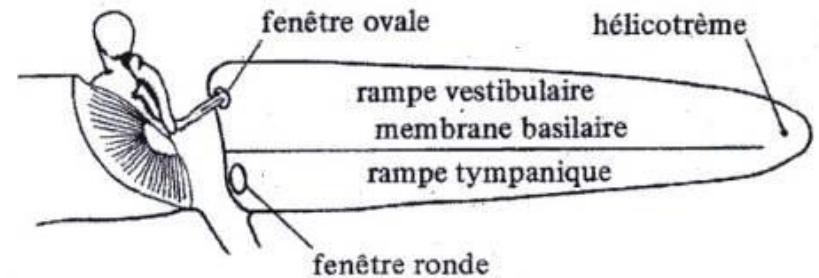
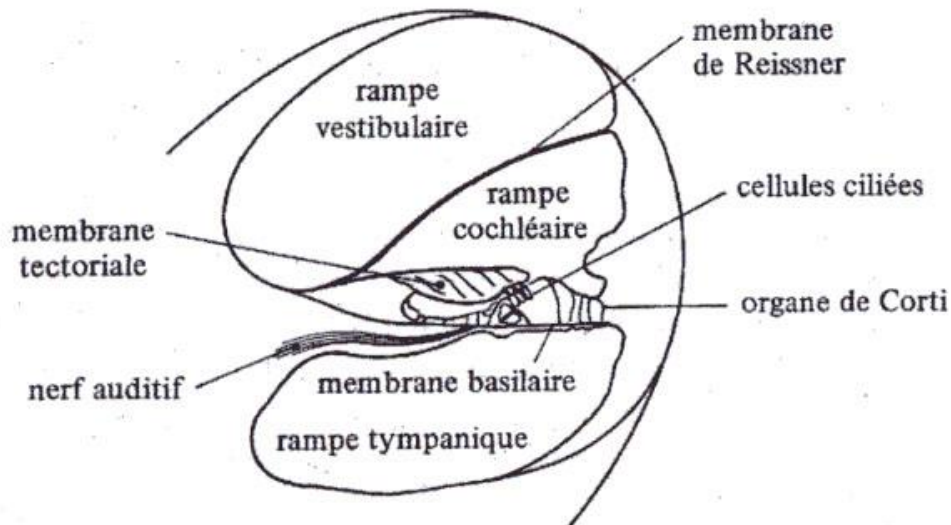
Magnitude of movements
for high frequencies

Basilar membrane function

Magnitude of movements
for low frequencies



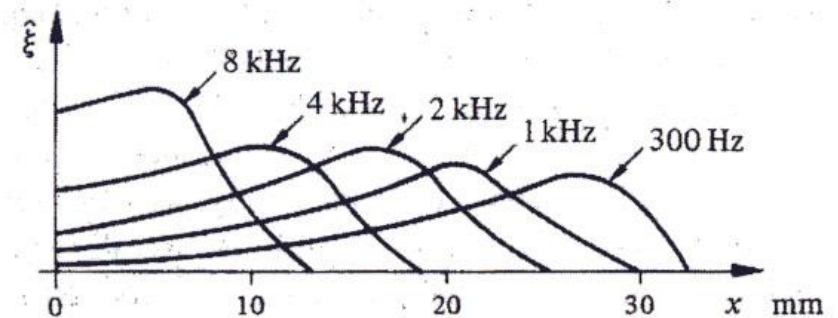
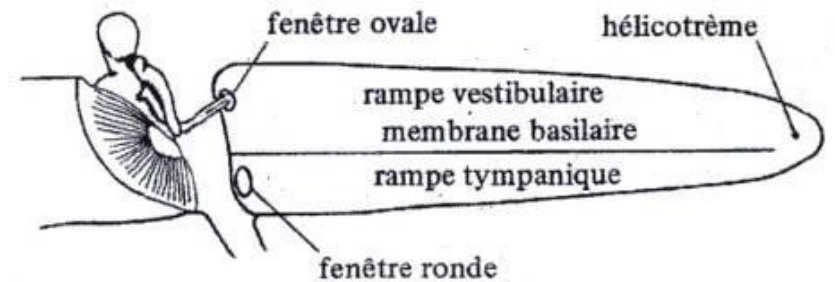
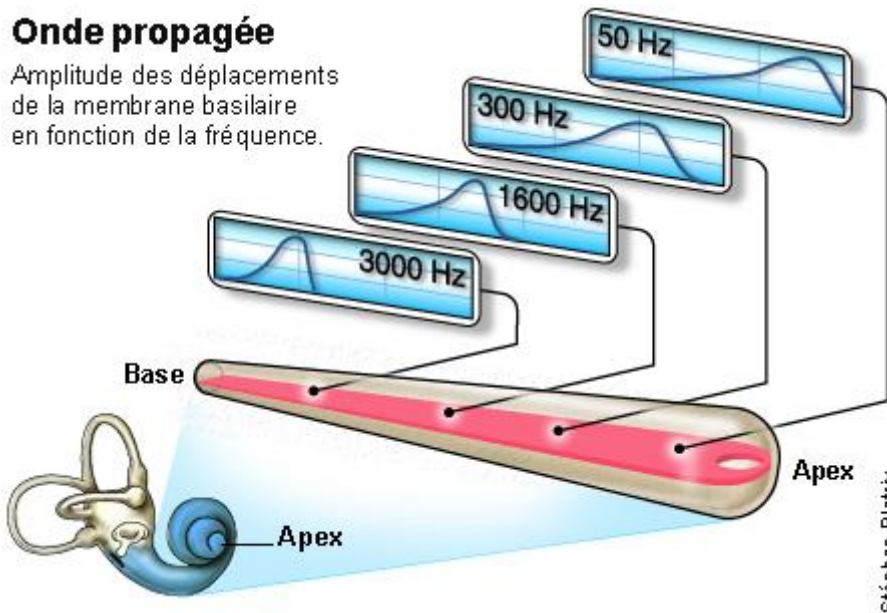
Basilar membrane function



Basilar membrane function

Onde propagée

Amplitude des déplacements de la membrane basilaire en fonction de la fréquence.



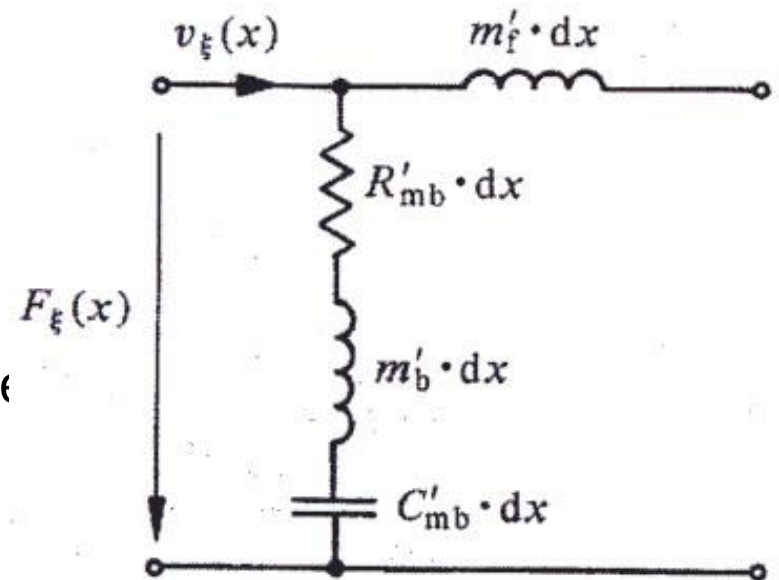
Courbes de von Békésy

Model of cochlea

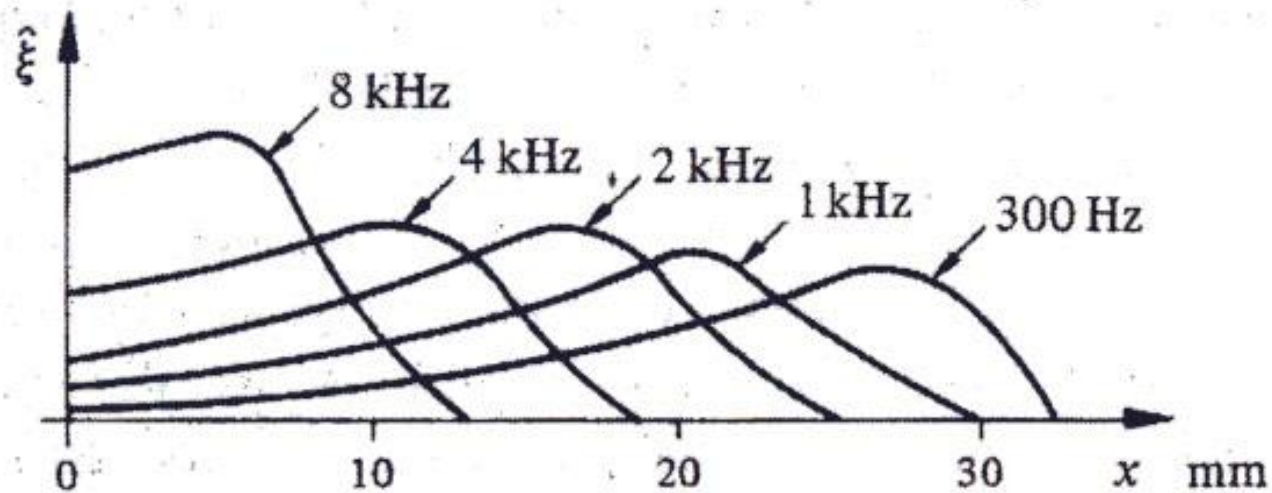
Simple model: transmission line

Membrane element dx :

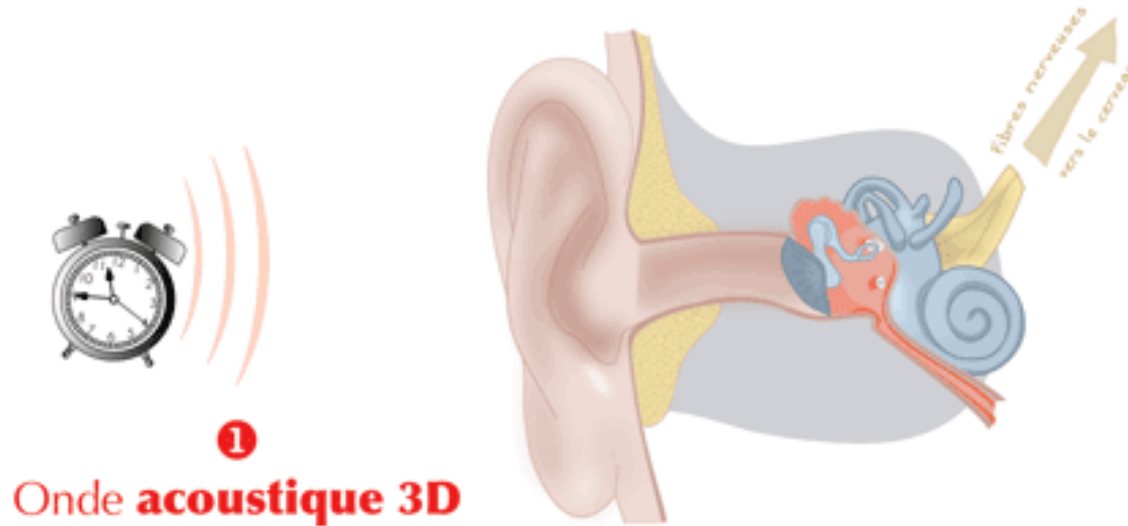
- lineic resistance R'_{mb} (losses)
- lineic mass m'_b (of the membrane)
- lineic compliance C'_{mb} (elasticity of the membrane) – depends on x !!!
- lineic mass of liquid m'_f



Model of cochlea



The ear as an electroacoustic system



rights: Eric Bavu,CNAM

More animation: <http://www.youtube.com/watch?v=PeTriGTENoc>

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