Hearing Systems – Part 3 of 3

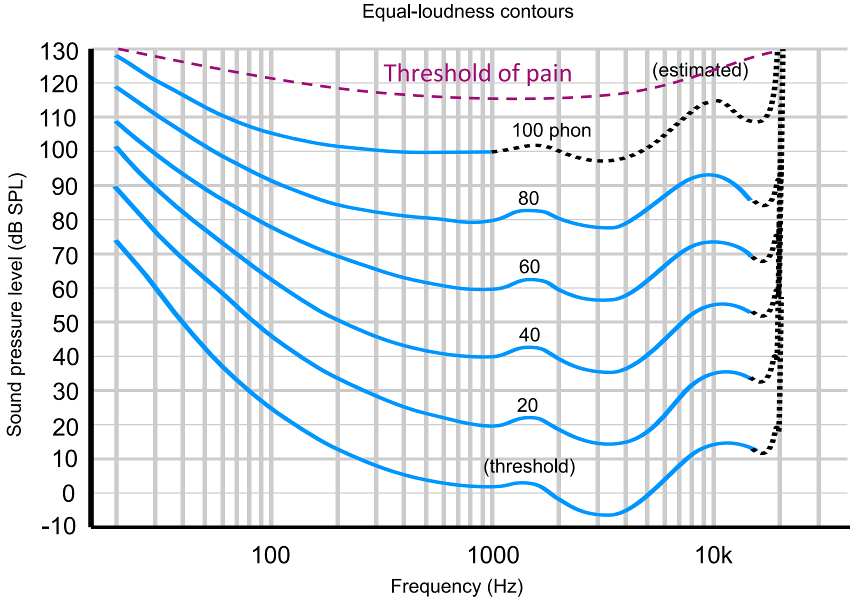
https://hearingsystems.github.io/

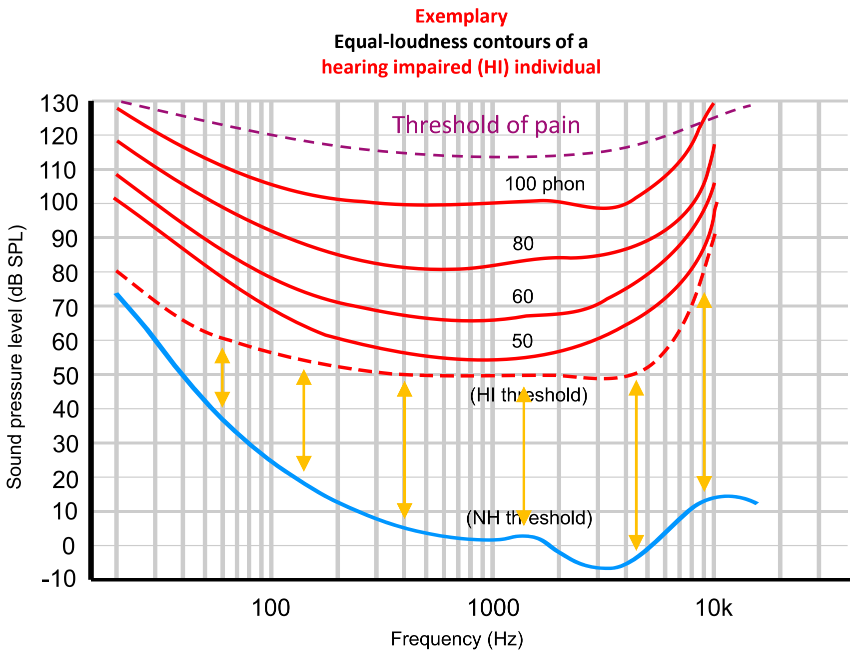
TU Ilmenau – Audio Signal Processing & Audio Systems

January 24, 2024

Dr.-Ing. Tamas Harczos

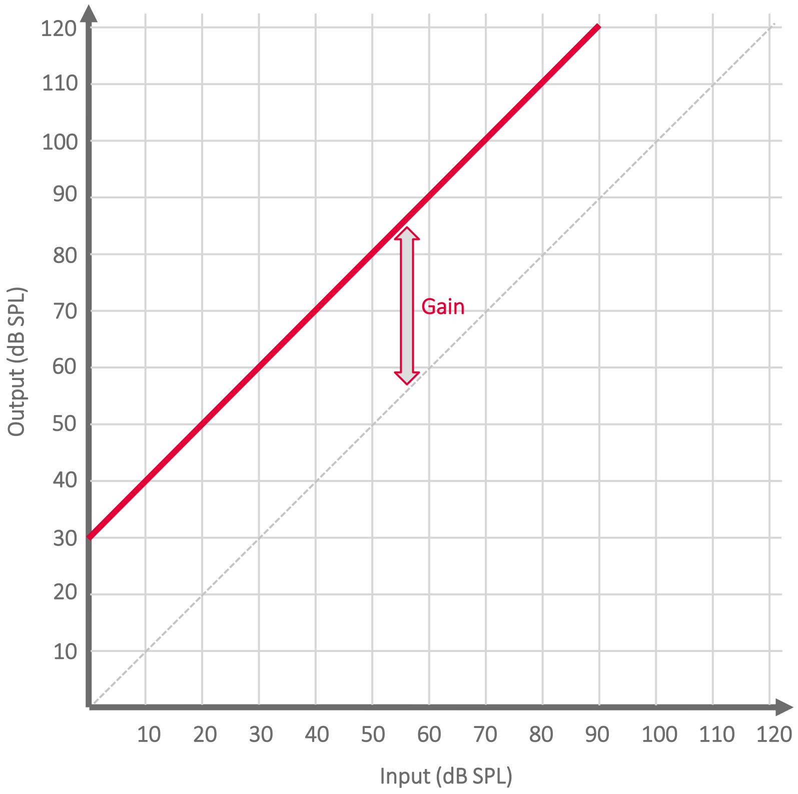
•• Recap: Equal-loudness contours





Based on: Strope & Alwan, 1995

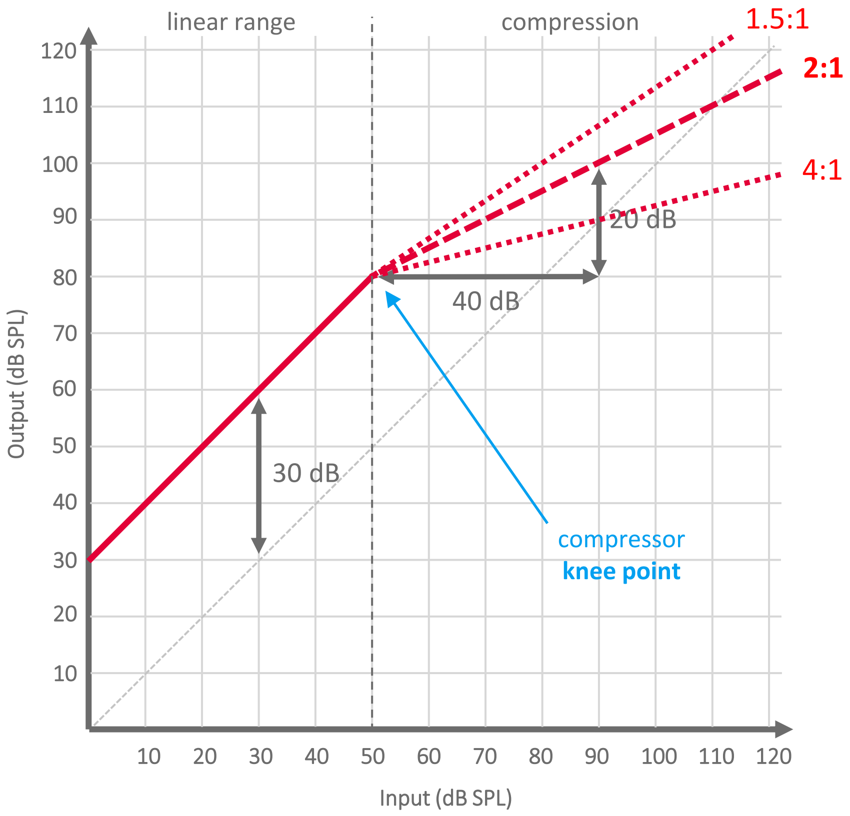
•• Hearing aids: Wide dynamic range compression



Linear amplification alone:

- Increases amplitude always with the same gain.
- Not conform with loudness perception of hearing impaired. (Will often cause uncomfortably loud percept.)
- Can lead to more hearing impairment.

•• **Hearing aids**: Wide dynamic range compression



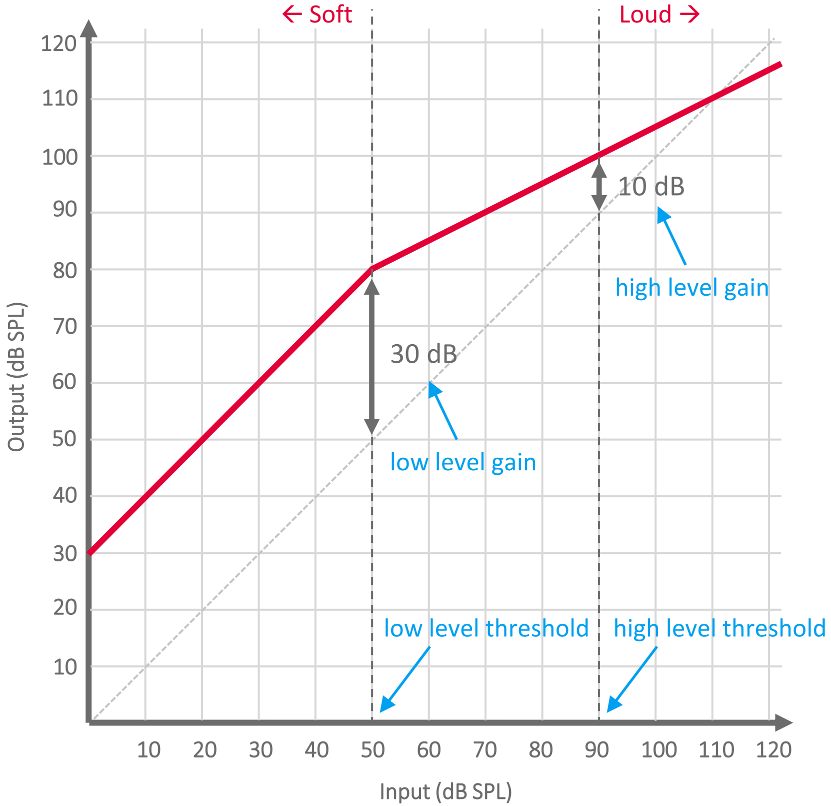
Compression:

- Example:

  40 dB increase in the input leads to 20 dB increase in the output, i.e.,

  → **compression ratio**: 40 dB : 20 dB = **2**:1
- Compression ratio can vary, but usually does not exceed 4:1 in the hearing aid field.

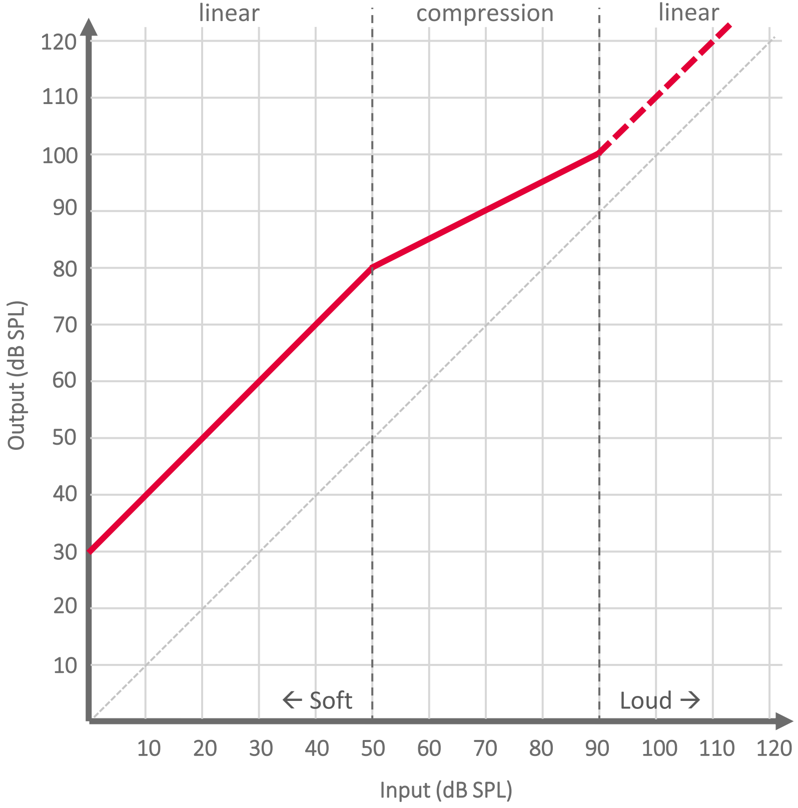
•• **Hearing aids**: Wide dynamic range compression



Compression:

- Low level gain: gain at ca. 50 dB SPL input
- High level gain: gain at ca. 90 dB SPL input

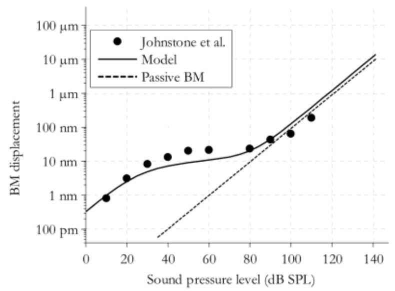
•• Hearing aids: Wide dynamic range compression



<u>Second linear range:</u>

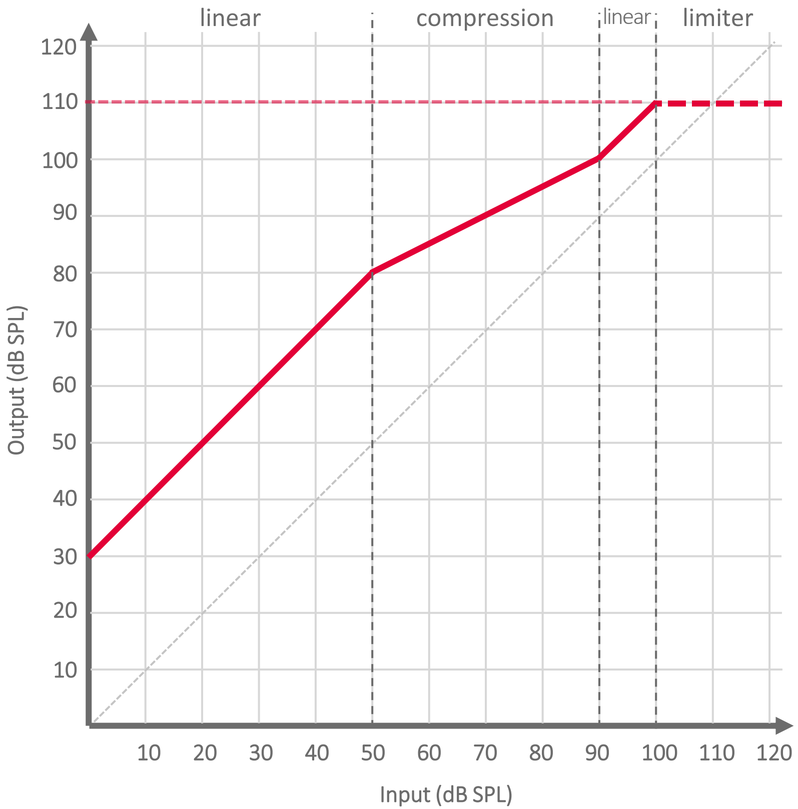
- Can be useful to allow the listener to realize that the input is very loud.
- Should be verified to not extend into the threshold of pain. (See "limiter" on next slide.)
- Remember the normal hearing ear handles loud noises very similarly! Basilar membrane nonlinearity:

Reminder



Adapted from: Johnstone et al., 1986

•• Hearing aids: Wide dynamic range compression

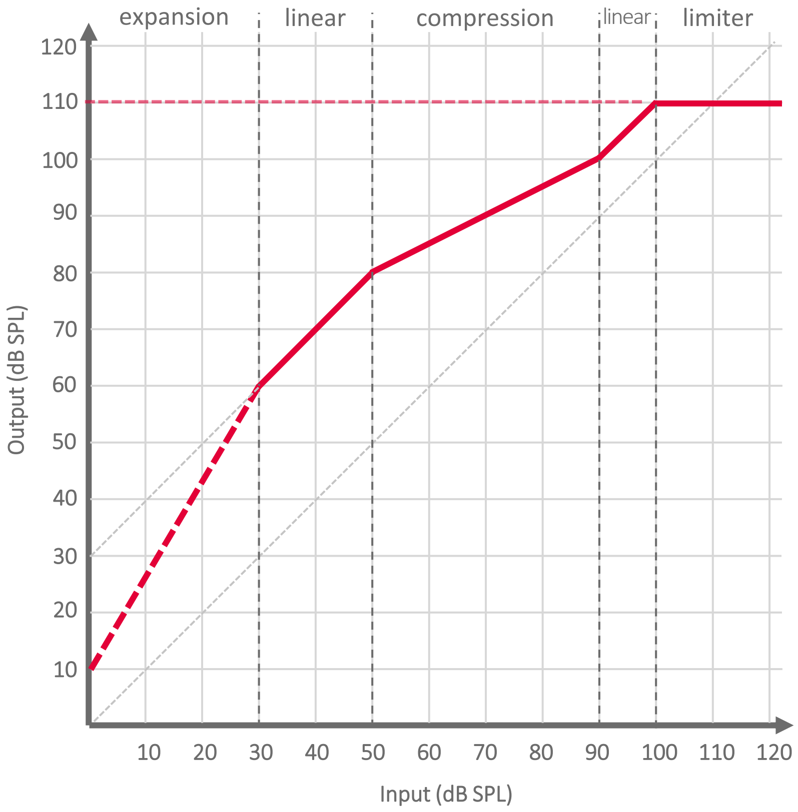


Limiter:

- Ensures not to cross the threshold of pain.
- Ensures technical limits not to be exceeded.

  (**MPO**: maximum power output of a hearing device. Limited for example by the power source, amplifier, and receiver.)
- Is equivalent to a compressor with ∞:1 compression rate.

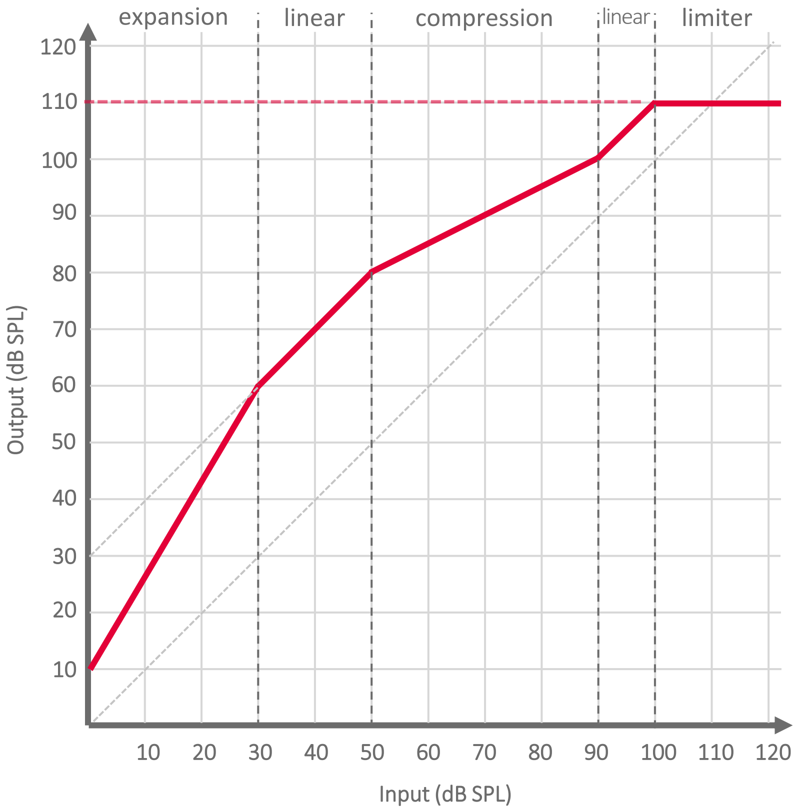
Hearing aids: Wide dynamic range compression



Expansion:

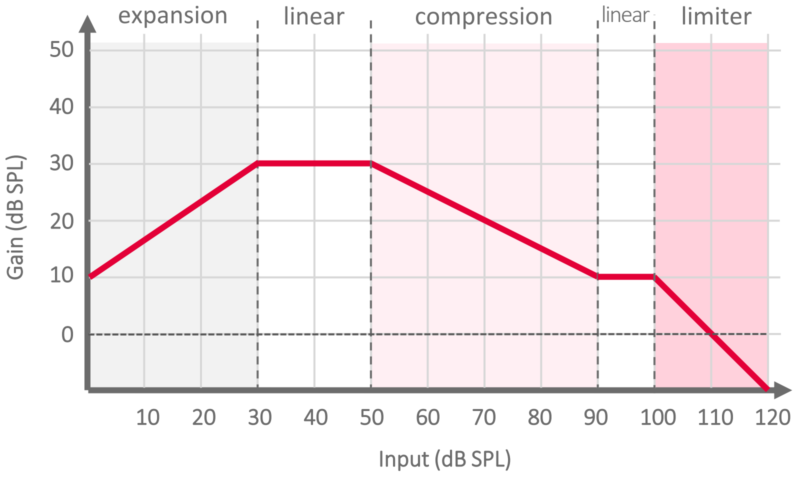
- Usually employed in the low SPL range.
  → Less gain added to soft noises.
- Reduces inherent noise of the system (e.g. that of microphones or preamps).
- Reduces irrelevant background noise.
  → Increases overall SNR.
- Typical expansion ratios: 1:1.5 - 1:3.
  (1:1.66 in the graph on the left.)

•• **Hearing aids**: Wide dynamic range compression



Gain plot:

- A shorter / compacter way to describe compression-expansion curves.



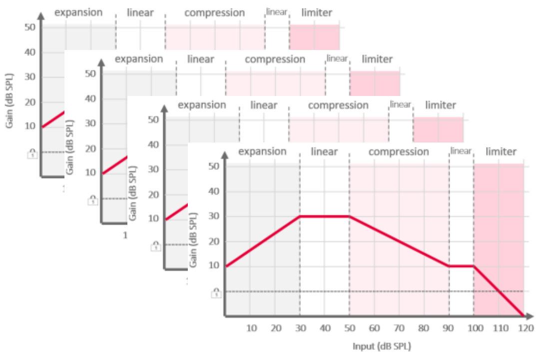
•• Hearing aids: Multi-channel WDRC

Multi-channel compression: Why?

- The dynamic range of hearing (normal or impaired), the amount of hearing loss, and also the dynamic range of speech **[KR16]** vary across frequency.

Multi-channel compression: How?

- Using multiple dynamic compressors, each fitted for a distinct frequency range.
- A computationally cheap, but high quality filter-bank with almost perfect reconstruction is needed. E.g. an FFT-based WOLA filter bank **[RC80]**.



[KR16] M. Kirchberger & F. Russo, "Dynamic Range Across Music Genres and the Perception of Dynamic Compression in Hearing-Impaired Listeners," *Trends in Hearing*, vol. 20, no. 4, doi: 10.1177/2331216516630549, 2016.

[RC80] R. E. Crochiere, "A weighted overlap-add method of short-time Fourier analysis/synthesis," *IEEE Trans. Acoustics, Speech and Signal Proc.*, vol. 28, no. 1, doi: 10.1109/TASSP.1980.1163353, 1980.

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Multi-channel compress

- The dynamic range … , and also the dynamic range of sp

Multi-channel compress

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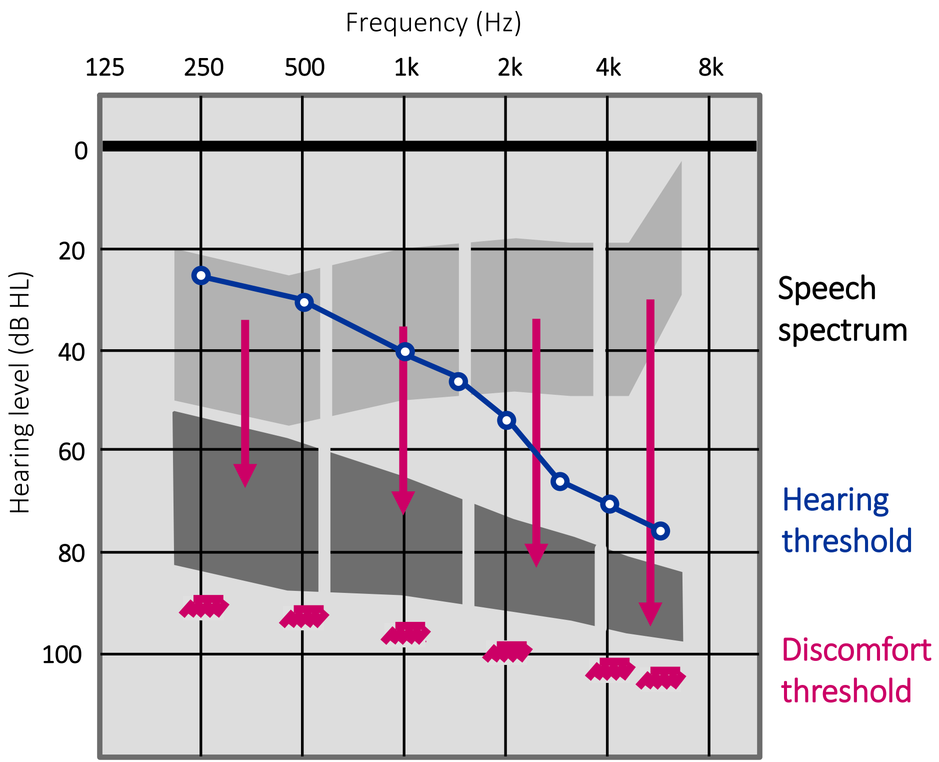
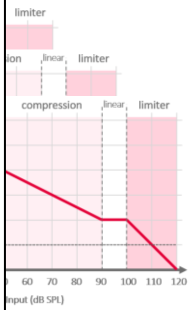


Adapted from: Kiessling & Steffens, 1991



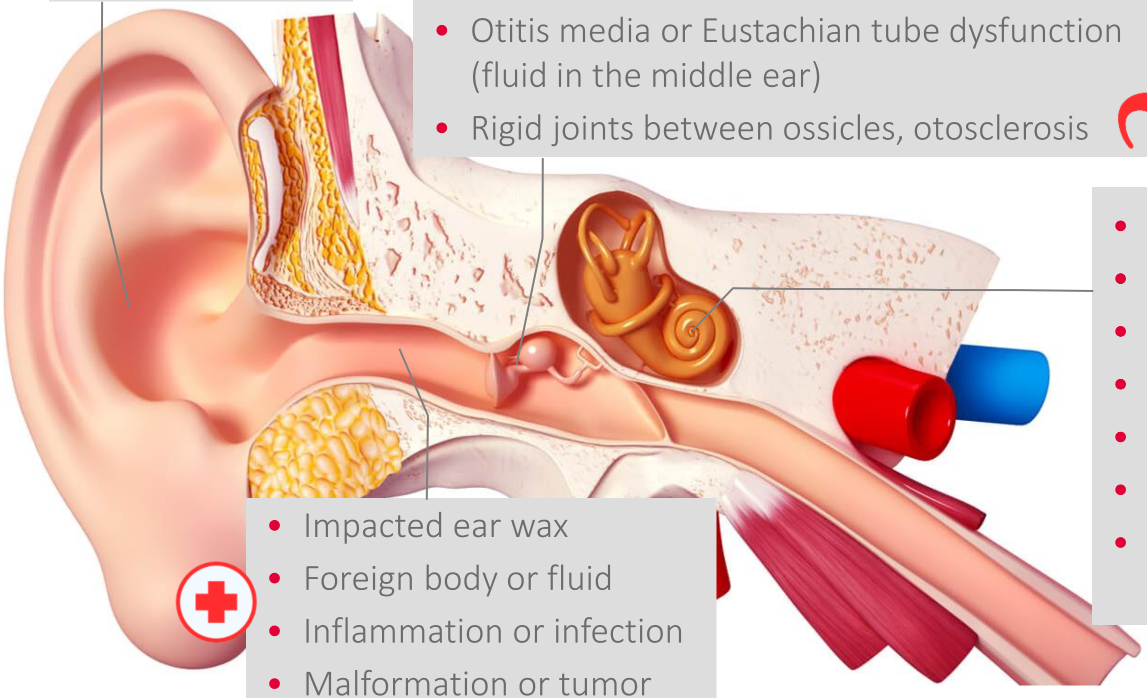
[KR16] M. Kirchberger & F … ynamic Compression in Hearing-Impaire … 5630549, 2016.

[RC80] R. E. Crochiere, "A … " *IEEE Trans. Acoustics, Speech and Signal Proc.*, vol. 28, no. 1, doi: 10.1109/TASSP.1980.1163353, 1980.

Recap: Causes of hearing impairment

- Malformation
- Foreign body

- Eardrum scars / malformation / perforation
- Barotrauma (can be temporary)
- Otitis media or Eustachian tube dysfunction (fluid in the middle ear)
- Rigid joints between ossicles, otosclerosis



- Aging (presbyacusis)
- Exposure to loud noise
- Trauma / Barotrauma / Head injury
- Genetic or hereditary hearing loss
- Viral infection of the hearing nerve
- Malformation of the inner ear or tumor
- Ototoxic drugs (antibiotics, some anti-inflammatory drugs, chemotherapy)

- Impacted ear wax
- Foreign body or fluid
- Inflammation or infection
- Malformation or tumor

Source: www.lobe.ca, 2021.

•• Cochlear implants: Early history

Alessandro Volta
50 V DC ear-to-ear

Source: hearinghealthmatters.org, 2021

Lundberg (1950),
Djourno & Eyries (1957)

Direct electrical stimulation of the auditory nerve with distinguishable percepts in human.

House's first clinical
multi-channel CI

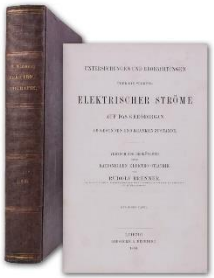
Source: Clark, 2013

Clarion implant
Advanced Bionics
(USA)

Source: cochlear.com, 2021

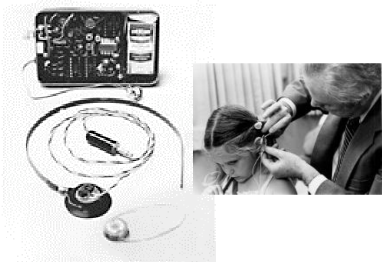
1790s | 1868 | 1950-57 | 1961 | 1982 | 1985 | 1996 | 2001 | 2006

Source: abebooks.com, 2021



Rudolf Brenner's
AC stimulation

Source: Eisenberg, 2005



William F. House's
single-channel CI

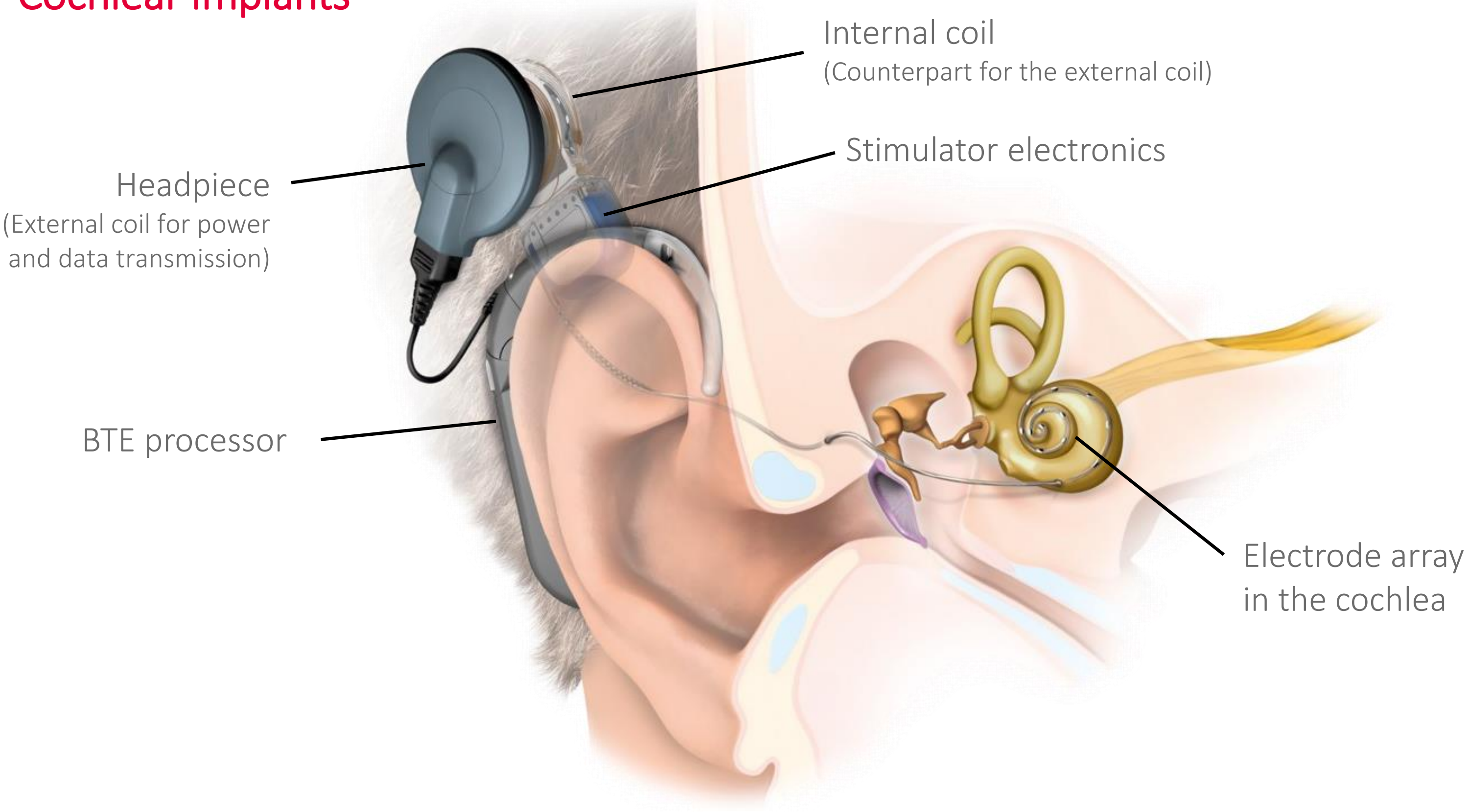
Nucleus implant
Cochlear Ltd. (AU)

Combi40+ implant
MED-EL GmbH (AT)

Venus CS-10A implant
Nurotron BioTech (CN)

Commercialization →

•• Cochlear implants



Source: medel.com, 2016

audifon hearing systems

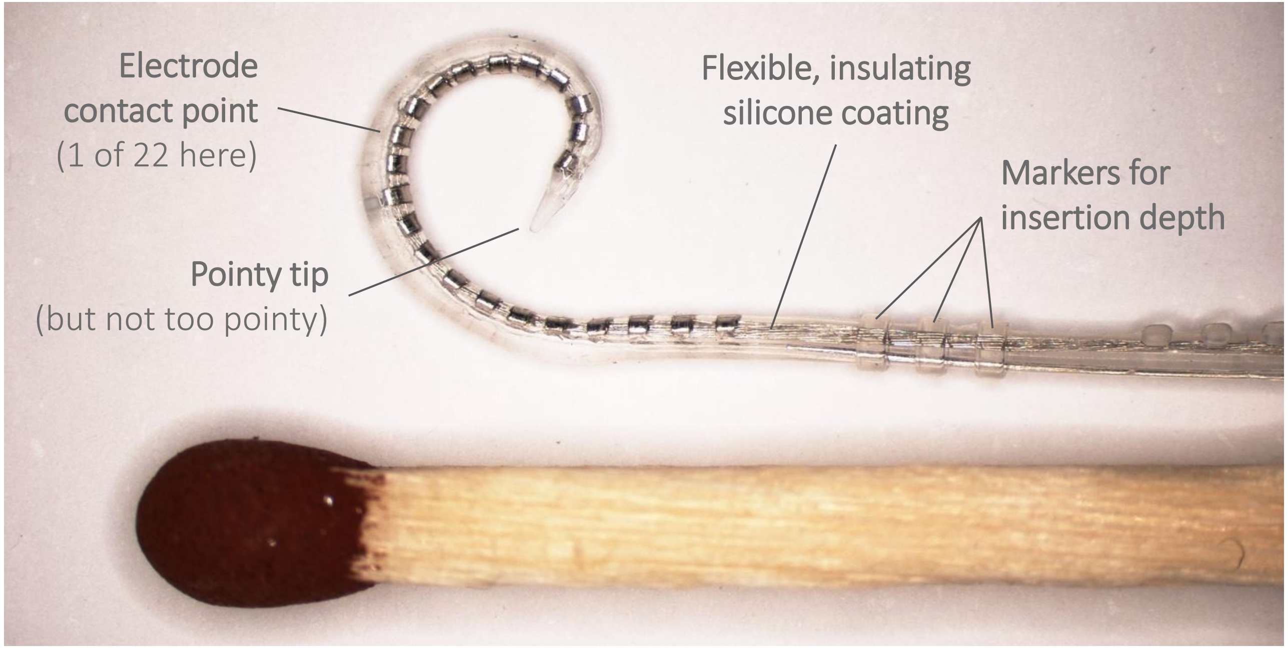
•• Cochlear implants

Source: cochlear.com, 2021

•• Cochlear implants

Source: cochlear.com, 2021 (unprocessed sound)

•• Cochlear implants: The electrode array



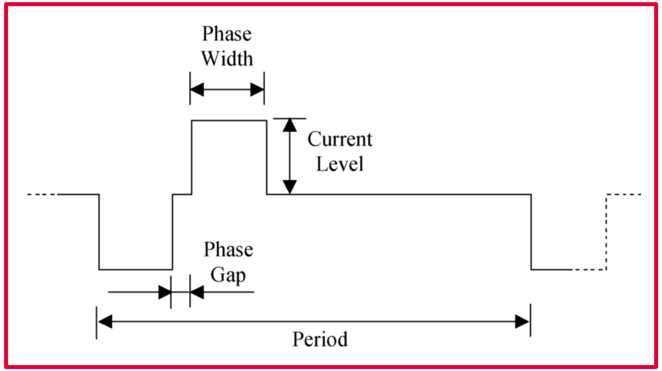
Source: earsurgery.org, 2021

Misplacement of the cochlear implant (CI) electrode array can happen. See e.g.:

G. Widmann, D. Dejaco, A. Luger et al., "Pre- and post-operative imaging of cochlear implants: a pictorial review," *Insights Imaging*, vol. 11, no. 93, doi: 10.1186/s13244-020-00902-6, 2020.

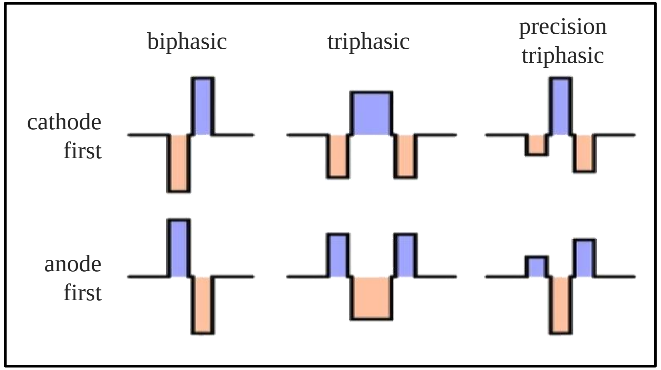
Cochlear implants: Electrical stimulation

- Electrical stimulation must be **charge-balanced**!
- Otherwise :
  → electrolysis happens (fluid*-filled cochlea);
  → chemical balance gets corrupted;
  → cells die in the cochlea.
- Most widespread is the biphasic (negative first) charge-balanced pulsed type stimulation.



Source: Tognola et al., 2005

- Other types of multiphasic pulse shapes:
  - triphasic,
  - precision triphasic.

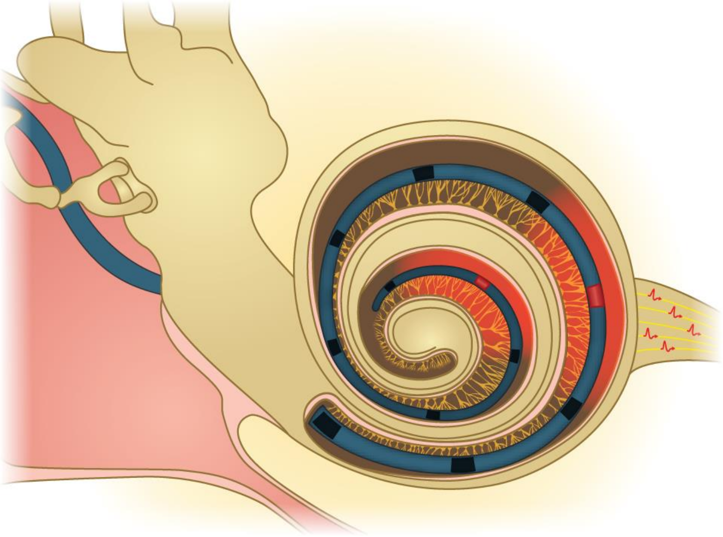


Source: Abdelhamed, 2019

*: **Endolymph** is a physiological fluid that fills the inner ear's labyrinth

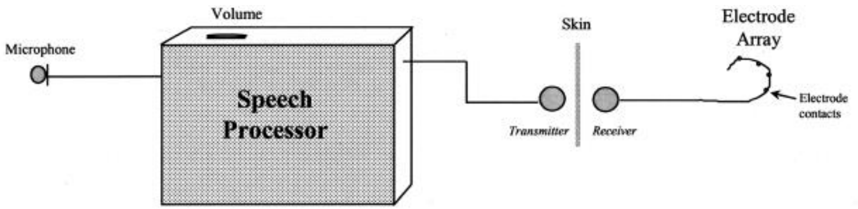
•• Cochlear implants: Current spread (or *spread of excitation*)

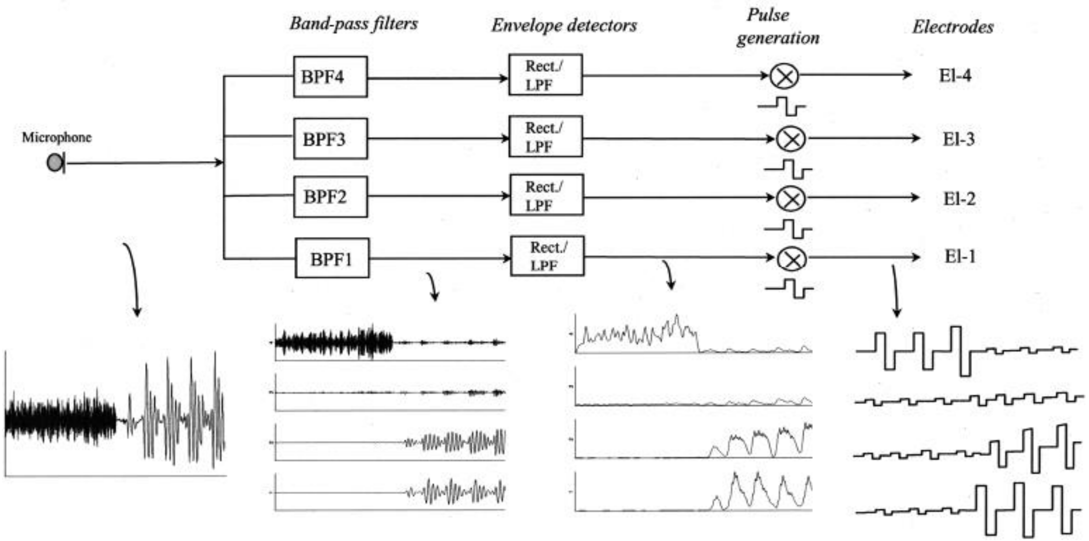
- Cochlea is filled with endolymph.
- An electric pulse (independent of its physical properties) from a single electrode cannot be focused.
- Current will spread out along the cochlea.
- Current will also spread (to some extent) through the bony wall of the cochlea towards neighbouring turns.
- This means, we will always stimulate a group of auditory nerve fibres and not just the ones in the direct proximity of each CI electrode contact.



Source: Jeschke & Moser, 2015

Cochlear implants: CIS signal processing strategy



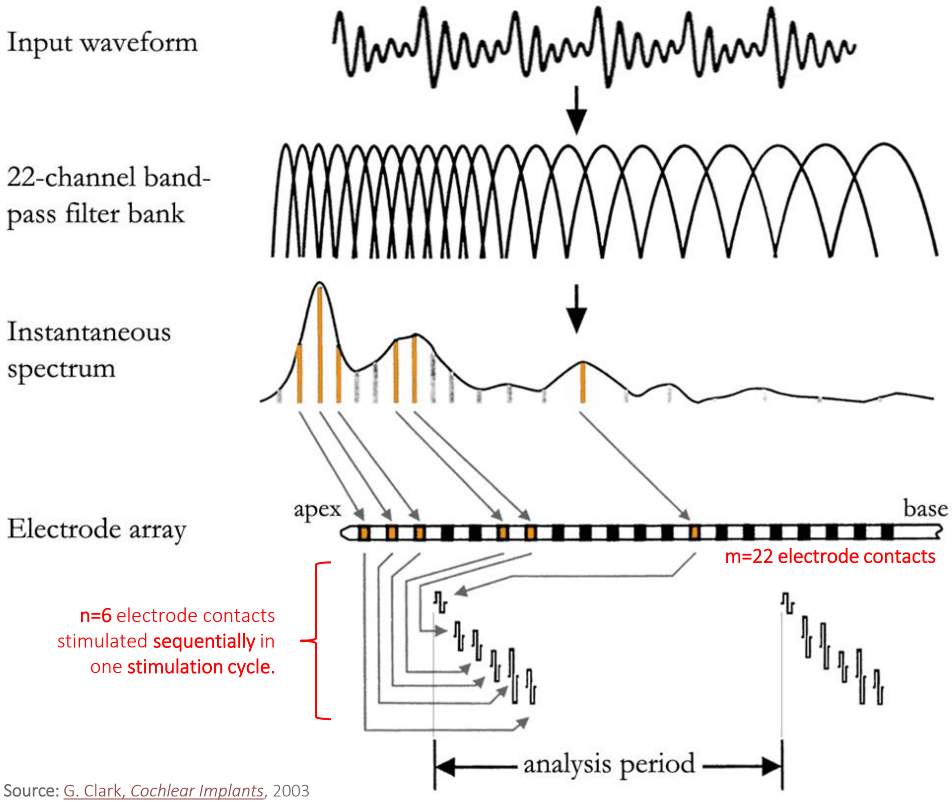


Continuous Interleaved Sampling (CIS) signal processing strategy

B. S. Wilson, C. C. Finley, D. T. Lawson, R. D. Wolford, and M. Zerbi, "Design and evaluation of a continuous interleaved sampling (CIS) processing strategy for multichannel cochlear implants," *J. Rehabil. Res. Dev*, vol. 30, no. 1, pp. 110–116, 1993.

Source: Waltzman & Roland, Cochlear Implants, 2006

•• Cochlear implants: ACE signal processing strategy



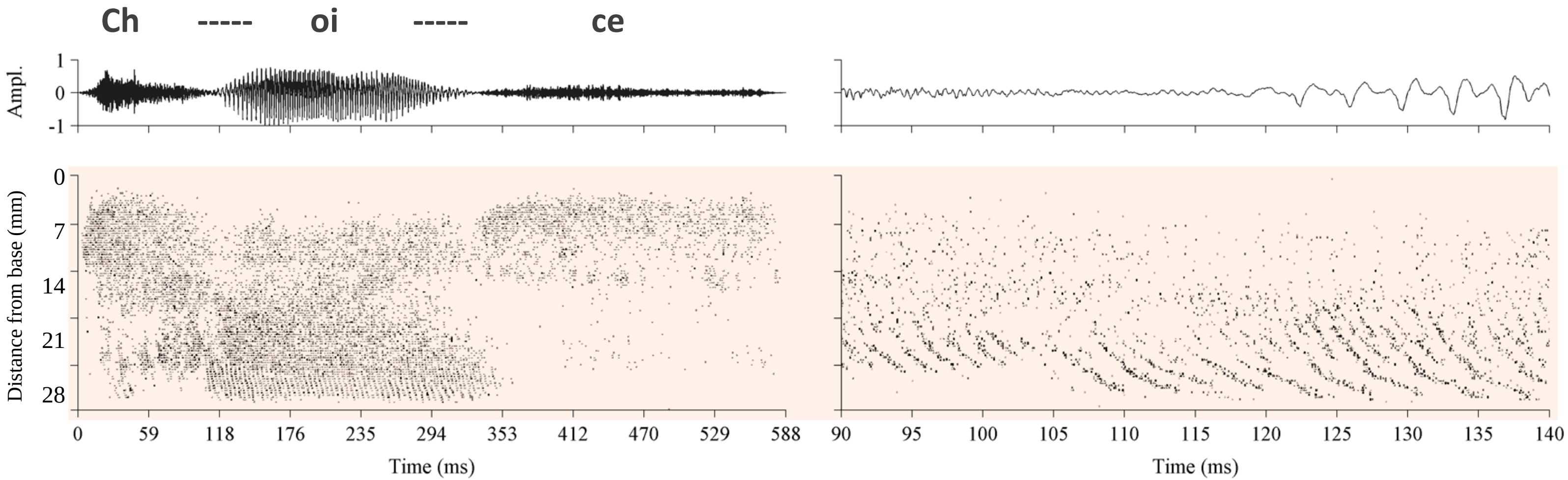
Source: G. Clark, *Cochlear Implants*, 2003

Advanced Combination Encoder **(ACE)** signal processing strategy

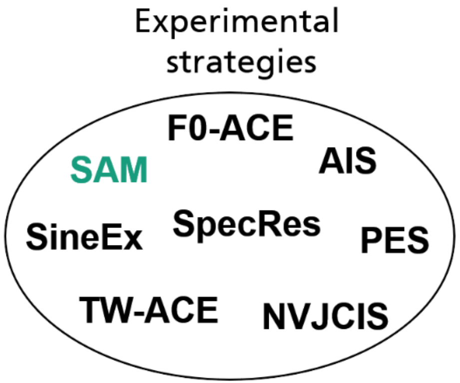
The most widespread CI strategy today.

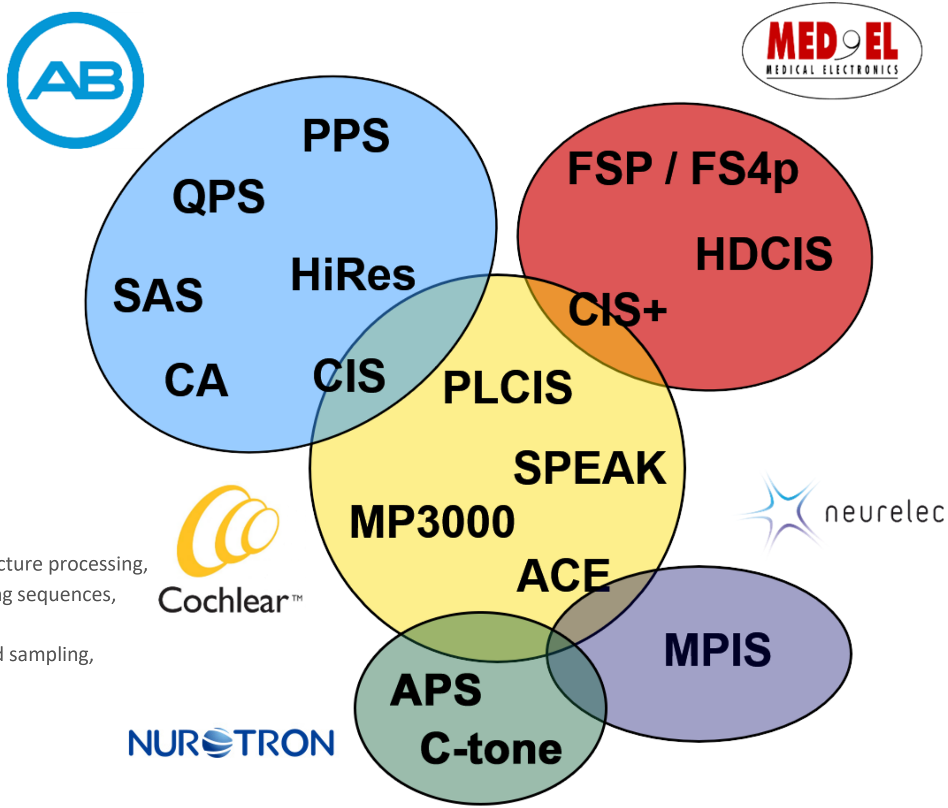
A. E. Vandali, L. A. Whitford, K. L. Plant, and G. M. Clark, "Speech Perception as a Function of Electrical Stimulation Rate: Using the Nucleus 24 Cochlear Implant System," *Ear and Hearing*, vol. 21, no. 6, pp. 608-624, doi: 10.1097/00003446-200012000-00008, 2000.

•• **Cochlear implants**: Stimulation patterns (cochleagram vs. electrodogram)



Cochlear implants: Other signal processing strategies





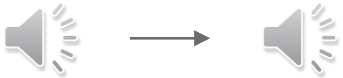
ACE: advanced combination encoder, **AIS**: asynchronous interleaved stimulation,
APS: advanced peak selection, **CA**: compressed analog, **CI**: cochlear implant,
CIS: continuous interleaved sampling, **F0-ACE**: ACE incorporating F0 cues, **FSP**: fine structure processing,
FS4p: FSP with parallel stimulation and four channels featuring channel-specific sampling sequences,
HDCIS: high-definition CIS, **HiRes**: high resolution (CIS),
MP3000: ACE incorporating simultaneous masking effects, **MPIS**: main peak interleaved sampling,
NVJCIS: novoicing jitter CIS, **PES**: pitch excited sampler, **PLCIS**: phase-locked CIS,
PPS: paired pulsatile sampler, **QPS**: quadruple pulsatile sampler,
SAS: simultaneous analog stimulation, **SineEx**: sinusoid extraction strategy,
SpecRes: spectral resolution strategy, **SPEAK**: spectral peak strategy

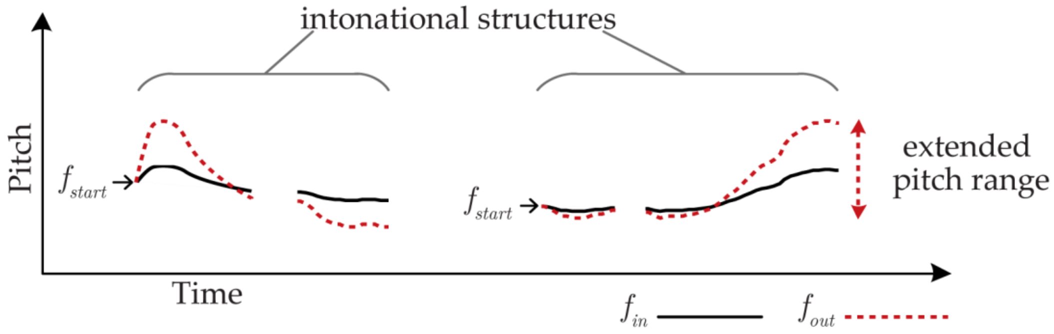
•• Hearing aids (HA) vs. Cochlear implants (CI)

- System size
  BTE processor is about the same size for both, but **CI has more system parts** (RF link, implanted stimulator, implanted electrode array).
- Power consumption
  Signal processing requires about the same power for both, but **CIs need extra current** for electrical stimuli and RF link.
- Core signal processing
  Both do spectral decomposition via an analysis filter-bank, but while HAs need to synthesize audio on the output, CIs calculate parameter for electrical stimuli.
- Additional algorithms / features
  Very similar: directionality, dynamic range compression, noise reduction, binaural algorithms, but CIs do not need feedback canceller. Both can be streamed to wirelessly and be remote controlled.
- Current issues
  Both: speech in noise enhancement, power consumption and size, connectivity, user-friendly handling.
  *CIs: reverb, **pitch discrimination*** (12/16/22/24 channels, does not matter ← ***current spread***).

Cochlear implants: Ways to improve pitch sensitivity

- **Train cochlear implant users**
  Use the brain's plasticity. Needed anyway in CI therapy, but has its limits.
- **Enhance pitch changes**
  Smart preprocessing can increase speech melody changes in real-time ([PREX project], [Fraunhofer IDMT]).





F. Kuhnke, L. Jung, and T. Harczos, "Compensating for impaired prosody perception in cochlear implant recipients: A novel approach using speech preprocessing," in *Proc. 5th Int. Symp. Audit. Audiol. Res. (ISAAR 2015): Individual hearing loss - Characterization, modelling, compensation strategies*, The Danavox Jubilee Foundation, pp. 309–316, Nyborg, Denmark, 2016.

F. Kuhnke, "Implementation and evaluation of a real-time pitch range extension algorithm for cochlear implants," M.Sc. Thesis (Technical University Ilmenau, Department of Electrical Engineering and Information Technology, Institute of Media Technology), 66 pages, 2014.

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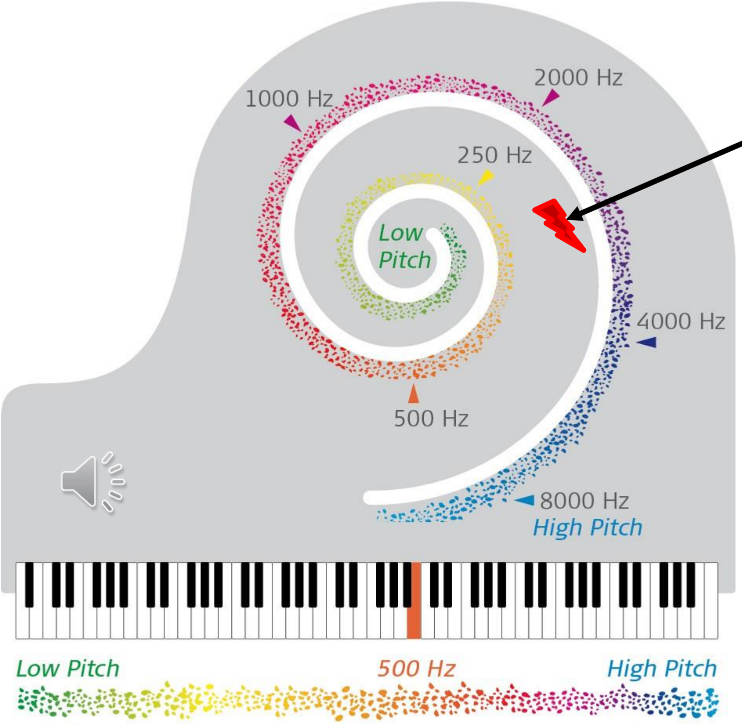
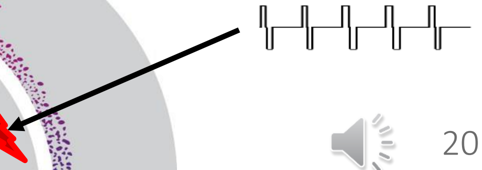
- **Improve temporal pitch cues**
  Better stimulation strategies (SAM project, Dissertation, Fraunhofer IDMT)

•• Pitch perception



Source: medel.com, 2021

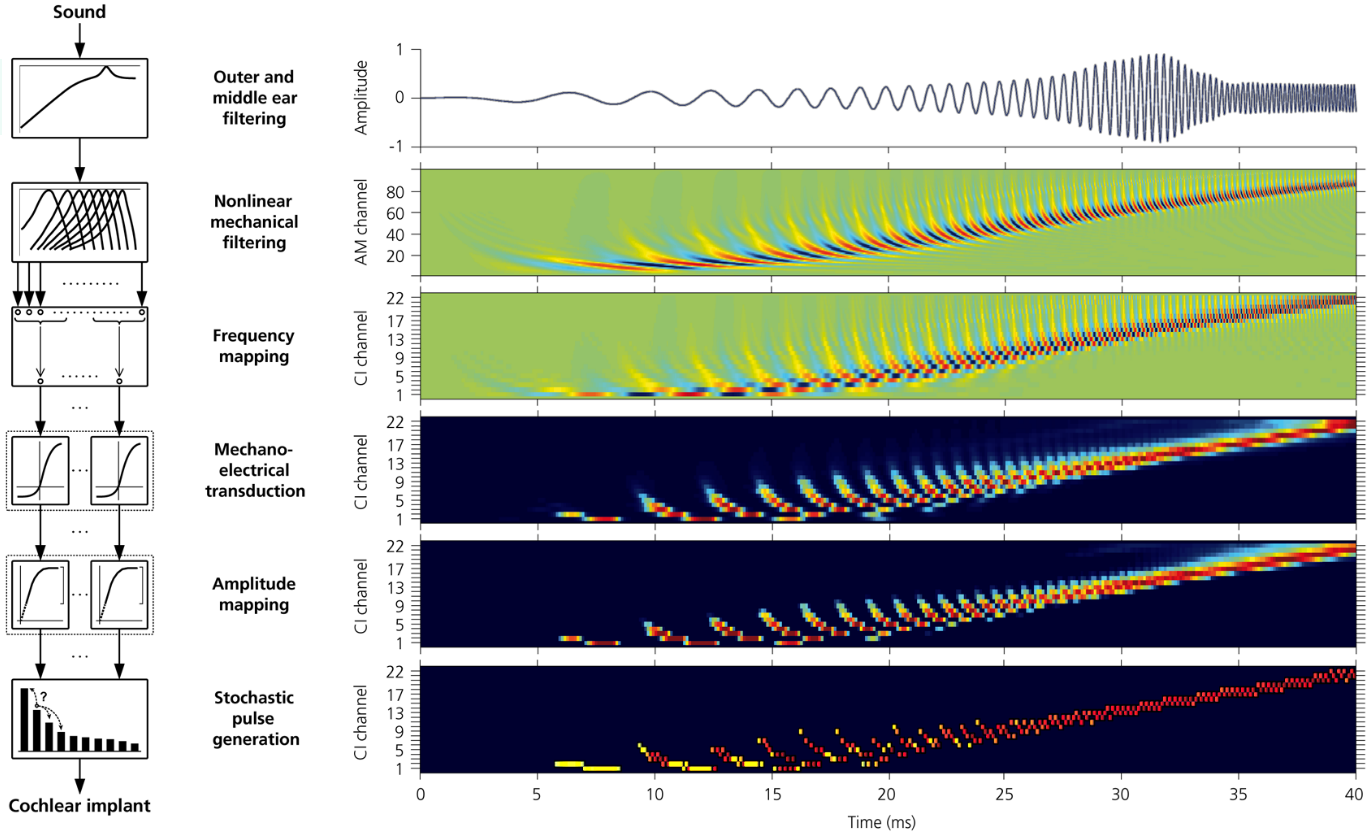


20 Hz

80 Hz

160 Hz

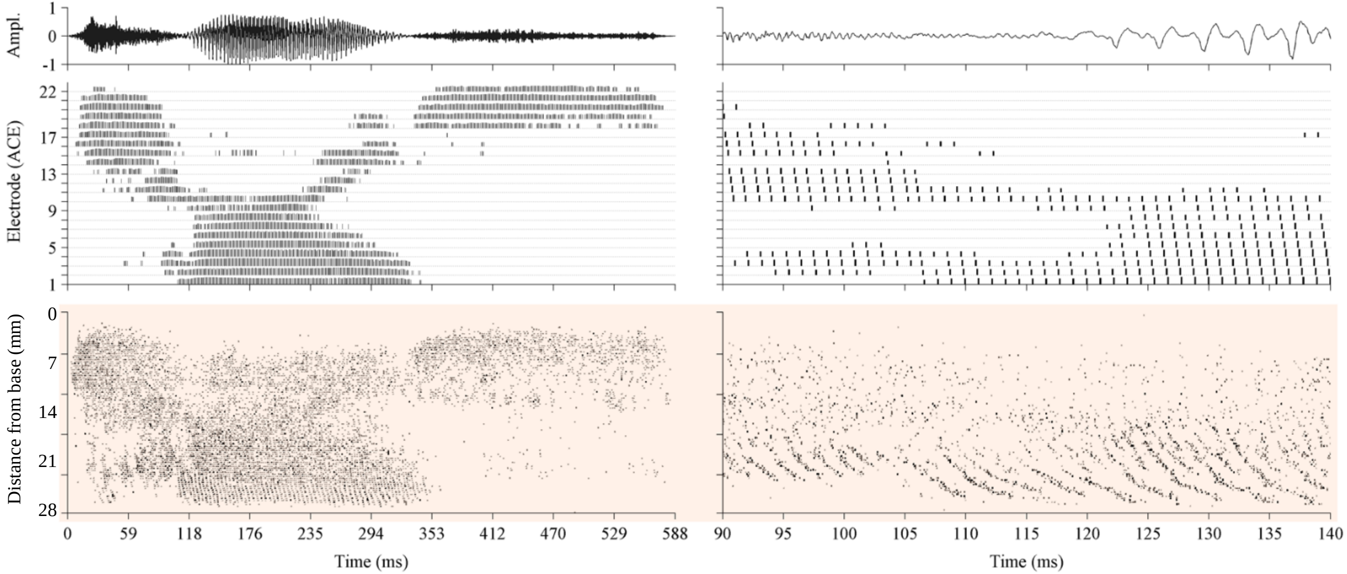
Cochlear implants: SAM signal processing strategy



Stimulation based on Auditory Modeling (SAM) signal processing strategy

T. Harczos, "Cochlear implant electrode stimulation strategy based on a human auditory model," PhD Dissertation, urn: urn:nbn:de:gbv:ilm1-2015000204, 2015.

•• Cochlear implants: Stimulation patterns (ACE vs. SAM)



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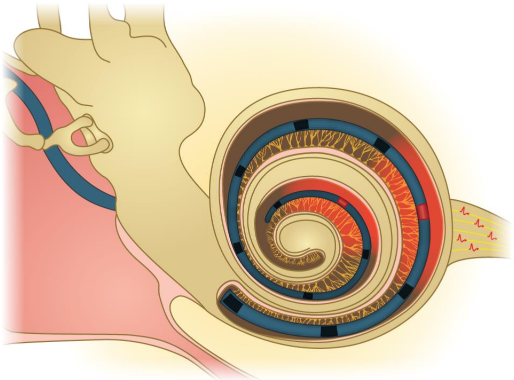
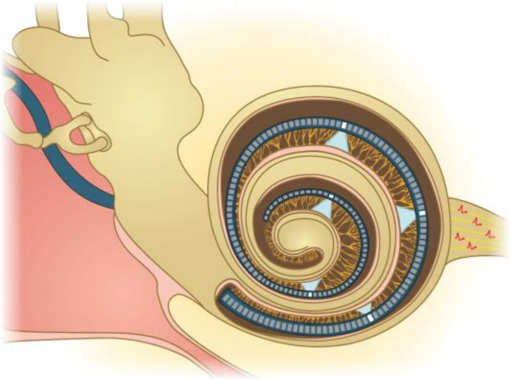
- **Improve place pitch cues** (reducing current spread)
  - Better electrode design (“modiolus-hugging” or “adhering” electrodes),
  - Current steering (parallel stimulation over multiple electrode contact points)
  - Optogenetic stimulation (optical cochlear implants).

Optogenetic cochlear implants

Electrical stimulation



Optical stimulation



Source: Jeschke & Moser, 2015

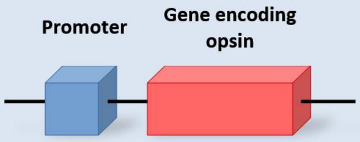
Challenges of optogenetic cochlea stimulation:

- **Light-sensitive neurons**: efficient, reliable and safe opsin* expression via *genetic manipulation* of the spiral ganglion neurons.
- **Stimulation technology** must be efficient, reliable and safe.

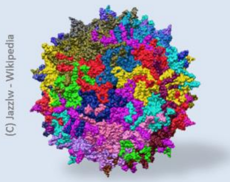
*opsin = light-gated ion channel

•• Optogenetics

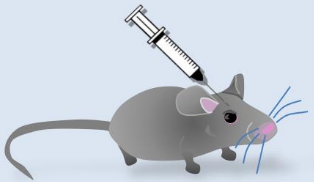
Take the gene for the light-sensitive protein (ChR) from **Chlamydomonas reinhardtii**



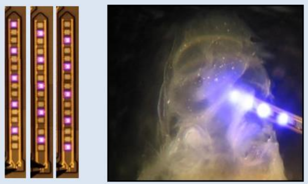
Build **genetic construct** (including promoter and gene encoding opsin)



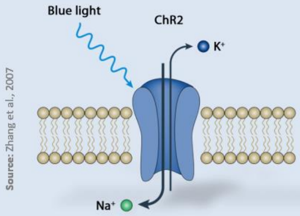
Insert genetic construct into **virus** (e. g. AAV)



Transfect animals (injection into nervous system) or use transgenic animals

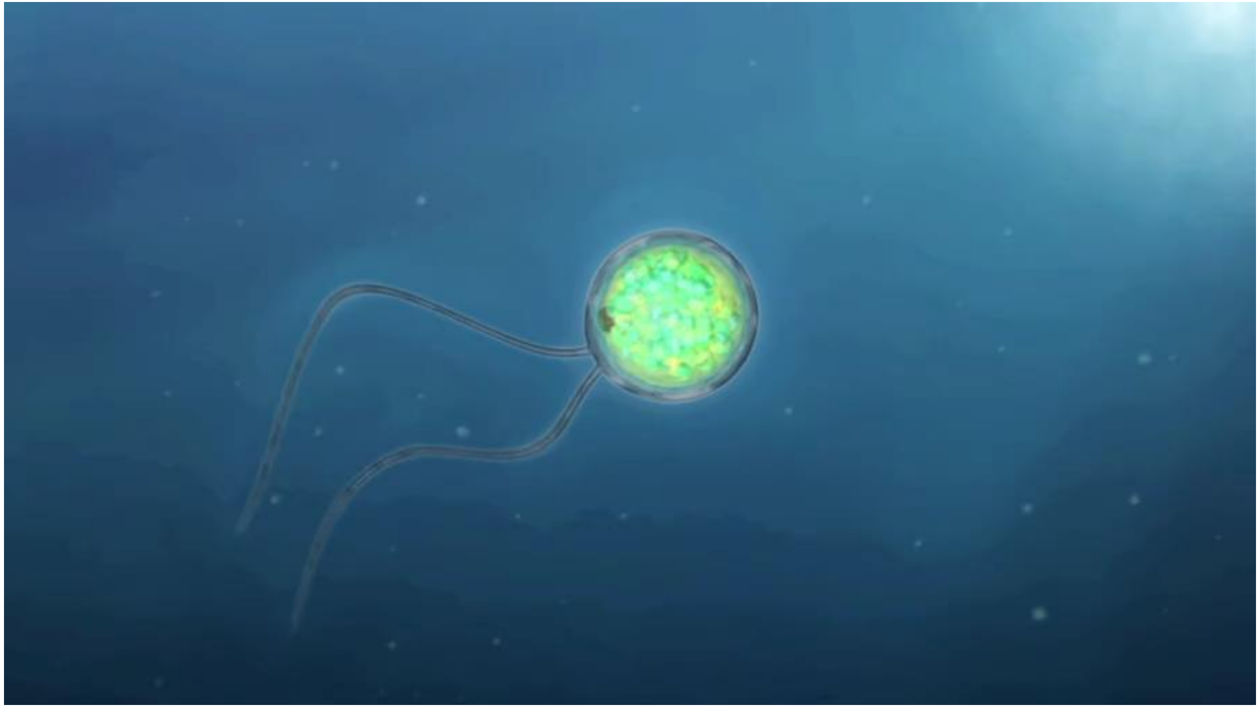


Insert **optical fiber** or **µLED-array** and apply light of opsin-specific wavelength



The **neurons** expressing the opsin can be **activated** with high temporal and spatial resolution

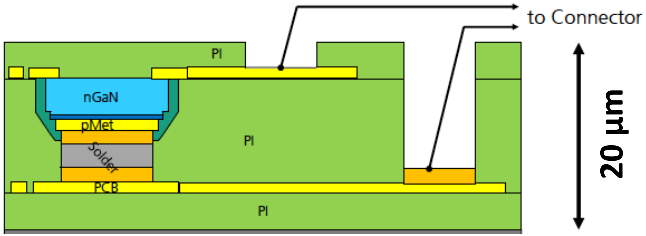
•• Optogenetics



Source: be.mit.edu, 2021

•• **Optogenetic cochlear implants**: Stimulation technology (optrodes)

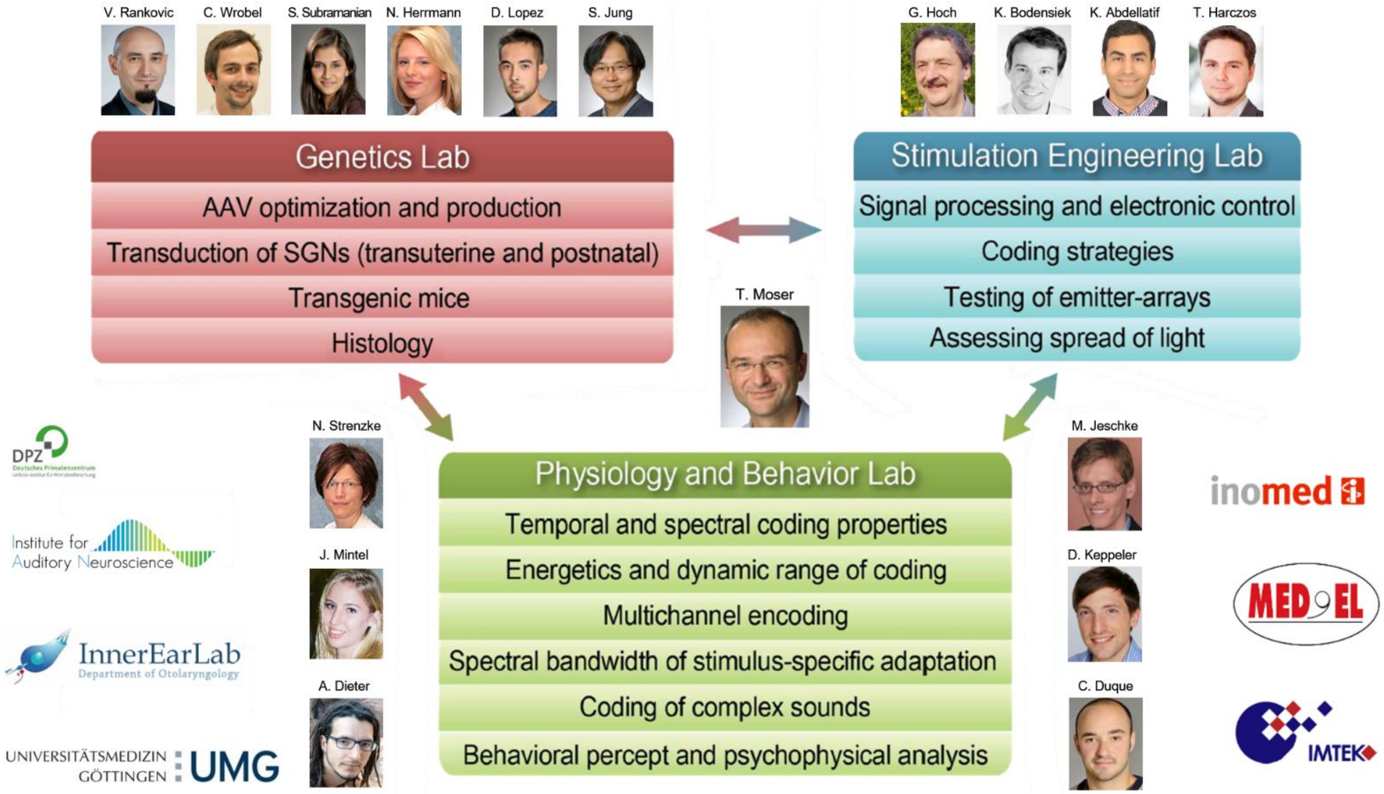
10 µLED / 4 mm



Source: Goßler et al., *JPhysD*, 2015

120 **µLEDs** / 12 mm

•• Optogenetic cochlear implants: The Team

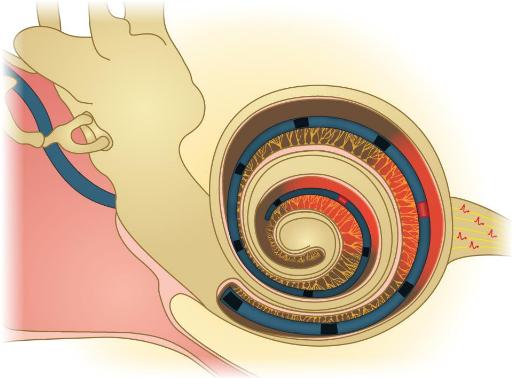


More info: http://www.auditory-neuroscience.uni-goettingen.de/hearing_the_light_EN.html

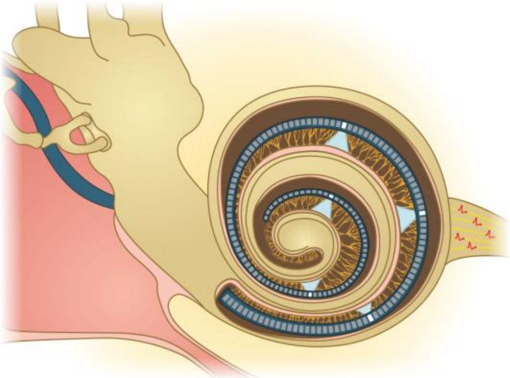
•• Optogenetic cochlear implants

Electrical stimulation

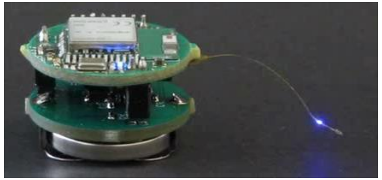
Source: Jeschke & Moser, 2015

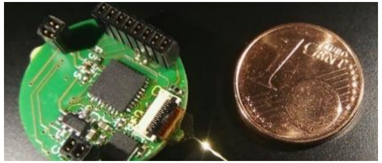


Optical stimulation



Research hardware





Challenges of optogenetic cochlea stimulation:

- **Light-sensitive neurons**: efficient, reliable and safe opsin* expression via *genetic manipulation* of the spiral ganglion neurons.
- **Stimulation technology** must be efficient, reliable and safe.

*opsin = light-gated ion channel

More info: Khurana & Harczos et al., "En route to sound coding strategies for optical cochlear implants," iScience, vol. 26, 2023 audifon hearing systems

•• Optogenetic cochlear implants: Demo with the research hardware

Music: Josh Armistead - **Lazer Beams**

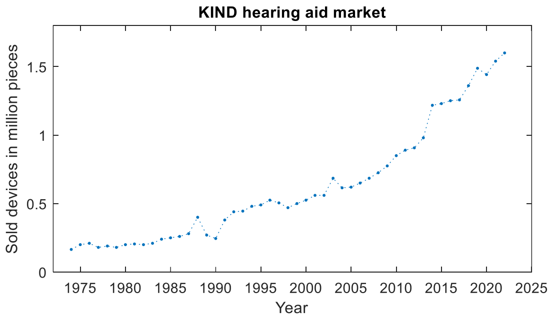
•• Hearing aid market

2022:

1 million **CI systems** sold **worldwide until 2022** [FZ22]

vs.

20.25 million **hearing aids** sold **in Europe during 2022** [EH22]



[FZ22] F.-G. Zeng, "Celebrating the one millionth cochlear implant," *JASA Express Lett.*, vol. 2, no. 077201, doi: 10.1121/10.0012825, 2022.

[EH22] European Hearing Instrument Manufacturers Association, "Hearing aid sales,“ url: https://www.ehima.com/about-ehima/hearing-aid-sales/, 2022.

•• Future of hearing systems

Hearing aids:

- convergence towards earbuds (similar form factor and features like noise-cancellation);
- more biometric sensors (like PPG) for health-monitoring;
- neuro-steering (EEG based attention decoding and filtering);
- better wireless connectivity (MFi, ASHA, LE Audio, Auracast)
  while keeping power consumption ultra low;
- remote fitting → self-fitting → remotely supervised AI-based auto-fitting;
- OTC (over-the-counter) hearing aids.

Cochlear implants:

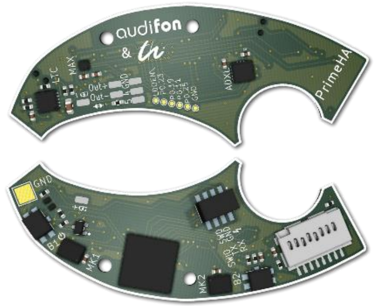
- fully implantable devices (maintenance-free for 6-15 years);
- optical cochlear implants (with the help of optogenetics).

Future of hearing systems

AI's take on future of hearing aids

- Generated by *Webjourney.ai*
- Prompt: "close-up of a future hearing aid on a human ear,"

PrimeHA: a platform to develop and test hearing aid algorithms



Main features:

- ARM Cortex M4f @ 64 MHz, 256 kB RAM, 1 MB NVM.
- Current consumption ~3-10 mA with BLE 5.1 radio.
- Audio input: 2x PDM MEMS microphones.
- Extras: motion sensor and µSD-card slot on board.
- Made of commercial off-the-shelf components.
- Fully C-programmable under free-for-all license.

Current use:

- Firmware framework development.
- Testing and optimizing audio signal processing algorithms like feedback canceller, multi-band compressor, noise reduction.
- Learning lessons on acoustically engineered mechanical design.

[AH23] A. Hintermaier, I. Pieper, and T. Harczos, "PrimeHA: not a hearing aid," VCCA, 2023.

Thank you very much!

Questions?

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