Aalto University
School of Electrical Engineering

Communication acoustics
Ch 19: Technical audiology

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Technical audiology

- What if we don’t hear?
  - Why don’t we hear? (mechanisms)
  - How to measure ? (audiometry)
  - How to improve hearing? (hearing instruments)
- Technical devices:
  - Audiometric equipment
  - Hearing aids
  - Cochlear implants

Hiljainen maailma

"A silent world"
https://areena.yle.fi/1-50192470

Technical audiology

SFS-EN 15927

A robust foundation of knowledge and proficiencies in audiology and acoustics is a vital necessity for providing hearing and communication rehabilitation which meets the clients' needs and expectations and the current standards of technological and medical progress.

Necessary knowledge . . .

EN 60118-4, Electroacoustics - Hearing aids - Part 4: Induction loop systems for hearing aid purposes - Magnetic field strength
EN 60118-7, Electroacoustics - Hearing aids - Part 7: Measurement of the performance characteristics of hearing aids for production, supply and delivery quality assurance purposes
EN 60645-1, Electroacoustics - Audiological equipment - Part 1: Puretone audiometers
EN 60645-2, Audiometers - Part 2: Equipment for speech audiometry
EN 60645-5, Electroacoustics - Audiometric equipment - Part 5: Instruments for the measurement of aural acoustic impedance/admittance
EN 61669, Electroacoustics - Equipment for the measurement of real-ear acoustical characteristics of hearing aids
EN 61672-1, Electroacoustics - Sound level meters - Part 1: Specifications
EN ISO 389-1, Acoustics - Reference zero for the calibration of audiometric equipment - Part 1: Reference equivalent threshold sound pressure levels for pure tones and supra-aural earphones
EN ISO 389-2, Acoustics - Reference zero for the calibration of audiometric equipment - Part 2: Reference equivalent threshold sound pressure levels for pure tones and insert earphones
EN ISO 389-3, Acoustics - Reference zero for the calibration of audiometric equipment - Part 3: Reference equivalent threshold force levels for pure tones and bone vibrators
EN ISO 389-4, Acoustics - Reference zero for the calibration of audiometric equipment - Part 4: Reference levels for narrow-band masking noise
EN ISO 389-8, Acoustics - Reference zero for the calibration of audiometric equipment - Part 8: Reference equivalent threshold sound pressure levels for pure tones and circumaural earphones
EN ISO 8253-1, Acoustics - Audiometric test methods - Part 1: Basic pure tone air and bone conduction threshold audiometry
EN ISO 8253-2, Acoustics - Audiometric test methods - Part 2: Sound field audiometry with pure-tone and narrow-band test signals
EN ISO 8253-3, Acoustics - Audiometric test methods - Part 3: Speech audiometry
ISO 12124, Acoustics - Procedures for the measurement of real-ear acoustical characteristics of hearing aids
ISO 16832, Acoustics - Loudness scaling by means of categories.
etc . . .

Hearing disorders and impairments

- Hearing thresholds?
  - 0 dB HL (i.e., hearing level) is the normal hearing reference (ISO 389-9)
  - = dB ref HL, i.e., in reference to the frequency specific hearing threshold of normal human auditory system (note the difference to dB SPL)
  - Deviations of this reference are called hearing threshold shifts
- Hearing loss is (kuulonalenema / kuulovamma)
  - Degradation of hearing sensitivity
    - Quantified often in terms of hearing threshold shift
  - However, hearing thresholds do not tell everything!
    - Loss of hearing ability in some dimension

Equal loudness contours

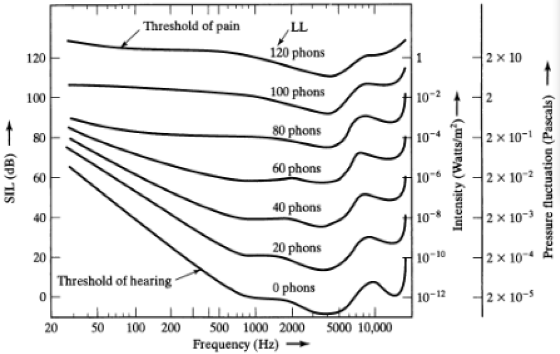


Figure 6-4 Equal loudness curves. The curve with the lowest level marks the threshold of hearing; the curve with the highest level marks the threshold of pain.

Technical audiology

- Categories of handicap
  - Disease (sairaus)
  - Impairment (vaurio)
  - Disability (toimintavajavuus)
  - Handicap (haitta)
- Hearing disorders: social classification
  - Hard-of-hearing persons (huonokuuloinen)
  - Deafened persons (kuuroutunut)
  - Deaf persons (kuuro)

Hearing degradation

- Hearing disabled population
  - WHO: 360 million people worldwide have a disabling hearing loss
  - $\approx$5 % of population
  - In Finland: $\approx$740 000 with hearing degradation 14 000 new hearing device fittings per year
  - Occurrence increases with age: at 65 years 37%, at 75 years 65%
  - Population continues to age: 2000 $\rightarrow$ 2020, a 7-fold increase in people in need of aural rehabilitation
- Effects of hearing degradation
  - Early language acquisition
  - Speech communication / Social impact
  - Listening comfort
  - Listening effort in communication
  - Music perception

Classification of impairments

Pure tone average = PTA

- A common measure of hearing degradation
- Average of hearing threshold values at 500, 1000, 2000, 4000 Hz
  - Mild: 20-40 dB HL
  - Moderate: 40-70 dB HL
  - Severe: 70-95 dB HL
  - Profound: equal to or over 95 dB HL

Hearing loss and dementia

- Strong link between hearing loss and dementia, first noticed already in 1989
- Compared to a normal-hearing person, a person with ...
  - mild hearing loss has 2 $\times$ risk
  - moderate hearing loss has 3 $\times$ risk
  - severe hearing loss has 5 $\times$ risk

  ... of developing dementia during the next 10 years (Lin *et al.*, 2011)
- But this risk can be removed by using a hearing aid!
  (Amieva *et al.*, 2018)

Hearing loss and dementia

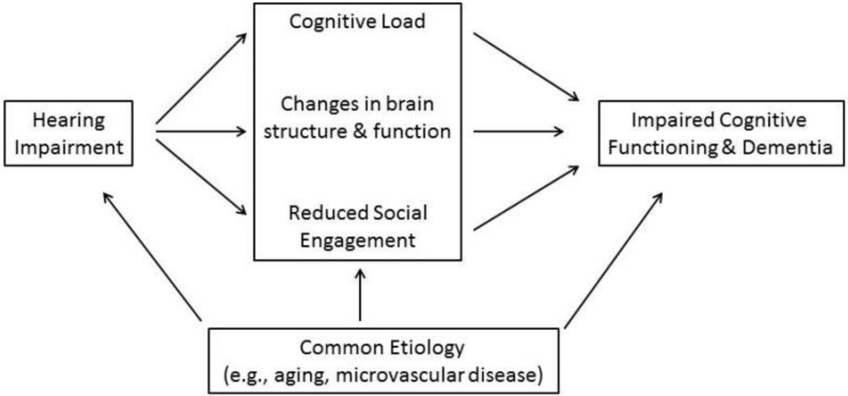


Figure: from Lin & Albert (2014)

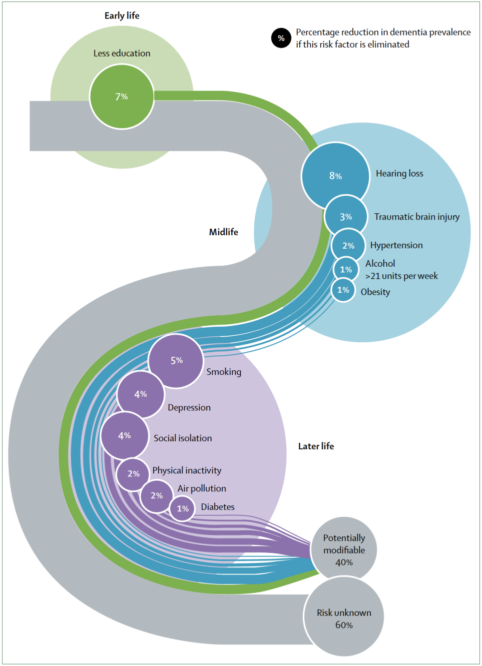


Figure 7: **Population attributable fraction of potentially modifiable risk factors for dementia**

Classification of impairments

- Conductive hearing loss
  - External and middle ear problems
- Sensorineural hearing loss
  - Inner ear and retrocochlear problems
- Central hearing loss
  - Higher neural levels
- Psychic hearing problems
  - No clear physiological reason

Conductive hearing loss

Sources of origin

- Blocked ear canal, tumor, or deformation
- Ear drum trauma
- Infection in the middle ear
- Mucous otitis media (glue ear, liimakorva)
- Otoclerosis (stiffening of ossicles, kuuloluuketjun jäykistyminen)
- Malfunction of the eustachion tube

Consequence: hearing threshold shift

Sensorineural hearing loss

Sources of origin:

- Excess noise exposure
- Age-related hearing loss (presbyacusis)
- Cancer, inborn hearing loss, head trauma
- Ototoxic substances

Consequences:

- Hearing threshold shift
- Decreased dynamic range
- Decreased frequency selectivity -> increased masking
- Tinnitus and hyperacusia

Central and psychic hearing problems

Central hearing loss

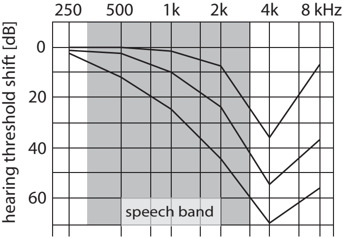
- Higher neural levels
- Problems in sound separation or speech analysis
- Slow vs. fast speech
- Problems in localization (spatial separation)
- Tinnitus

Psychic hearing problems

- No clear physiological reason

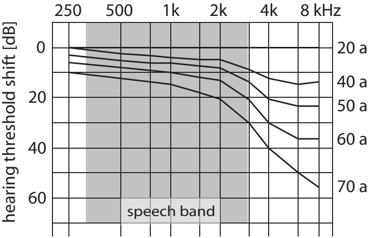
Effects of hearing impairments

Hearing threshold shift



a)

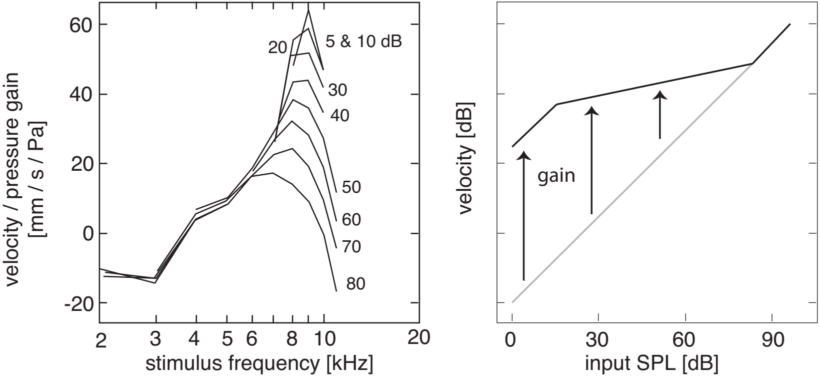
Loud noise effect
(impulse noise)



b)

Effect of age
(presbyacusis)

Outer hair cells in healthy cochlea



Adopted from Ruggero et al. (1997)

Hair cell damage mechanisms

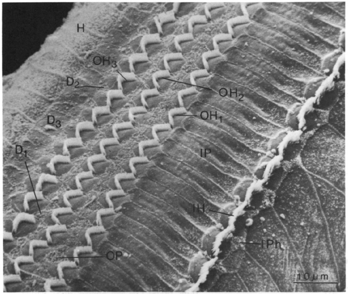


Fig. 4. Surface view of chinchilla organ of Corti showing inner phalangeal cell (IPh), inner hair cells (IH), inner pillar cell (IP), outer pillar cell (OP), and 3 rows of outer hair cells (OH_1, OH_2, OH_3) and Deiters' cells (D_1, D_2, D_3). H, Hensen's cell.

Figure: Healthy Organ of Corti, from Lim (1986)

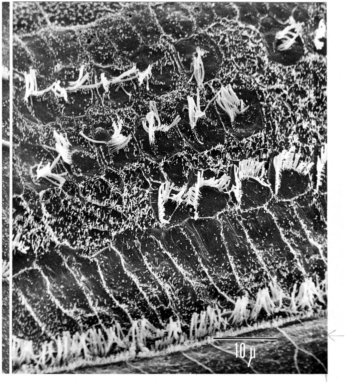
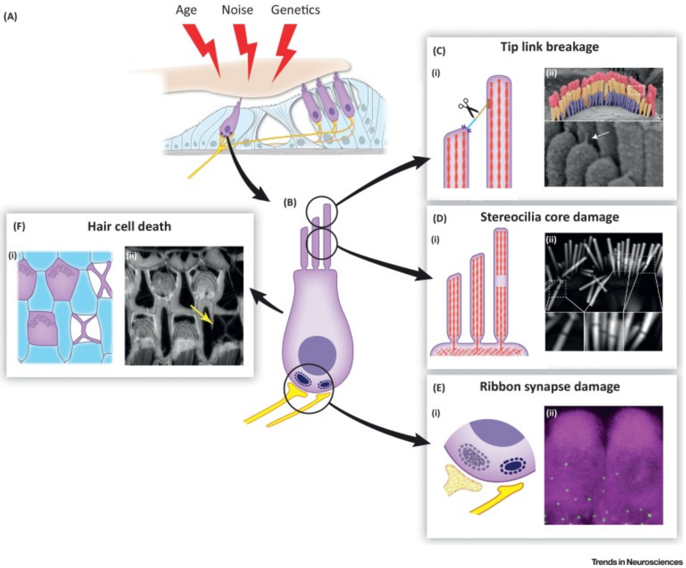
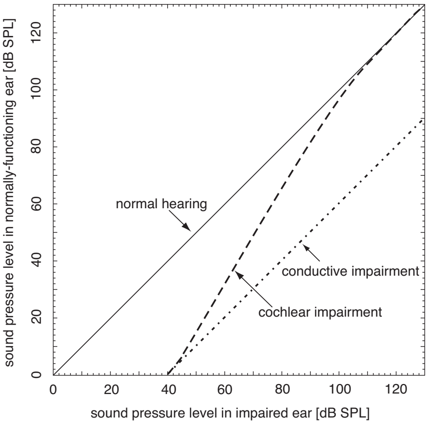


Figure: Damaged Organ of Corti, from Encyclopædia Britannica

Hair cell damage mechanisms



Sensorineural effects: recruitment



Adapted from Moore (2007)

Basilar membrane input-output function

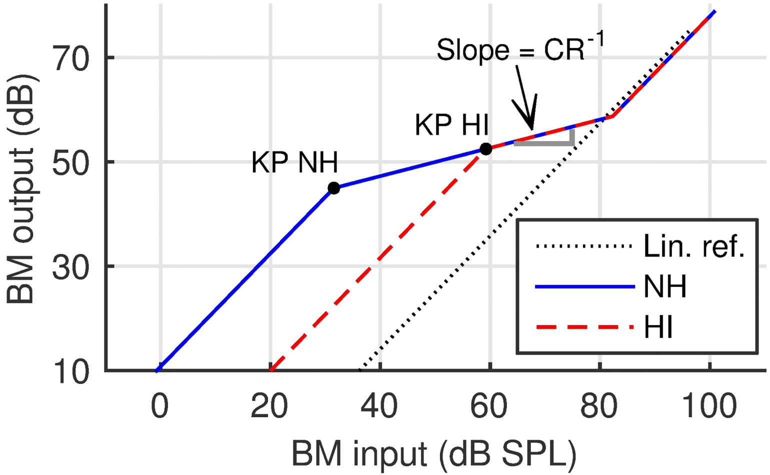
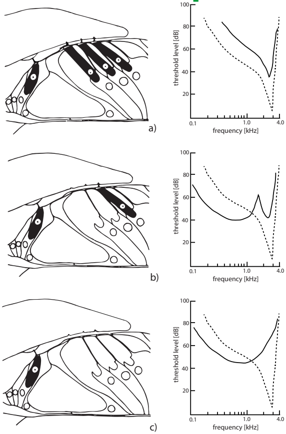


Figure: from Fereczkowski *et al.* (2017)

Sensorineural effects: Decreased frequency selectivity



Inner hair cell damage

Outer hair cell partial damage

Outer hair cell full damage

Adapted from Liberman and Dodds (1984)

Sensorineural effects:
Decreased frequency selectivity

- Frequency selectivity decreases
- Critical bands broaden
- More energy to each critical bands
- Increased masking effect (even 10-12 dB!)
- Problems in sound source separation and speech intelligibility in noise/reverberation
- Speech communication problems
- Larger signal-to-noise ratio needed

Tinnitus and hyperacusia

Tinnitus

- Sinusoidal tone, hum, broadband noise, pulsation, etc.
- Source can be at different levels
  - Basilar instability
  - Neural phantom sound
- No cure known
- Treatments available, results are mixed
  - Tinnitus maskers
  - Tinnitus Retraining Therapy (TRT)

Hyperacusia

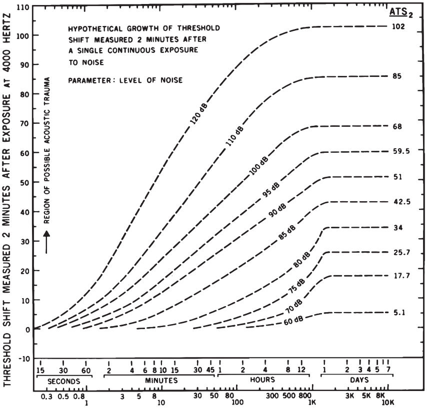
- oversensitivity to sound

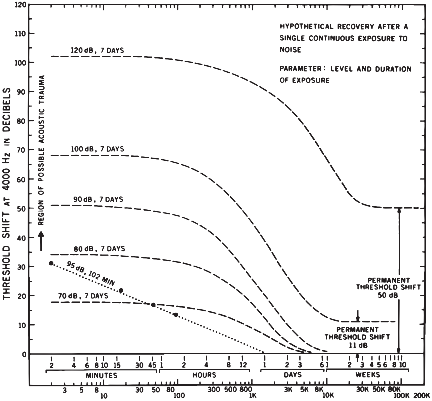
Noise

Noise = harmful or disturbing sound

- Harmfulness
  - Risk of hearing loss
- Disturbance
  - e.g., decrease in work efficiency
- Annoyance
  - A more subjective concept
- Subjective handicaps can have further indirect consequences
  Psychic or physical

Temporary vs. permanent threshold shift





Adapted from Miller (1974)

Noise as a cause of hearing loss

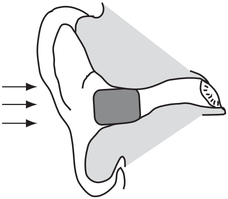
Noise measurement, A-weighted equivalent level

$$L_{\mathrm{eq}} = 10 \log_{10} \frac{\sum \Delta t_i \, 10^{L_i/10}}{T}$$

Other factors:

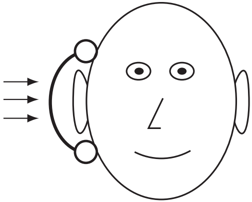
- Vibration
- Smoking
- Genetic effects
- Combined = often more than their sum

Hearing protectors



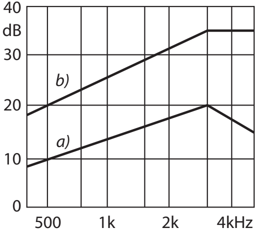
a)

Ear plugs



b)

Ear muffs



c)

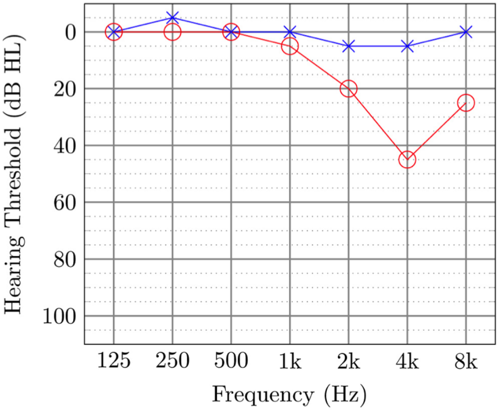
Attenuation

Adapted from Toivanen (1976)

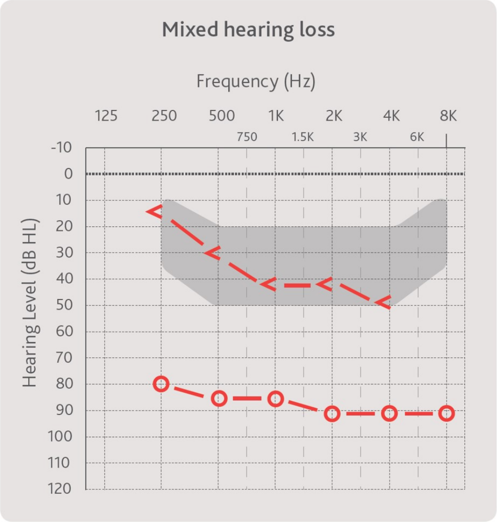
Pure-tone audiometry

Audiometer and calibrated headphones

Pure-tone audiometry



Mixed hearing loss audiogram



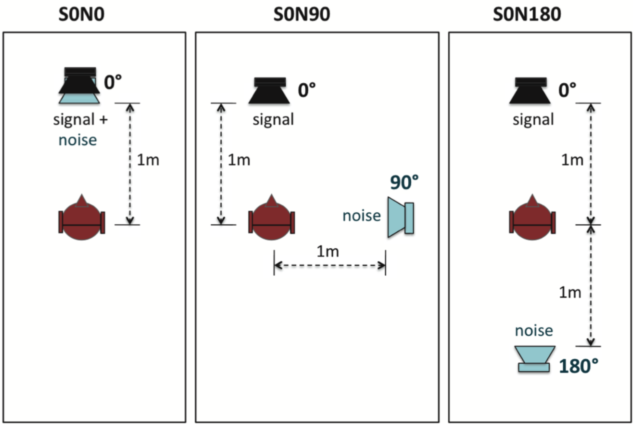
Speech audiometry

- Testing of speech intelligibility
  - This is the major problem so why not test it?
- Signal: words or sentences
- In silence or with background noise (=masker)
- Measures such as:
  - Speech-recognition threshold (SRT)
  - Percent-intelligibility

Sound-field audiometry

- Loudspeakers instead of headphones
- Overcomes problems with headphones:
  - Acoustic coupling btw headphone and ear is somewhat unpredictable
  - Hearing aids dont generally have microphones in ear canal
  - Listening scenario is more natural
  - Spatial aspects of sound
  - Real-world representative results?
- However:
  - More expensive, more complex

Sound-field audiometry

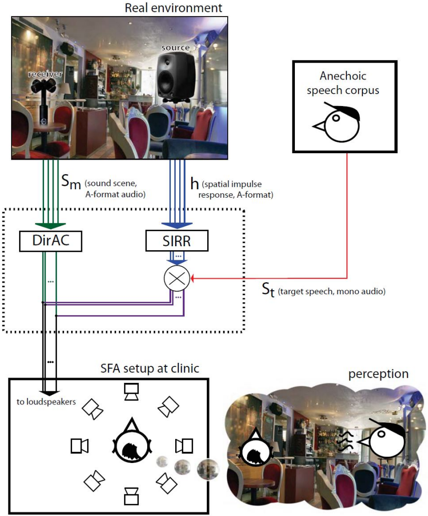


Adapted from Rychtarikova (2011)

Sound-field audiometry

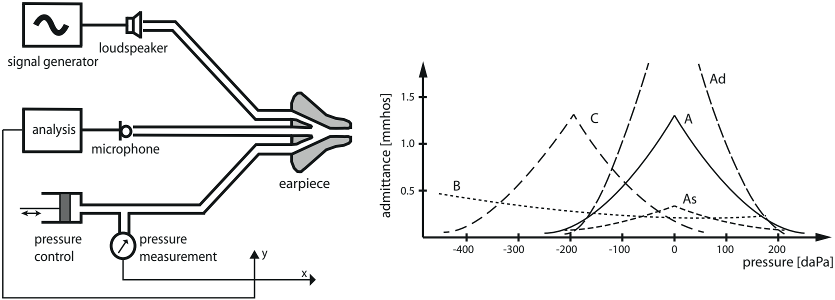
Minnaar et al. (2010)

Sound-field audiometry



Koski et al. (2013)

Ear drum impedance measurement



- A = normal middle ear function,
- As (for A-shallow) = stiffened middle ear system,
- Ad (for A-deep) = flaccid eardrum,
- B = fluid in the middle ear or perforation of the eardrum,
- C = negative pressure in the middle ear.

Campbell and Mullin (2012)

Auditory dysfunction and diagnostics, summary

	Function	Dysfunction
Outer ear	Directional filtering	Malformation
Middle ear	Impedance matching: air → fluid	Conductive hearing loss (e.g. otosclerosis)
Inner ear	Transform: vibration → neural activity Spectral analysis (place code)	Cochlear hearing loss (e.g. noise-induced, age-related)
Auditory nerve/ brainstem	Coding of information Interaural differences Modulation processing	Retrocochlear hearing loss Deterioration of localization
Cortex	Speech perception Complex perception	Central hearing disorders (e.g. aphasia)

Diagnostics

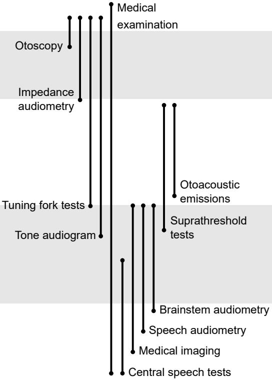


Figure: Adapted from Kollmeier (2008)

Hearing aid types

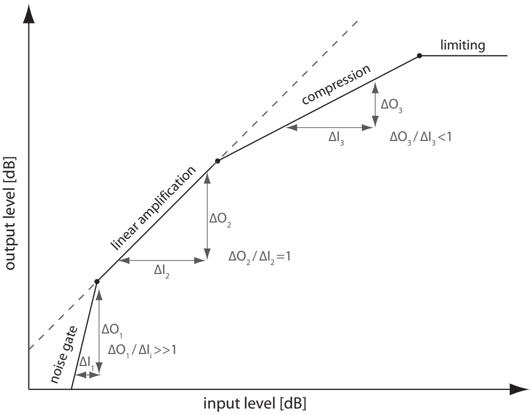
a) b) c)

- (a) behind-the-ear (BTE) hearing aid
- (b) in-the-ear (ITE) hearing aid
- (c) completely-in-the-canal (CIC) hearing aid

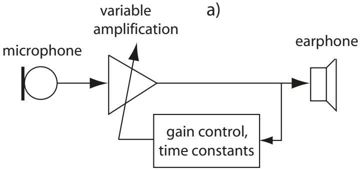
Signal processing in hearing aids

- Match the device with the individual needs of the user
- Different processing in each frequency band
  - Amplification
  - Compression
  - Limiting
- Noise suppression

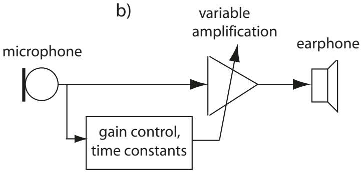
Gain control



Hearing aid gain control

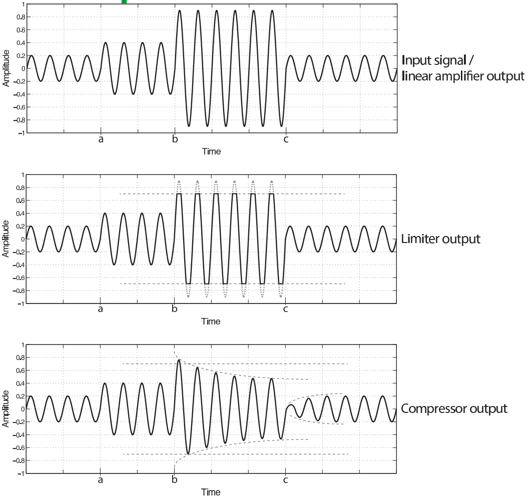


Feedback control



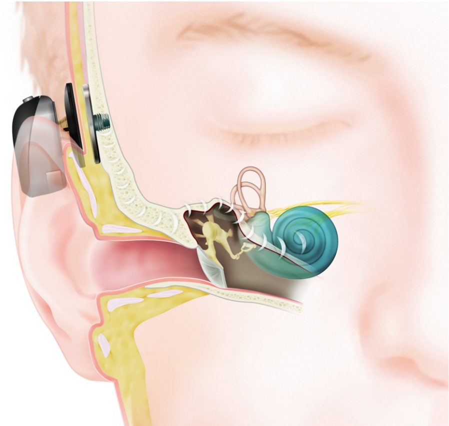
Feedforward control

Hearing aid output waveforms

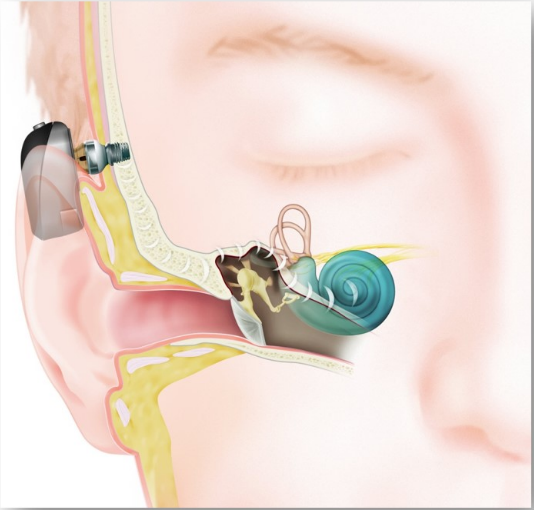


Bone-conduction devices

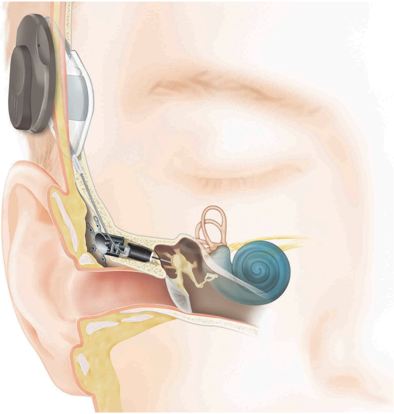
Bone-anchored hearing aid



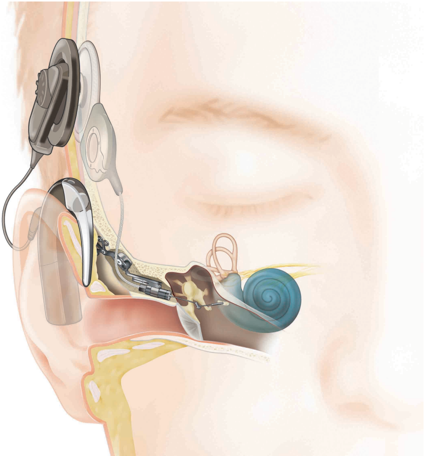
Bone-conduction devices



Acoustic implant versions



Acoustic implant versions

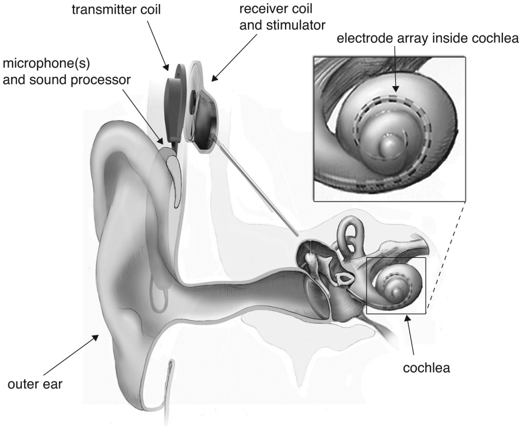


©Cochlear

Other features in hearing aids

- Directional microphones
    - Fixed or adaptive beam
- Noise cancellation
- Wind noise cancellation
- Feedback cancellation
- Speech enhancement, blind source separation
- Binaural processing
- Hearing aid + FM-transmitter
- Pre-set modes for different situations

Cochlear implants



Adapted from National Institutes of Health (2014)

Sound processing in cochlear implants

Continuous interleaved sampling (CIS)

- Division to frequency bands
- Amplitude envelope extraction
- Compression and low-pass filtering
- Each channel is used to modulate a pulse train
  (One pulse train signal per electrode contact)

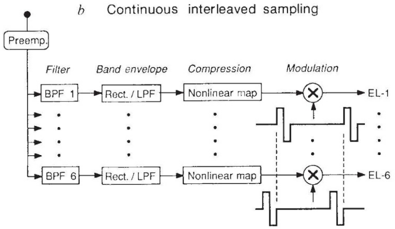


Figure: Block diagram of CIS coding strategy (Wilson *et al.*, 1991)

Sound processing in cochlear implants

Pulses are interleaved in time

- Minimum interference between channels
- Unfortunately: reduction of temporal information

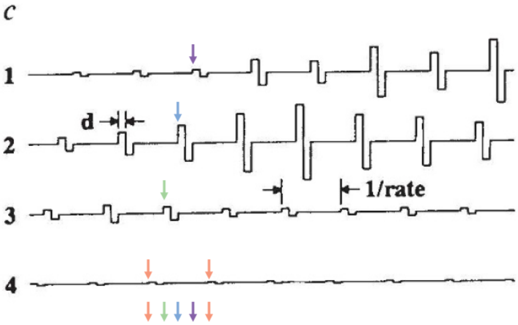
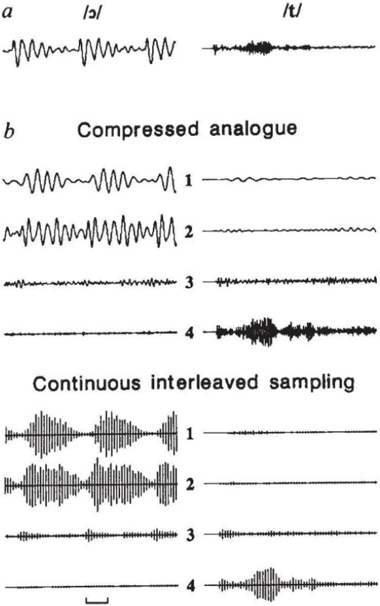
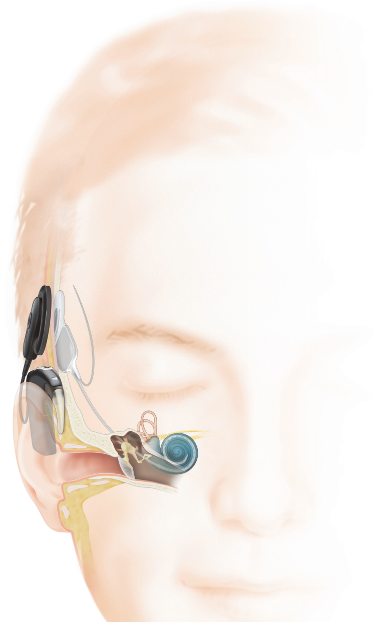


Figure: Interleaving of pulses

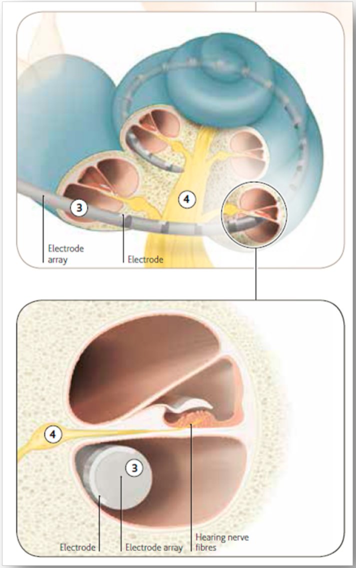


a
/ɔ/
/t/
b
Compressed analogue
1
2
3
4
Continuous interleaved sampling
1
2
3
4

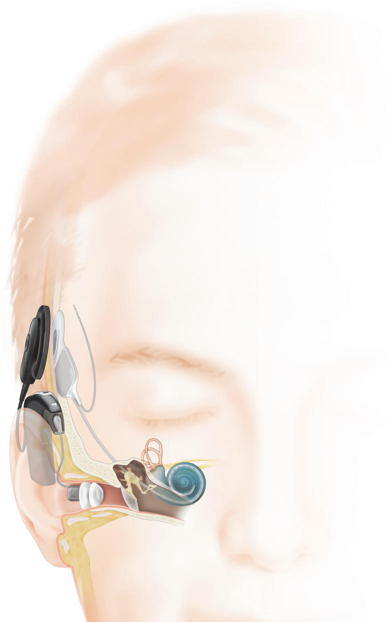
Cochlear implants



Cochlear implants



Hybrid cochlear implant



Hearing performance in cochlear implants

- Sound quality is significantly degraded
- High individual variations on hearing performance
- Phone conversation usually OK
- Bilateral implantation gives some spatial hearing
  - ILD's are available
  - ITD's are not generally available
  - Envelope ITD's may be used
  - Better speech intelligibility in noise

Cochlear implants

- $\approx$ 600 000 units fitted worldwide [Ear Foundation, 2016]
- In Finland: $\approx$ 200 devices implanted yearly (2018)
- For severe-to-profound hearing loss and/or when hearing aid does not provide sufficient help
  - Children: optimally, bilateral CI before language acquisition
  - Adults: mainly for postlinguistic hearing loss
    - Note: language acquisition issues, brain plasticity
- Price about 10000-20000 € per implant (2019)
- Also hybrid implants
  - Cochlear implant in high frequencies + hearing aid in low frequencies

References

These slides follow corresponding chapter in: Pulkki, V. and Karjalainen, M. Communication Acoustics: An Introduction to Speech, Audio and Psychoacoustics. John Wiley & Sons, 2015, *where also a more complete list of references can be found.*

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