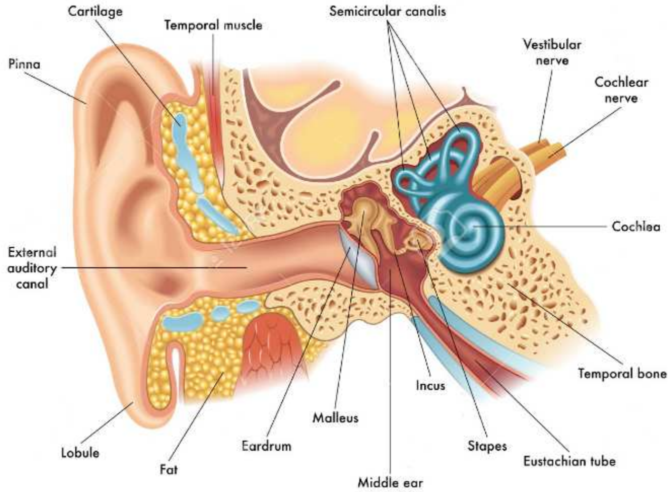
Outer ear and middle ear

Václav Vencovský

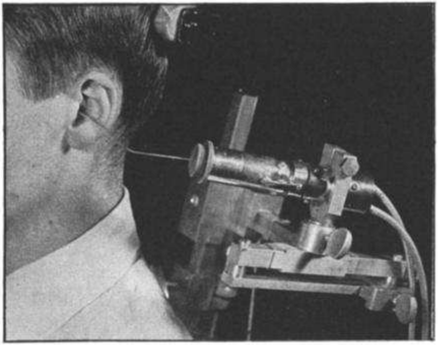
Department of Radioelectronics, Faculty of Electrical Engineering, Czech Technical University in Prague, Czech Republic

Human peripheral ear



Adapted from https://www.123rf.com/photo_66863654_stock-vector-ear-anatomy.html

Pressure at the eardrum



Taken from Wiener and Ross (1946) JASA:18, 401

- Wiener and Ross (1946) measured acoustic pressure in the auditory canal and compared it with acoustic pressure of a microphone placed in the center of the head (in the absence of the head)

Pressure at the eardrum

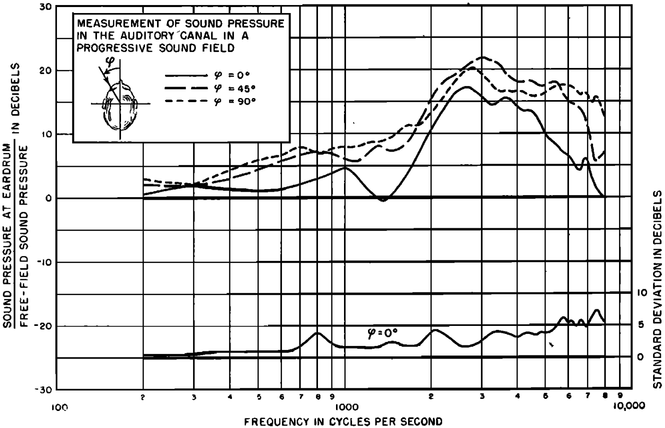
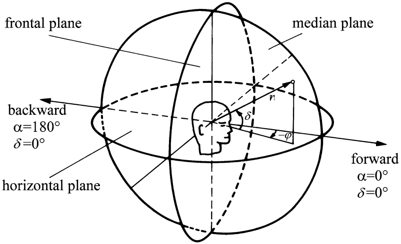


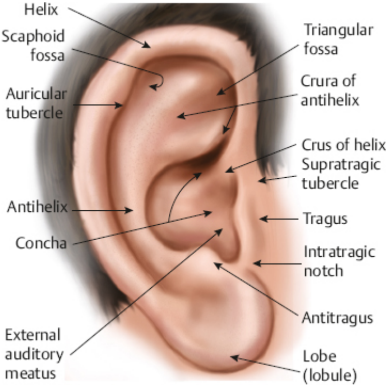
FIG. 5. Ratio of the sound pressure at the eardrum to the sound pressure in the free field at the center of the observer's head. The average of 6–12 male ears is shown for various azimuths as a function of frequency.

Taken from Wiener and Ross (1946) JASA:18, 401

Pinna and body effect



Blauert (1997) Spatial Hearing



Taken from `https://entokey.com/anatomy-and-physiology-of-the-auditory-system/`

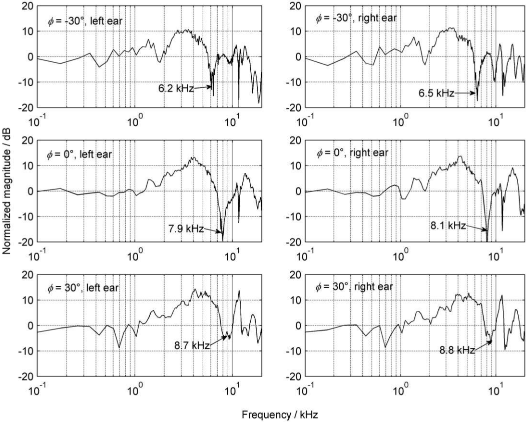
Head-related transfer functions (HRTFs)

Taken from Pec et al. (2007) EUSIPCO

Taken from Zhong and Xie (2014) Head-related transfer functions and virtual auditory displays

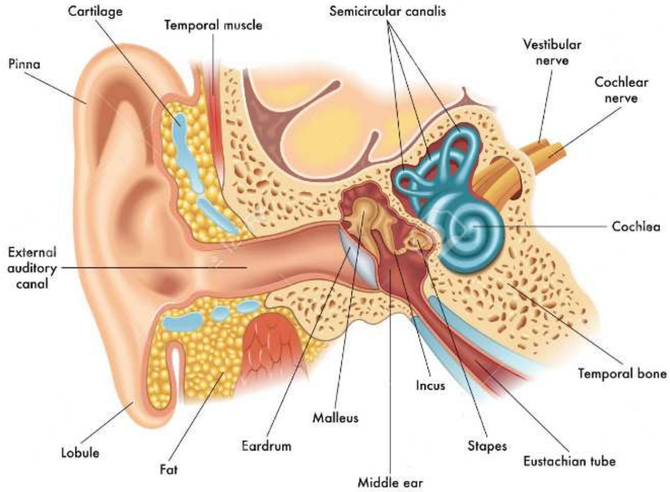
Head-related transfer functions (HRTFs)

HRTF for different elevations ϕ



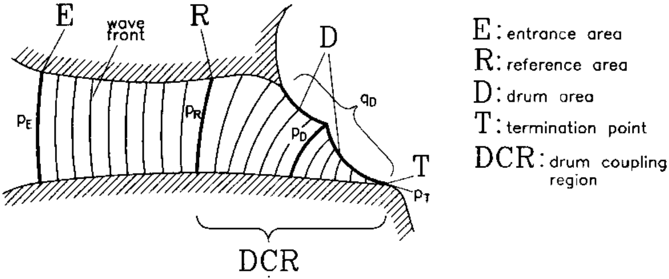
Taken from Zhong and Xie (2014) Head-related transfer functions and virtual auditory displays

Auditory canal/external auditory meatus



Adapted from https://www.123rf.com/photo_66863654_stock-vector-ear-anatomy.html

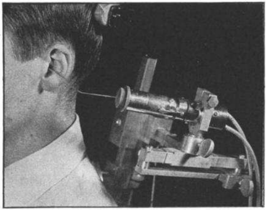
Auditory canal as a wave guide



Adapted from Hudde (1998) Acta Acustica 84:720-738

- Auditory canal is about 2.5 cm long tube (wave guide) with diameter *approx*8 cm ended by eardrum (tympanic membrane)
- We can approximate the auditory canal by a tube closed on one side
- Such a system resonates at the multiples of $\lambda/4$

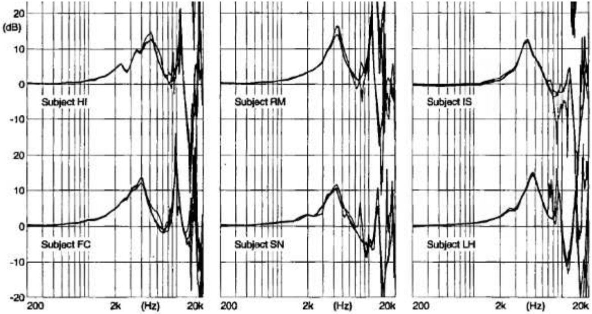
Transfer characteristic of the auditory canal



Taken from Wiener and Ross (1946)
JASA:18, 401

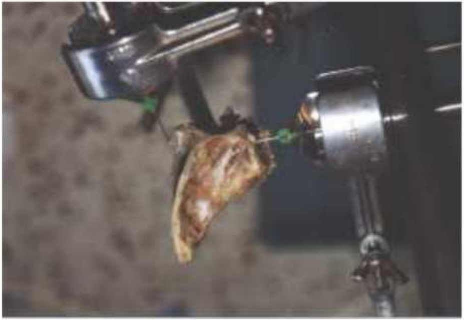
- Transfer function of the auditory canal can be mesaured by a probe

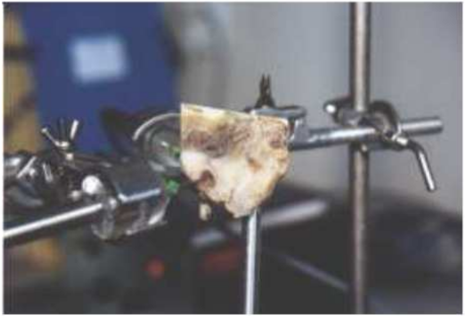
- Such measurement was, e.g. conducated by Hammershøi and Møller (1996)



Adapted from Hammershøi and Møller (1996) JASA 100:408–427

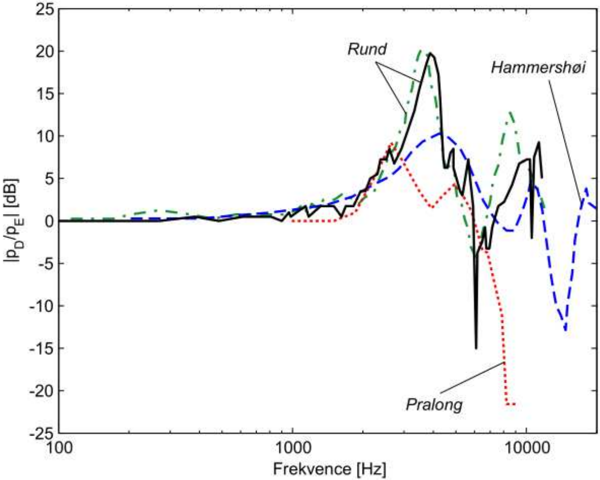
Transfer characteristic of the auditory canal





Adapted from Rund (2004) Přenos akustického tlaku vnějším zvukovodem lidského ucha. Ph.D. Thesis

Transfer characteristic of the auditory canal



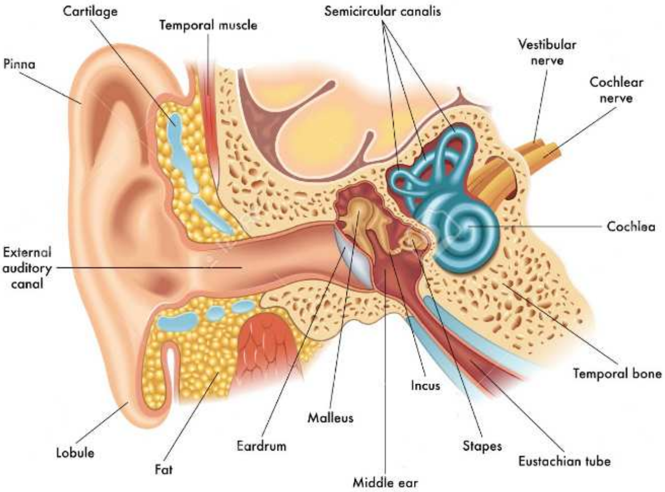
Taken from Bureš (2008) Modelování lidské sluchové dráhy a vnímání zvuku Ph.D. Thesis

Shapes of auditory canal

- Shape of the auditory canal differ across subjects

Taken from Rund (2004) Přenos akustického tlaku vnějším zvukovodem lidského ucha. Ph.D. Thesis

Middle ear



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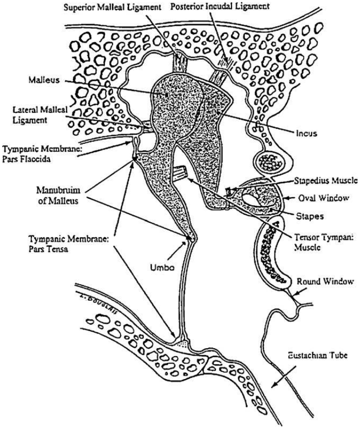
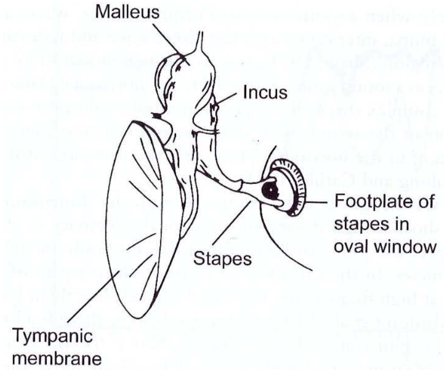
Middle ear

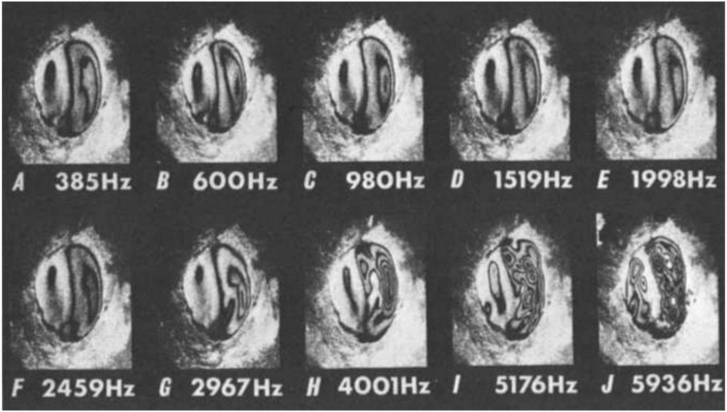


Taken from Volandri et al. (2012) Med. Eng. Phys.



Taken from Pickles (2008) An Introduction to the Physiology of Hearing

Eardrum (tympanic membrane)



Taken from Khanna and Tonndorf (1972)

Impedance transformer

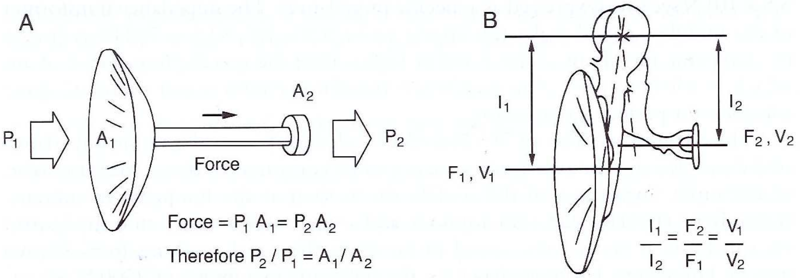
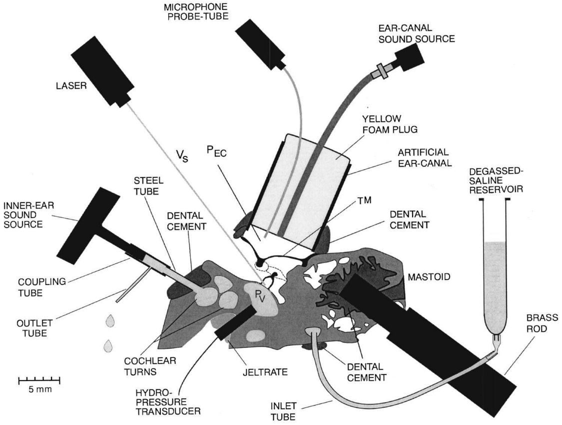


Fig. 2.5 The two mechanisms of the middle ear acoustic impedance transformer. (A) The main factor is the ratio of the areas of the tympanic membrane and the oval window. The middle ear bones are here represented by a piston. (B) The lever action increases the force and decreases the velocity. *A*, area; *F*, force; *L*, length; *P*, pressure; *V*, velocity.

Pascal et al. (1998) assumed $A_1 \approx 53\,\text{mm}^2$, $A_2 \approx 3.2\,\text{mm}^2$, and $l_1/l_2 = 1$

Taken from Pickles (2008) An Introduction to the Physiology of Hearing

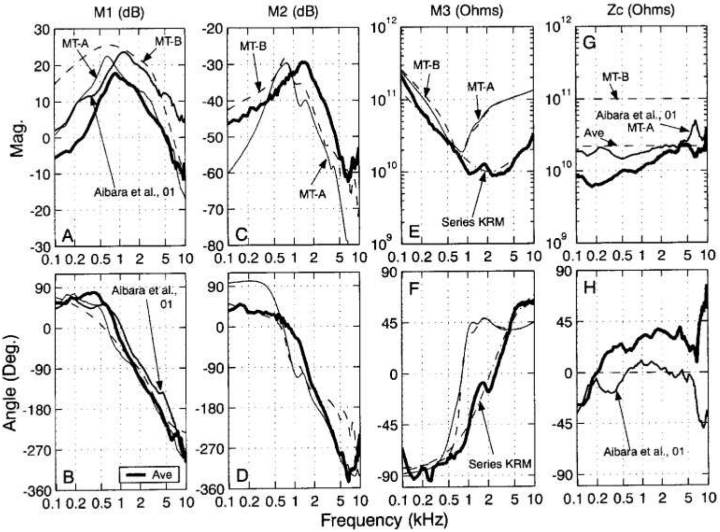
Measurement of middle-ear transfer function



Taken from Puria (2003) JASA

Transfer characteristics of the middle ear

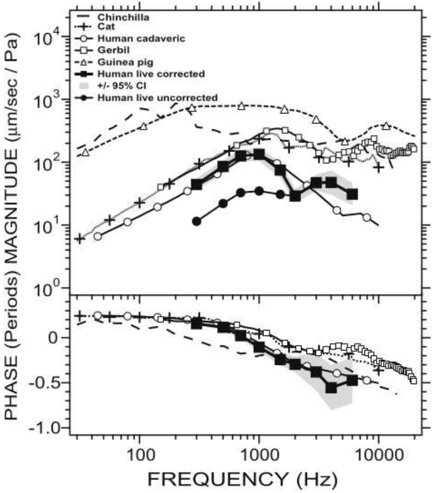
- Vestibular pressure relative to the pressure at the eardrum $\hat{M}1(\omega) = \dfrac{\overrightarrow{\hat{P}}_{v}(\omega)}{\overrightarrow{\hat{P}}_{\mathrm{ec}}(\omega)}$
- Eardrum pressure relative to the vestibular pressure when the ear is driven from within the cochlea $\hat{M}2(\omega) = \dfrac{\overleftarrow{\hat{P}}_{\mathrm{ec}}(\omega)}{\overleftarrow{\hat{P}}_{v}(\omega)}$.
- Reverse impedance of the middle ear $\hat{M}3(\omega) = \dfrac{\overleftarrow{\hat{P}}_{v}(\omega)}{\overleftarrow{\hat{V}}_{\mathrm{st}}(\omega) S_{\mathrm{ow}}}$
- Stapes velocity relative to the eardrum pressure $\hat{M}4(\omega) = \dfrac{\overrightarrow{\hat{V}}_{\mathrm{st}}(\omega)}{\overrightarrow{\hat{P}}_{\mathrm{ec}}(\omega)}$
- Input impedance of the cochlea $\hat{Z}_{\mathrm{c}}(\omega) = \dfrac{\overrightarrow{\hat{P}}_{v}(\omega)}{-\overrightarrow{\hat{V}}_{\mathrm{st}}(\omega) S_{\mathrm{ow}}}$



Taken from Puria (2003) JASA

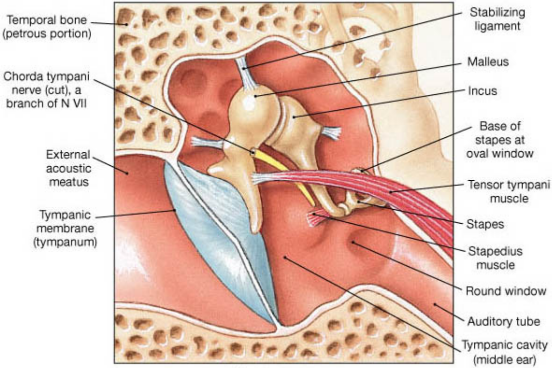
Measurement of middle-ear transfer function

- Latest measurements of the middle-ear transmission were conducted in alive humans during surgery for cochlear implantation (Chien et al., 2009)
- Figure shows mesurement in human cadavers (Kringlebotn and Gudersen, 1985) and alive humans (Chien et al., 2009)
- In addition, transfer function for several other mammalian species are shown



Taken from Chien et al. (2009) JASA

The middle ear muscles



(b) The middle ear

Taken from
`http://droualb.faculty.mjc.edu/LectureNotes/Unit5/special_sensesSpring2007withfigures.htm`

1. Tensor tympani
   - attached to the malleus near tympanic membrane
   - invertvated by the trigeminal (fifth) cranial nerve
2. Stapedius muscle
   - attached to the stapes
   - inervated by the facial (seventh) cranial nerve

The middle ear muscles

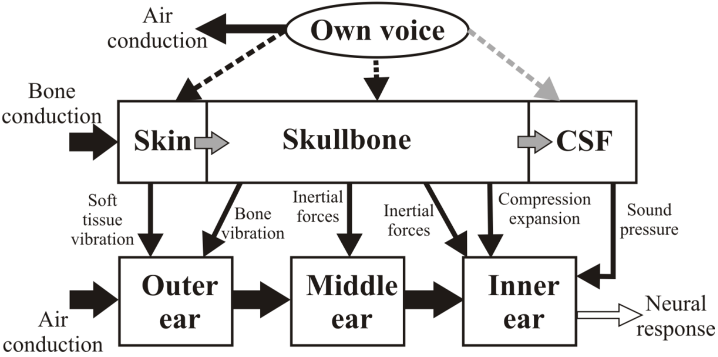
- Contraction of the muscles affects the middle ear transmission
- The main effects are observed at low frequencies (below about 2 kHz) since the muscle contraction changes (increases) stiffness in the ossicular chain
- Contraction of the muscless attenuates middle ear tranmission at low frequencies (below about 2 kHz), however, some effects can be observed also at higher frequencies
- The muscles are contracted:
  - in response to loud sound (more than 75 dB above the absolute threshold)
  - by vocalization
  - tactile stimulation of the head or by body movement
  - in some subjects, even voluntarily

Suggested function of the middle ear muscles according to Pickles (2007)

- Protection of the ear from noise demage (however, the reflex is slow, so the protection is questionable for impulse sounds)
- Automatic gain control for stimulus intensities above the reflex threshold (only at low frequencies)
- Effect on amount of masking due to the presence of low frequency tones – reduces the upward spread of masking

Bone conduction

- Sound can approach the cochlea also via bone vibration
- This approach is used during audiometry or hearing aids in subjects with impariment in the outer or middle ear
- In addition, the approach might be promising in future applications (for more information see Stenfelt (2011)



Taken from Stenfelt (2011)

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