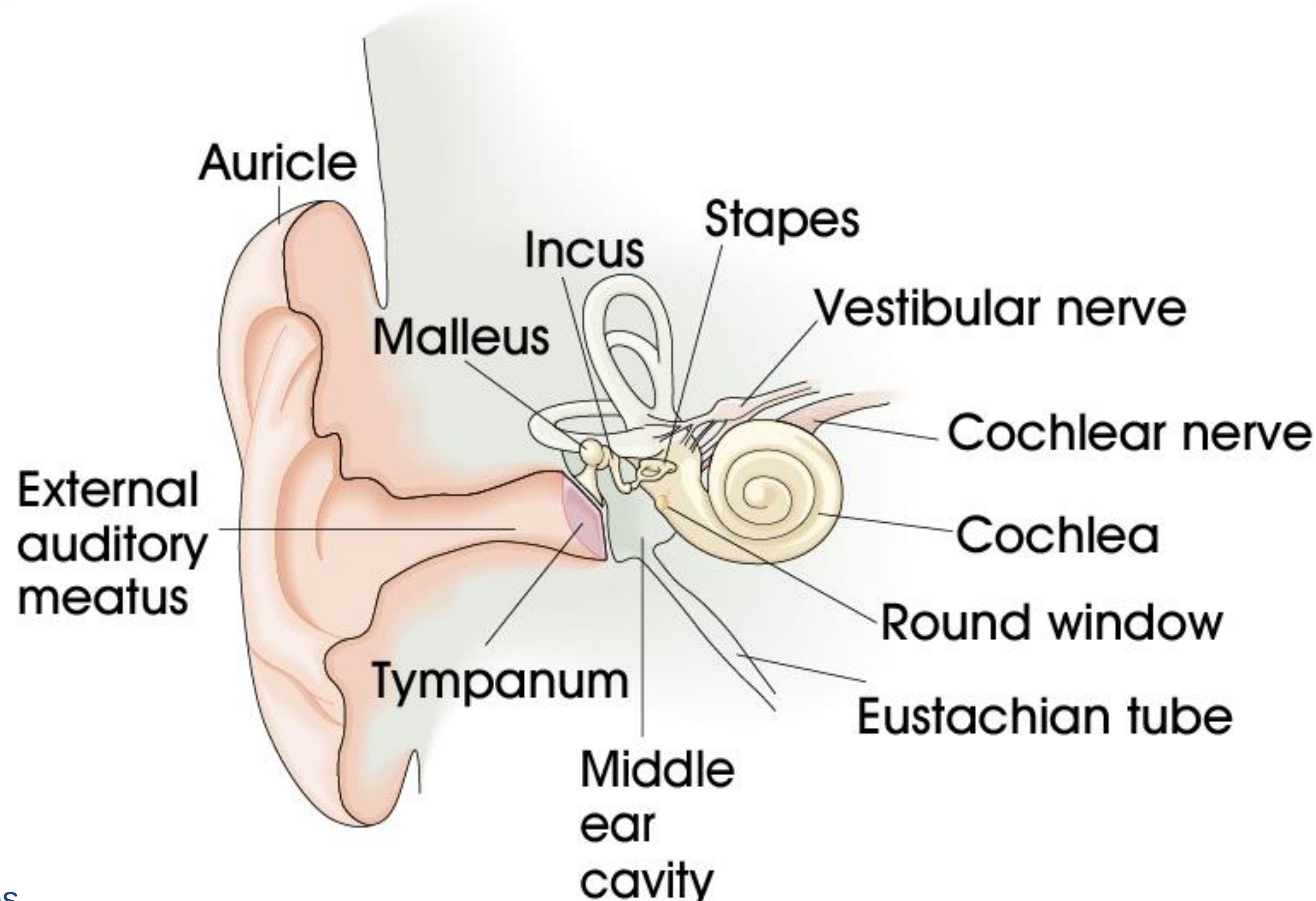
Electrophysiology of the Auditory System

Waldo Nogueira

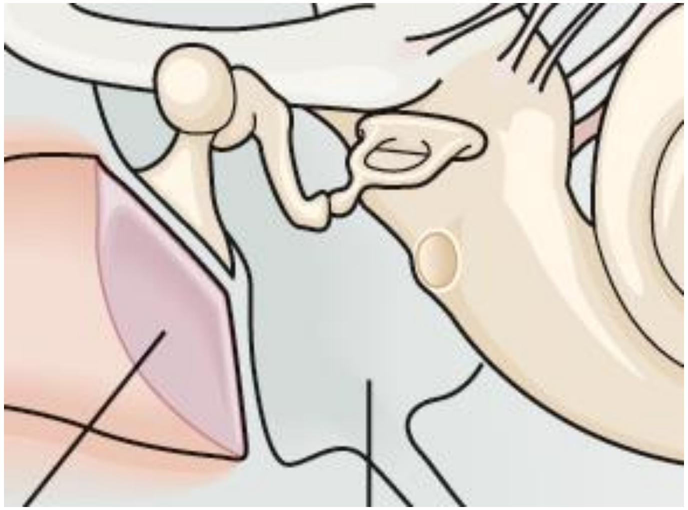
06.10.2022, Milan

Auditory System: Ear



Principles

Middle Ear: Engineering; diseases



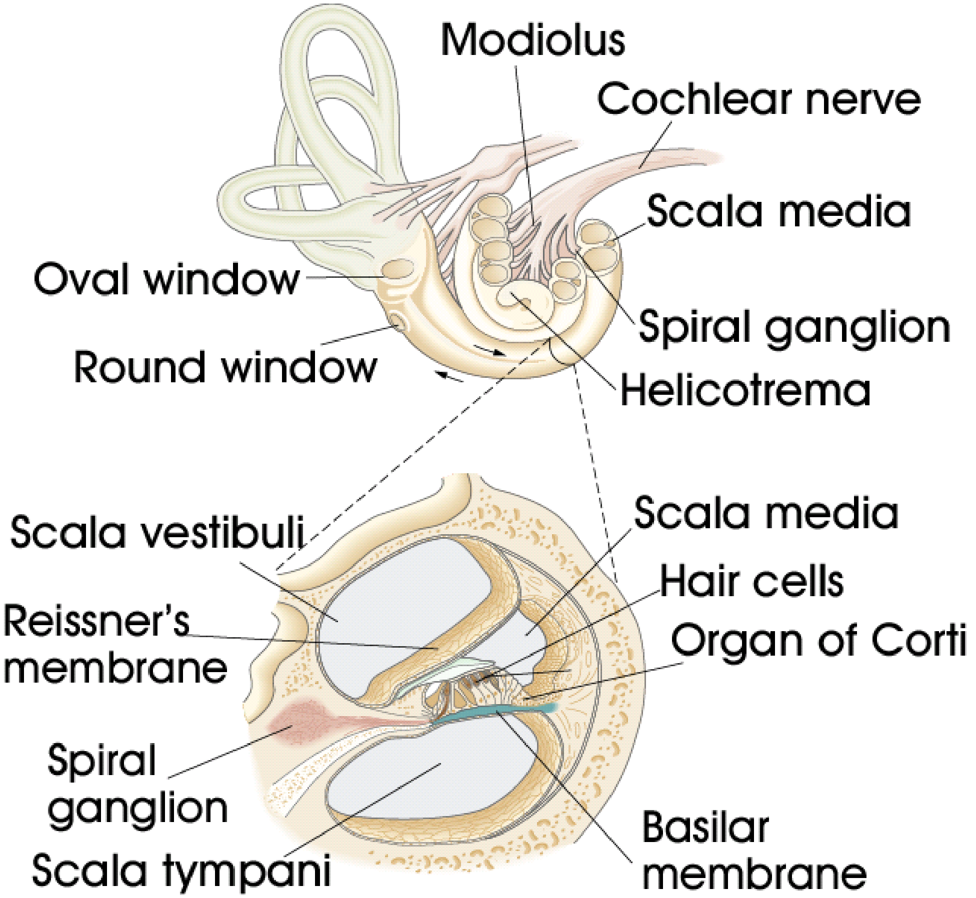
- Perfect design to transmit tiny vibrations from air to fluid inside cochlea
- Stapedius muscle: damps loud sounds, 10 ms latency.

- CONDUCTIVE (vs. SENSORINEURAL) hearing loss
  - Scar tissue due to middle-ear infection (otitis media)
  - Ossification of the ligaments (otosclerosis)
- Rinne test: compare loudness of (e.g.) tuning fork in air vs. placed against the bone just behind the auricle.
- Surgical intervention usually highly effective

Principles of Neural Science, Chapter 30

Inner ear: Cochlea

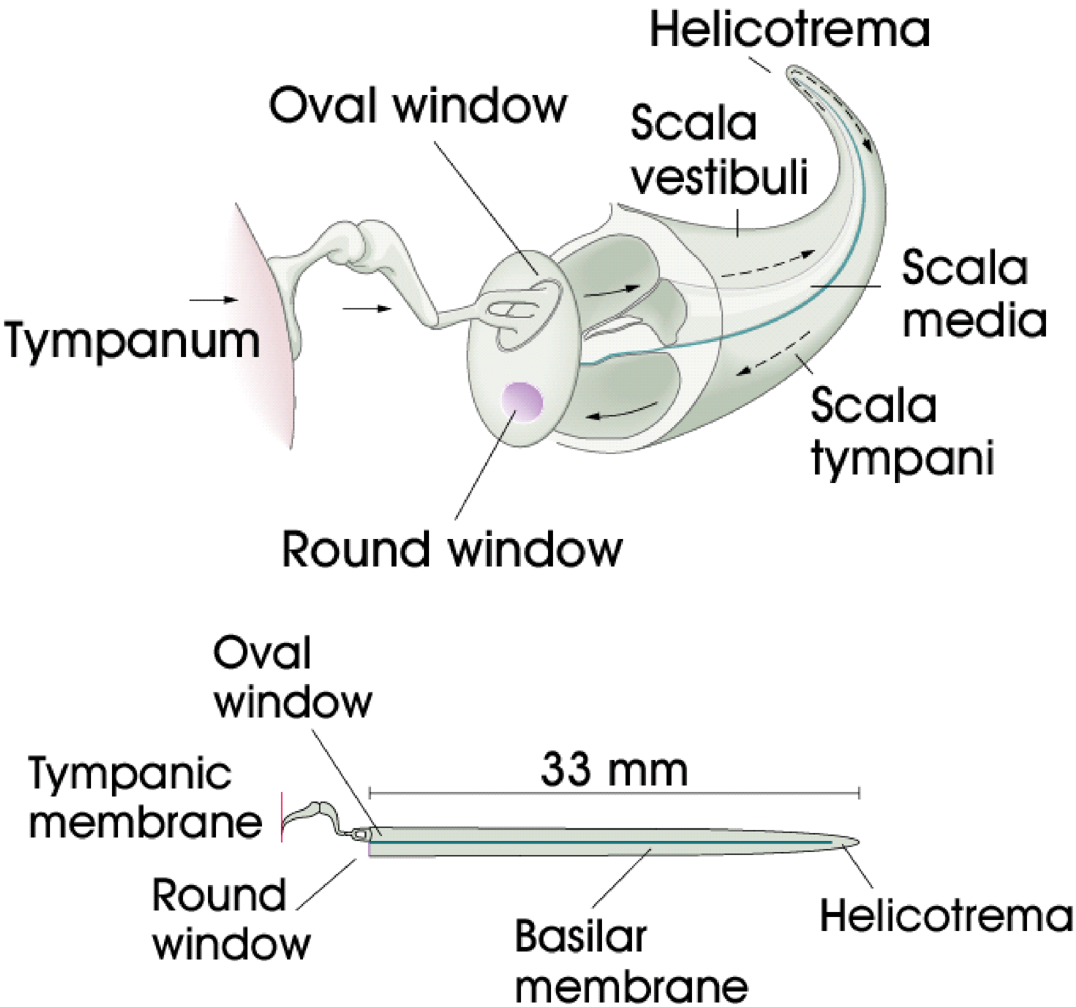
- 3 fluid-filled cavities
- Transduction: organ of Corti: 16,000 hair cells, basilar membrane to tectorial membrane



PNS Fig 30-2

Basilar Membrane

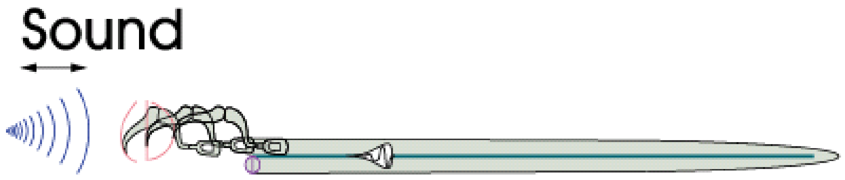
- Incompressible fluid, dense bone (temporal).
- Traveling wave (vibrations) IN THE FLUID
- Basilar membrane: Individual elements (vibraphone, not didgeridoo).



PNS, Fig 30-3

Basilar Membrane: tonotopy, octaves

- Thick & taut near base
- Thin & floppy at apex
- Couples with vibrating fluid to give local peak response.

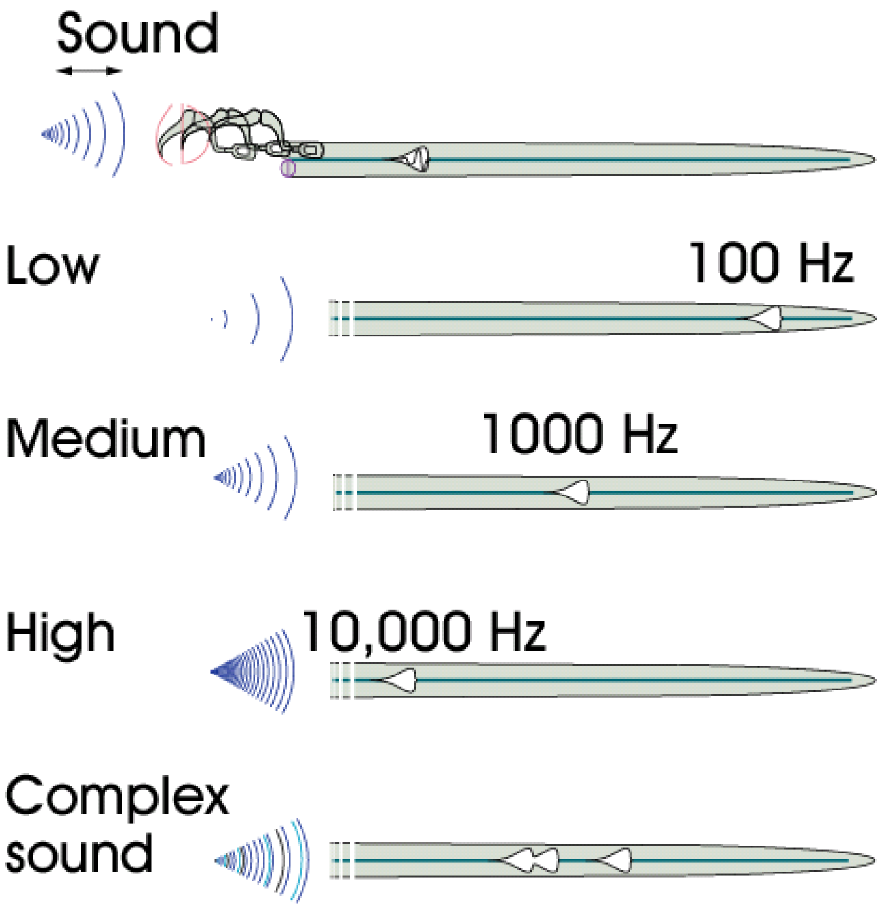


PNS Fig 30-3

Basilar Membrane: tonotopy, octaves

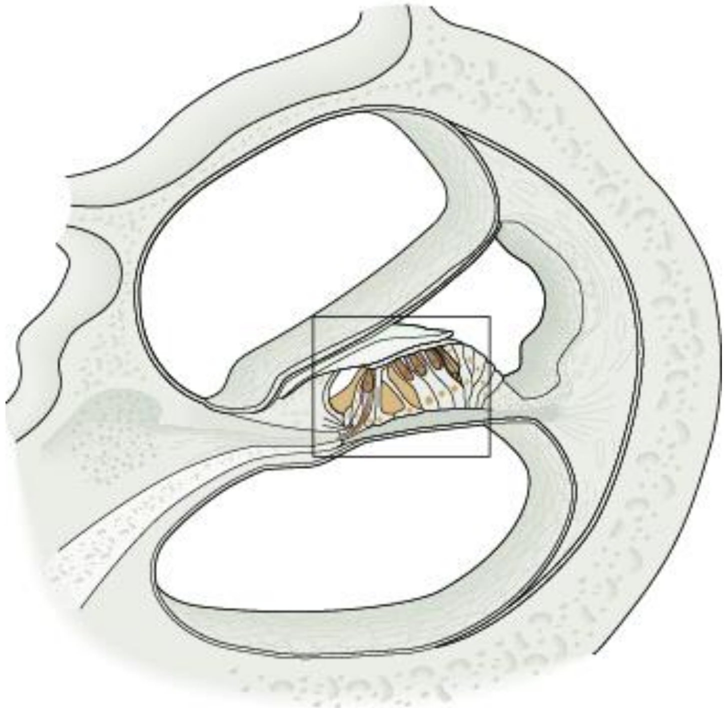
- Thick & taut near base
- Thin & floppy at apex
- Couples with vibrating fluid to give local peak response.

- Tonotopic PLACE map (...homunculus)
- LOGARITHMIC: 20 Hz -> 200 Hz -> 2kH -> 20 kHz, each 1/3 of the membrane
- Two-tone discrimination
- Timing

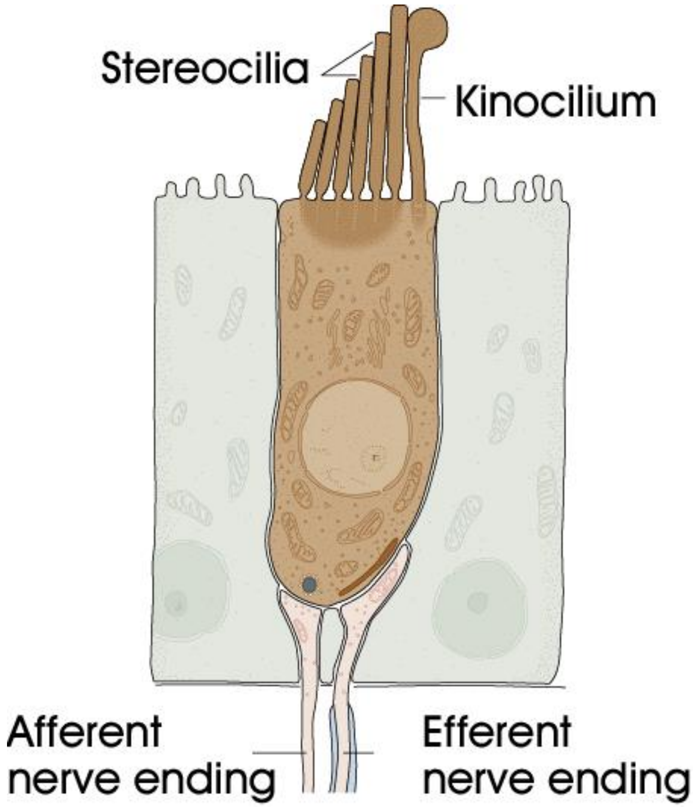


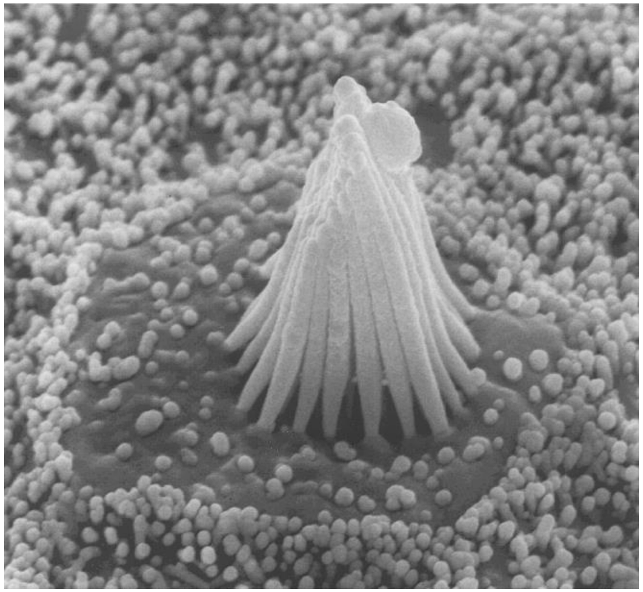
PNS Fig 30-3

Organ of Corti



Auditory System: Hair Cells





Auditory system AND Vestibular system (semicircular canals)

PNS Fig 31-1

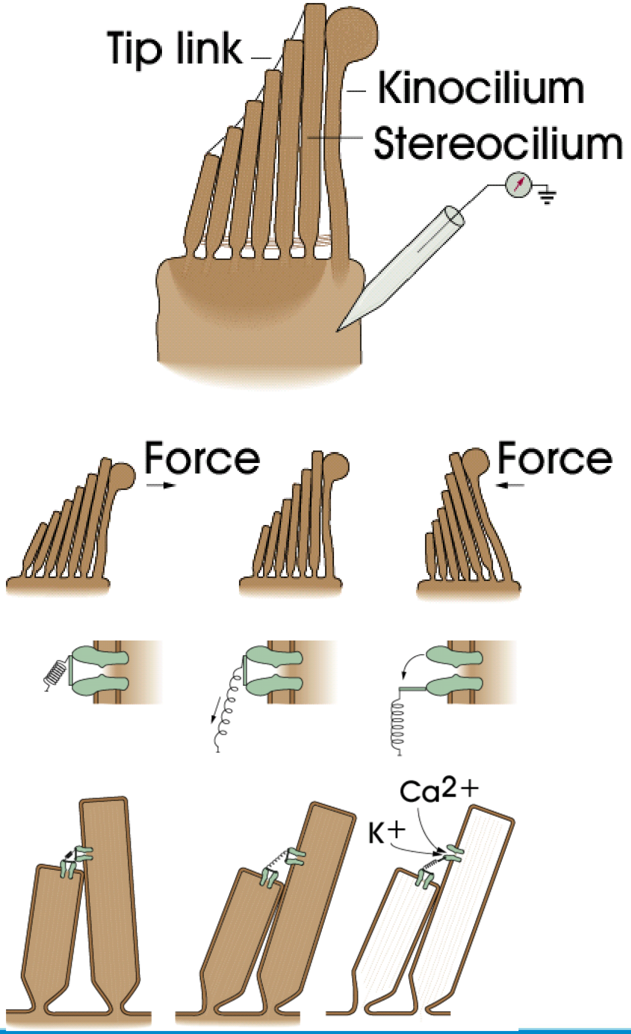
Auditory System: Hair Cells

Hearing 4all

Medizinische Hochschule Hannover

- Force towards kinocilium opens channels & K^+, Ca^{2+} enter, depolarizing cell by 10s of mV. Force away shuts channels.

- Tip links (em): believed to connect transduction channels (cation channels on hairs)

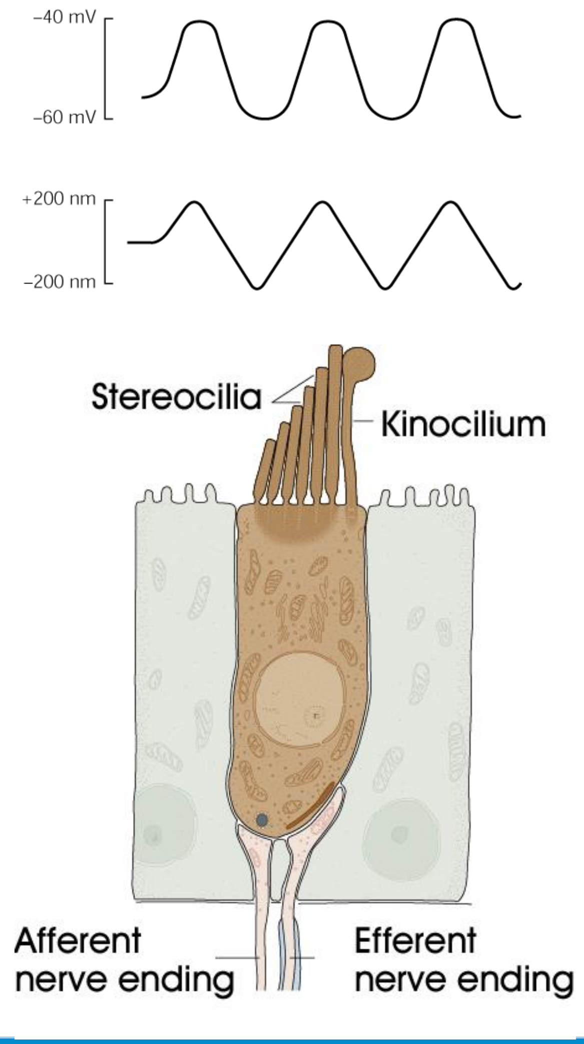


PNS Fig 31-2, 31-3

Auditory System: Hair Cells

- Force towards kinocilium opens channels & K^+, Ca^{2+} enter, depolarizing cell by 10s of mV. Force away shuts channels.
- Tip links (em): believed to connect transduction channels (cation channels on hairs)

- Cell depolarized / hyperpolarized
  - frequency: basilar membrane
  - timing: locked to local vibration
  - amplitude: loudness
- Neurotransmitter (Glu?) release
- Very fast (responding from 10 Hz – 100 kHz i.e.10 μsec accuracy).

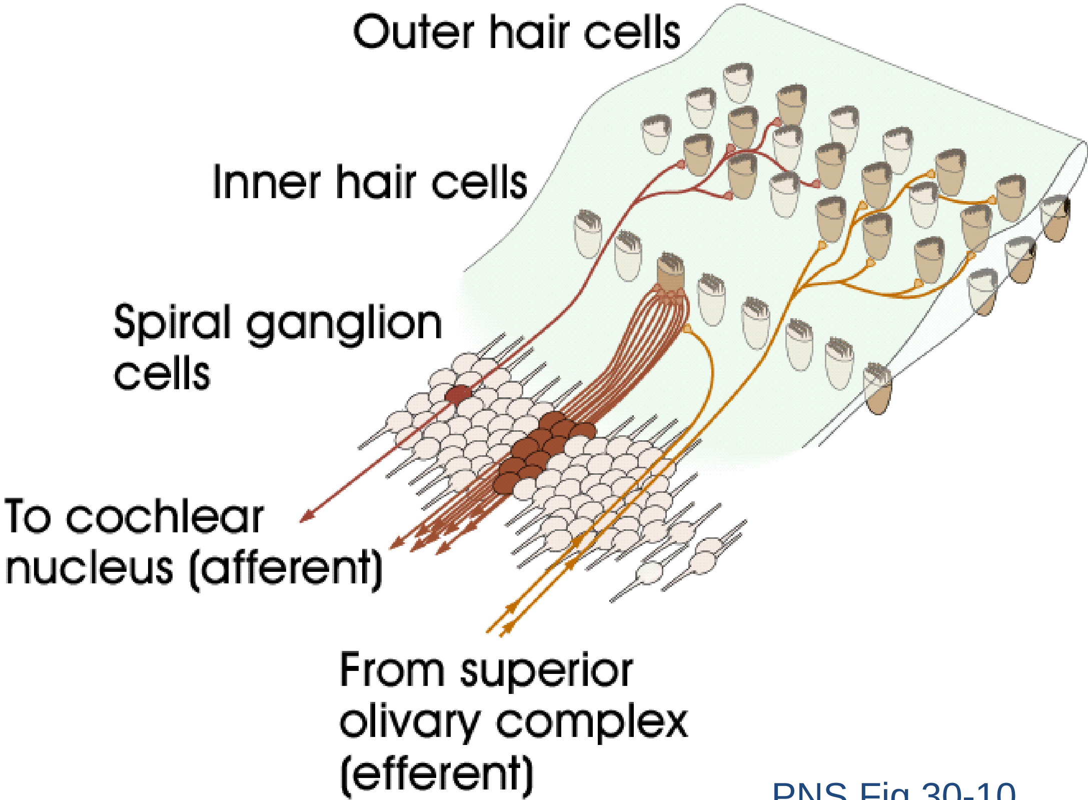


PNS Fig 31-2

Hair Cells: Tricks to enhance response

- Inner hair cells: MAIN SOURCE of afferent signal in auditory (VIII) nerve. (~ 10 afferents per hair cell)

- Outer hair cells: primarily get EFFERENT inputs. Control stiffness, amplify membrane vibration. (5,000,000 X range)



PNS Fig 30-10

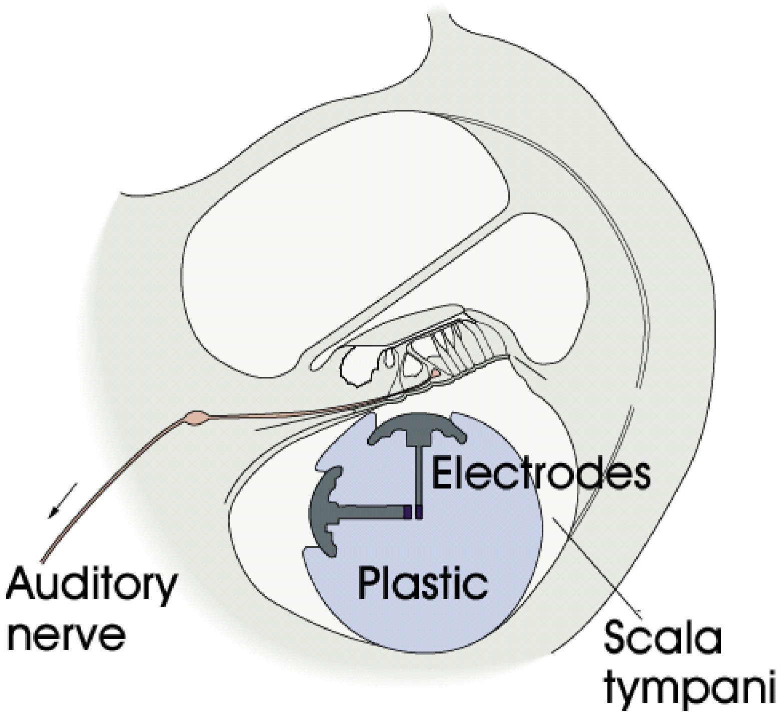
Ear:
a finely tuned machine

Optimally engineered to:

- pick up the very faint vibrations of sound &
- extract perceptually relevant features
  - pitch
  - loudness
  - complex patterns
  - timing

Cochlear prosthesis

- Most deafness: SENSORI-NEURAL hearing loss.
- Primarily from loss of cochlear hair cells, which do not regenerate.
- Hearing loss means problems with language acquisition in kids, social isolation for adults.
- When auditory nerve unaffected: cochlear prosthesis electrically stimulating nerve at correct tonotopic site.

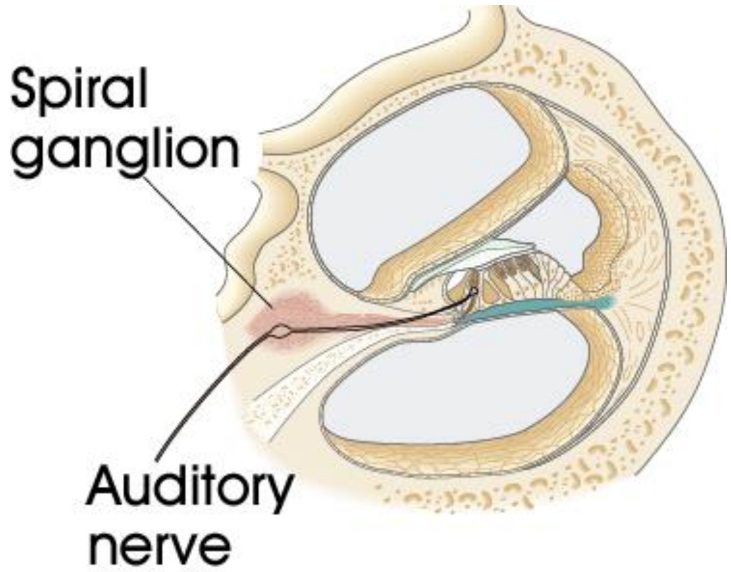


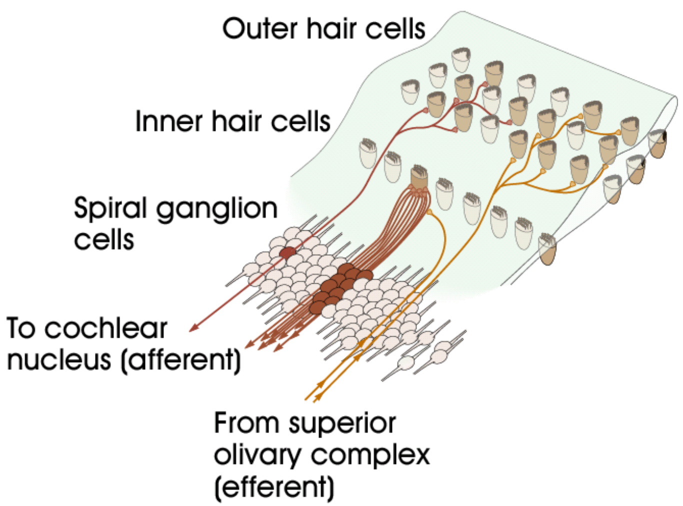
PNS Fig 30-18

Auditory Nerve (VIII cranial nerve)

- Neural information from inner hair cells: carried by cochlear division of the VIII Cranial Nerve.

PNS Chapter 30

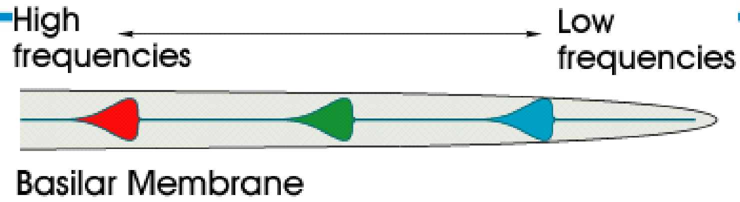




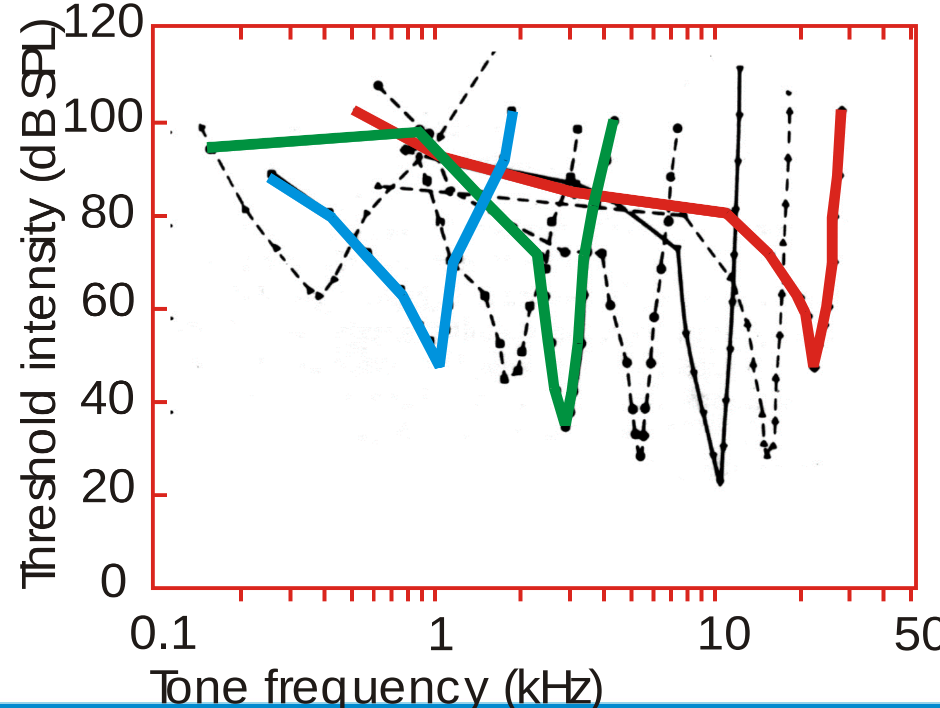
- Bipolar neurons, cell bodies in spiral ganglion, proximal processes on hair cell, distal in cochlear nucleus.

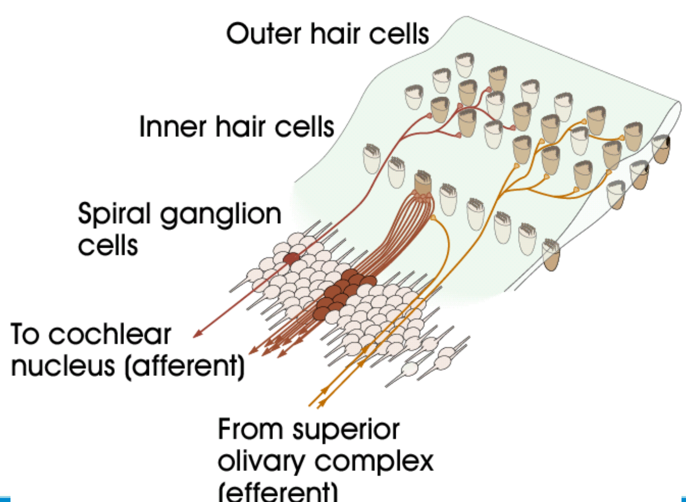
Auditory Nerve (VIII): Receptive fields

- Receptive fields: TUNING CURVE from hair cell
- "Labeled line" from "place" coding.
- Note: bandwidths equal on log frequency scale. Determines two-tone discrimination.



Tuning curves for single auditory fibres (guinea pig)

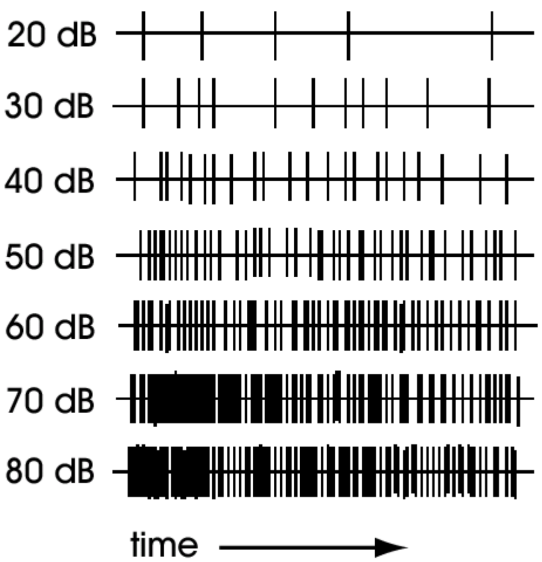




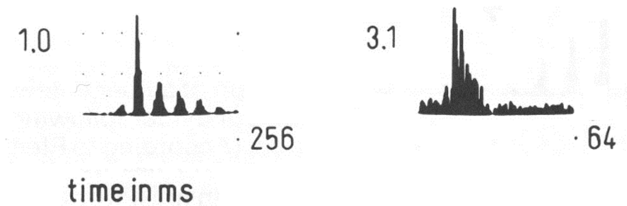
Auditory Nerve (VIII): Receptive fields

- Receptive fields: TUNING CURVE from hair cell.
- “Labeled line” from “place” coding.
- Note: bandwidths equal on log frequency scale. Determines two-tone discrimination.
- Loudness: spike rate (+ high-threshold fibers)
- Phase-locking to beyond 3 kHz
- Match: to frequency, loudness and timing

Auditory nerve activity (spikes)

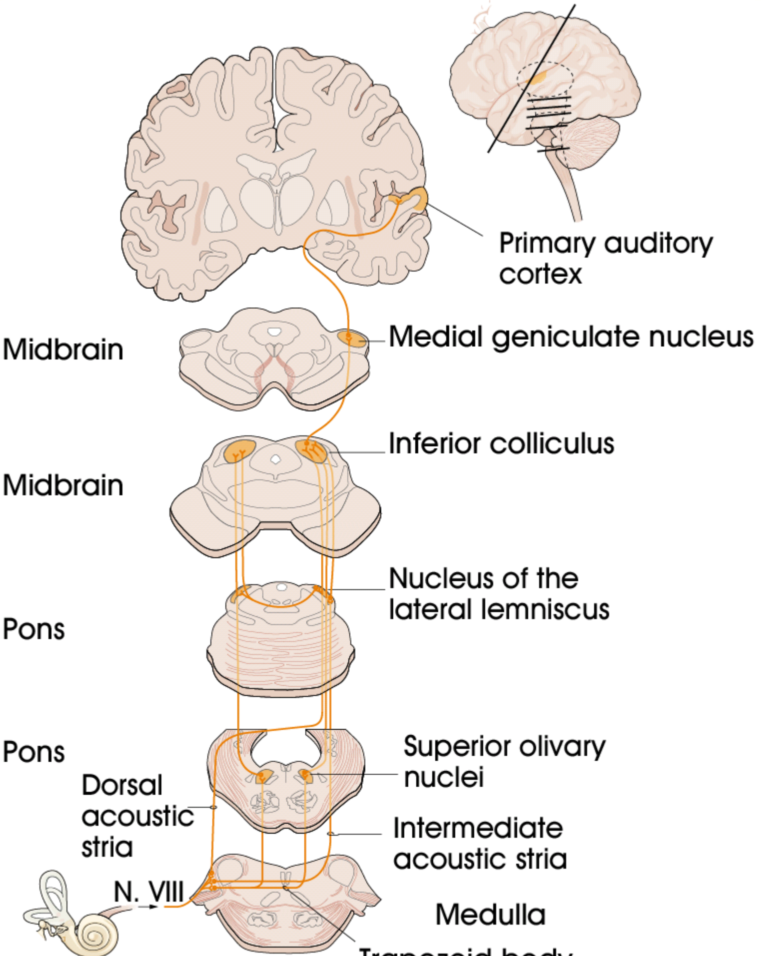


Characteristic freq (kHz)



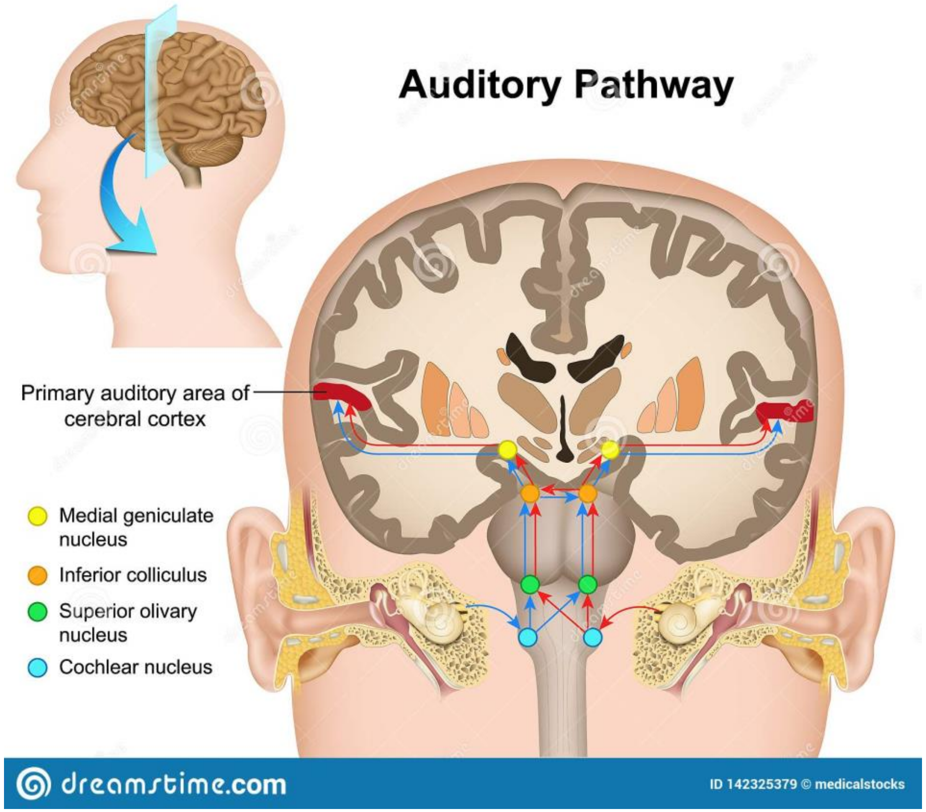
Reminder.
Auditory System: Central Pathways

- Very complex. Just some major pathways shown.
- Extensive binaural interaction, with responses depending on interactions between two ears.
- Unilateral lesions rarely produce unilateral deficits.



Reminder. Auditory System. Central Pathways.

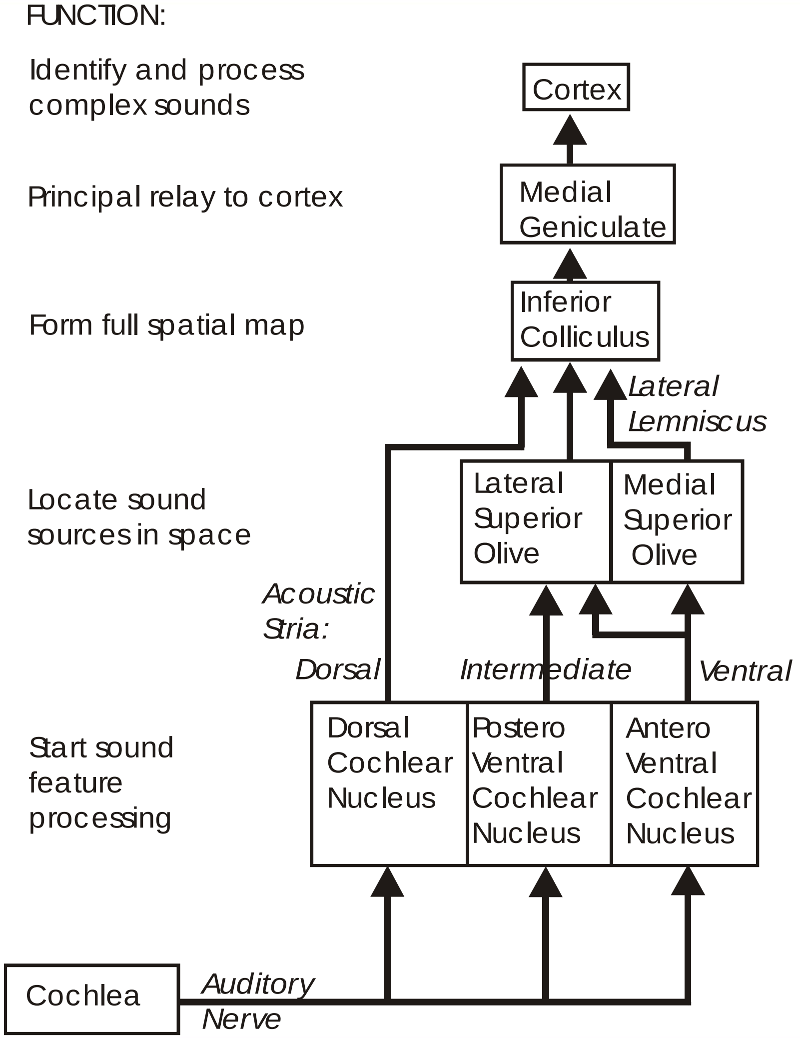
- Auditory system has multiple levels.
- Main nuclei of the auditory pathway:
  - Cochlear nucleus (CN)
  - Superior olivary complex (SOC)
  - Inferior colliculus (IC)
  - Medial geniculate nucleus (MGN)
- SOC receives information from cross and uncrossed pathways → brain processes information from ipsilateral and contralateral listening side.



https://www.dreamstime.com/illustration/auditory-pathway.html

Auditory System: Central Pathways

- General principles.
  - Parallel pathways, each analyzing a particular feature
  - Streams separate in cochlear nucleus: different cell types project to specific nuclei. Similar to “what” and “where”
  - Increasing complexity of responses (like vision, touch)



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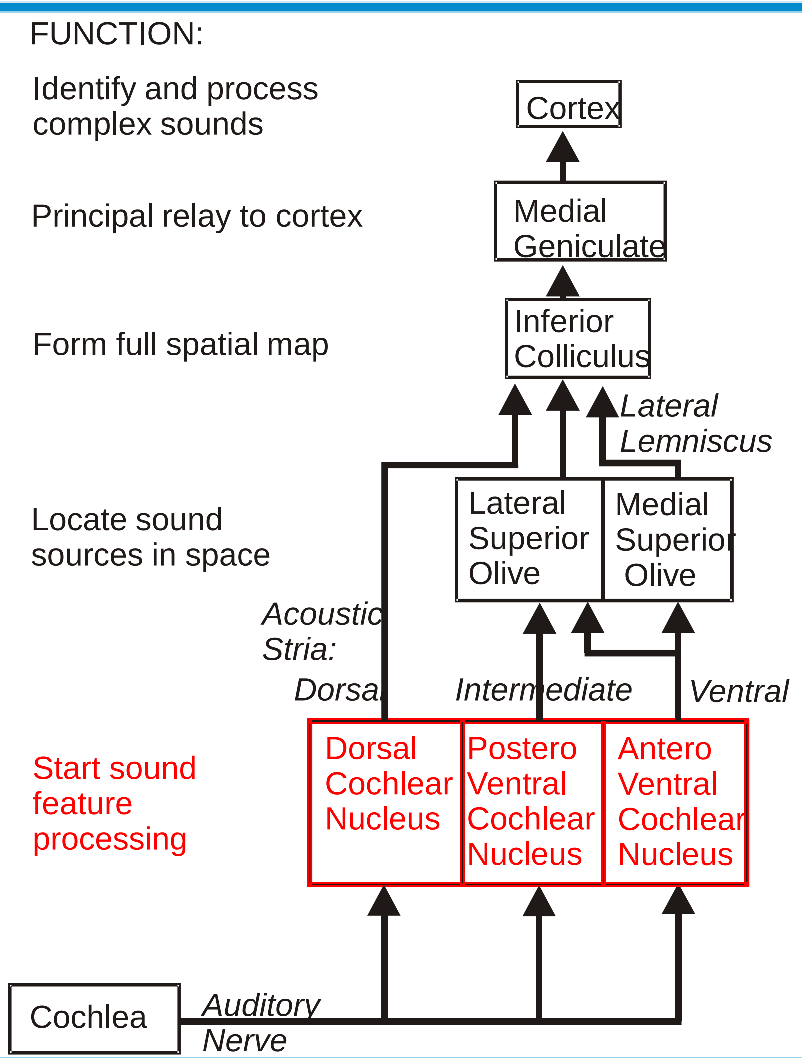
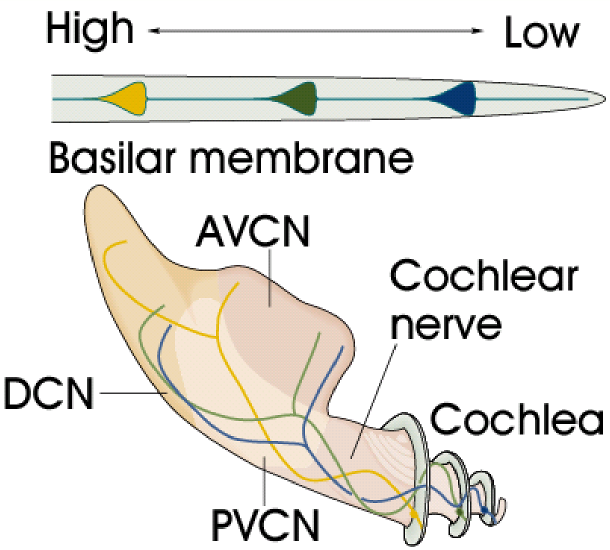


Cochlear Nucleus

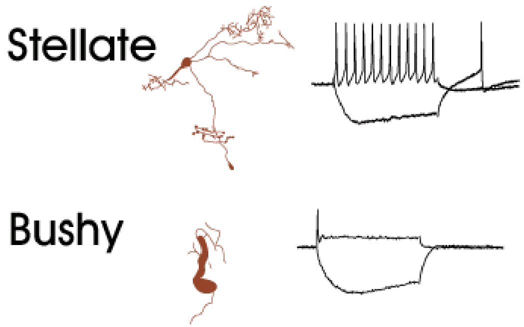
- VIII nerve: branches -> 3 cochlear nuclei.
  - Dorsal Cochlear Nucleus (DCN)
  - Posteroventral Cochlear Nucleus (PVCN)
  - Anteroventral Cochlear Nucleus (AVCN)

- Tonotopy (through innervation order)



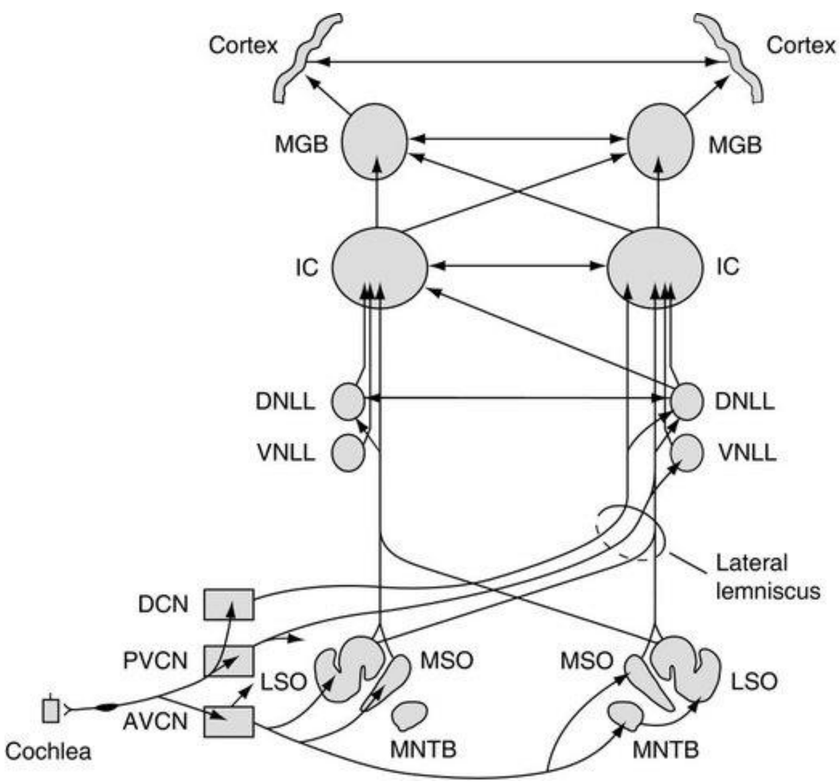
PNS Fig 30-13

- Start of true auditory feature processing.
  - Distinct cell classes: stellate (encode frequency), bushy (encodes sound onset), fusiform (envelope?)
  - Different cell types project to different relay nuclei.



PNS Fig 30-14

Auditory System: Central Pathways



FUNCTION:

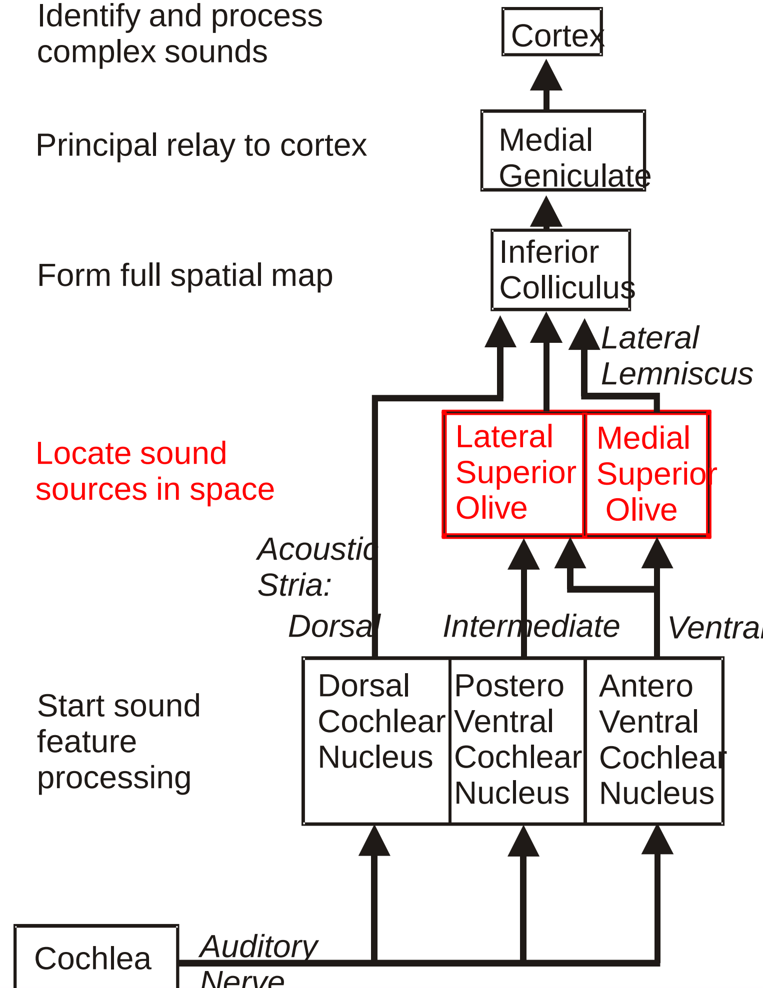
Identify and process complex sounds

Principal relay to cortex

Form full spatial map

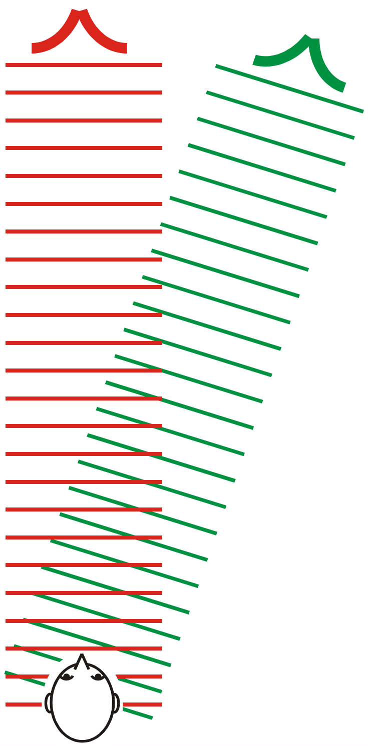
Locate sound sources in space

Start sound feature processing

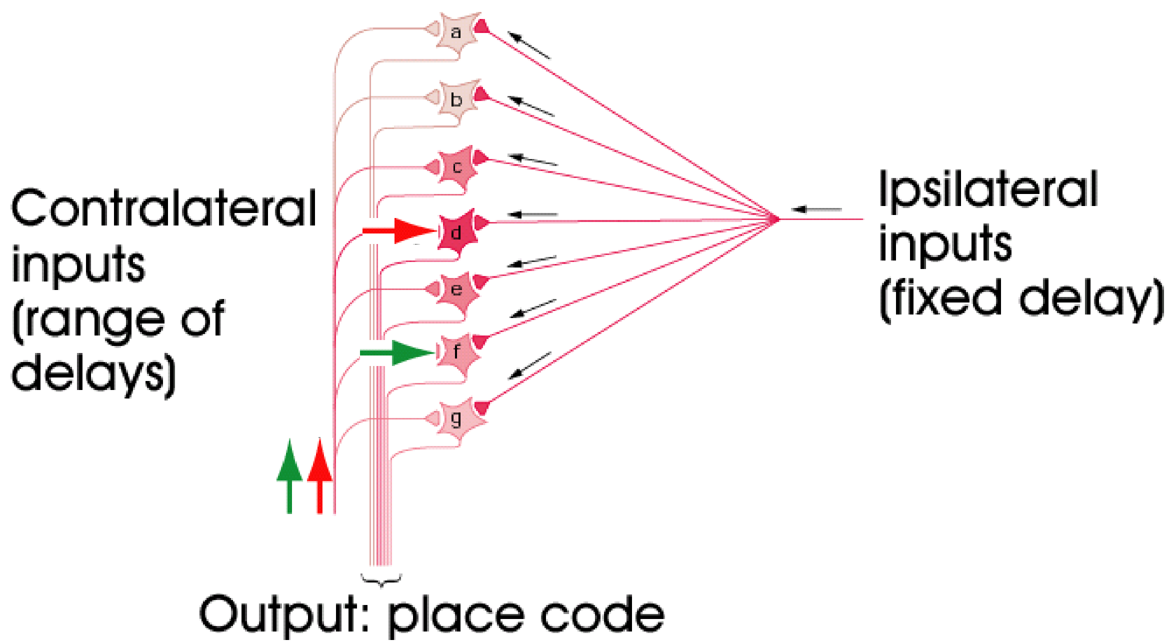


Superior Olive: Locates sound sources

- **Medial Superior Olive:** interaural time differences:
  - Delay Lines: Coincidence detector (accurate up to 10 microseconds).
  - Timing code converted to place code for angular location.
  - Tonotopic: matching across frequency bands.

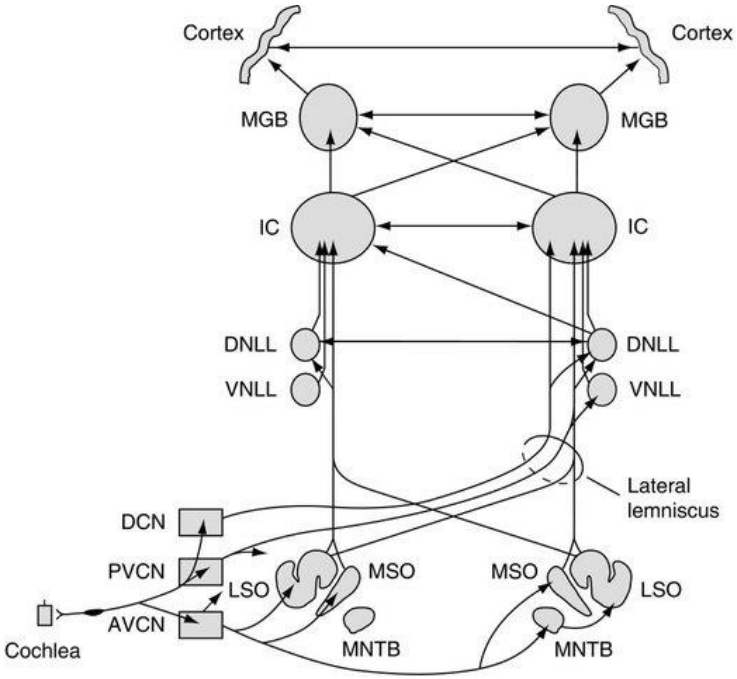


PNS Fig 30-15



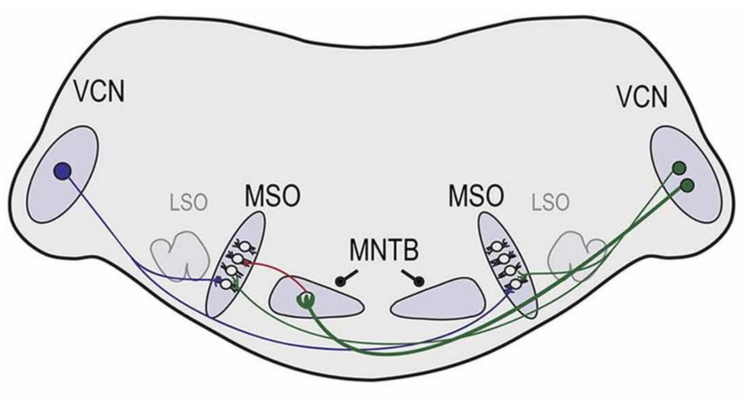
Superior Olive: locates sound sources

- **Lateral Superior Olive**: interaural **intensity** differences.
  - Works best at **high** frequencies, the head casts a better shadow.
  - Again, organized tonotopically to match across frequencies.

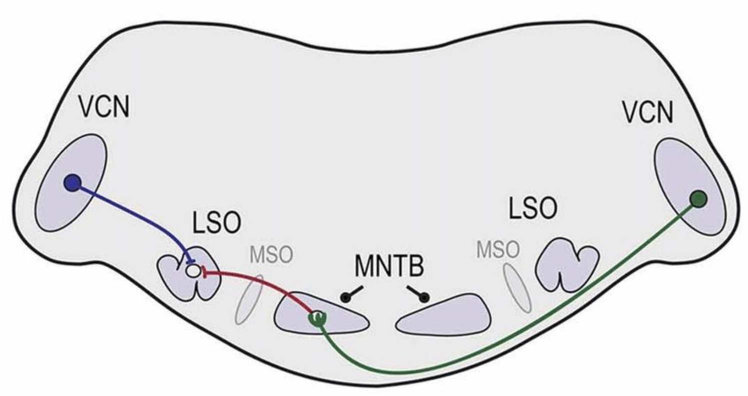


Physiological Binaural Pathways (I)

Mammalian ITD pathway



Mammalian ILD pathway



ITD sensitivity is established in the medial superior olive (MSO) by coincidence detection of excitatory inputs from both ears.

The nucleus is tonotopically organized

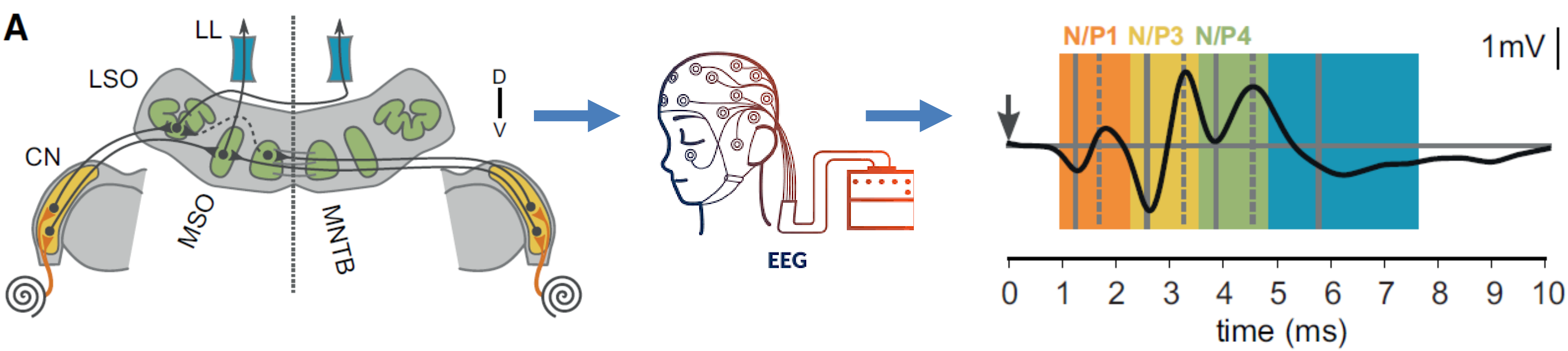
ILD sensitivity is established in the lateral superior olive (LSO) by ipsilateral excitatory input from the VCN (bushy cells) and inhibitory input from the contralateral medial nucleus of the trapezoid body (MNTB)

Brainstem Response

- With electroencephalography (EEG) it is possile to measure evoked response of the brainstem.
- Each peak of the evoked response corresponds roughly to the response of the nucleus along the brainstem.

Schematics of the brainstem binaural pathways:

Auditory brainstem response (ABR):



CN – cochlear nucleus; LSO – lateral superior olive;
MSO – medial superior olive; LL – lateral lemniscus

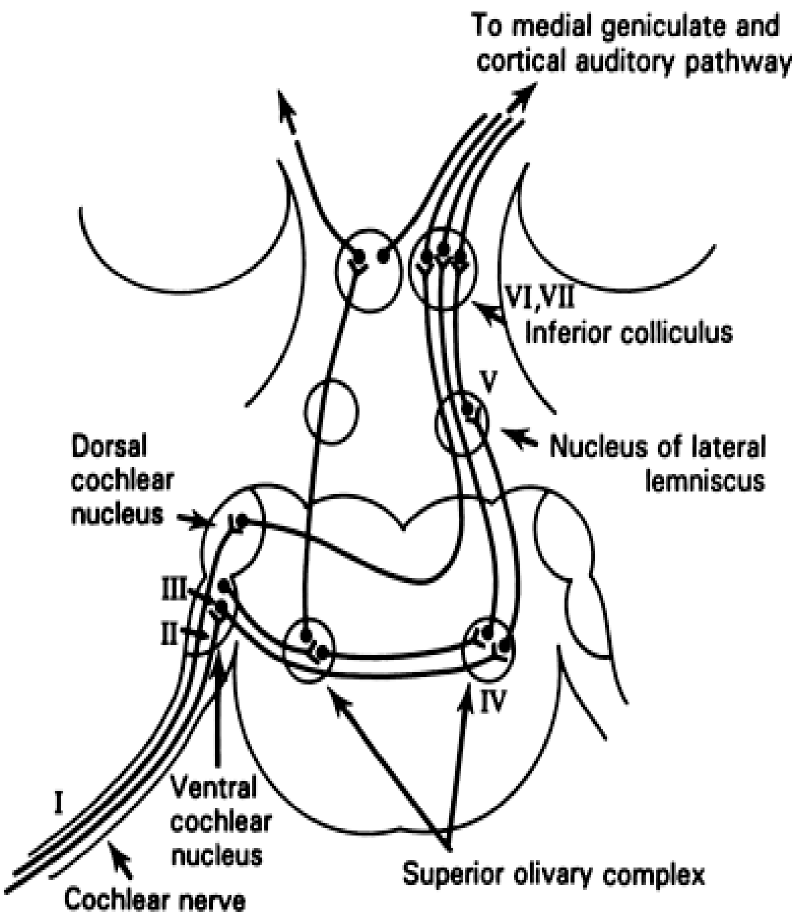
From Benichoux et al. (2018)

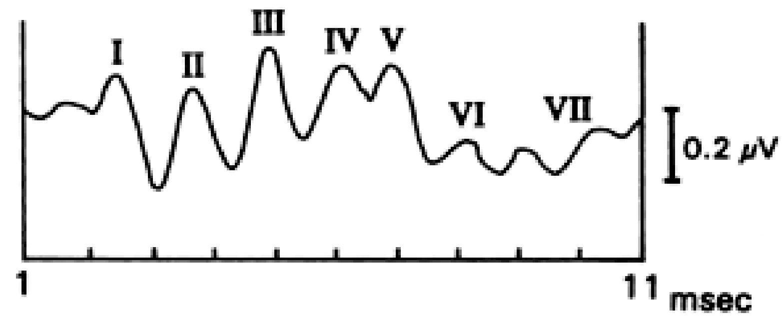
Auditory Brainstem Response (ABR) or Brainstem Evoked Response Audiometry (BERA)

Method	Clinical Application

• First described by Jewett and Williston 1971
• Evoked by short (~100 µs) clicks
• < 10 ms latency
• Intensity: > 80 dBHL
• > 1000 sweeps
• Filter settings: HP: 100 Hz, LP: 3000 Hz
 	
• Electrode montage:
    • Non-inverting: High forehead (Fz) or top middle of head (Cz)
    • Inverting reference: Left and right mastoids or earlobes
    • GND: Forehead
 	
• Waveform peaks are labeled I-VII
	• Screening tool to assess auditory nerve function
	• Newborn screening for deafness
	• Intraoperative monitoring of nervous system
	• Monitoring in IC units
	• Diagnosis of demyelinating disorders
	• Hearing threshold detection (amplitude increases with intensity)

Electrophysiological Measures
ABR or BERA





- Wave I - Compound Action Potential (CAP) from distal portion of auditory nerve
- Wave II – Proximal portion of auditory nerve
- Wave III – Cochlear nucleus
- Wave IV – Superior olivary complex and other midline brainstem structures
- **Wave V – Inferior colliculus**
- Wave VI and VII – Thalamic and cortical regions

[https://www.evokedpotential.com/the-auditory-brainstem-response.html]

Auditory Electrophysiology

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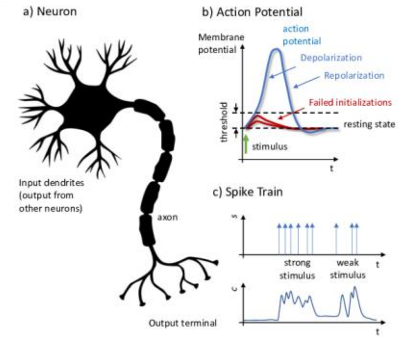
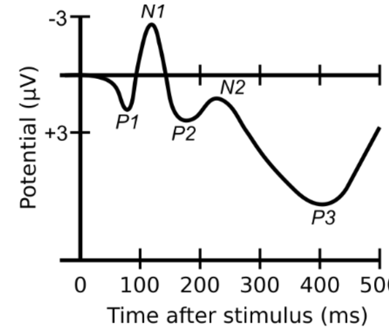
Mailan

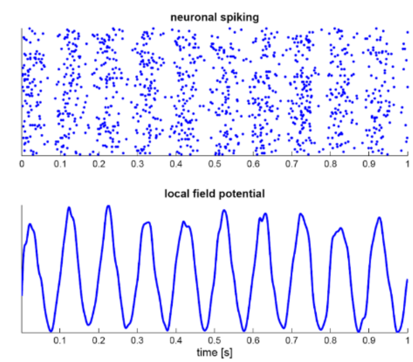
2022

Neural Signals

- Spikes – Action Potentials
  - Play a central role in communication among a population of neurons by providing for the propagation of signals along the axon of the neurons towards the axon terminals, which can then connect with other neurons at synapses.
- Evoked potentials
  - Electrical potential in a specific pattern recorded from a specific part of the nervous system, especially the brain, of a human or other animals following presentation of a stimulus such as a light flash or a pure tone.
- Brain oscillations or brainwaves:
  - Rhythmic or repetitive patterns of neural activity in the central nervous system.







Auditory Electrophysiology

Medizinische Hochschule Hannover

- Introduction to Auditory Brainstem Response (ABR)
- Electrocochleography: ECochG
  - Pre-Op/Intra-Op/Post-Op and Monitoring
- Otoacoustic Emissions (OAEs)
- Evoked Compound Action Potential (ECAP)
- Auditory Brainstem Responses (ABRs)
- Mid Latency Responses (MLRs)
- Corticual Auditory Evoked Potentaisl (CAEPs)
  - ACCs
  - ASSRs
- Neural Oscillations:
  - Alpha, Theta, Gamma, etc
  - Neural Tracking to speech

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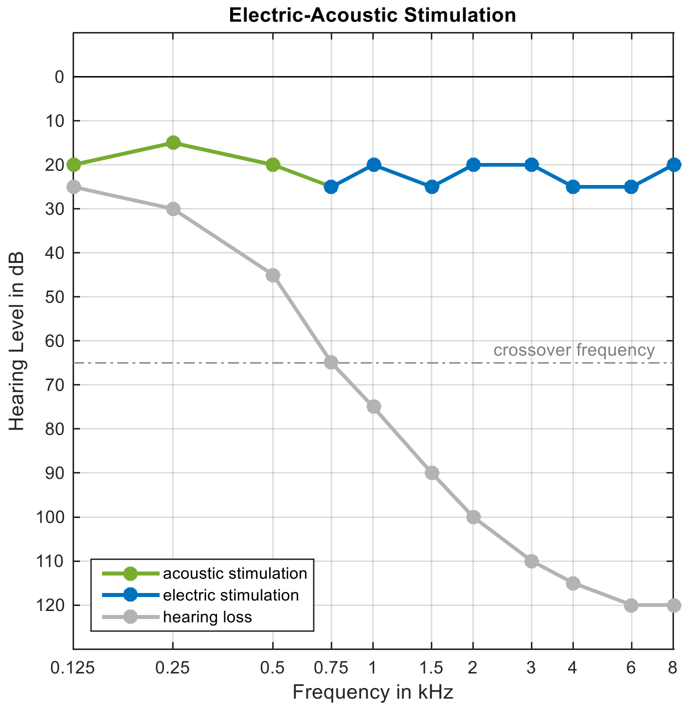
ECochG:
Motivation is to Preserve Hearing for EAS-Cochlear Implant Users

Figure from MED-EL



- Soft surgical techniques (Lenarz et al., 2009; von Ilberg et al., 1999) and,
- More flexible arrays (Hochmair et al., 2015), make it possible to insert an electrode while preserving the residual acoustic hearing

ECochG: Motivation is to Preserve Hearing for EAS-Cochlear Implant Users

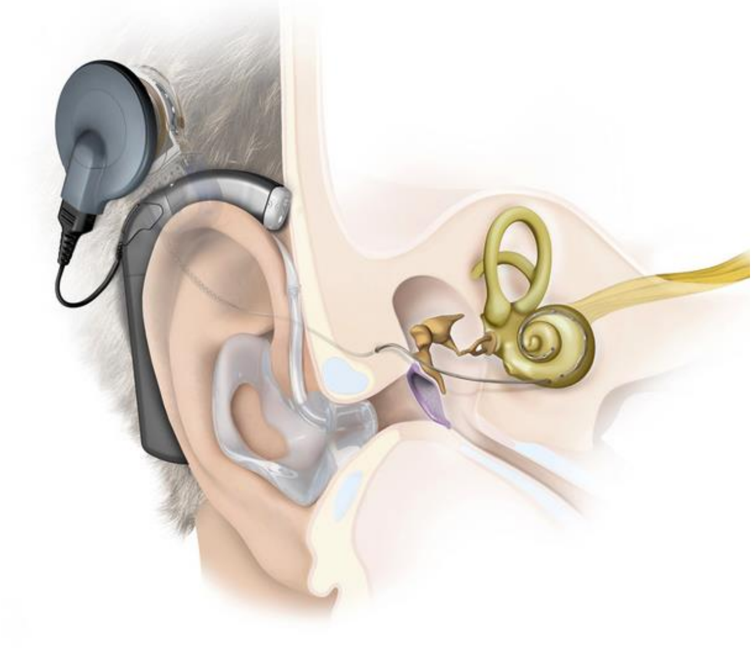
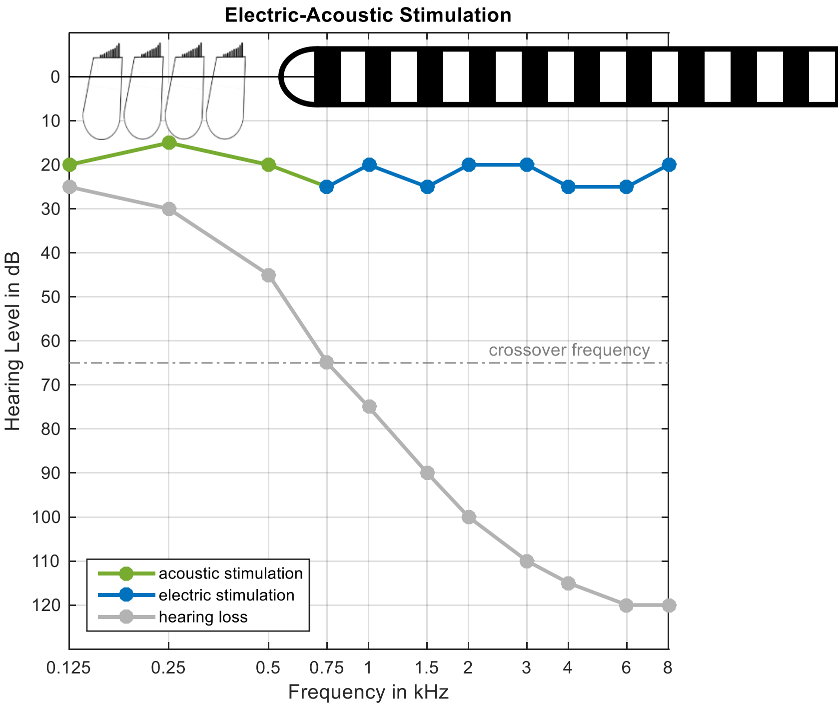


Figure from MED-EL



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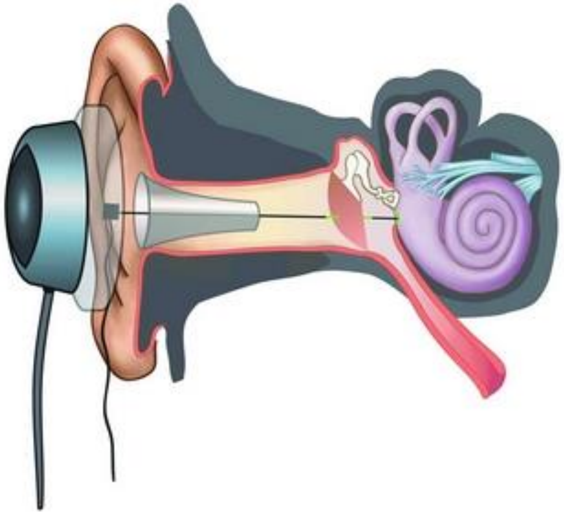
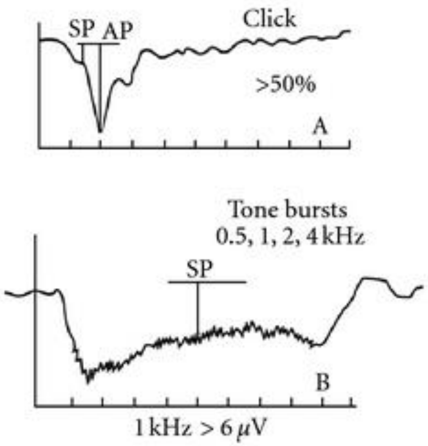
- More flexible arrays (Hochmair et al., 2015), make it possible to insert an electrode while preserving the residual acoustic hearing

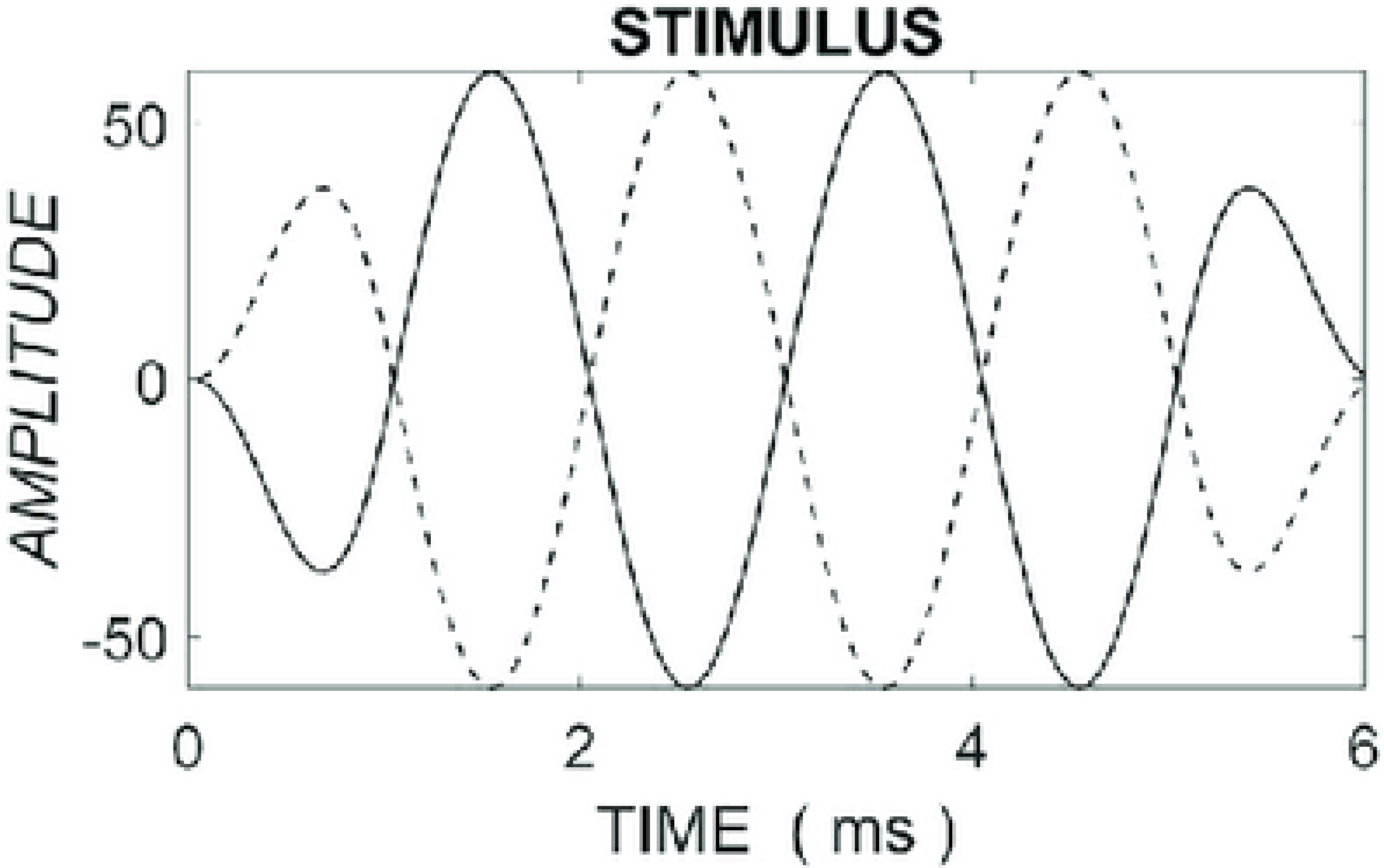
Electrocochleography (ECochG)

- Used to measure cochlear potentials and is essentially a surgical technique.
- Using a microscope, a needle electrode is inserted through the timpanic membrane (if intact) and placed on the promontory of the middle ear.
- Represents a near-field recording, transtympanically recorded cochlear potentials are 20 times larger in amplitude than those recorded noninvasively from an electrode in the ear canal.

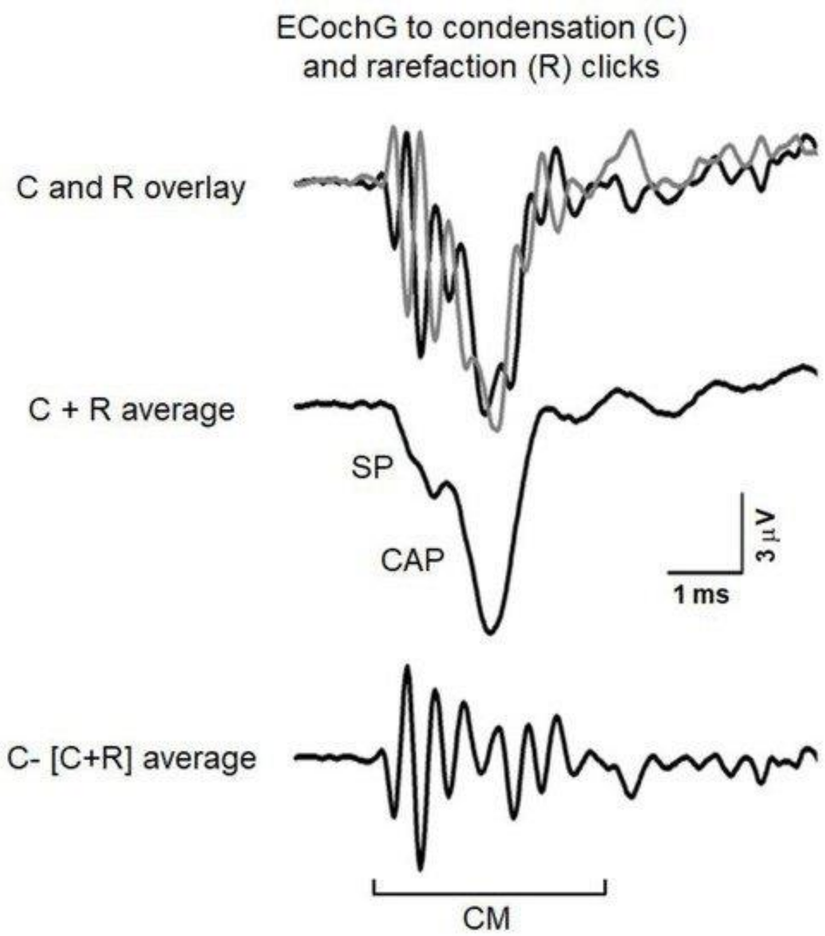




ECochG: Stimuli, condensation, rarefraction

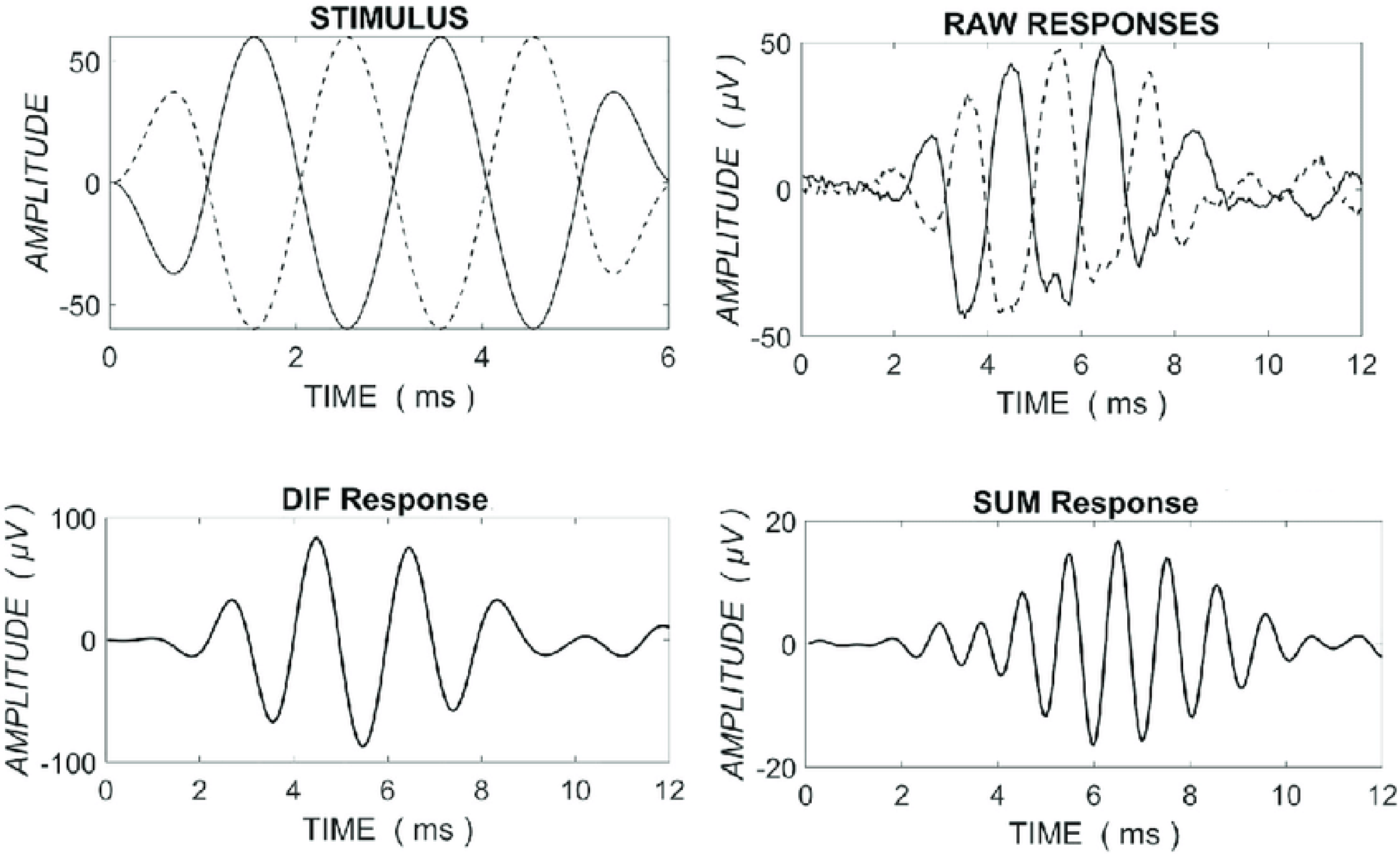


ECochG



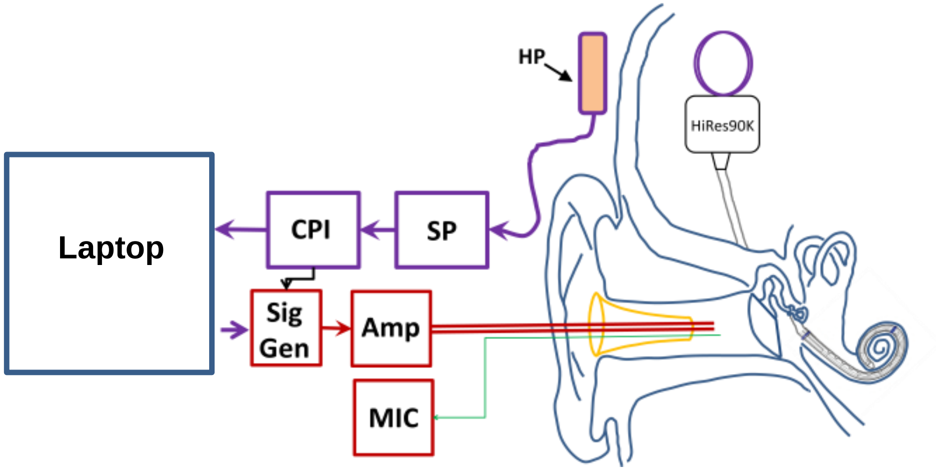
- ECochG potentials recorded in a normally-hearing individual at 110 dB nHL.
- The procedure utilized to separate the cochlear microphonic (CM) from the compound action potential (CAP) and summating potential (SP) is illustrated.
- The ECochG responses to condensation (C) and rarefaction (R) clicks are superimposed in the top panel.
- The CAP together with the superimposed SP was obtained by averaging the recordings to condensation and rarefaction clicks (C + R average) through the attenuation of the out-of-phase cochlear microphonics (middle panel).
- The CM shown in the lower panel results from subtracting the (C + R) average from the ECochG response to condensation clicks (Santarelli et al. 2021).
- Cochlear microphonics in the presence of an abnormal ABR are typical of an auditory neuropathy (Sininger and Oba, 2001).

ECochG to tone stimuli DIF and SUM Response

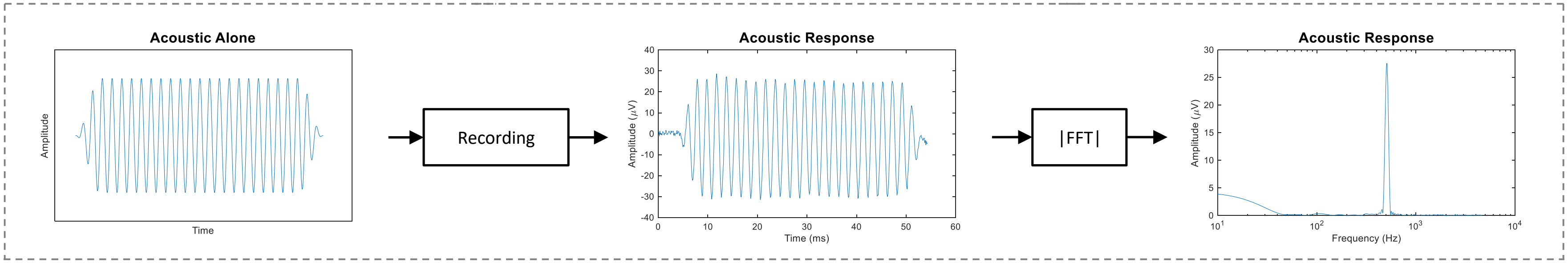


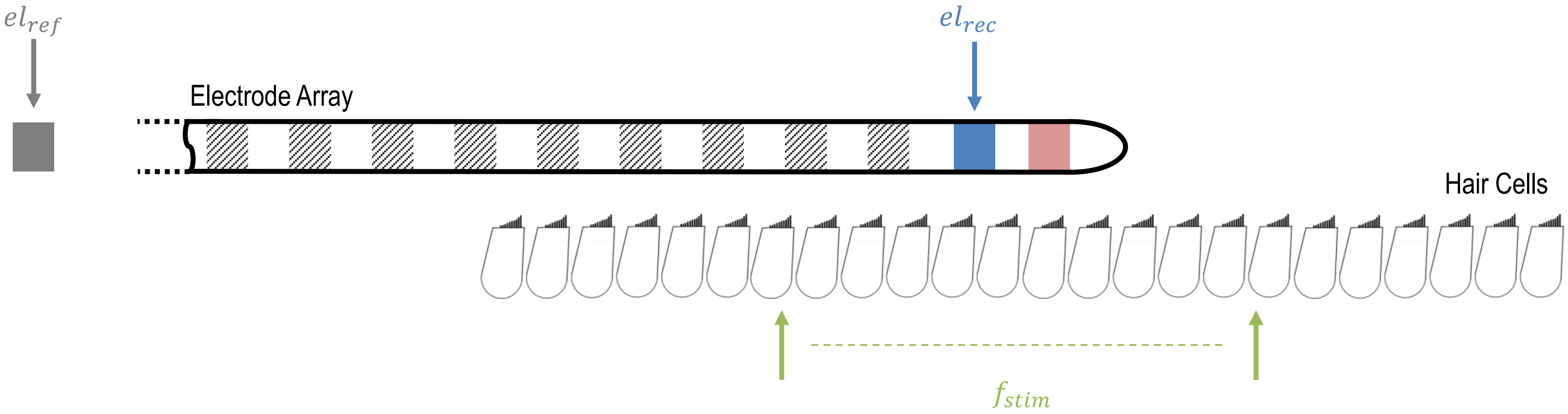
Intracochlear ECochG with Advanced Bionics

Medizinische Hochschule Hannover



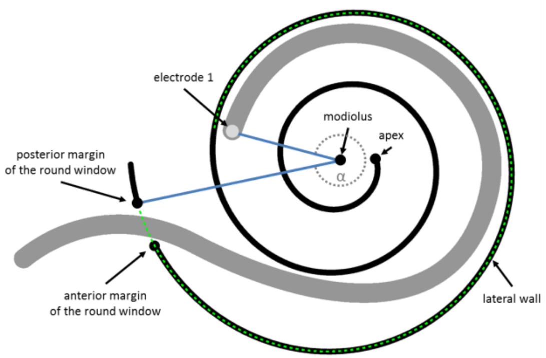
ECochG / Cochlear Microphonics using cochlear implant electrodes as sensors
Post Cochlear Implantation



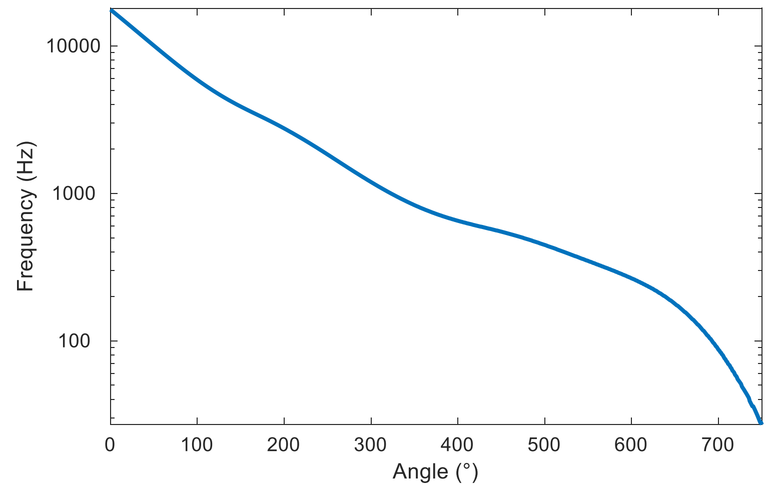


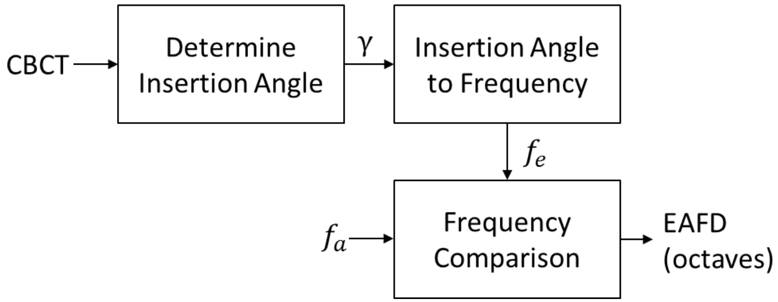
Electric-Acoustic Frequency Difference EAFD

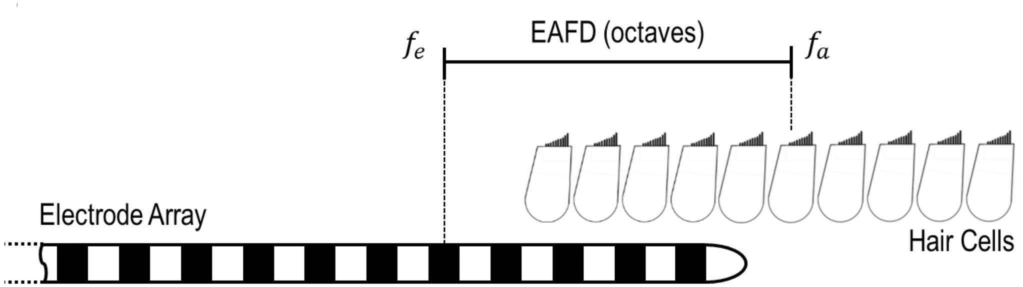
Insertion angle form CBCT



Stakhovskaya pitch map





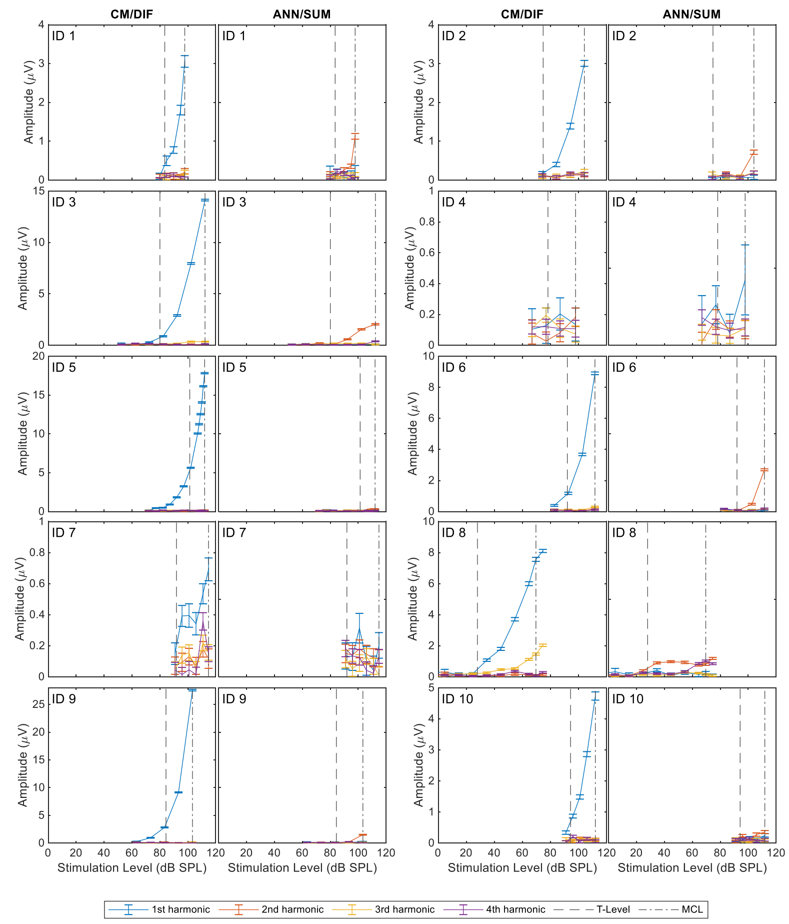


ECochG amplitude growth
N=10 Advanced Bionics subjects

Hearing4all

Medizinische Hochschule Hannover

- CM/DIF amplitude responses could be recorded for acoustic stimulation at MCL in 9 of 10 subjects.
- ANN/SUM amplitude responses could be recorded for acoustic stimulation at MCL in 8 of 10 subjects.
- The mean CM/DIF response was 8.76 µV and the mean ANN/SUM response was 0.98 µV.
- Significant CM/DIF amplitudes at the psychoacoustic detection threshold could be recorded for 8 of the 10 subjects.
- No significant ANN/SUM amplitude responses could be recorded at psychoacoustic detection thresholds.



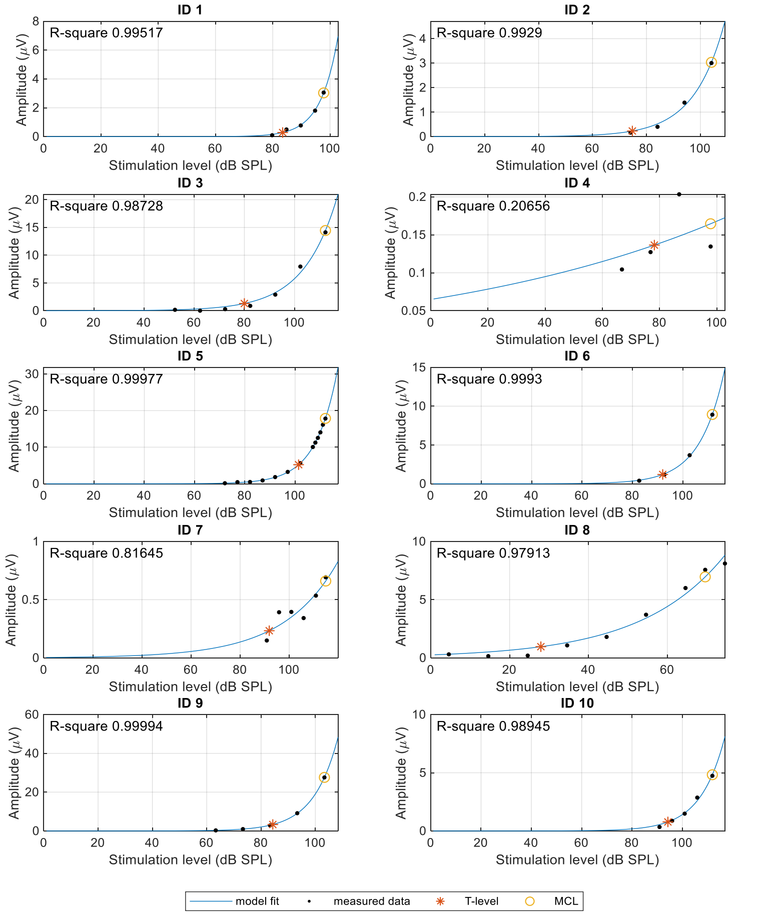
Krüger et al 2020, JASA

ECochG amplitude growth functions

Hearing 4all

Medizinische Hochschule Hannover

- CM/DIF amplitude responses could be recorded for acoustic stimulation at MCL in 9 of 10 subjects.
- ANN/SUM amplitude responses could be recorded for acoustic stimulation at MCL in 8 of 10 subjects.
- The mean CM/DIF response was 8.76 µV and the mean ANN/SUM response was 0.98 µV.
- Significant CM/DIF amplitudes at the psychoacoustic detection threshold could be recorded for 8 of the 10 subjects.
- No significant ANN/SUM amplitude responses could be recorded at psychoacoustic detection thresholds.
- The CM/DIF threshold was in mean -17.5 dB below the psychoacoustic detection threshold.



Cochlear monitoring: electrocochleography to check residual hearing during and after cochlear implantation possible.

S. Haumann, M. Bradler, A. Büchner, V. Helmstädter, H. Maier, T. Lenarz, R.B. Salcher

Medizinische Hochschule Hannover

Klinik und Poliklinik für Hals-Nasen-Ohrenheilkunde

Direktor: Prof. Prof. h.c. Dr. med. Thomas Lenarz

Medizinische Hochschule Hannover

DHZ Deutsches HörZentrum Hannover

VIANNA

Hearing4all

Motivation

- Overall Objective:
- To support residual hearing preservation in cochlear implant (CI) insertions by monitoring inner ear function.

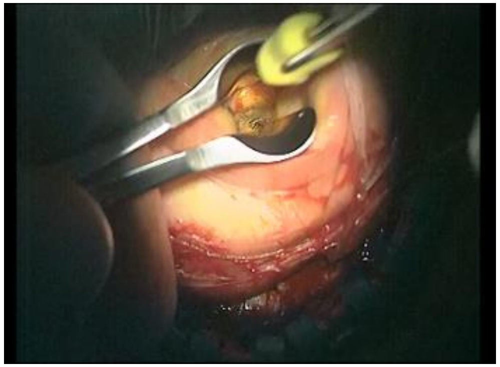
  → Biofeedback for the surgeon

- Correlation to hearing threshold
- Indicators of damage
- Identification of critical steps
- Development of an online alarm system

Methods

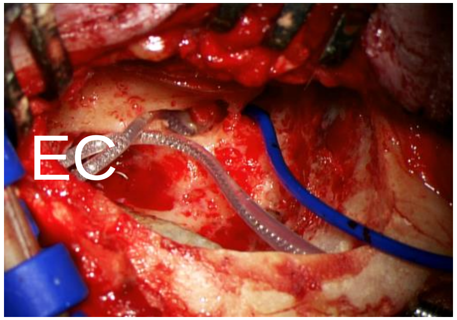
- Recording of electrocochleography (ECochG) before, during and after electrode insertion as well as during follow-up

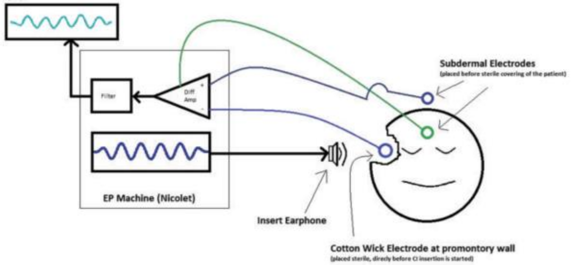
- Acoustic stimulation with plug-in earphones and tone bursts of different frequencies



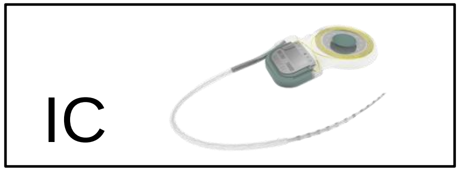
Methods (2)

- Extracochlear potentials (EC)
  - Conducted through clinical device (here Natus/Nicolet Viking EDX)
  - Cotton Wick electrode outside the cochlea (oval window, close to the promontory)
  - Manufacturer independent, works with all CIs

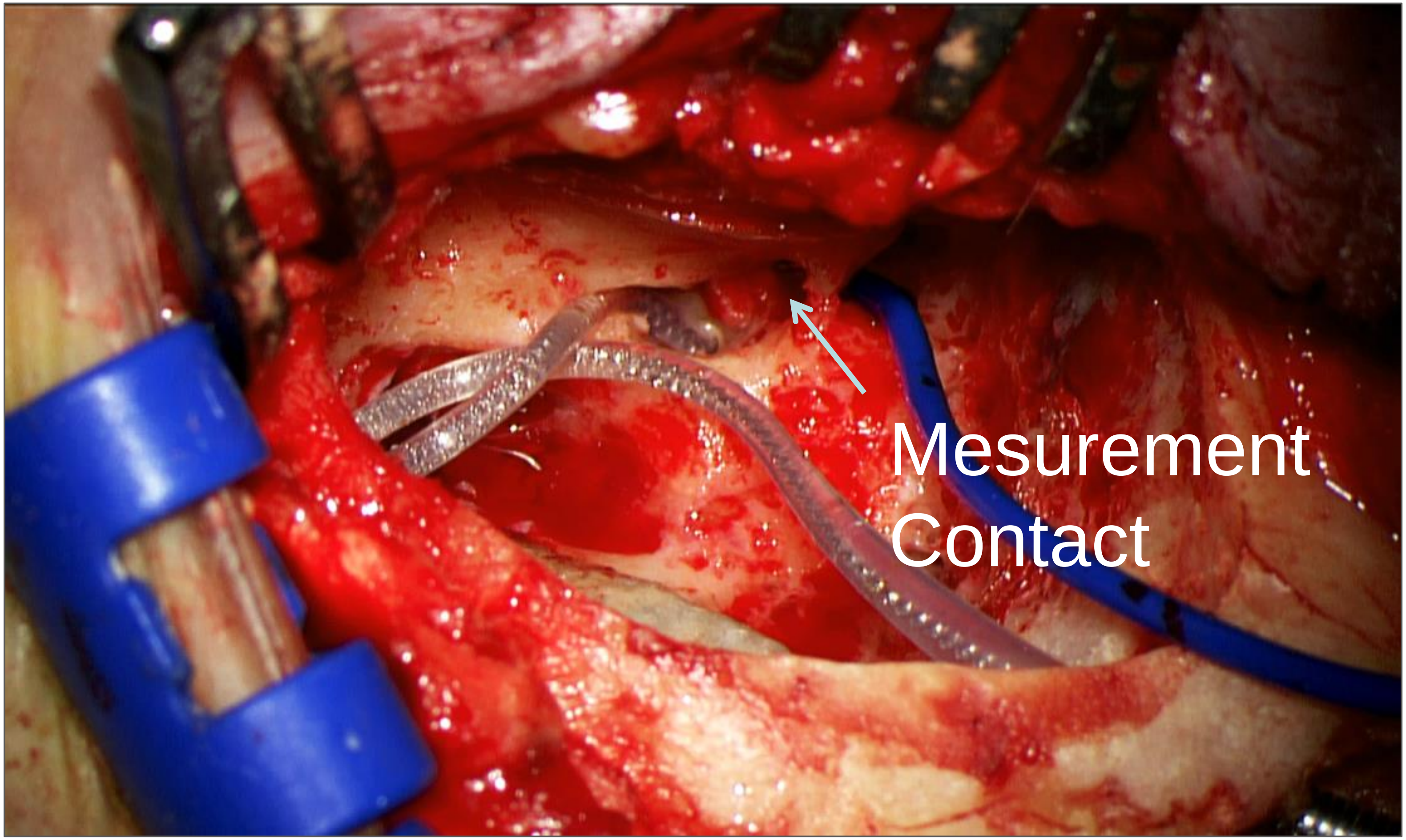




- Intracochlear potentials
  - Conduction by means of CI electrode, different conduction strategies depends on each manufacturer



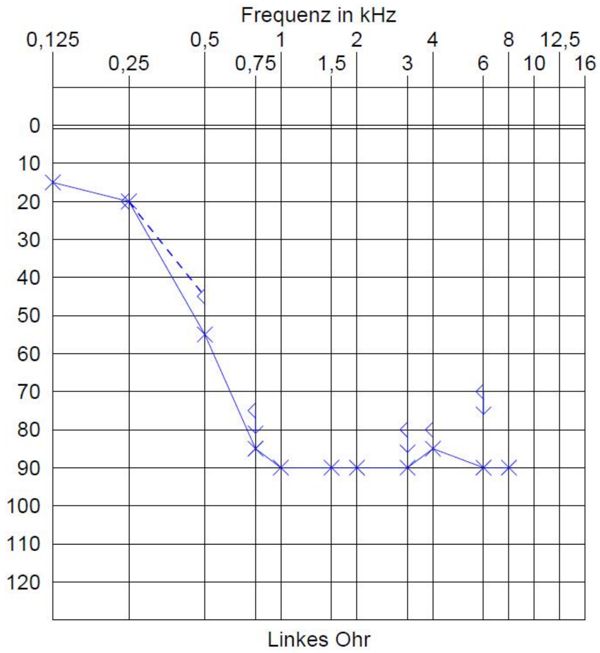
Extracochlear Potentials (Cotton Wick)



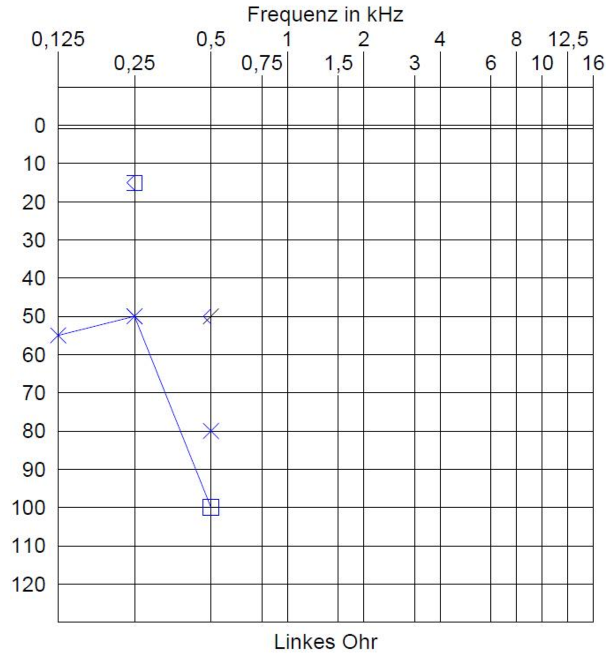
Female Patient, 33 Years

Nucleus SRA (522) left, partial insertion

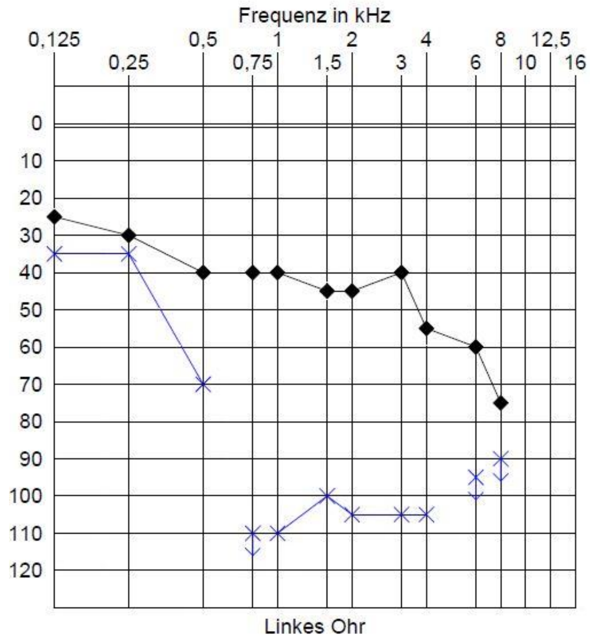
Course of the pure tone audiogram



Pre-op



Post-op

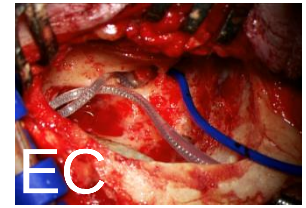


First-fitting

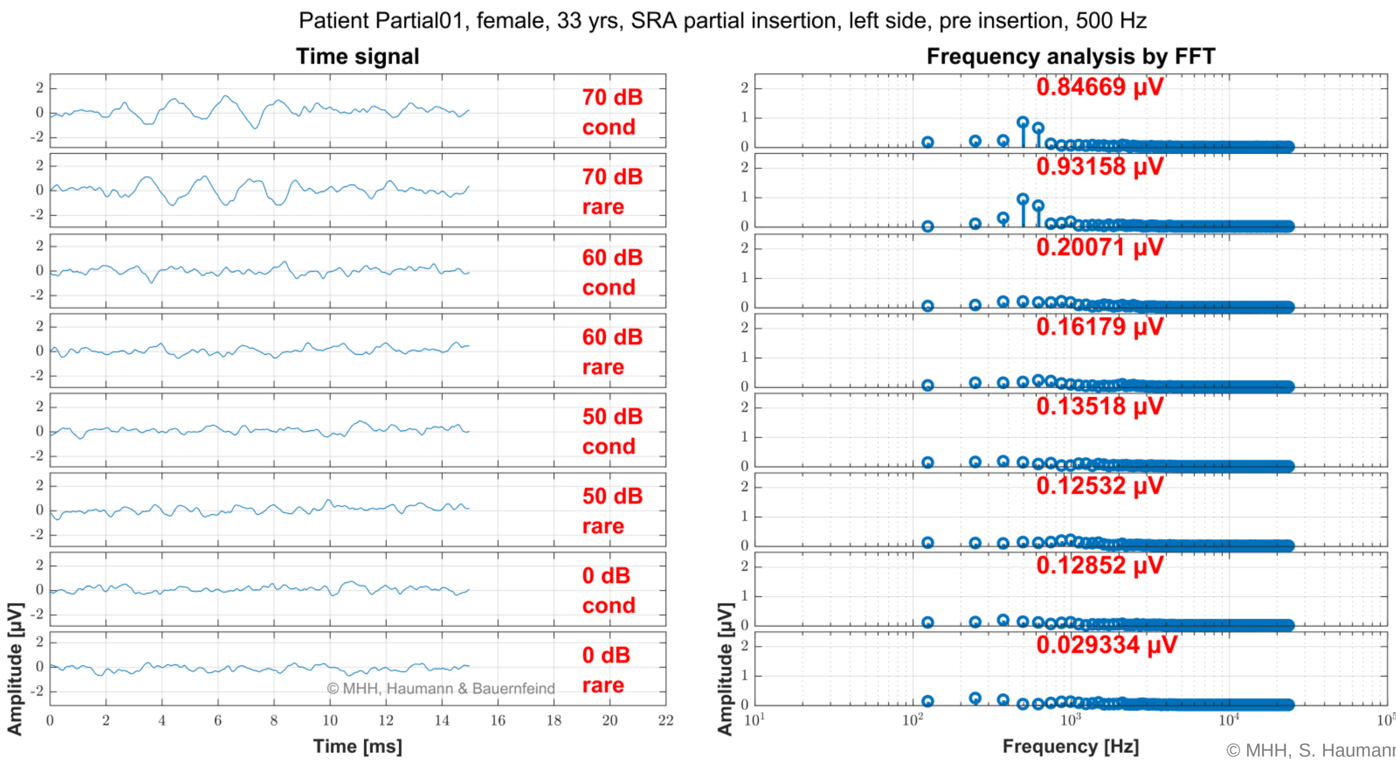
Extracochlear Measures (Cotton Wick)

before Insertion

500 Hz



Time Domain



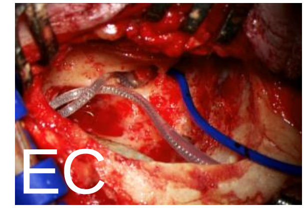
Frequency Analysis (FFT)

PTA 55 dB

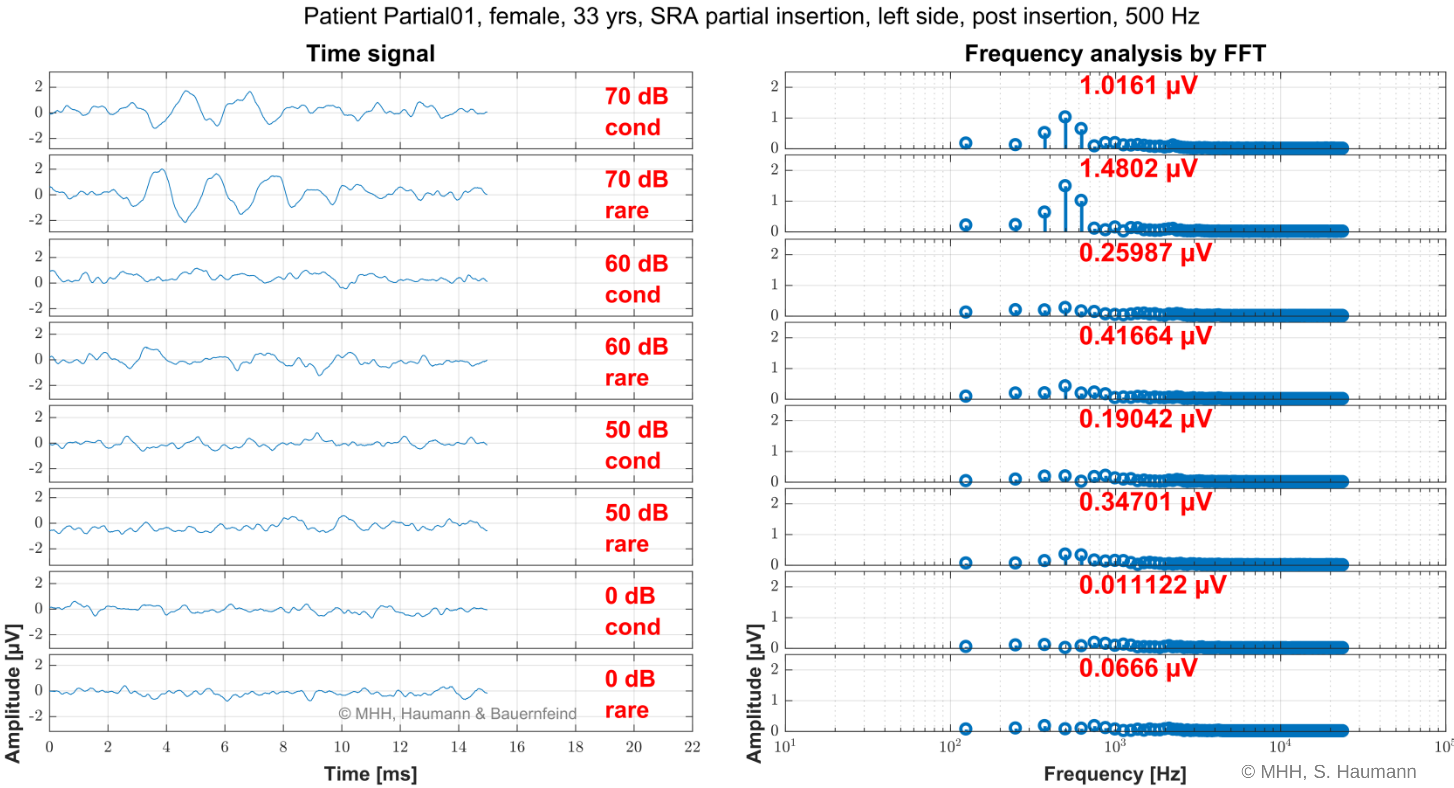
Extracochlear Measures (Cotton Wick)

after Insertion

500 Hz



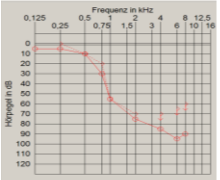
Time Domain



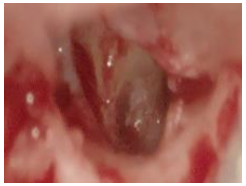
Frequency Analysis (FFT)

PTA EA 70 dB

EC before Insertion vs. Pre-op Audio

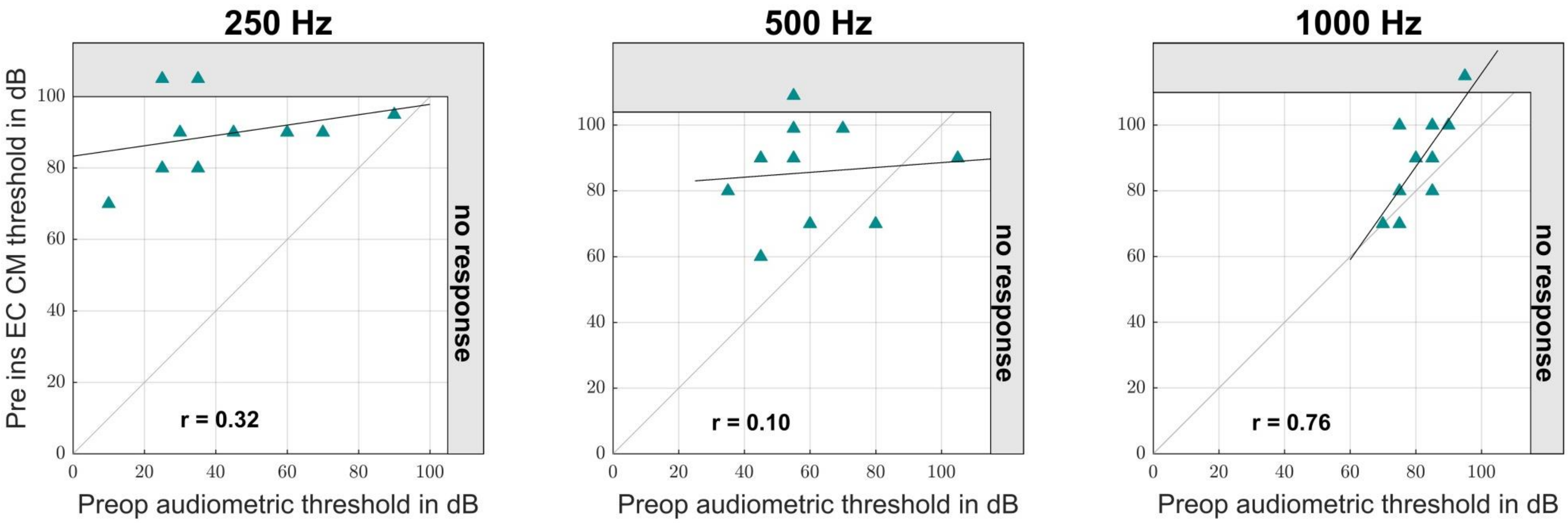


Pre-op audio



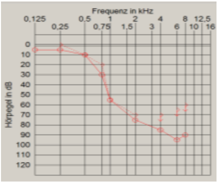
Pre ins

EC

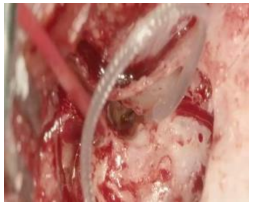


Modified after: S. Haumann, M. Imsiecke, G. Bauernfeind, A. Büchner, V. Helmstaedter, T. Lenarz und R.B. Salcher (2019): Monitoring of the Inner Ear Function During and After Cochlear Implant Insertion Using Electrocochleography, Trends in Hearing, in Druck

EC after Insertion vs. postoperative Audio

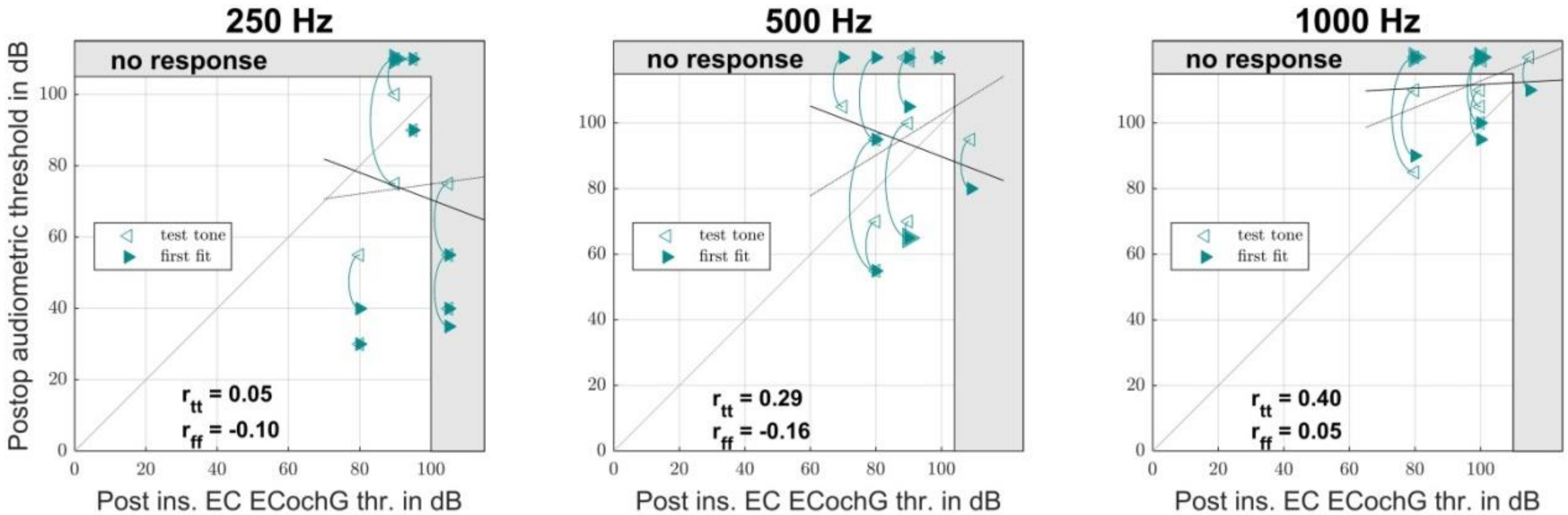


postop audio



Post ins

EC



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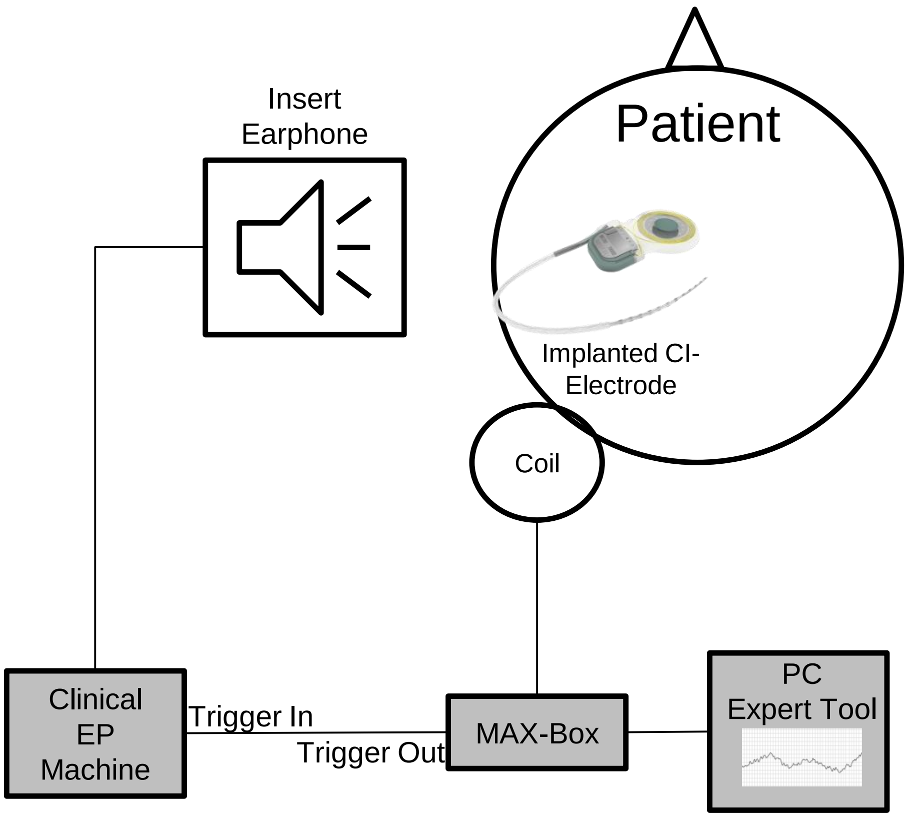
Intracochlear Potentials with MedEl

- Measurements via regular MedEl-CI and special software tool.
- Current study: Intraoperative measurement and postoperative observation over one year (trial, initial fitting, after 3, 6 and 12 months)
- Measured frequencies: 250 Hz, 500 Hz, 1000 Hz
- Apical contact
- Patients
  - n=10 Patients intra-op
  - n=8 of which completed (by the year-end)

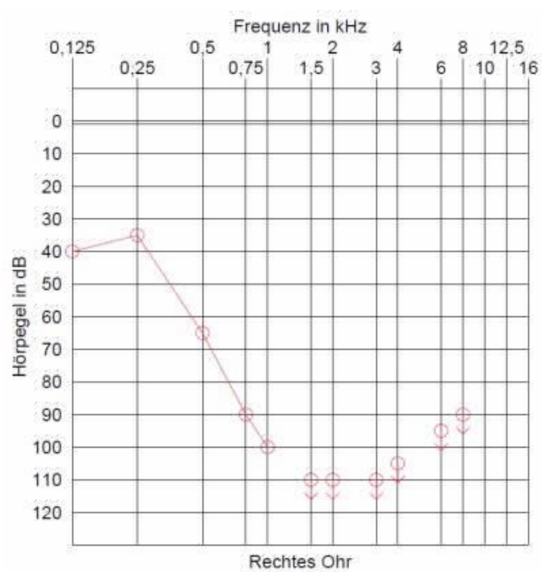


Female Patient, 30 Years, First fitting

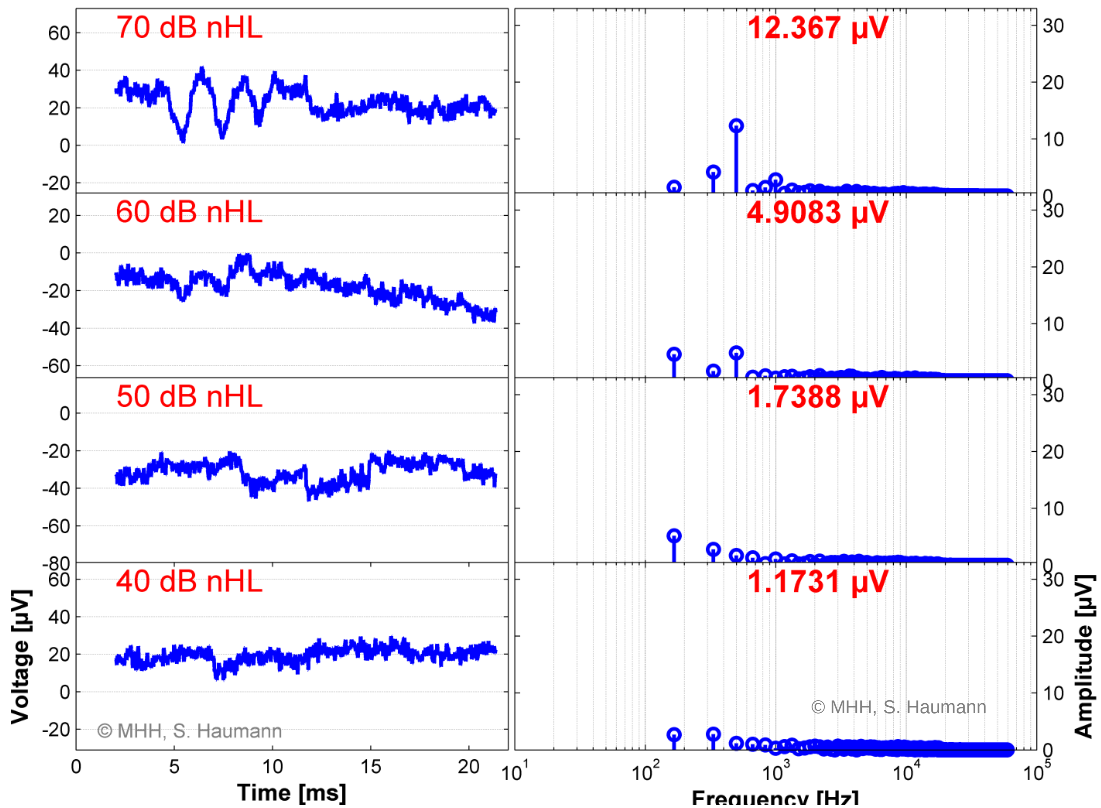
(MedEl Flex24 right)

Subjective Impression

Pure tone audiogramm,
65 dB @500 Hz



500 Hz



Loud

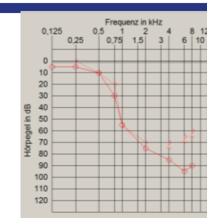
middle

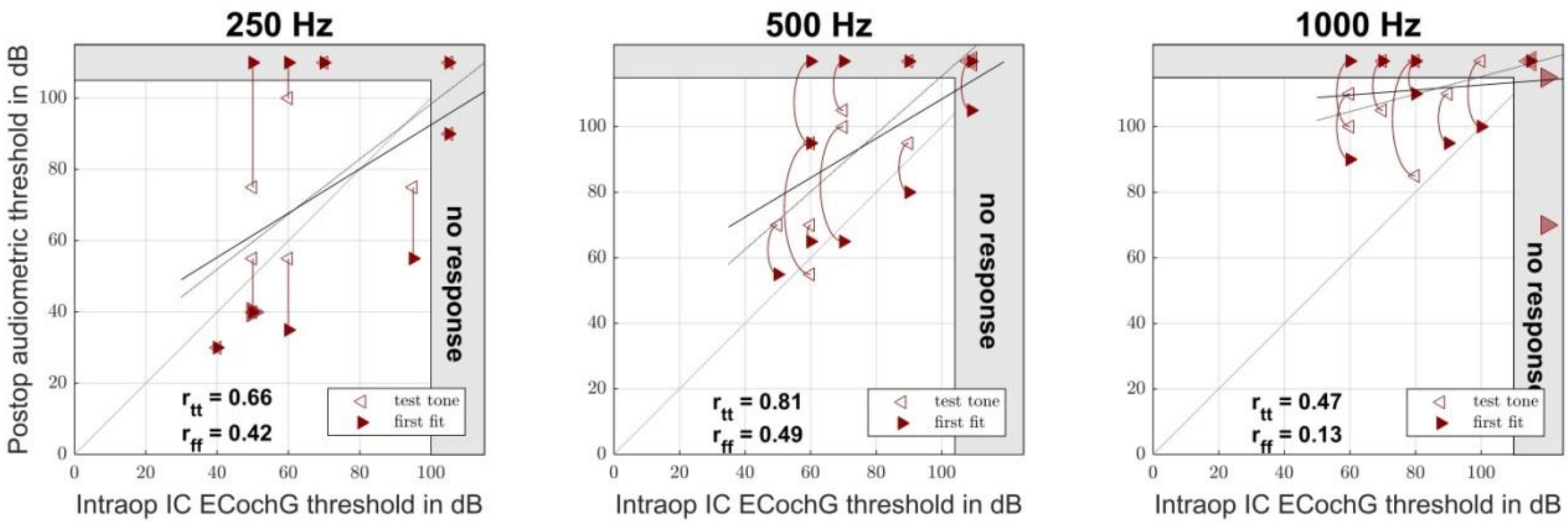
soft

nothing

IC after Insertion vs. Post-operative Audio

IC

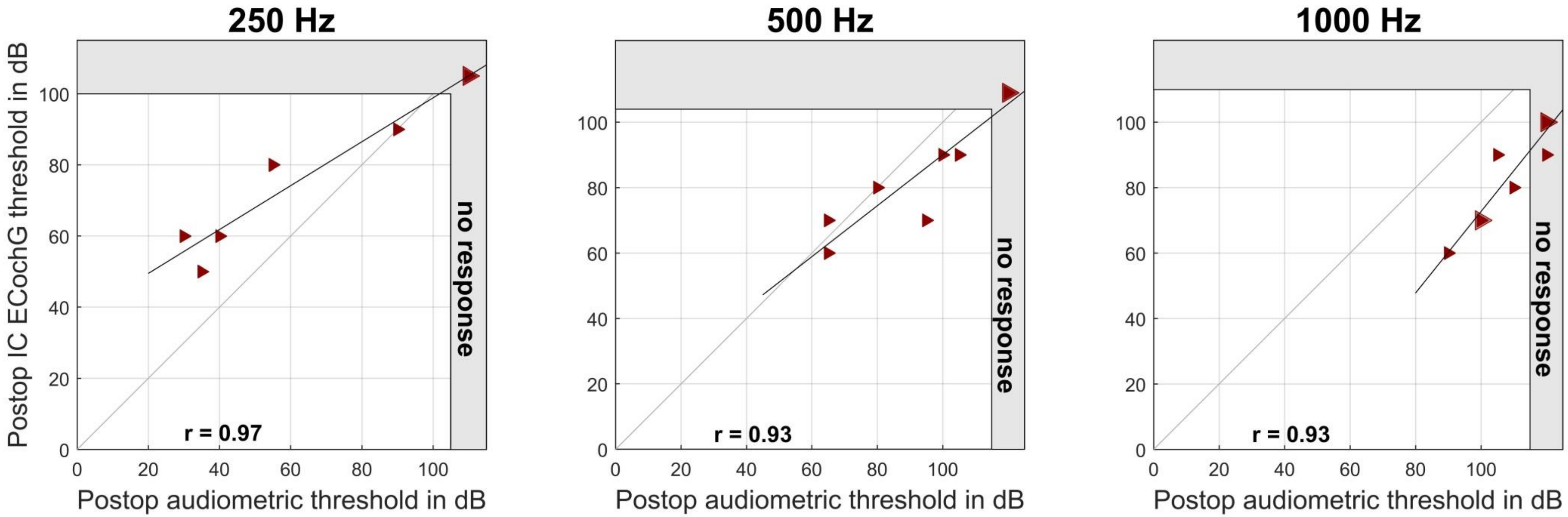




Modified after: S. Haumann, M. Imsiecke, G. Bauernfeind, A. Büchner, V. Helmstaedter, T. Lenarz und R.B. Salcher (2019): Monitoring of the Inner Ear Function During and After Cochlear Implant Insertion Using Electrocochleography, Trends in Hearing, in Druck

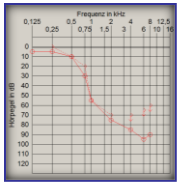
Post-operative

EcochG Recordings vs. Pure tone audiogram at first fitting

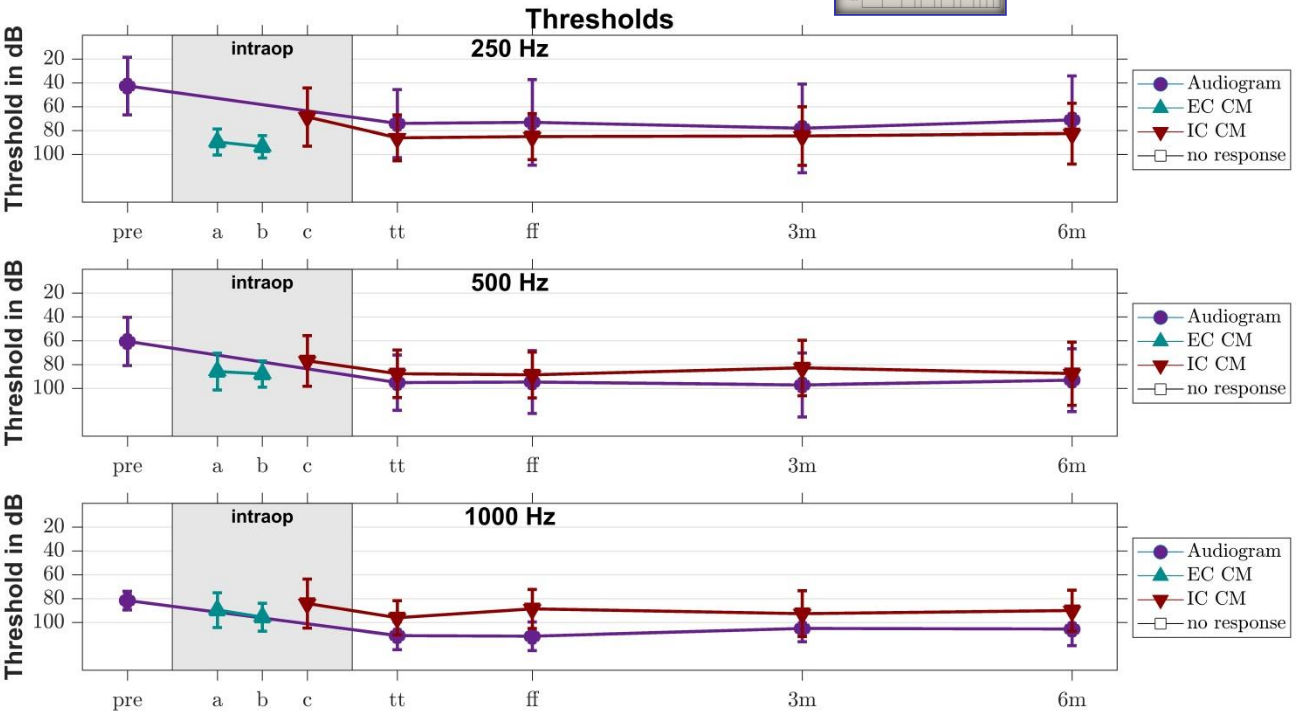


Modifiziert nach: S. Haumann, M. Imsiecke, G. Bauernfeind, A. Büchner, V. Helmstaedter, T. Lenarz und R.B. Salcher (2019): Monitoring of the Inner Ear Function During and After Cochlear Implant Insertion Using Electrocochleography, Trends in Hearing, in Druck

Time course with different recording methods



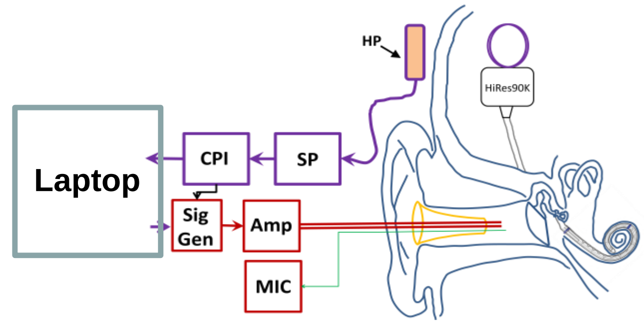
n=10, M ± SD



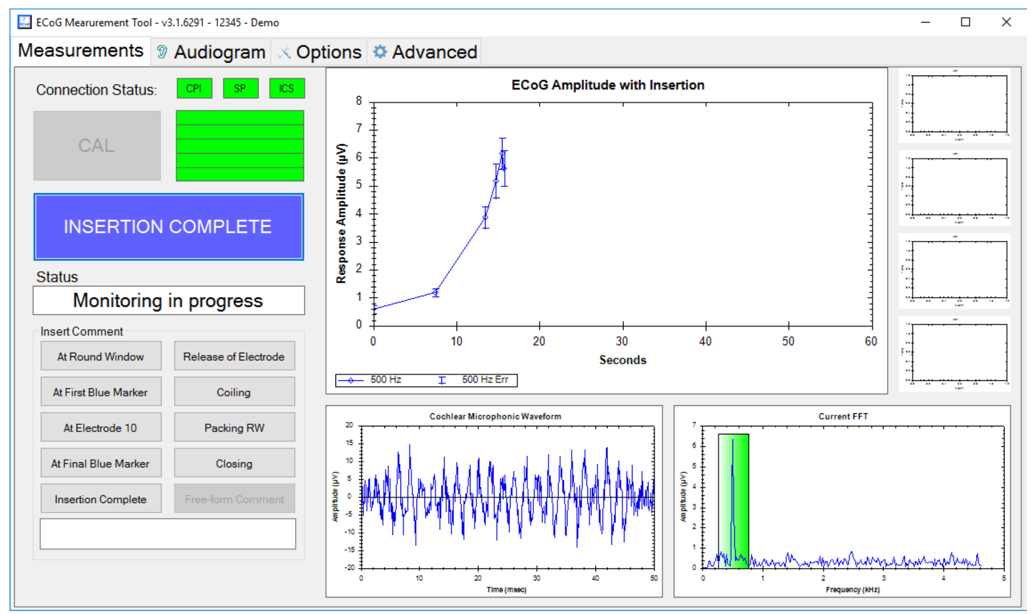
pre – Preop, a – EC vor Insertion, b – EC nach Insertion, c – IC nach insertion, tt – Probeton, ff – Erstanpassung, 3m – 3 Monate, 6m – 6 Monate

Modified after: S. Haumann, M. Imsiecke, G. Bauernfeind, A. Büchner, V. Helmstaedter, T. Lenarz und R.B. Salcher (2019): Monitoring of the Inner Ear Function During and After Cochlear Implant Insertion Using Electrocochleography, Trends in Hearing, in Druck

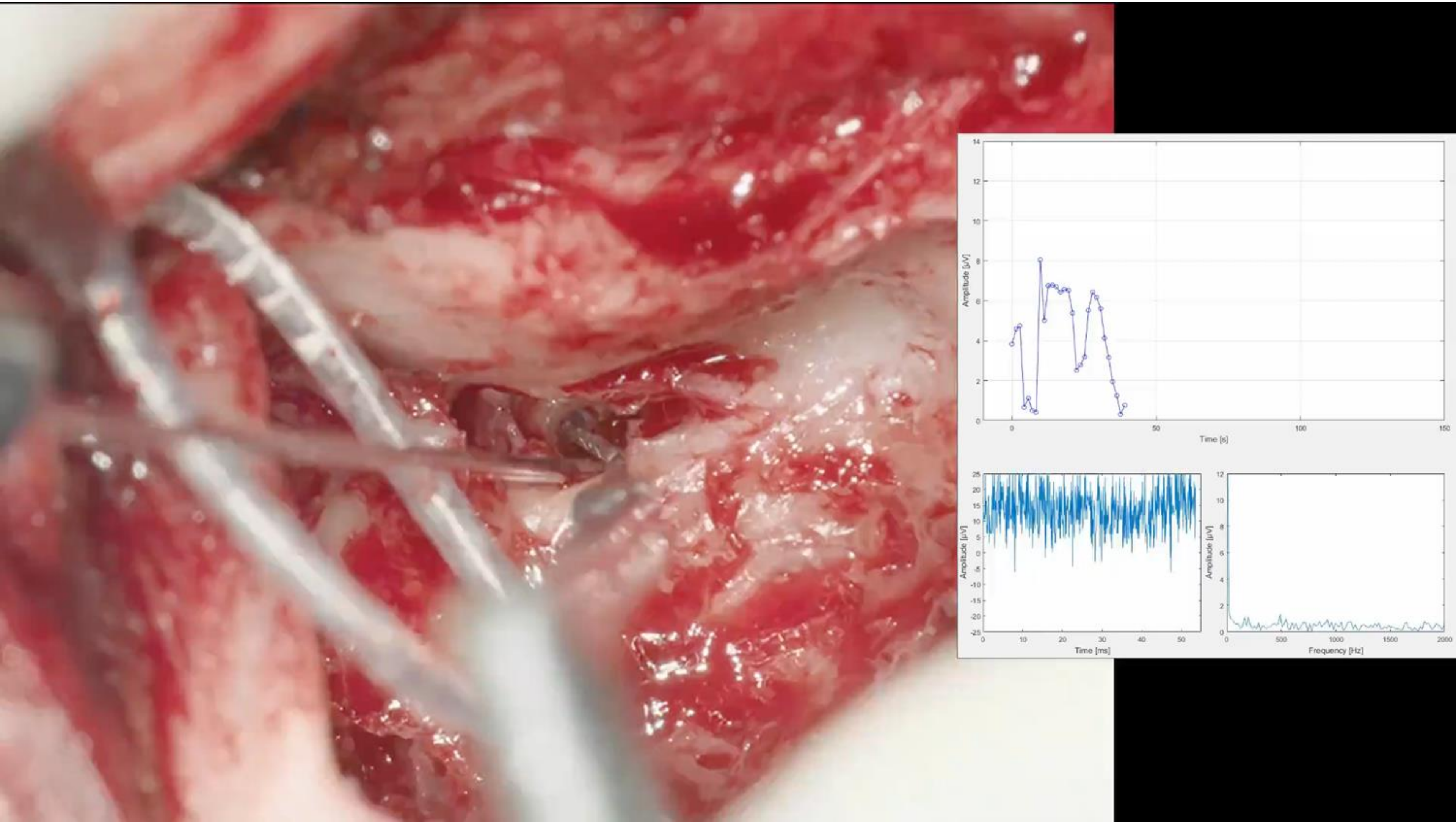
Intracochlear Potentials with Advanced Bionics



- Recording via telemetry
- Most apical contact of the CI electrode is used for recording
- Acoustic stimulation through plug-in earphones
- Real-time measurement of CM amplitude during insertion

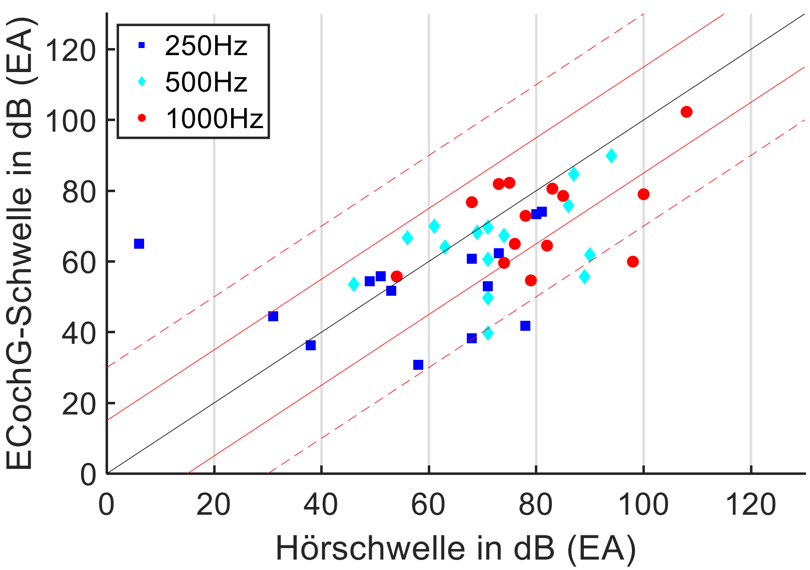


ECochG: Monitoring during Insertion

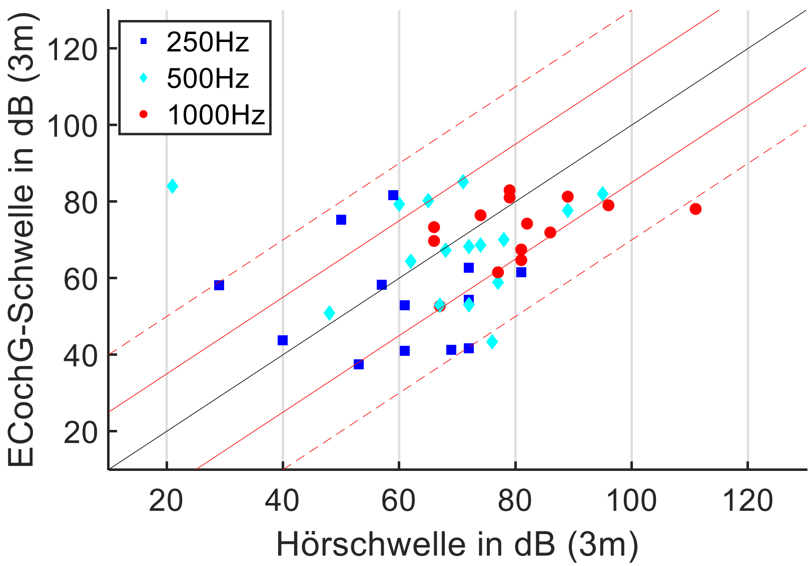


Post-operative Data: ECochG vs. Thresholds

First Fitting



3-Month-Appointment



Summary and Outlook

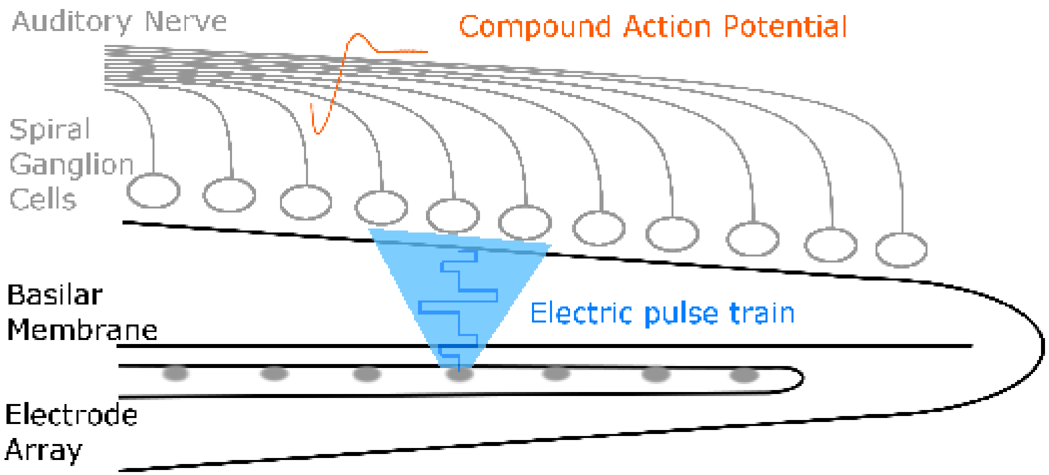
- Extracochlear and intracochlear potentials can be recorded well
- Intracochlear derived potentials are many times larger than extracochlear at the promontory
- Especially intracochlearly measured potentials show promising correlations between ECochG thresholds and auditory thresholds
- Good correlations between intracochlear ECochG and audiometric thresholds when measured at the same appointment
- Relationships appear to be stable over the long-term
- Data collection and analyses continue, investigations of amplitude/amplitude progression

Summary and Outlook

- Different recording strategies depending on the problem
  - Recordings with the clinica ERA device:
    - Very fast and therefore a good basis for possible online monitoring
    - but do not allow long-term monitoring in follow-up care (invasive additional equipment).
  - Recordings with CI-Hard/Software:
    - slower, but possibly fast enough for future online monitoring
    - Fully integrated Long-term observations very well possible

ECAP and Neural Health

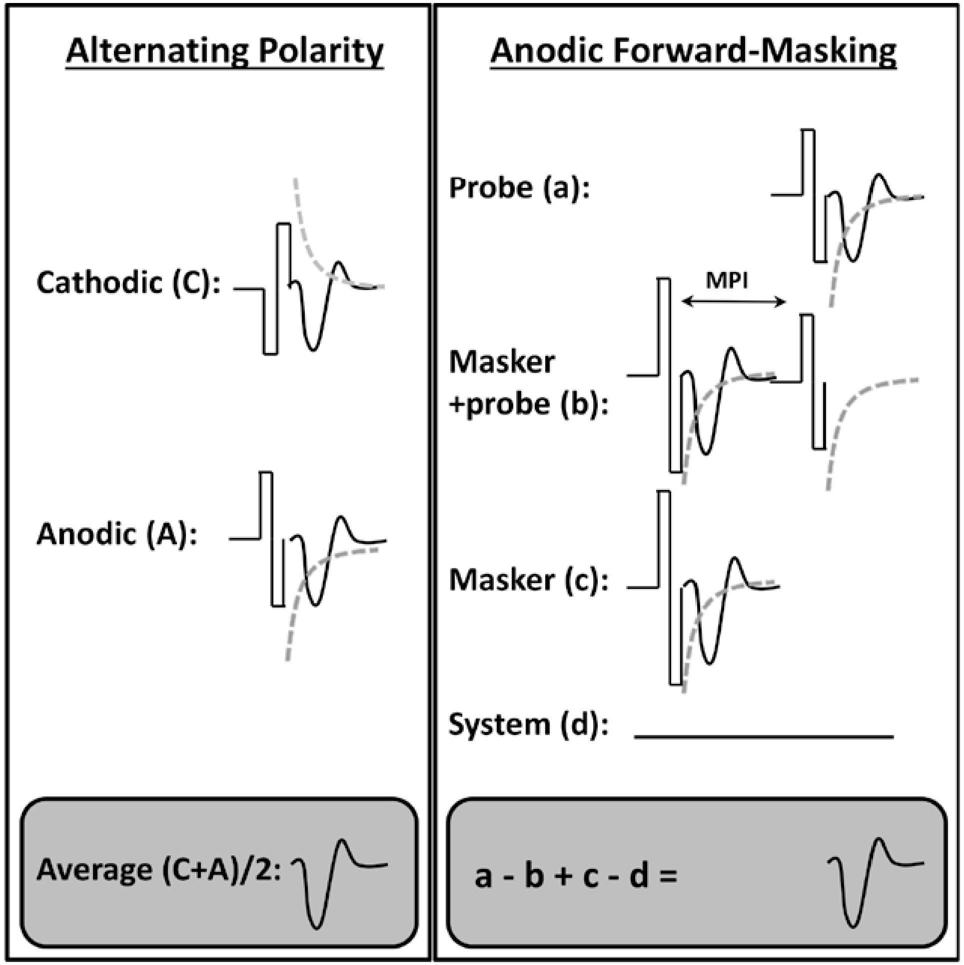
0: Electric Stimulation



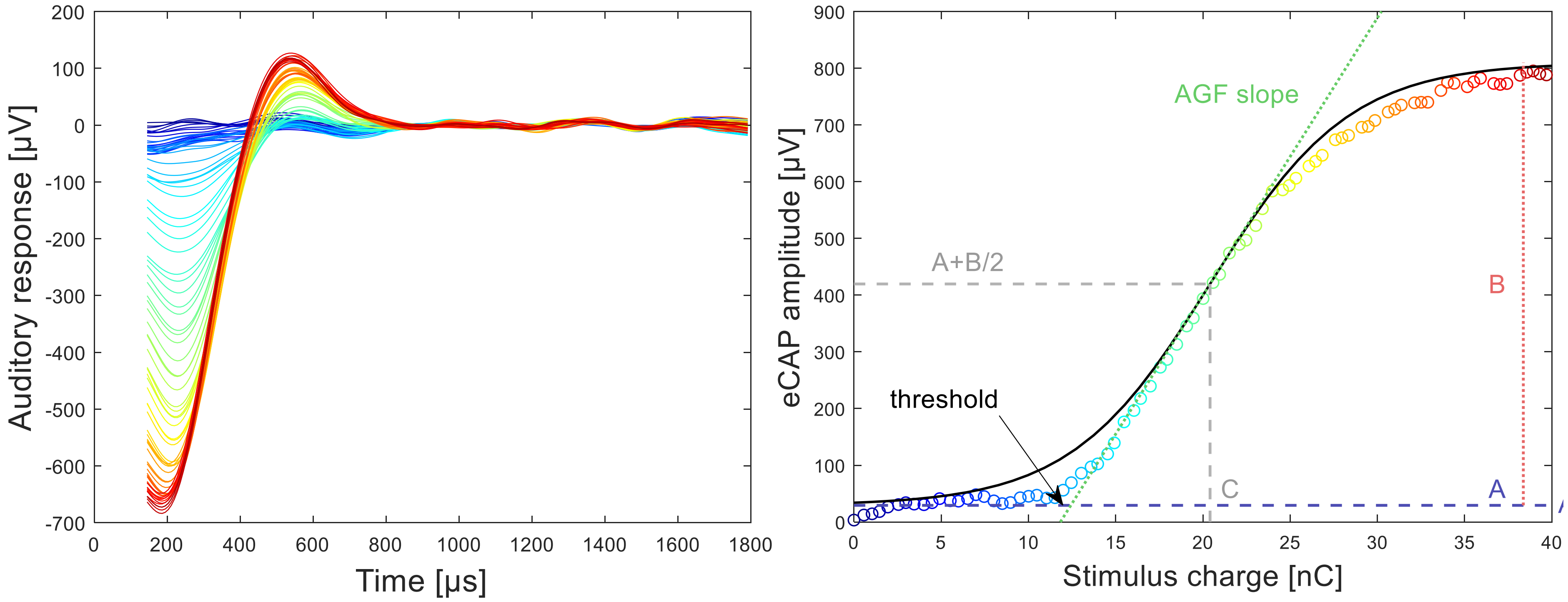
- Schematic of electric stimulation of spiral ganglion cells
- Electric pulse elicits compound action potential
- eCAP travels along auditory nerve

0: Artifact reduction algorithm

- Electric stimulation elicits artifact when measuring electric potential
- Artifact reduction by alternating polarity or forward masking paradigm
  - Forward masking: refractory period cancels out response
  - AP: Artifact cancels out



E: Background continuous eCAP

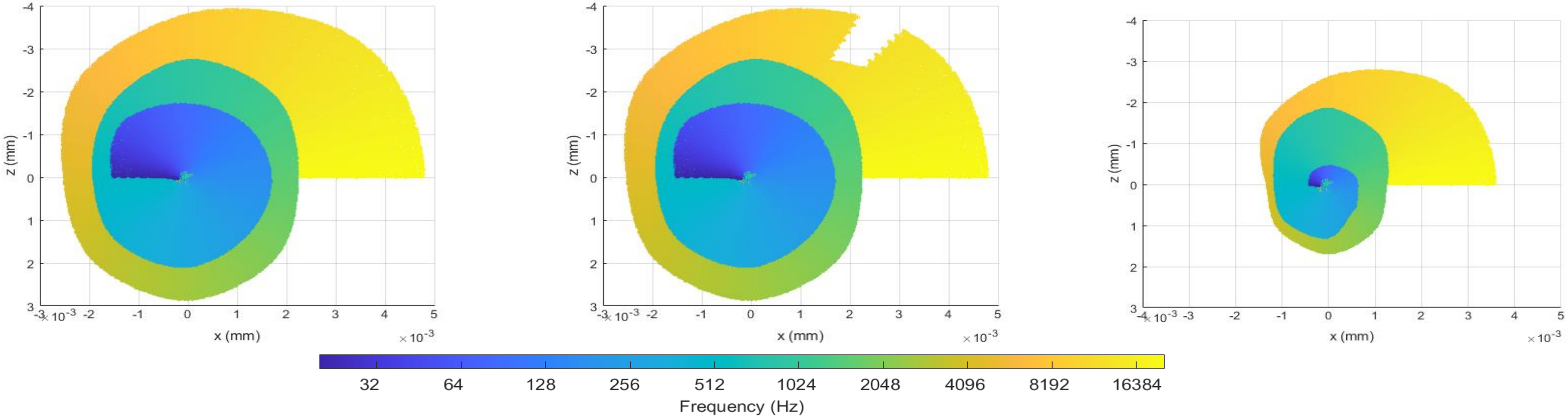


- Continuous increase of stimulation intensity
- Recording of evoked responses, estimation of eCAP amplitude by N_1 to P_2 difference
- Sigmoid fit of amplitude growth function (Strahl et al., 2018, DGA)

Neural Health

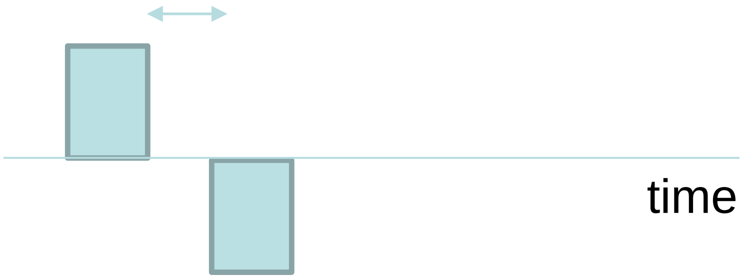
Picture from
Helge Rask-Andersen

Healthy | 50% degeneration locally | 50% degeneration



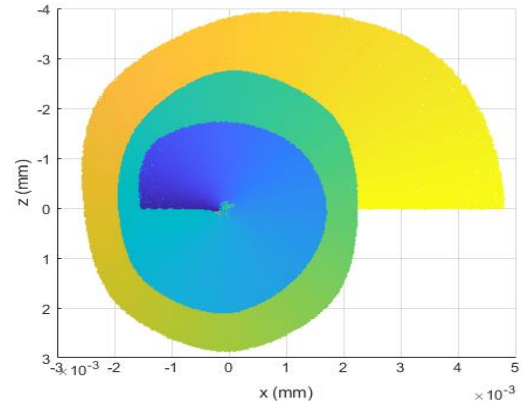
Neural Health from IPG Effect

Short IPG

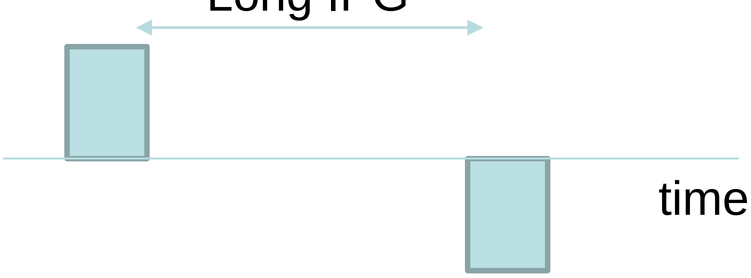


Good Neural Health

Long IPG more effective than short IPG

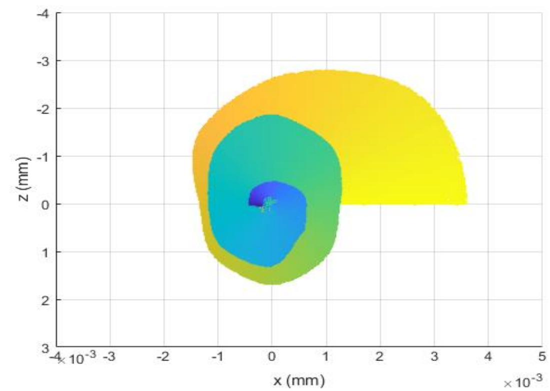


Long IPG

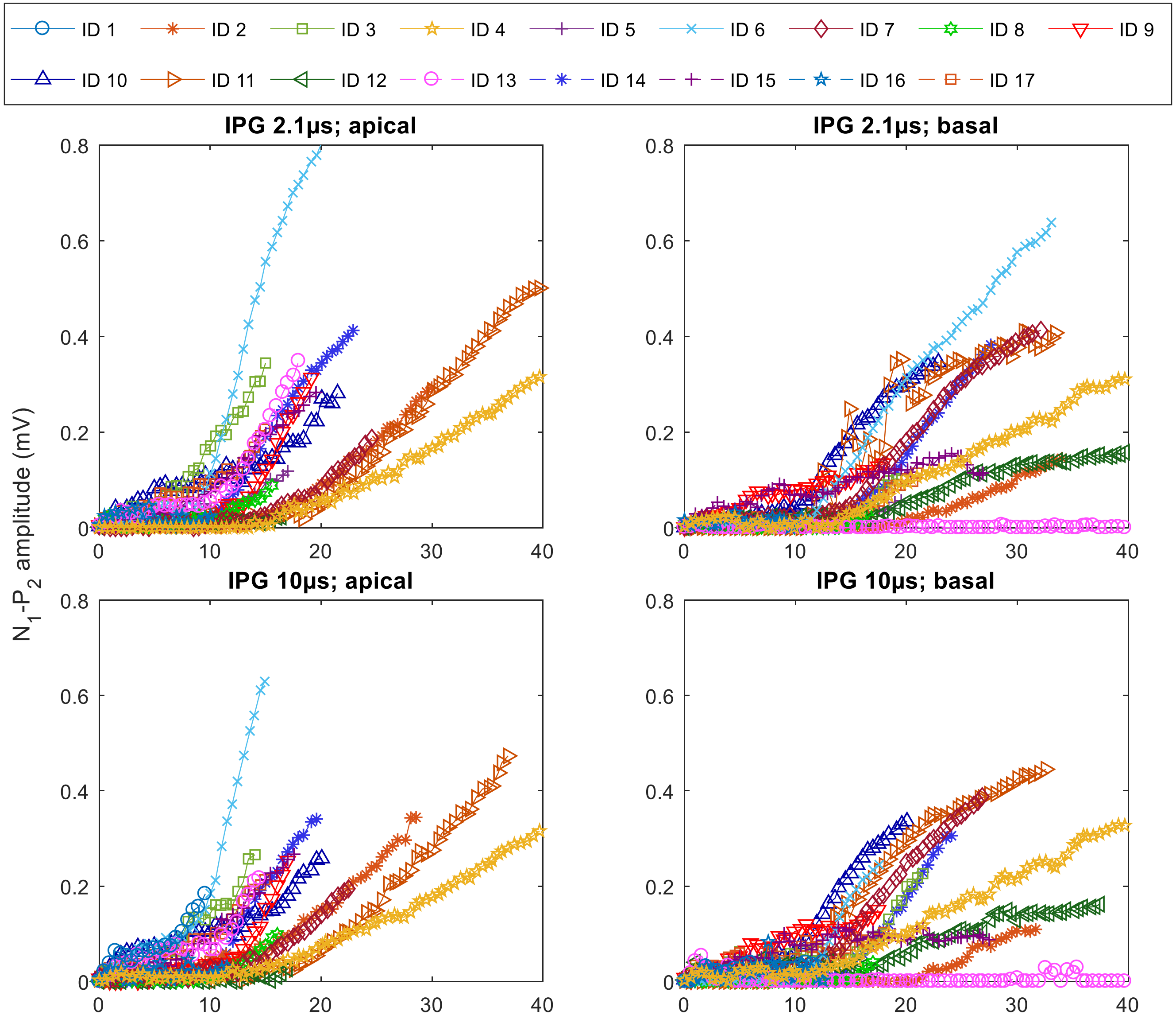


Poor Neural Health

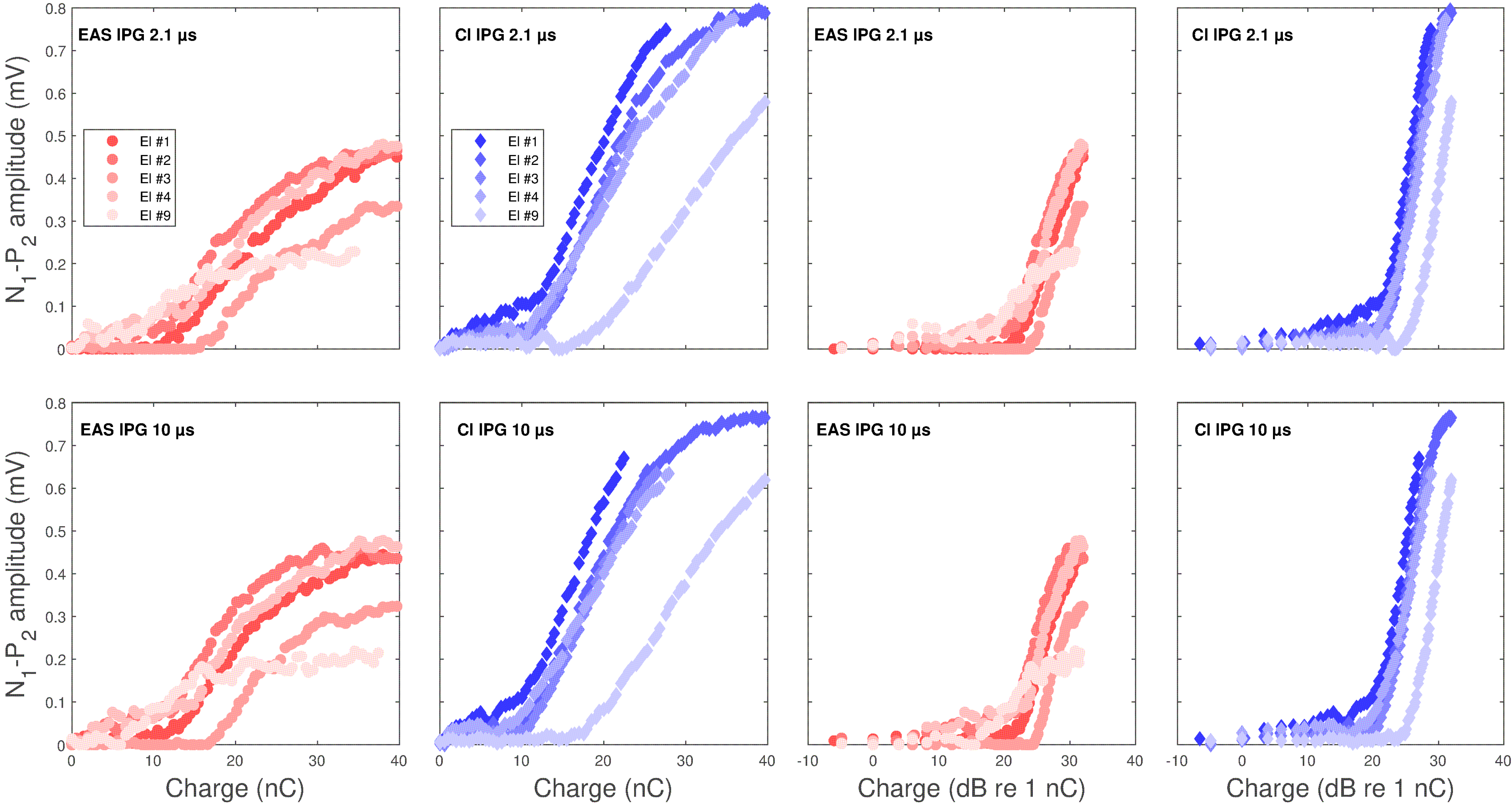
Long and short IPG equally effective



E: eCAP IPG and electrode

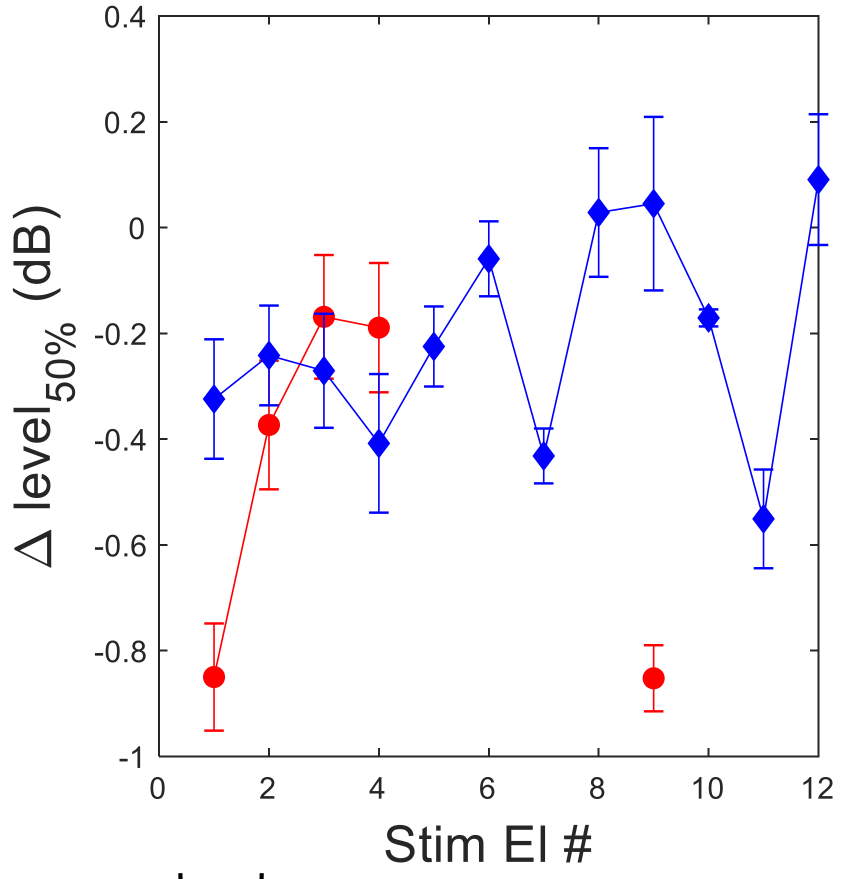


E: Exemplary eCAP AGFs



- Amplitude growth of eCAP in dependency of group, location and interphase gap

E: Difference characteristics per electrode



p < 0.005

p = 0.006

E: Summary: eCAP AGF and Neural health

- Sucessful eCAP AGFs measured in ≈ 60% of cases
- IPG showed significant effect on thresholds and $level_{50\%}$ and latency across all electrodes
- eCAP characteristics showed some variation across electrode numbers and locations
- Difference per IPG of dynamic range and $level_{50\%}$ for EAS users electrode 1 vs 3 and 1 vs 4
- No significant correlation to speech perception or duration of hearing loss, inter-subject variability very high

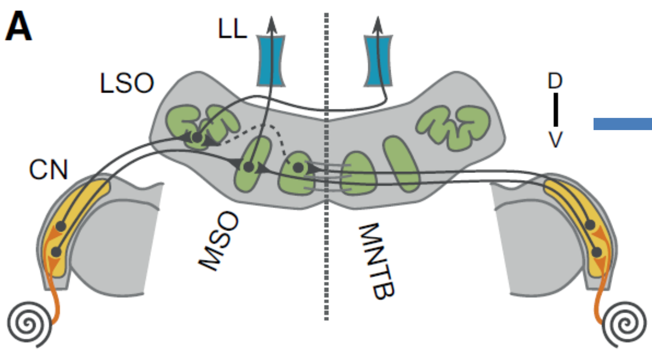
Summary Lecture

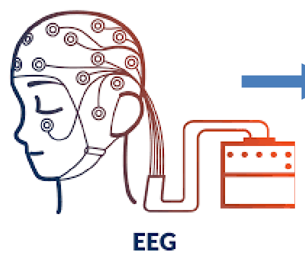
- Physiology of the Auditory System
- Electrophysiology
  - ECochG
  - ECAPs

Brainstem Response

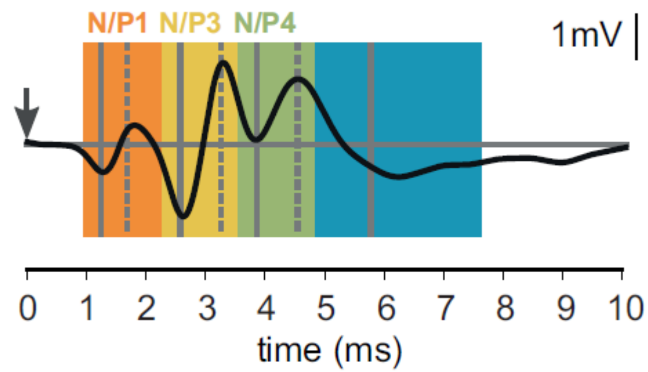
- With electroencephalography (EEG) it is possile to measure evoked response of the brainstem.
- Each peak of the evoked response corresponds roughly to the response of the nucleus along the brainstem.

Schematics of the brainstem binaural pathways:





Auditory brainstem response (ABR):



CN – cochlear nucleus; LSO – lateral superior olive;
MSO – medial superior olive; LL – lateral lemniscus

From Benichoux et al. (2018)

Electrophysiological Measures ABR or BERA

Auditory Brainstem Response (ABR) or Brainstem Evoked Response Audiometry (BERA)

Method

- First described by Jewett and Williston 1971
- Evoked by short (~100 µs) clicks
- < 10 ms latency
- Intensity: > 80 dBHL
- > 1000 sweeps
- Filter settings: HP: 100 Hz, LP: 3000 Hz

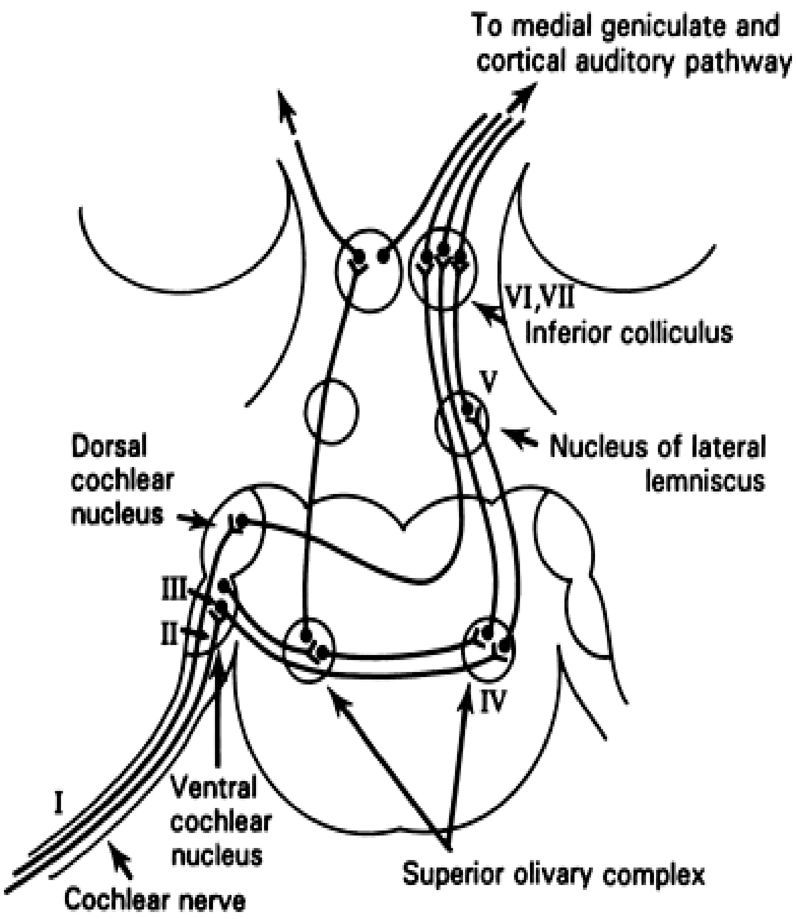
- Electrode montage:
  - Non-inverting: High forehead (Fz) or top middle of head (Cz)
  - Inverting reference: Left and right mastoids or earlobes
  - GND: Forehead

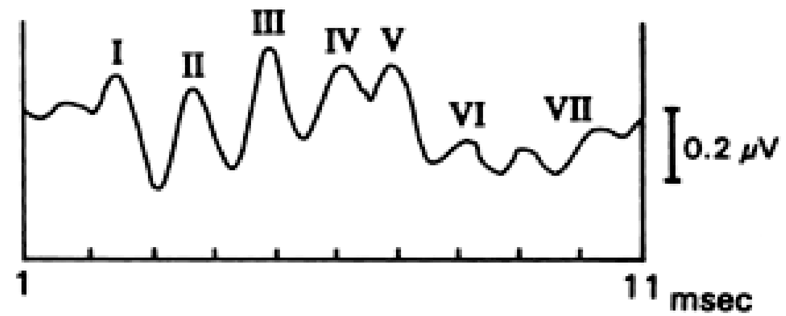
- Waveform peaks are labeled I-VII

Clinical Application

- Screening tool to assess auditory nerve function
- Newborn screening for deafness
- Intraoperative monitoring of nervous system
- Monitoring in IC units
- Diagnosis of demyelinating disorders
- Hearing threshold detection (amplitude increases with intensity)

Electrophysiological Measures
ABR or BERA



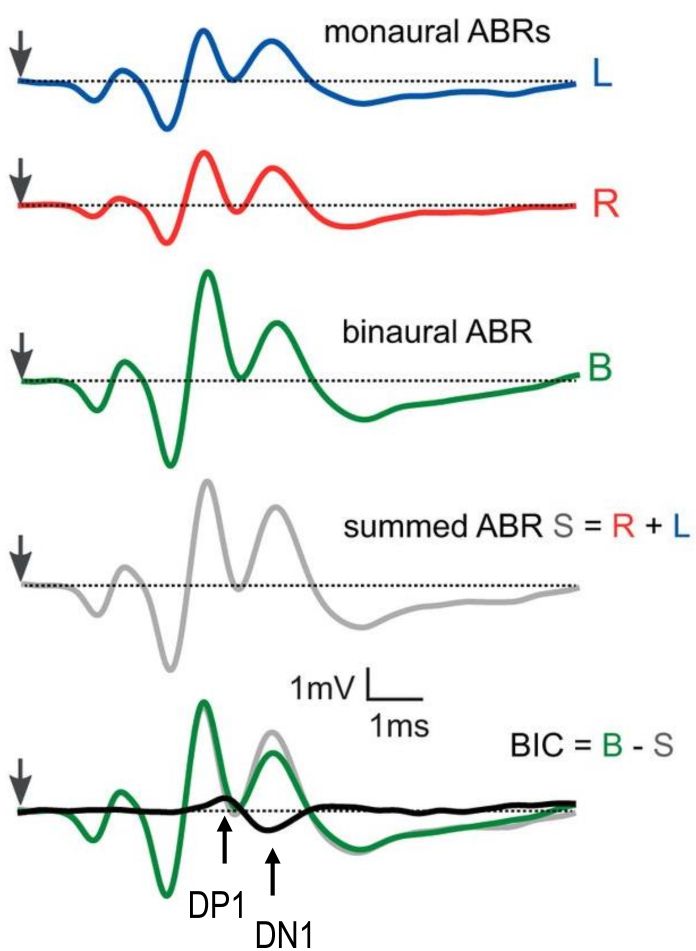


- Wave I - Compound Action Potential (CAP) from distal portion of auditory nerve
- Wave II – Proximal portion of auditory nerve
- Wave III – Cochlear nucleus
- Wave IV – Superior olivary complex and other midline brainstem structures
- **Wave V – Inferior colliculus**
- Wave VI and VII – Thalamic and cortical regions

[https://www.evokedpotential.com/the-auditory-brainstem-response.html]

Binaural Interaction Component (BIC)

- In the absence of neural binaural processing → the sum of left and right monaural ABRs should be equal to the binaural ABR.
- BIC = deflection of binaural response from sum of monaural responses.



From Benichoux et al. (2018)

How does BIC depends on ITD and ILD

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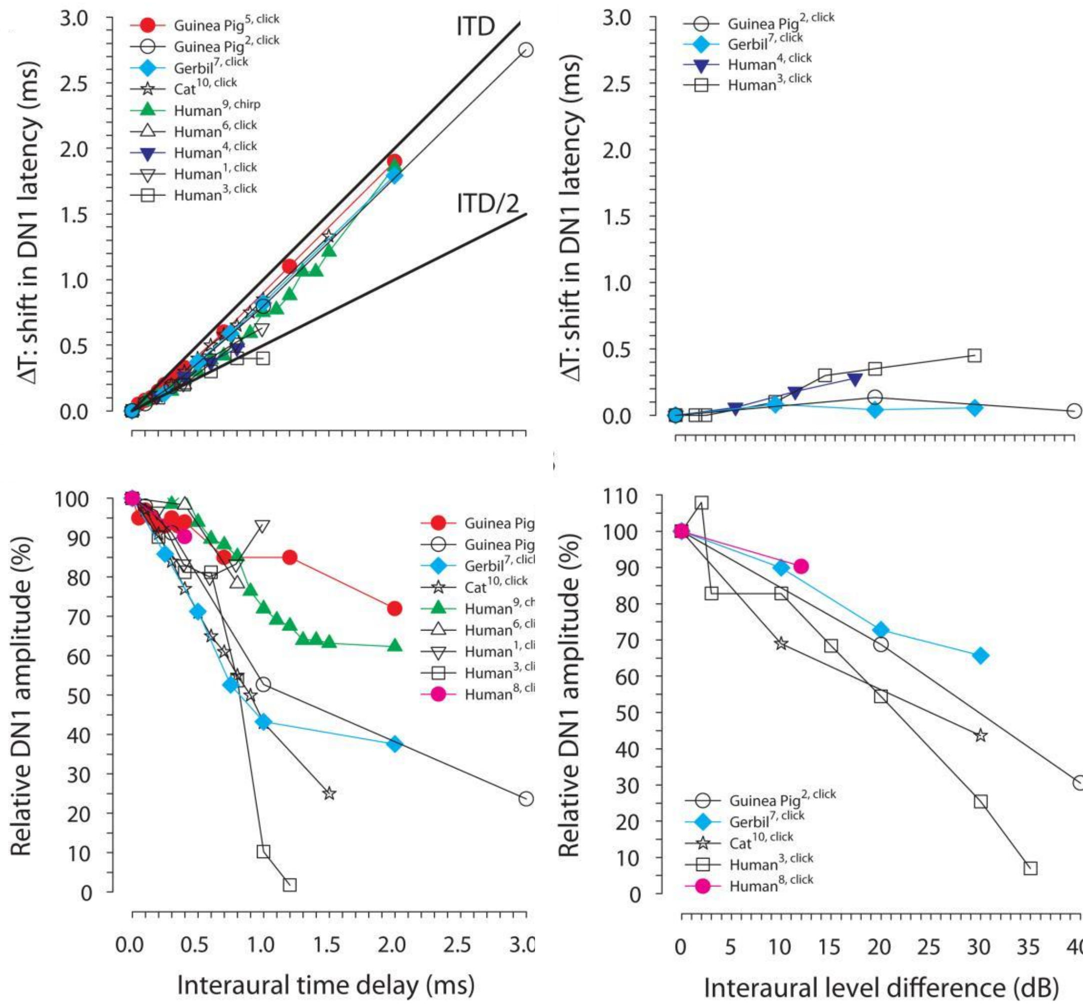
Laumen et al. (2016)

- Latency shift and relative amplitude in relation to ITD=0 (left) and to ILD=0 (right).
- With increasing ITD, the latency of DN1 is increased and the amplitude is decreased.
- The change of the amplitude with ITD shows a higher variability
- BIC can be measured beyond of naturally occurring ITD.
- Effect of ILDs on BIC has been investigated less extensively. Existing study show that ILD affects amplitude of DN1 more than its latency.
- Non-invasive studies of the effects of ITD or ILD on BIC cannot draw conclusions about the origin of the BIC because they represent the sum of activity of the two separate binaural pathways involving both MSO and LSO.



BIC recording

Technical considerations to record BIC:

- Rate of stimulus presentation;
- Stimulus amplitude effect (i.e. „Acoustic Crosstalk“);
- Noise reduction and SNR;
- Electrode Placement;
- Effect of stimulus waveform;
- Effects of body temperature (for animal studies).

ABR / BIC in clinical use

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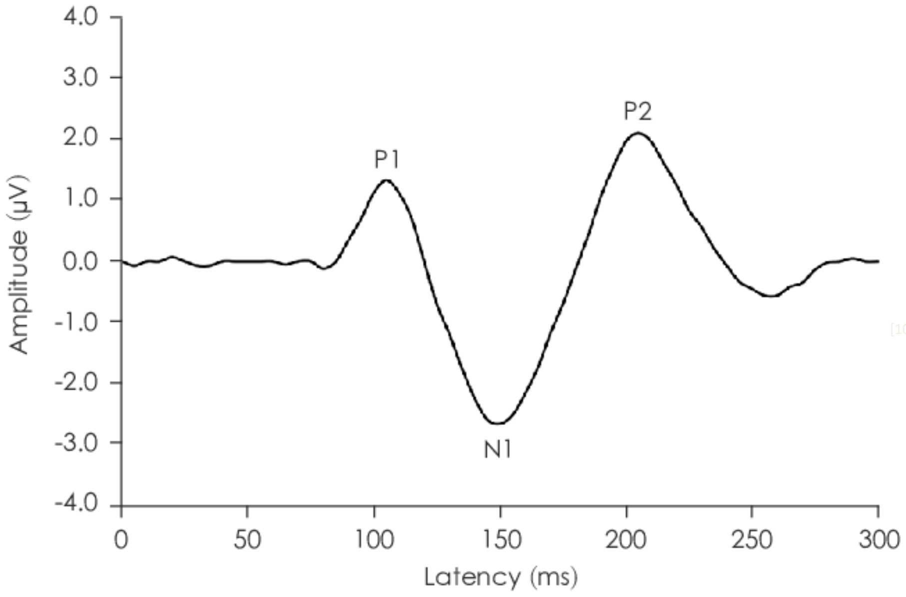
- BIC has 76% sensitivity to identify auditory processing disorder (Delb et al. 2003).
- Binaural hearing dysfunction related to multiple sclerosis manifests detectable changes in ABR and BIC (Furst et al. 1990).
- In bilateral CI users → to find CI electrode pair producing the largest BIC (Hu and Dietz 2015).
- In bimodal CI users → analysis of wave V latency of ABR to estimate an inteuraural delay, compensation of which improves localization ability (Zirn et al. 2015).

Cortical Auditory Evoked Potentials

- Cortical Auditory Evoked Potentials (CAEPs) – is an electric potential from auditory cortex following the presentation of the stimuli.

- The analysis of P1-N1-P2 complex from the CAEPs recording can be used as an objective measurement of the speech perception.



[10]

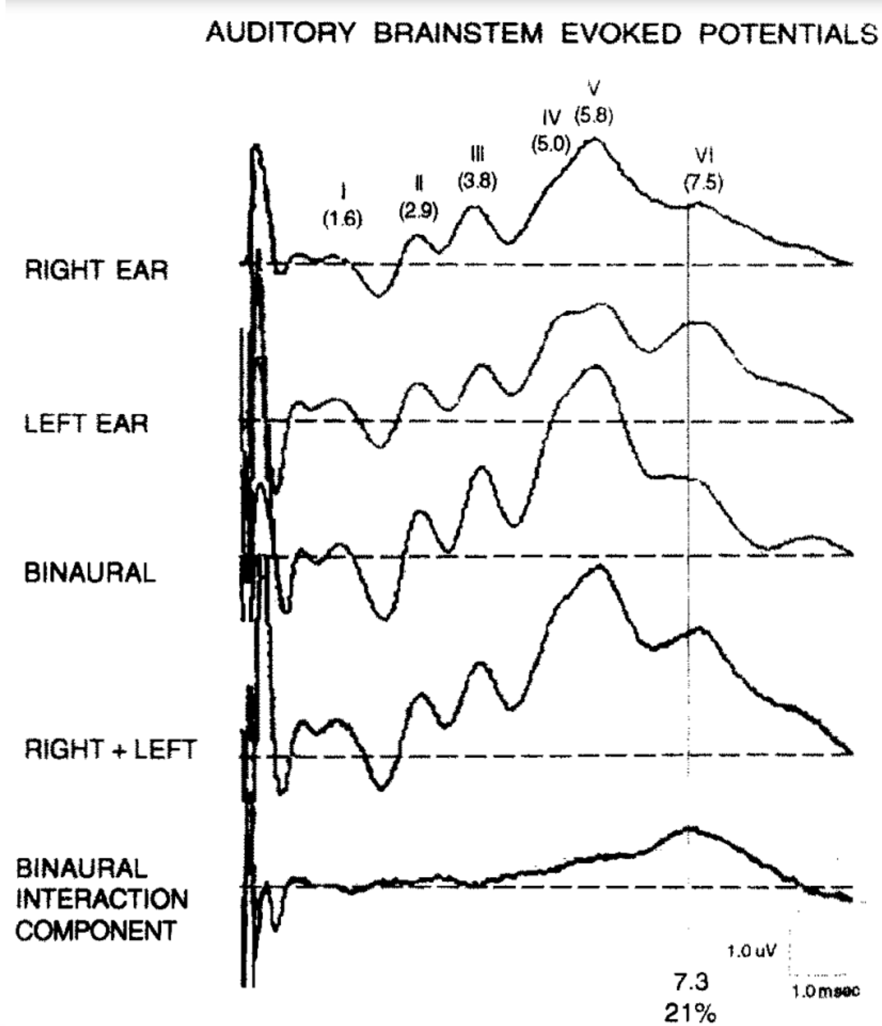
Stimuli for BIC

- Rarefaction acoustic clicks using a 100 microsecond duration were presented at 11 .I /s for both the brainstem auditory evoked p~~tentials and the middle-latency auditory evoked potentials, and at 1.7/s for the long-latency auditory evoked potentials.

- The stimulus was presented at 60 dB above monaural threshold for wave V of the brainstem auditory evoked potentials across all conditions

Brainstem BIC

- The grand average of the brainstem auditory evoked potentials across 17 subjects for the sum of the monaural brainstem auditory evoked potentials, the binaural brainstem auditory evoked potentials and the binaural interaction component.
- Note the long duration of the binaural interaction peaking at 7.3 ms. The binaural response visually appears larger than the sum of the monaural responses due to the presence of a stow sustained potential.



Middle Latency BIC

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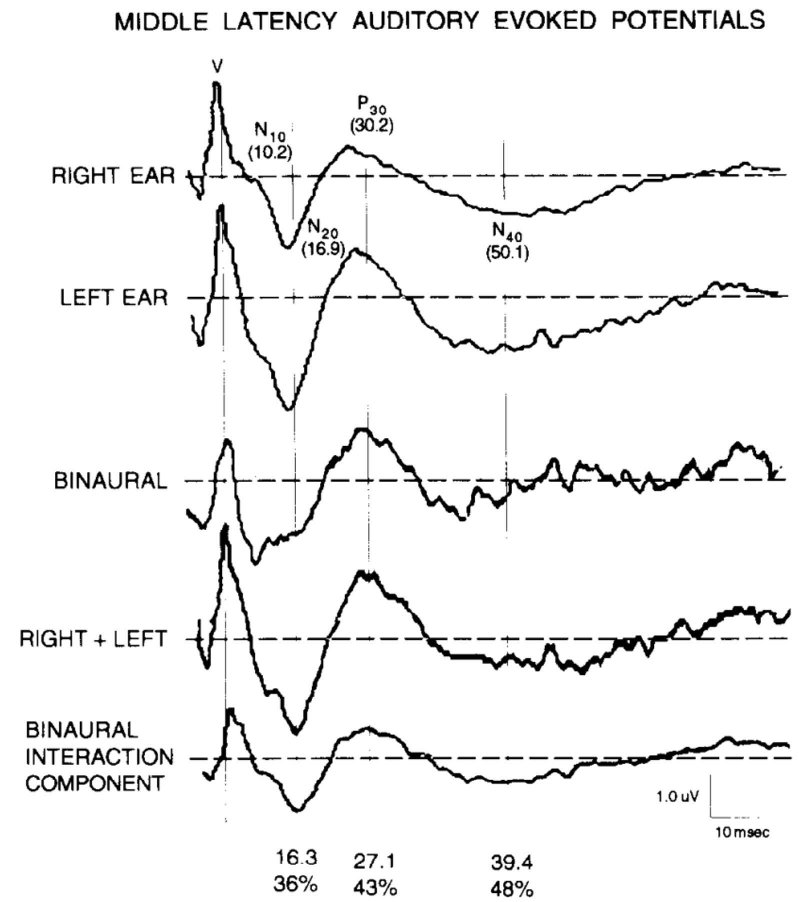
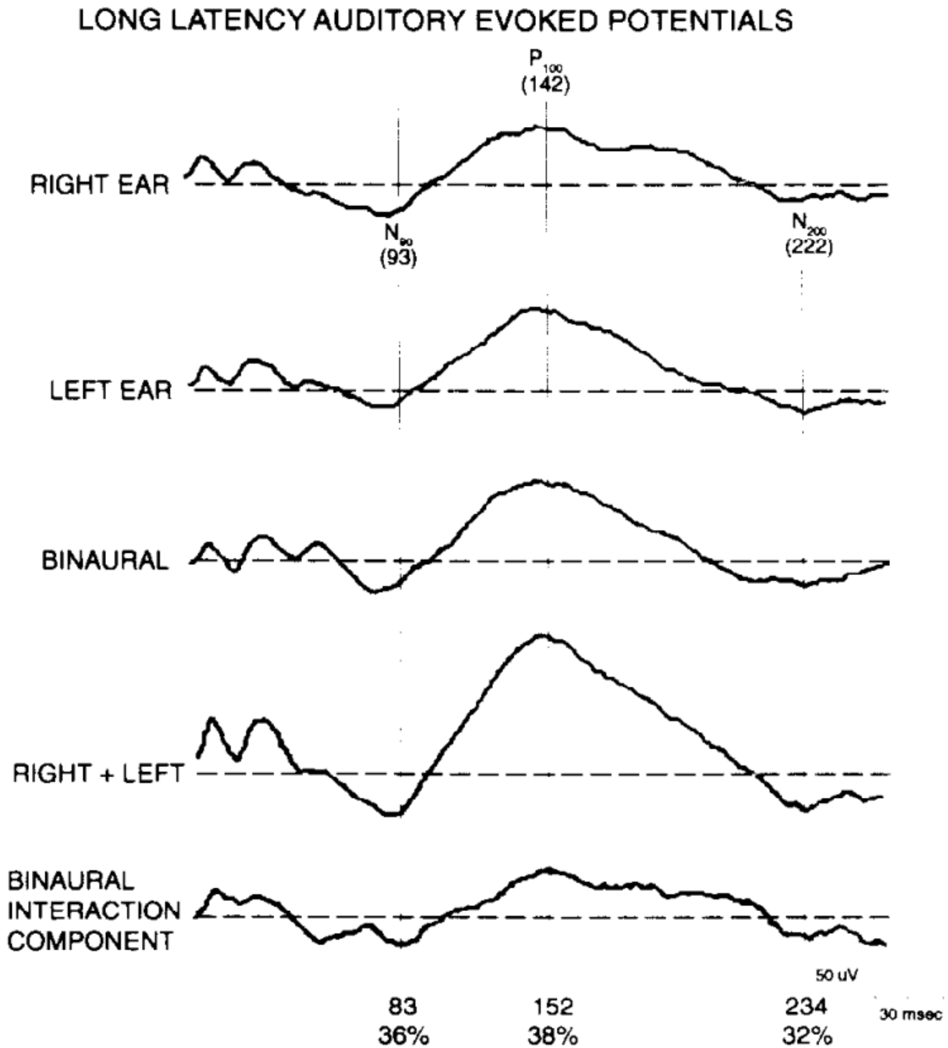
APG

- The grand average of the middle-latency auditory evoked potentials across 17 subjects for the sum of the monaural middlelatency auditory evoked potentials, the binaural middle-latency auditory evoked potentials and the binaural interaction component.
- The binaural interaction appears with each of the major components and amounts to almost 50% of the sum of the monaural potentials for the N40 component.



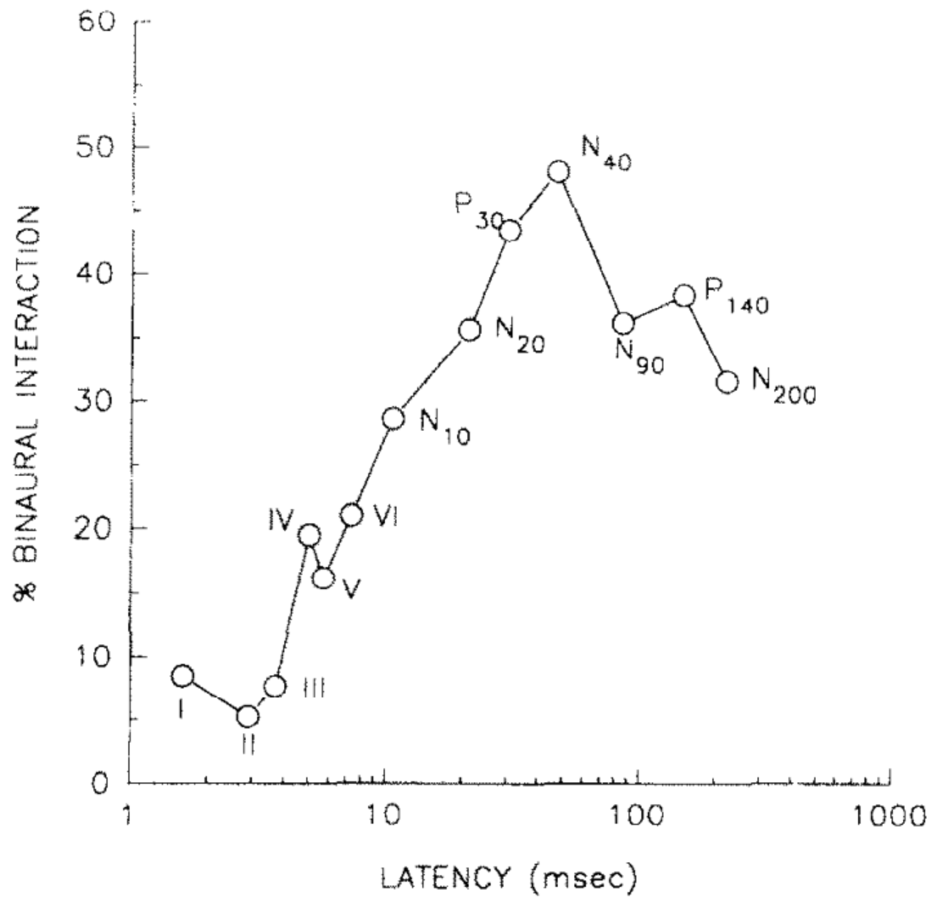
Cortical BIC

- .The grand average of the long-latency auditory evoked potentials across 17 subjects for the sum of the monaural long-latency auditory evoked potentials, the binaural long-latency auditory evoked potentials and the binaural interaction component.
- The binaural interaction component appears with each component amounting to approximately 40% of the sum of the monaural responses.



BIC across the auditory pathway

- Percent binaural interaction at each of the major components of the auditory evoked potentials



Electrophysiological Measures
Acoustic Change Complex (ACC)

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Method	Clinical Application

Method

- Elicited in response to a change in an ongoing sound
- Change in e.g.:
  Spectrum, Time, Intensity (spatial location)
- < 300 ms latency
- > 100 sweeps
- Filter settings: HP: 1 Hz, LP: 30 Hz

- Electrode montage:
  - Non-inverting: High forehead (Fz) or top middle of head (Cz)
  - Inverting reference: Left and right mastoids or earlobes
  - GND: Forehead

- Waveform peaks are labeled P1'-N1'-P2'

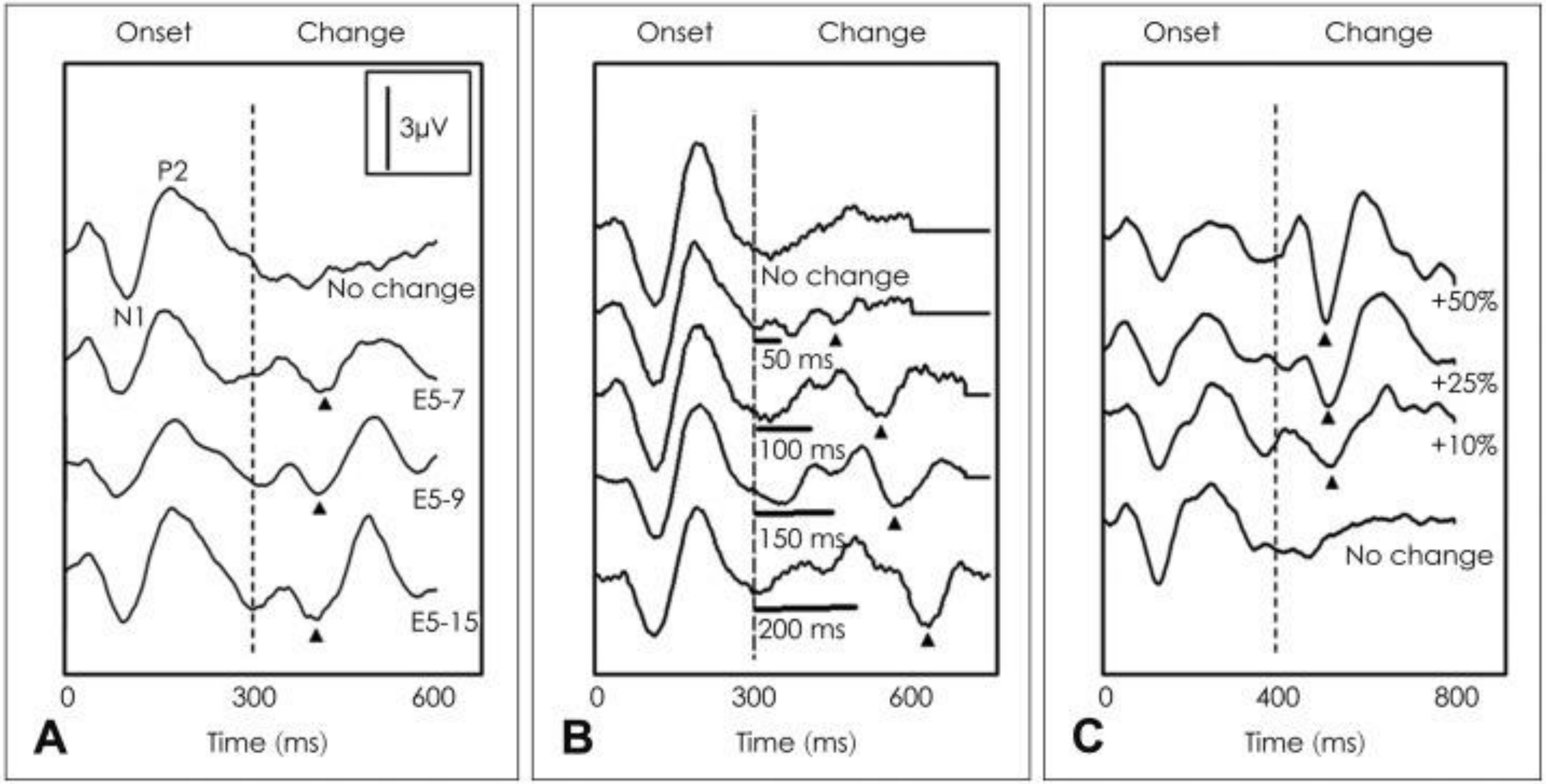
Clinical Application

- Currently non
- Promising tool for objective evaluation of discrimination
- ACCs to sound coming from different directions

Electrophysiological Measures
Acoustic Change Complex (ACC)

Change in…

…Spectrum (electrode) …Time (gaps) …Intensity



[Kim. J Audiol Otol., 2015]

Electrophysiological Measures
Auditory Steady State Response (ASSR)

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Method	Clinical Application

Method

- Neural entrainment to modulated stimuli
- Carrier frequency (500 to 4000 Hz) and (amplitude or frequency) modulation frequency
- ASSRs are generated throughout the auditory pathway:
  Low modulation frequency → cortical regions
  High modulation frequencies → sub-cortical regions
- Typical ASSR modulation frequencies: 40 and 90 Hz

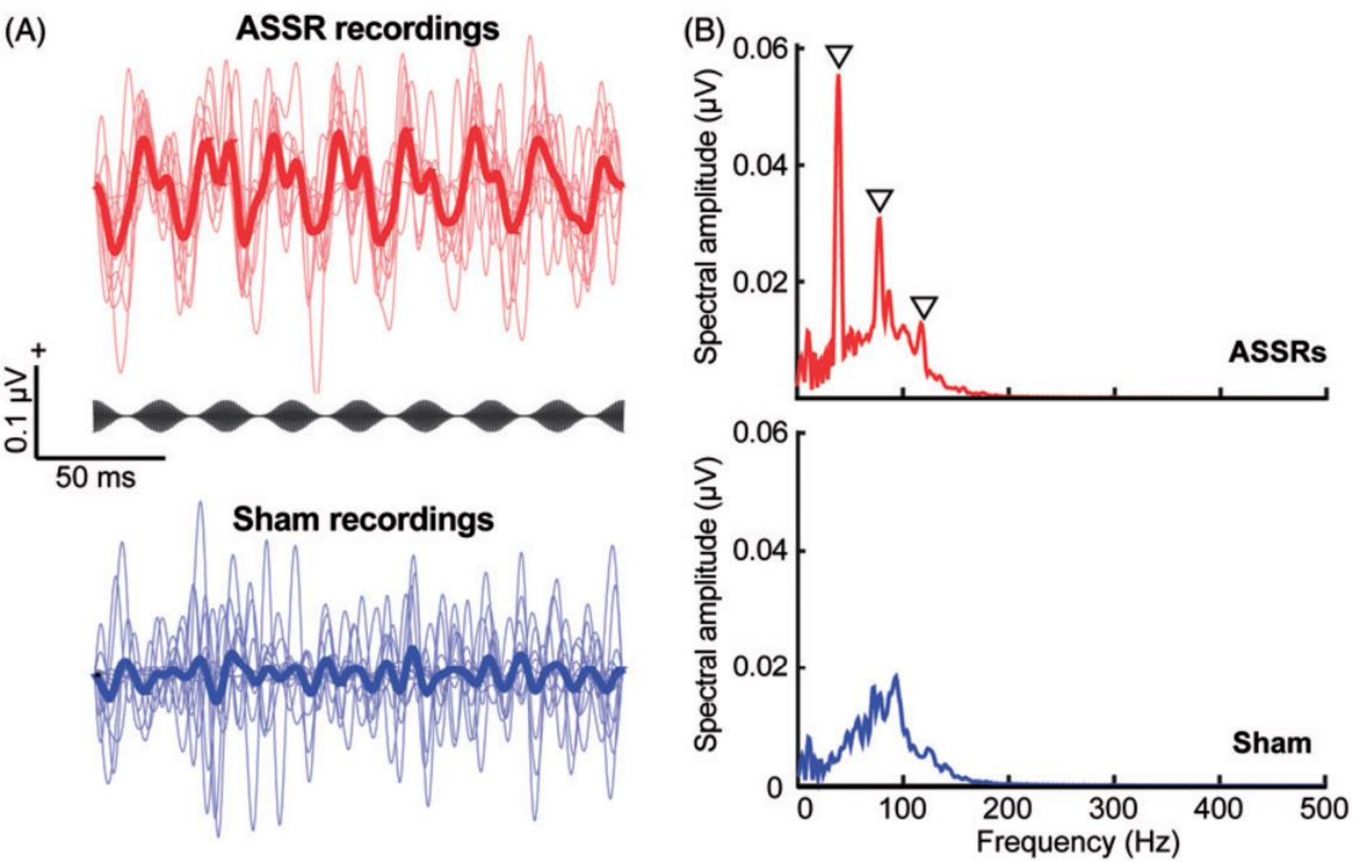
- Electrode montage:
  - Non-inverting: High forehead (Fz) or top middle of head (Cz)
  - Inverting reference: Left and right mastoids or earlobes
  - GND: Forehead

- Amplitude and phase is analyzed in spectral domain

Clinical Application

- Test integrity of auditory pathway
- Estimate hearing thresholds
- Monitoring the state of arousal during anesthesia
- Potential applications in the diagnosis of neurologic pathology
- Research:
- Correlation of ASSR and speech perception
- ASSRs to binaural stimuli that change in phase with a given rate

Electrophysiological Measures
Auditory Steady State Response (ASSR)



[Bidelman and Bhagat. Int J Audiol, 2016]

Independent Component Analysis

- As EEG recorder at uV it can be easily contaminated by artifacts such as ocular / muscle / respiratory activity or cochlear implant electrical artifact.
- One of the commom approcahes to suppress artifacts is independent component analysis (ICA).
- ICA linearly separates the EEG into independent components or sources under the assumptions that:
  - Source signals are independent from ach other;
  - Individual source signals has non-Gaussian distribution.