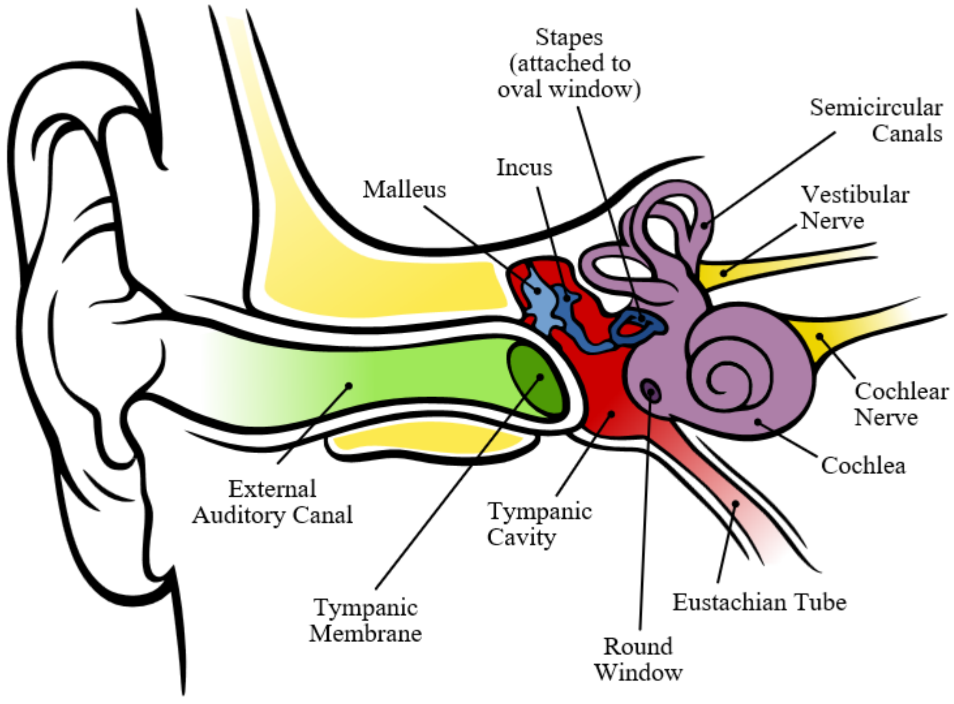
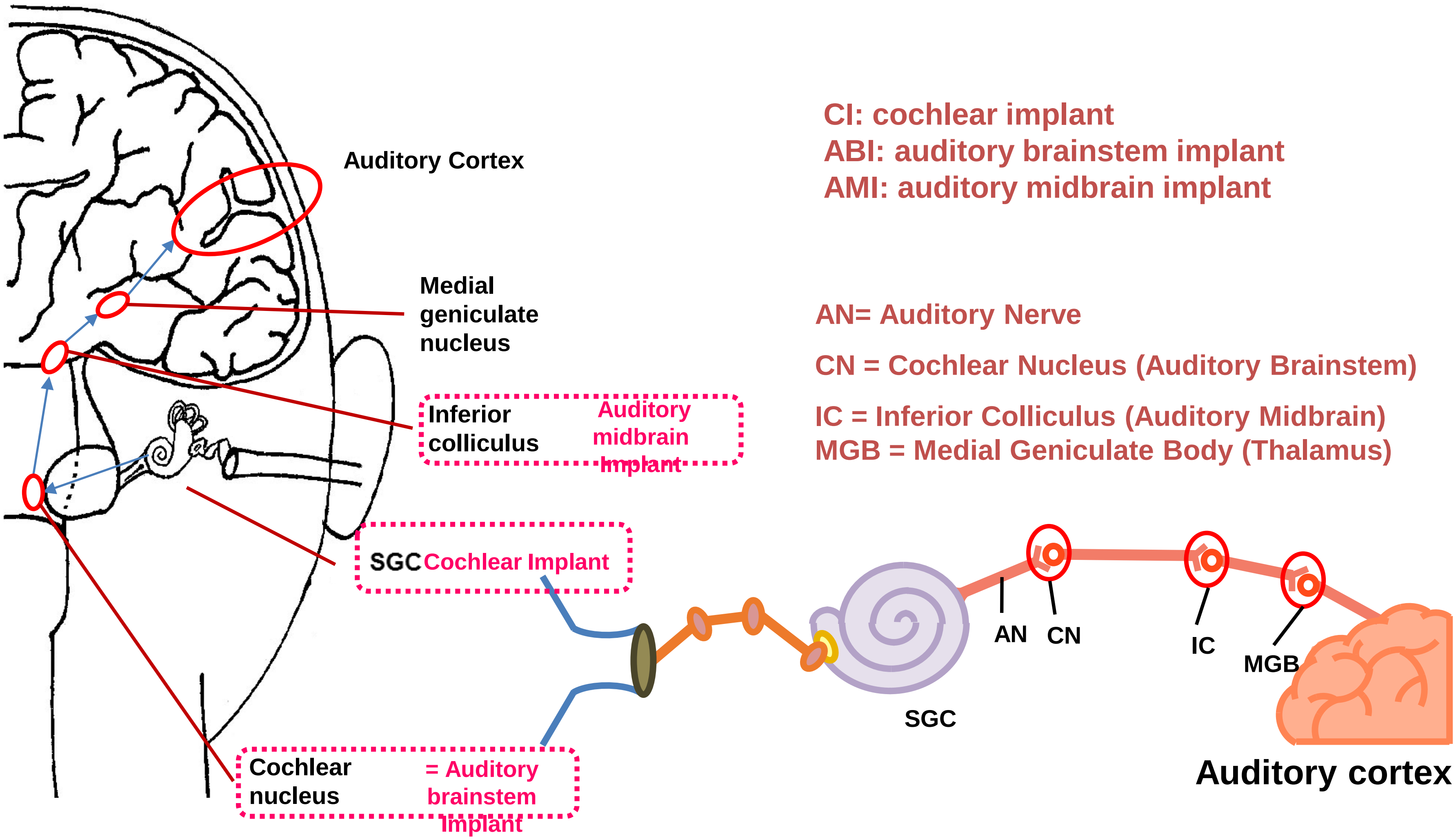
Auditory system



Auditory system - Wikipedia

Auditory System Pathways and Prostheses



CI: cochlear implant
ABI: auditory brainstem implant
AMI: auditory midbrain implant

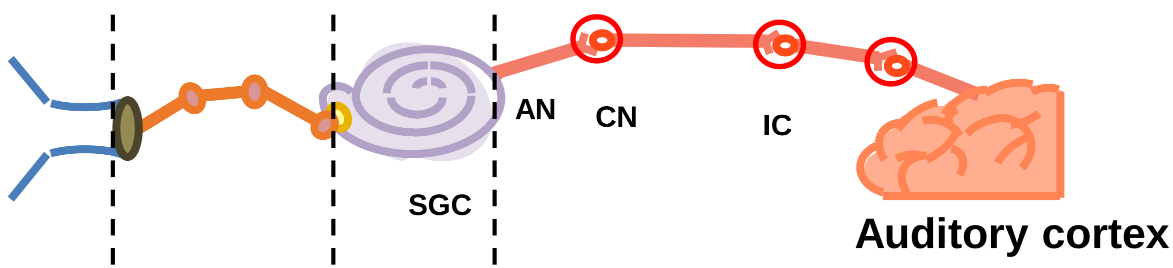
AN= Auditory Nerve

CN = Cochlear Nucleus (Auditory Brainstem)

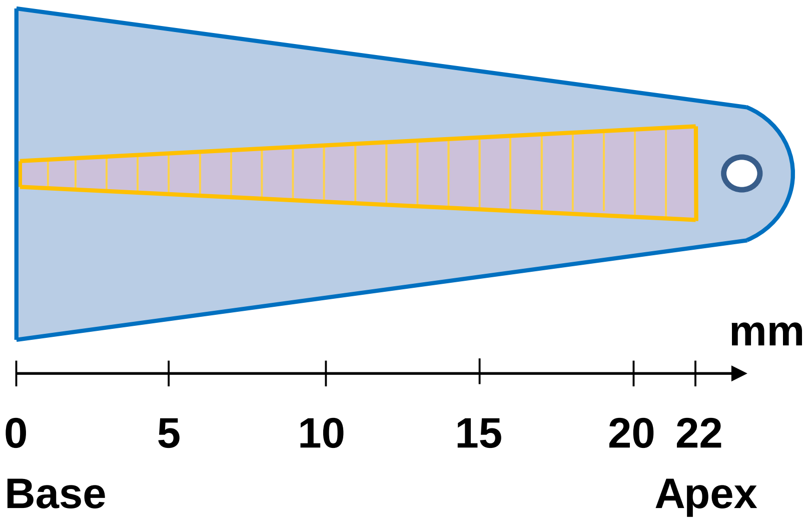
IC = Inferior Colliculus (Auditory Midbrain)
MGB = Medial Geniculate Body (Thalamus)

The cochlea

- Cochlea is the first system to perform auditory processing of the incoming acoustic signal (sound)
- **It will extract frequency, intensity (and other timing cues) of that signal and transmit those to the higher auditory pathway**

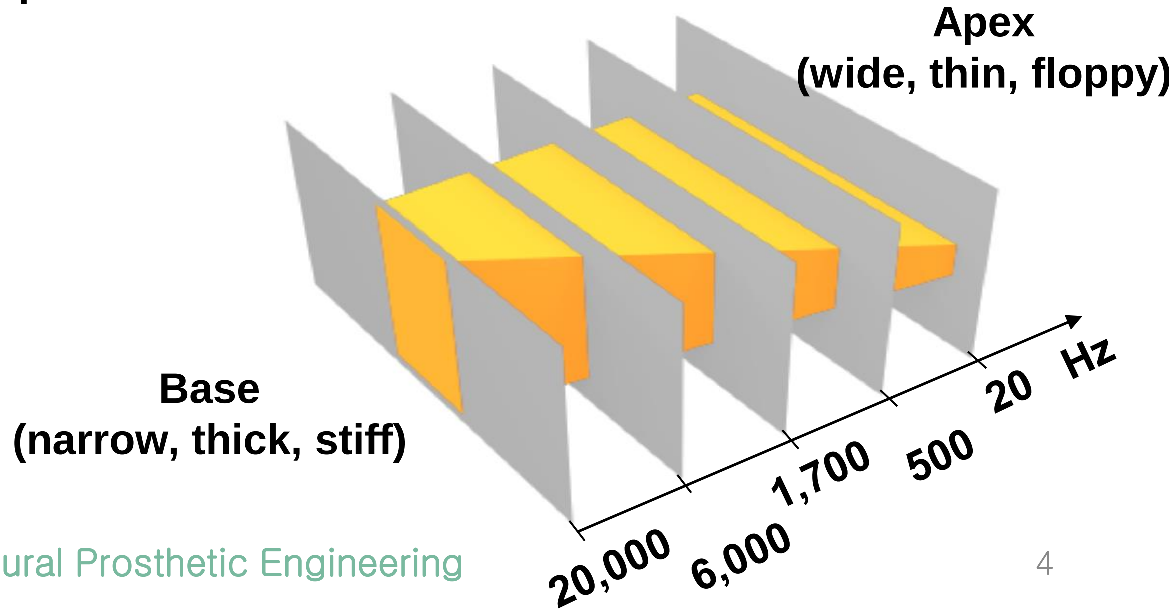


Basilar Membrane



- widest (0.42–0.65 mm) and least stiff at the apex of the cochlea, and narrowest (0.08–0.16 mm) and most stiff at the base

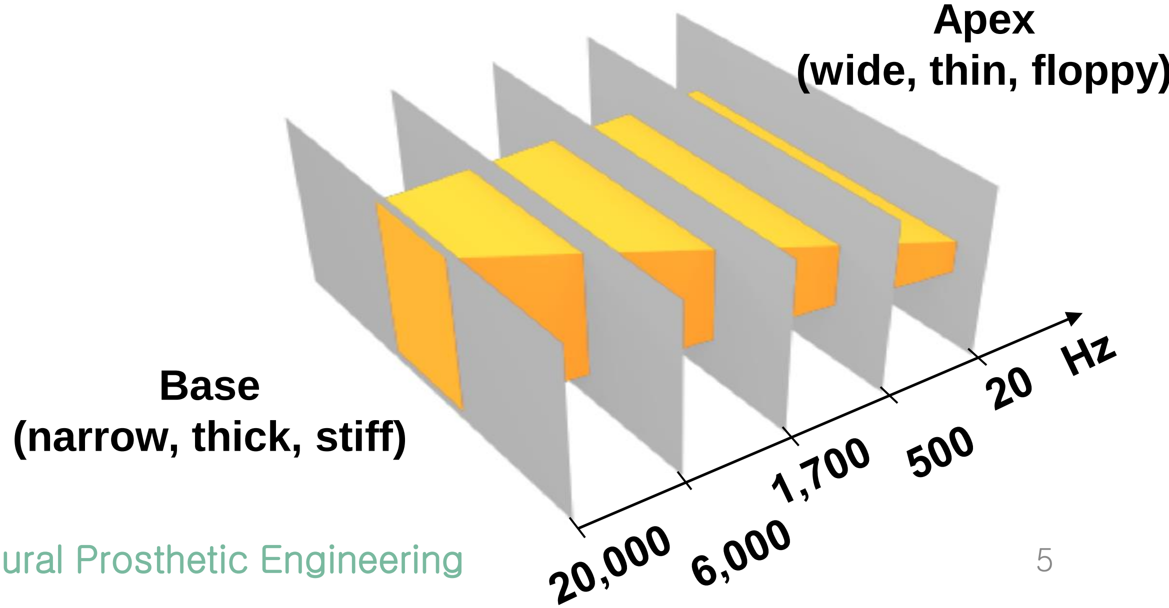
Oghalai JS. The cochlear amplifier: augmentation of the traveling wave within the inner ear. *Current Opinion in Otolaryngology & Head & Neck Surgery.* 12(5):431-8, 2004



Tonotopic arrangement of the BM

Different frequencies produce traveling waves that reach their maximum deflections at different places along the cochlear partition

- High-frequency stimuli cause maximal displacement of the BM in the basal region of cochlea
- Low-frequency sounds cause maximal displacement of the BM in the apical region of the cochlea



Basilar Membrane as a good frequency analyzer

The cochlear operation of frequency analysis is dependent on the following mechanical properties of the BM

- Graded width

a. The width of the BM increases from base to apex

b Wider or more mass results in lower resonant frequency

- Graded stiffness

a. The stiffness of the BM decreases from base to apex

b. Stiffness results in higher resonant frequency

- Graded mass

a. The BM increases in mass from the base to apex

b. Greater mass results in lower resonant frequency

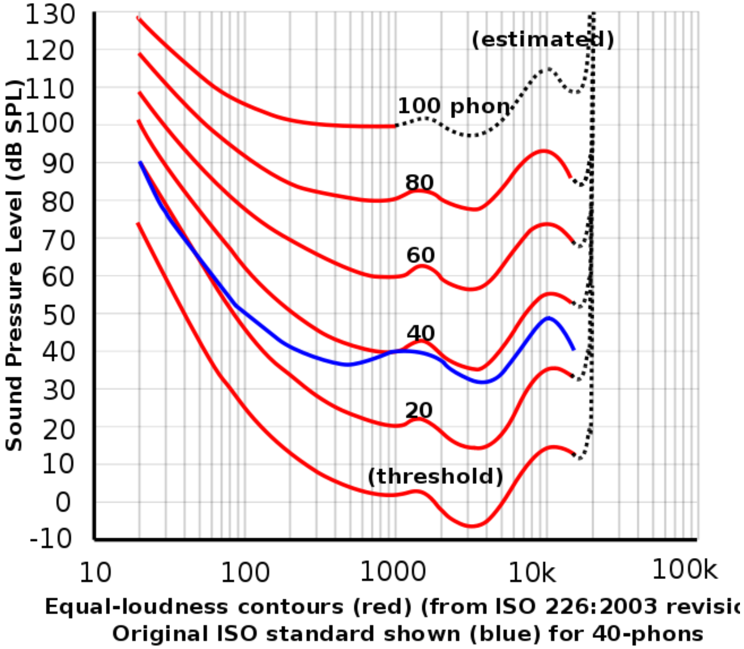
Hearing Loss

The range of human hearing

- Sound frequency
  -over 20-20000Hz

- Sound intensity expressed in Sound Pressure Level (SPL) in dB

SPL = 20 x $\log_{10}(P_x / P_{ref})$
where $P_{ref} = 2.5 \times 10^{-5}$ N/m^2 (is the approximate threshold of human hearing at 1KHz)



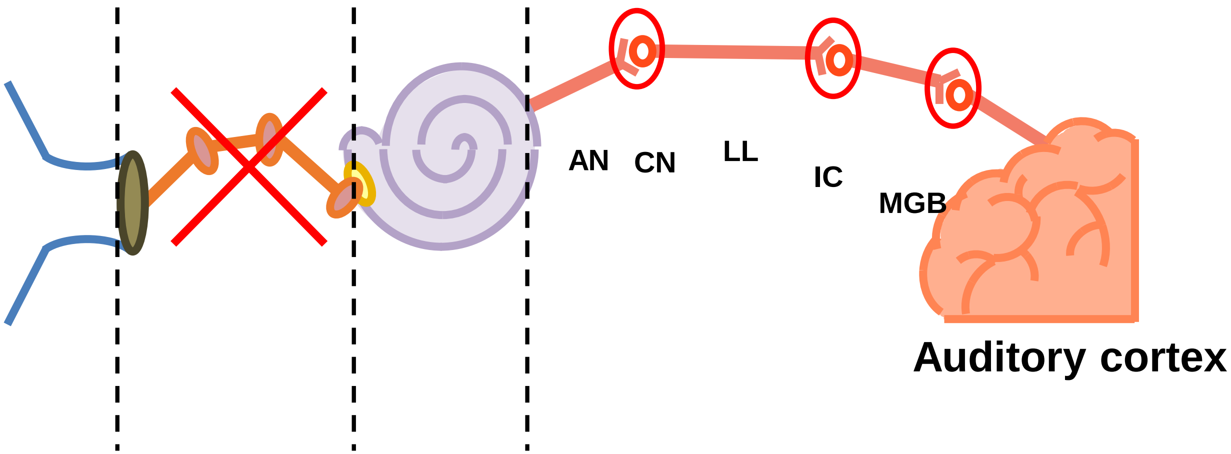
http://en.wikipedia.org/wiki/Image:Lindos1.svg

Degree of Hearing Loss

Degree of Hearing Loss	Hearing Loss Range (dB SPL)
Normal	10 - 15
Slight	16 - 25
Mild	26 - 40
Moderate	41 - 55
Moderately Severe	56 - 70
Severe	71 - 90
Profound to total	91 and above

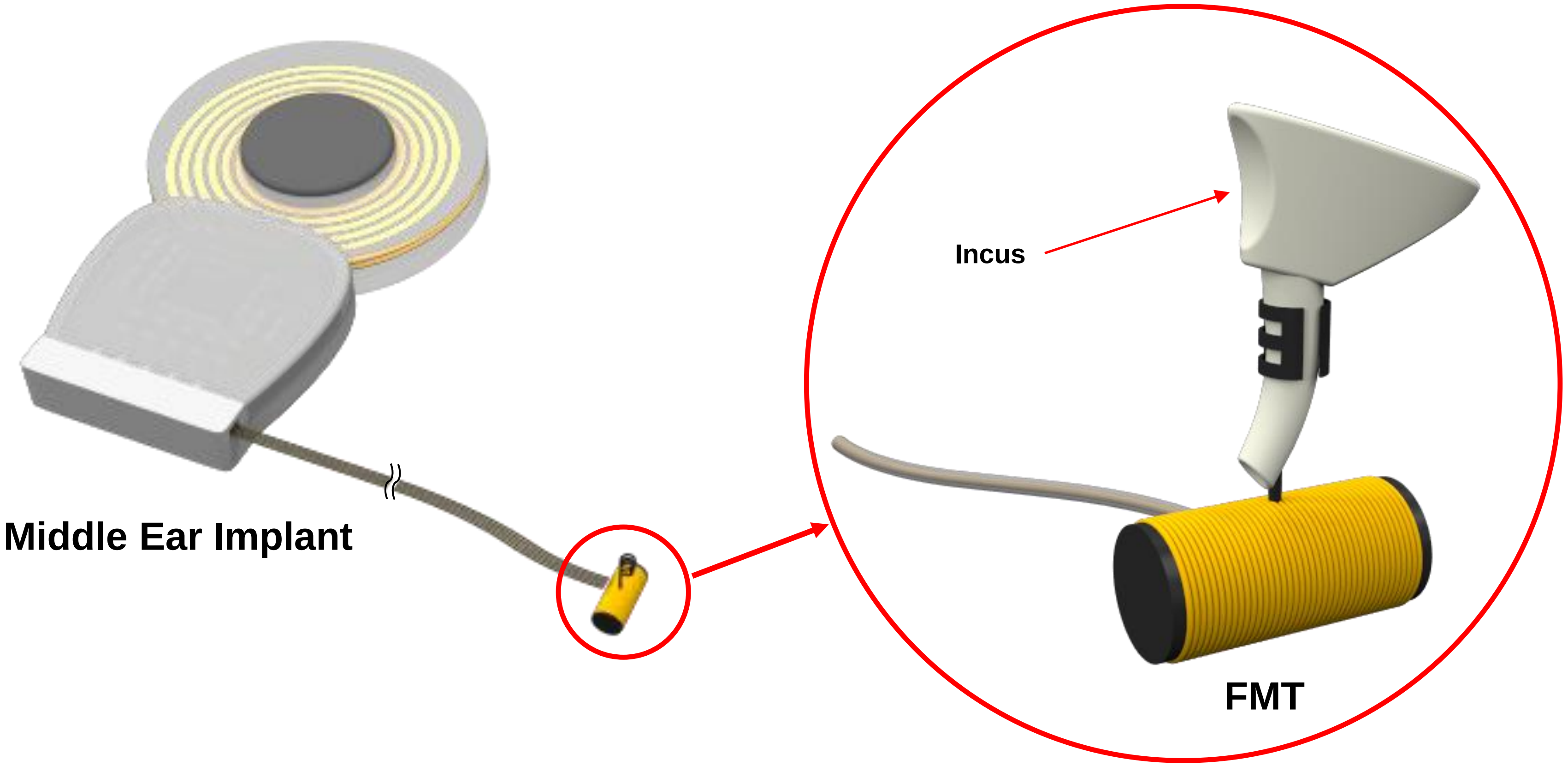
Various sound levels (dB SPL)
Quiet Nature <20
Library 35 Living Room 40
Conversation Speech, quite office 60
Average Street noise, average TV audio 70
Night Club Dance Floor 100
Close in Thunder, Loud Rock Concert 120
Gun Shot 150

Conductive Hearing Loss



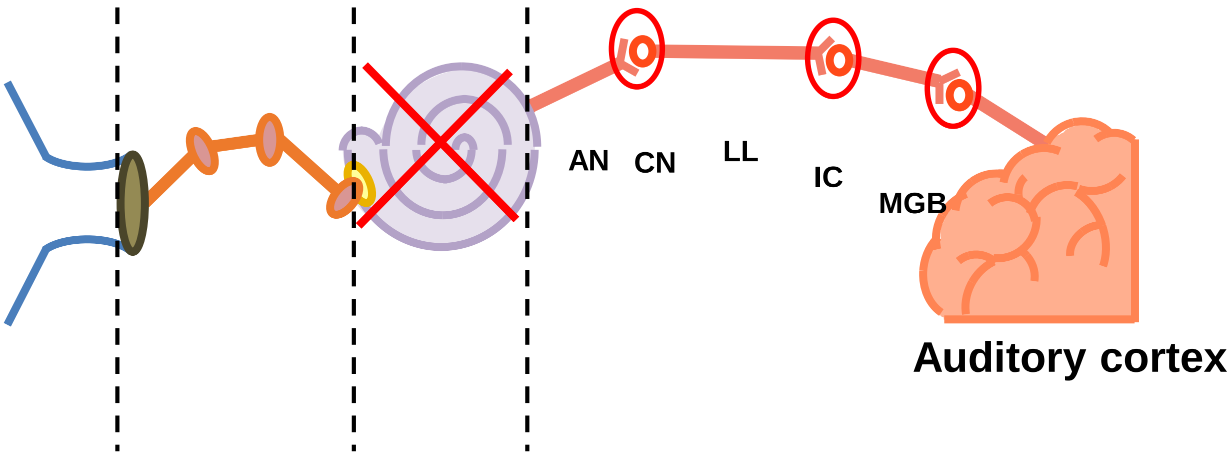
- Middle ear damage
- Conductive Hearing loss is overcome by
  - Hearing Aid (HA)
  - Bone Anchored Hearing Aid (BAHA)
  - Middle Ear Implant using Floating Mass Transducer

Middle ear implant



Floating mass transducer

Sensorineural Hearing Loss



Sensorineural hearing loss

: 'Hair cell' or 'auditory nerve' damage in inner near

→ Overcome by 'cochlear implant'

Congenital sensorineural hearing loss

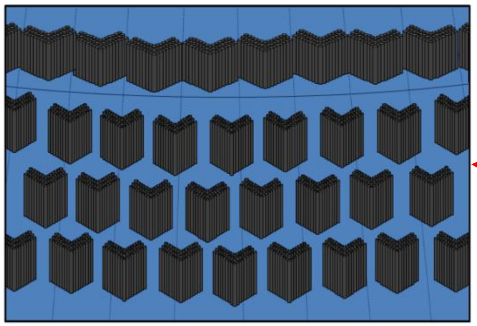
- Two types of sensorineural hearing loss:
- Congenital and Acquired sensorineural hearing loss.
- Congenital sensorineural hearing loss happens during pregnancy. Some causes include:
  - Prematurity
  - Maternal diabetes
  - Lack of oxygen during birth
  - Genetics
  - Diseases passed from the mother to the child in the womb, such as rubella.

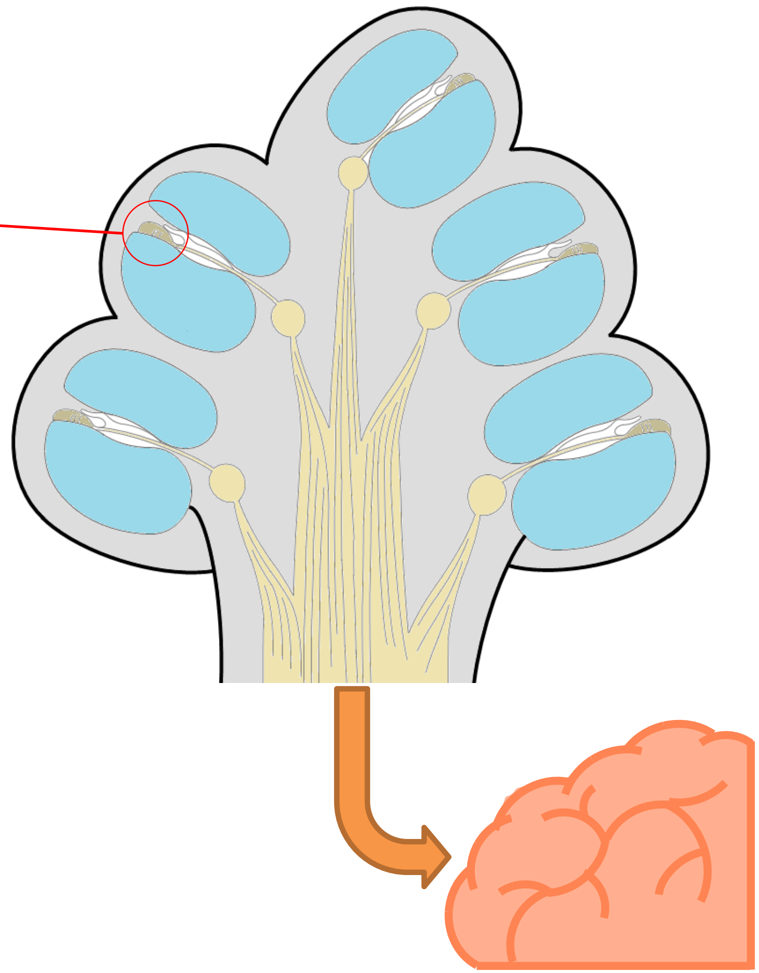
Acquired sensorineural hearing loss

Causes include:

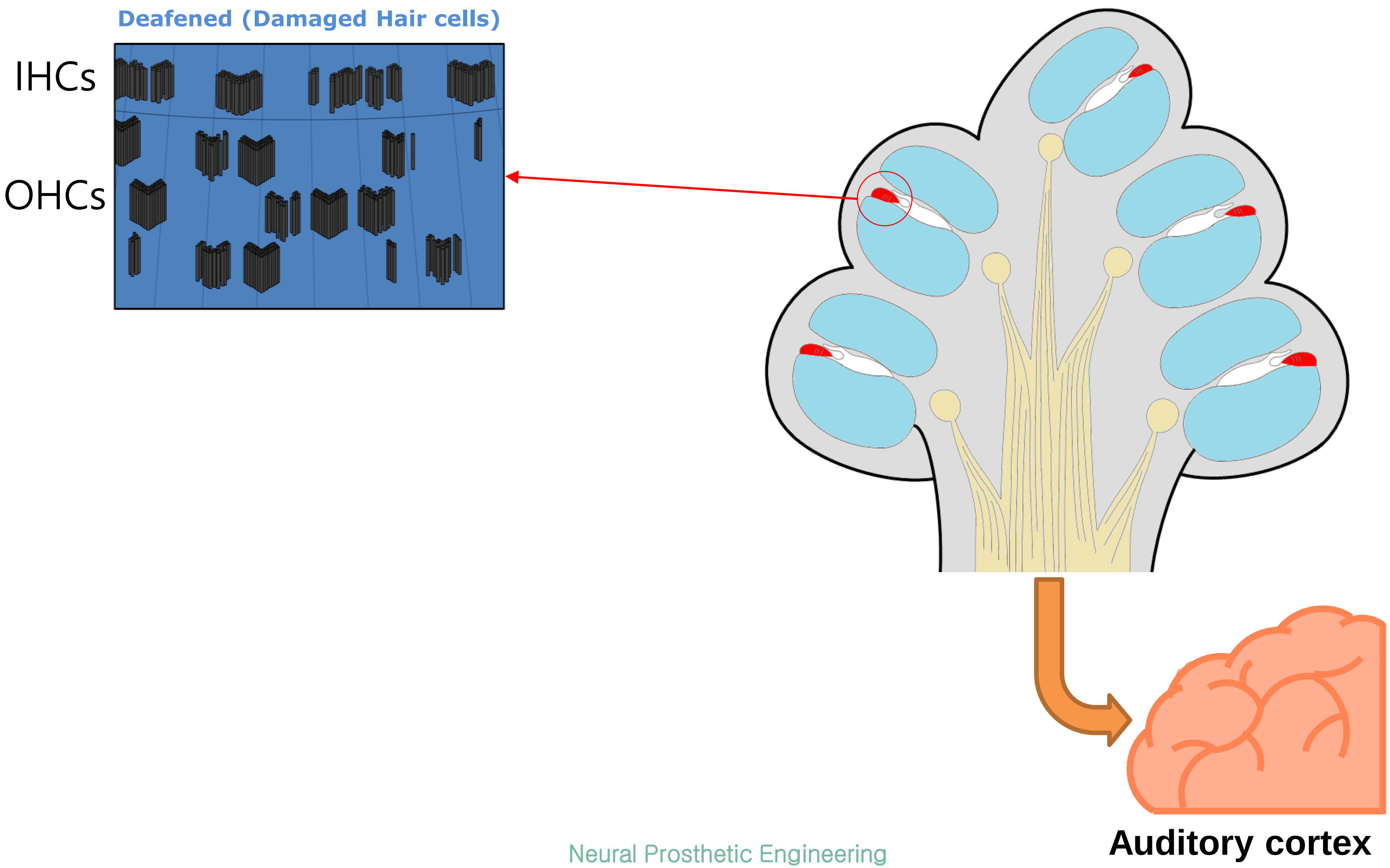
- Aging:
- Noise: approximately 15 percent between the ages of 20 and 69 suffer from noise-induced hearing loss (NIHL). Exposure to a one-time loud noise, such as an explosion, or to sounds louder than 85 decibels over an extended period of time.
- Disease and infections: Meniere's disease, Viral infections, such as measles, meningitis
- Head or acoustic trauma: Damage to your inner ear can also be caused by a blow to the head Tumors
- Medications: more than 200 medications and chemicals are ototoxic

Normal Haircells

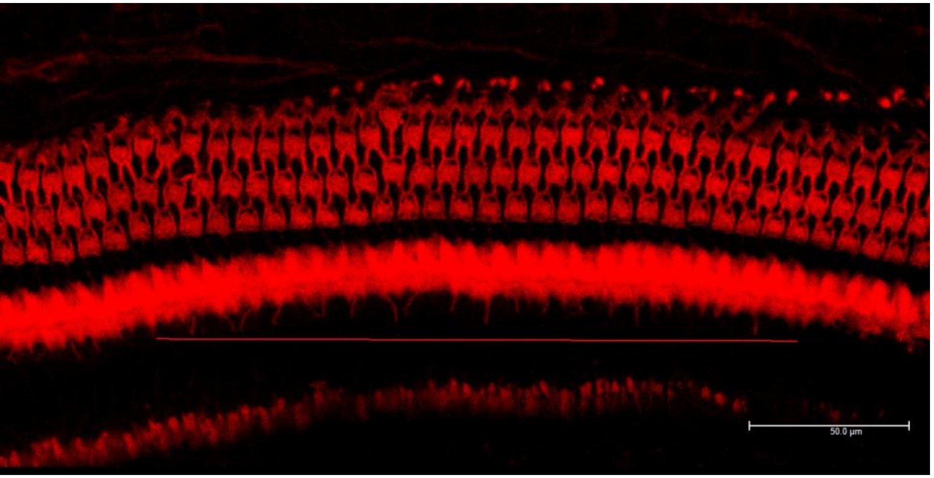




Impaired Hearing Due to Damaged Haircells



Normal vs. Damaged Hair cells



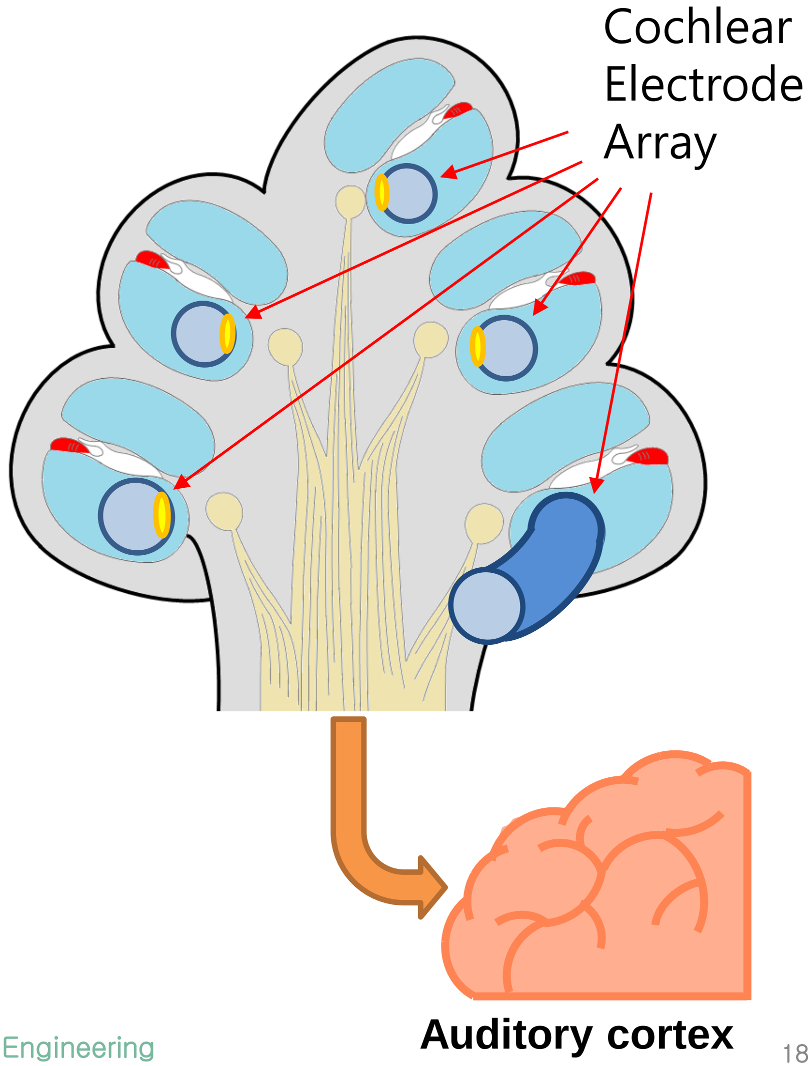
Normal Haircell SD rat 14 week old
immunofluorecence _apical turn

Damaged Haircell SD rat 14 week old
immunofluorecence _middle turn

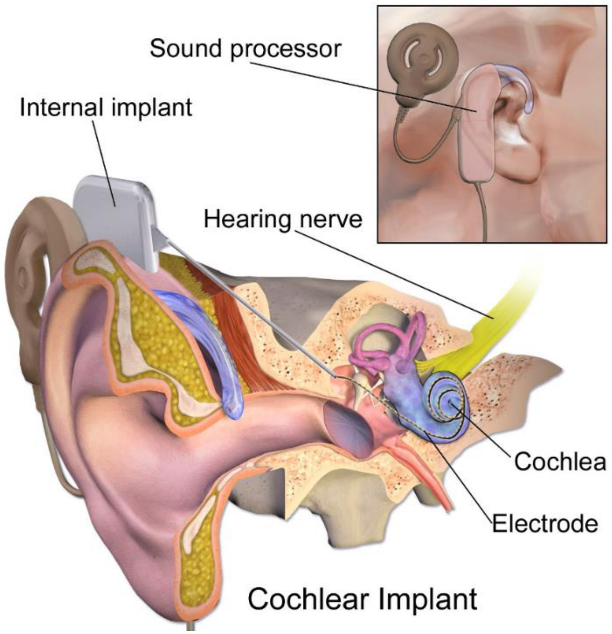
Courtesy of SNUH ENT SH OH Lab. DH Kim 2016 10

Restored Hearing by Cochlear Implantation

- Electrode placed in scala tympany
- Target cell is spiral ganglion in modiolus



CI: the success story



1. Spatially isolated space was available for the electrode array. The electrode array was still electrically connected to the target neurons.
2. Timely development of the transistor based microelectronics technologies that made the electronics small (wearable, implantable) but powerful.

File:Blausen 0244 CochlearImplant 01.png

Multiple devices available for hearing problems

Hearing Aids
Middle Ear Implant
Cochlear Implant
Auditory Brainstem Implant
Auditory Midbrain Implant

Some modification - F. G. Zeng (T*rends Amplif,*, 2004)

Constituting Elements of Cochlear Implant

Functions of cochlea replaced by elements of CI

- Sound collection —
  Microphone

- Tonotopy of Basilar Membrane—
  Bandpass analog filter bank or digital filtering (DSP hardware)

- Inner Hair Cells—
  Intracochlear Electrode Array (multi-channel)

- Auditory Nerve Stimulation—
  Electrical Stimulation of SGC

http://www.priorityhearing.com/
www.hearingreview.com/

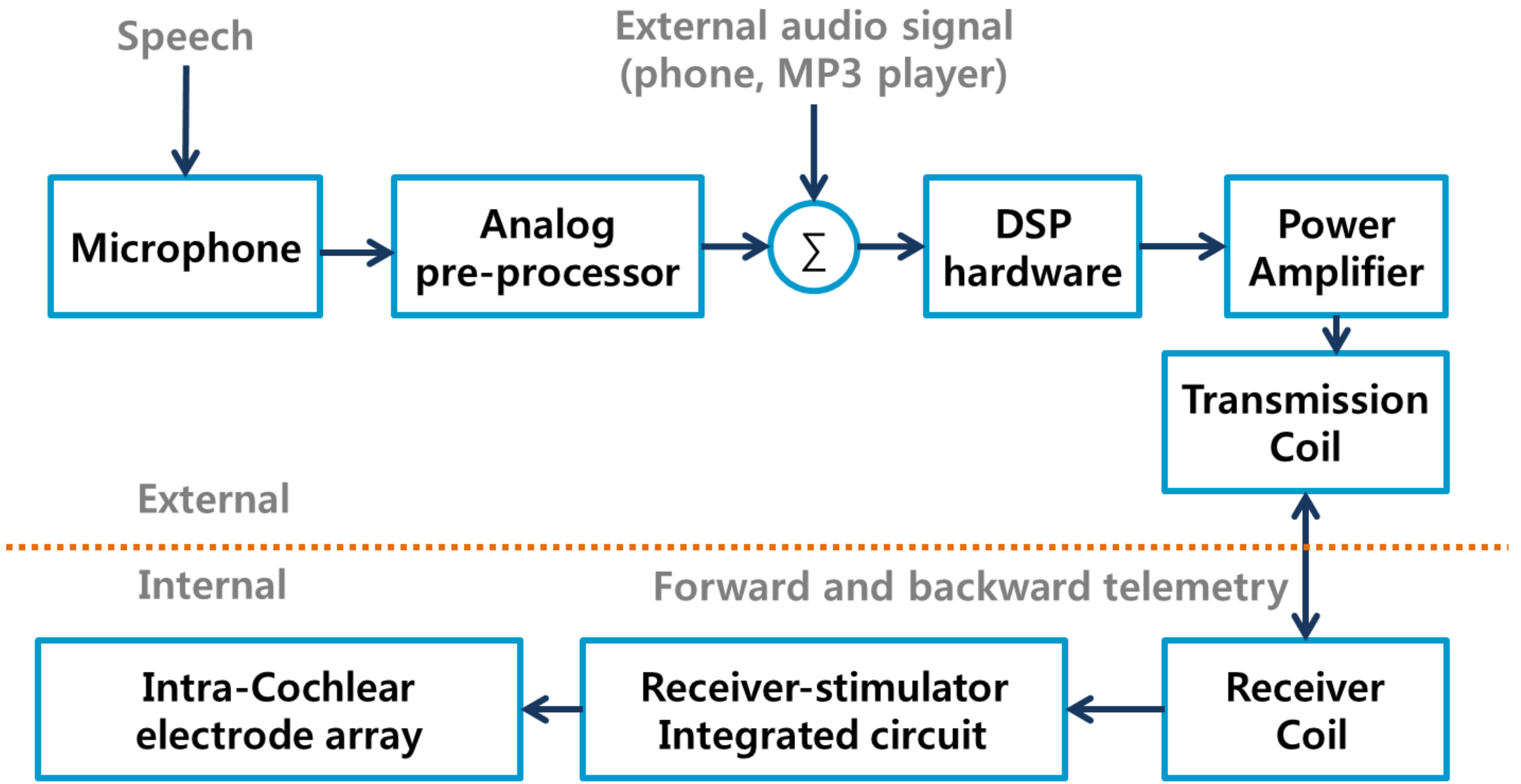
We need a few more details

- Analog Preprocessor
  - Amplify the signal (Pre-amp)
  - non-linear compression of dynamic range
- Wireless telemetry (transmitter and receiver)
  - Coding and modulation
  - Transmitting amplifier and transmitting coil antennae
  - Receiving coil antennae
  - Receiver (demodulation and decoding)
- Stimulator (Stimulation waveform generator)
- Power generation for the internal unit (rectifier and voltage regulator)

http://www.priorityhearing.com/
www.hearingreview.com/

In block diagram form,

- A brief conceptual block diagram



Microphone

Microphone

Cochlear Wireless Mini Microphone

Cochlear Wireless Phone Clip

Cochlear Wireless TV Streamer

Cochlear App Portfolio

Nucleus 6 Sound Processor

1. Coil
2. Coil Magnet
3. Coil Cable
4. Dual Omni Directional Microphones
5. Indicator Light
6. In-Built Telecoil
7. Buttons
8. Earhook
9. Processing Unit
10. Serial Number

www.cochlear.com

Microphone

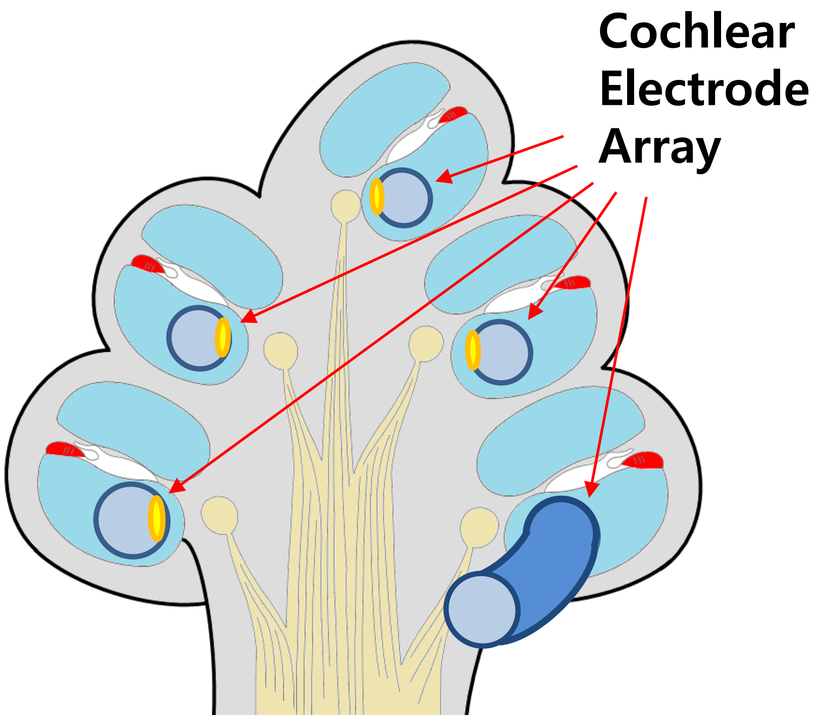
- Requirements of good microphone
  - Broad frequency response
  - Minimize responses to low-frequency vibrations (e.g., head movement, walking)
  - Good performance under adverse condition (e.g., cafeteria noise)
- How to address adverse conditions ?
  - Directional microphone
  - Multiple microphone
    - Selectivity of the directional pattern is increased compared to single microphone
    - Sounds originating between and in front of microphones are emphasized, otherwise suppressed

http://www.cochlear.com/

Cochlear Electrode Array

So fortunate to have space in ST

- Electrode placed in scala tympany
- Target cell is spiral ganglion in modiolus



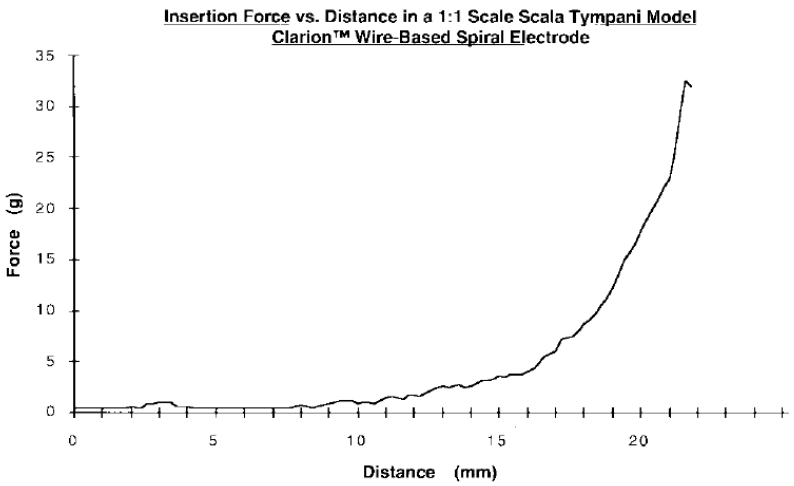
Requirements for Cochlear Electrode

- Requirements of Electrodes
  - Biocompatible : remain over lifespan
  - Mechanically stable
  - Facilitate atraumatic insertion
    - Flexible arrays, narrow cross-sectional area
    - Use lubricant (e.g., Hyaluronic acid)
  - Good spatial specificity of stimulation

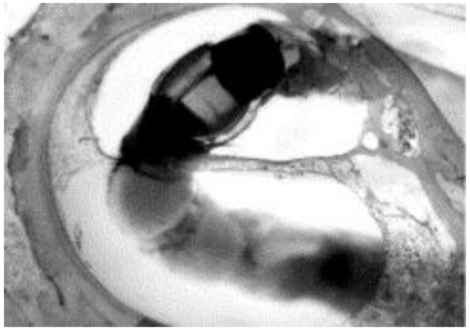
Insertion Trauma?

Considerations for safety of cochlear electrode arrays

- Insertion Force & Extraction Force
  - More Force is needed to advance into the Scala Tympani.
  - For reinsertion, the least extraction force is desirable for preservation of surrounding tissues.



- Insertion Trauma
  - Sharp edge or stiffness of the electrode may cause damages to surrounding tissues.



Insertion Trauma **

* SJ Rebscher et al., IEEE Transactions on Biomedical Engineering , vol. 46, no. 3, 1999

**P. Wardrop, D. Whinney, S. J. Rebscher, J. T. Roland Jr, W. Luxford, and P. A. Leake, Hearing Research, vol. 203, pp. 54-67, 2005.

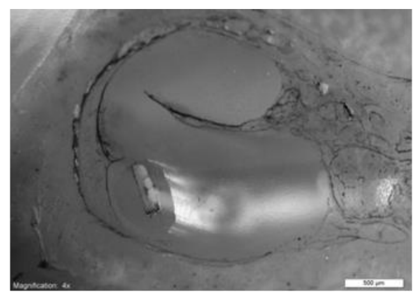
Before inserting in human,

■ Insertion study in human cadaver temporal bone

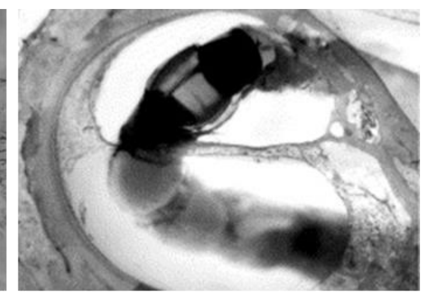
- Extent of Cochlear Trauma
  - 0: No Observable Trauma
  - 1: Elevation of the Basilar Membrane (BM)
  - 2: Rupture of BM
  - 3: Electrode in Scala Vestibuli
  - 4: Fracture of osseous spiral lamina or modiolar wall

Grade 0*

Grade 1*



Grade 2



Grade 3**

* A. A. Eshraghi, N. W. Yang, and T. J. Balkany, "Comparative study of cochlear damage with three perimodiolar electrode designs," *The Laryngoscope,* vol. 113, pp. 415-419, 2003.

** P. Wardrop, D. Whinney, S. J. Rebscher, J. T. Roland Jr, W. Luxford, and P. A. Leake, "A temporal bone study of insertion trauma and intracochlear position of cochlear implant electrodes. I: Comparison of Nucleus banded and Nucleus Contour™ electrodes," *Hearing Research,* vol. 203, pp. 54-67, 2005.

Multi-channel, it should be.

Single- vs. Multi-channel CI

- **Single-channel CI (single electrode) → no frequency information**

3M/House single channel cochlear implant

Appearance of electrodes for CI
(Nucleus 24 Contour, Cochlear Corp.)

www.cochlear.com

- **No. of current electrode sites: 8-32 (vs. No. of inner hair cells: 3,500)**

Performance vs. Number of channels

- **8 is enough**

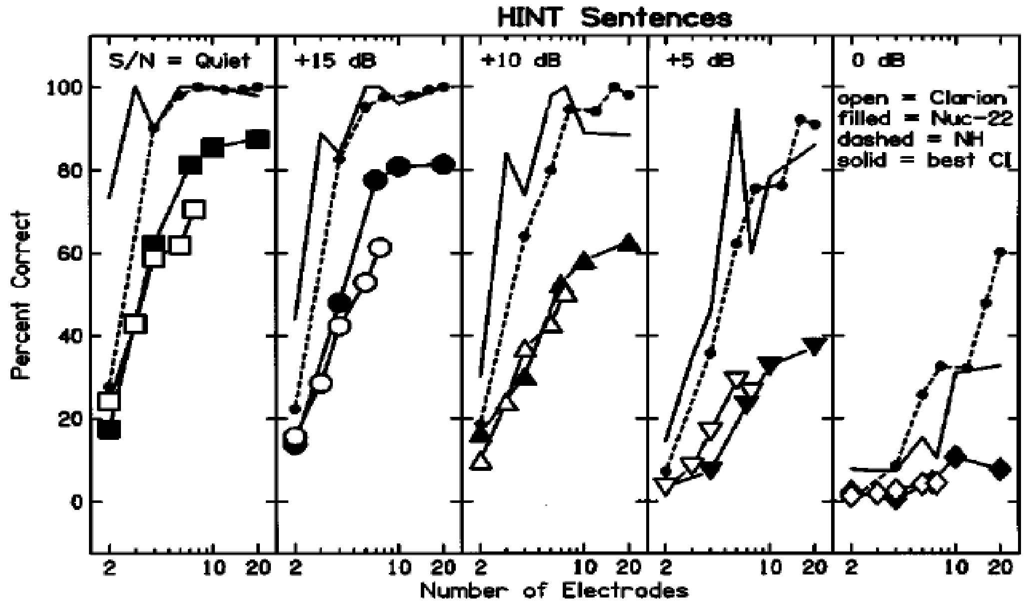


FIG. 4. Recognition of HINT sentences as a function of the number of spectral channels for normal-hearing listeners (dashed line with small filled symbols) or as a function of the number of electrodes used with Nucleus-22 cochlear implant listeners (filled symbols) and Clarion cochlear implant listeners (open symbols). The solid line plots the best performance level across all 19 cochlear implant listeners. From left to right the panels present consonant recognition as a function of decreasing signal-to-noise ratio.

L.M.Friesen et al., J. Acoust. Soc. Am, 2001

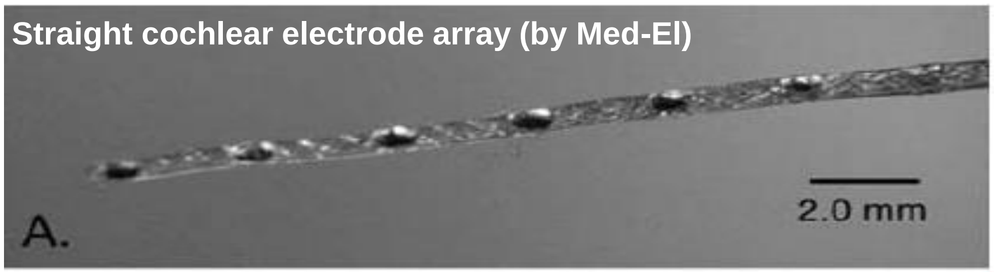
Spatial Specificity

- Spatial specificity of stimulation depends on…
  - The number and distribution of surviving ganglion cells
  - Whether neural processes peripheral to the ganglion cells are present or not
  - The proximity of the electrodes to the target neurons
  - The electrode coupling configuration (monopolar, bipolar)

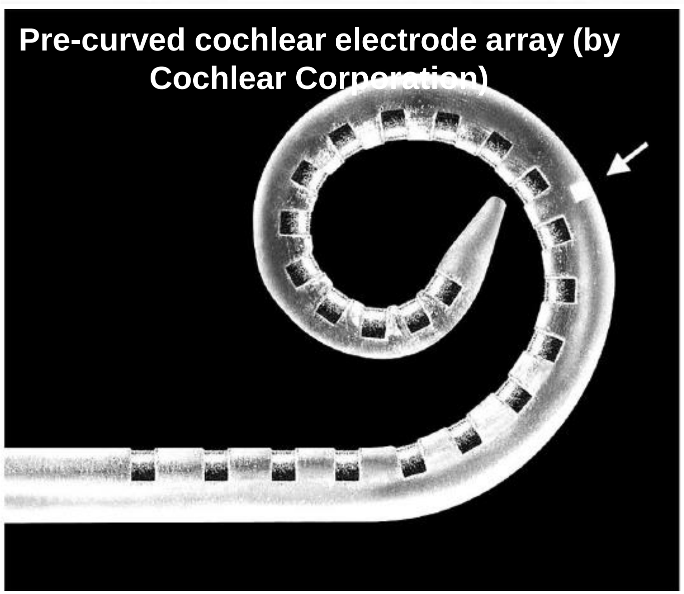
Straight vs. Pre-curved

Types of cochlear electrode array

- **Straight vs Pre-curved**



Straight cochlear electrode array (by Med-El)


Pre-curved cochlear electrode array (by Cochlear Corporation)

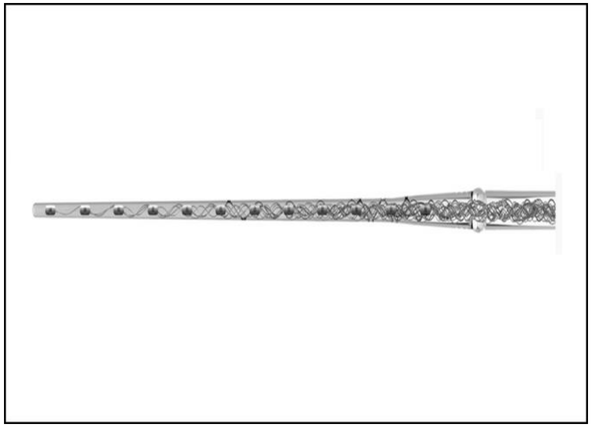
- Straight types
  - Deep insertion
  - Far from target cells
  - Lateral wall insertion

- Pre-curved types
  - Close to target cells
  - Using stylet (safety problem)
  - Perimodiolar insertion

Sheath vs. Stylet (Pre-curved)

- **Straight Electrode**

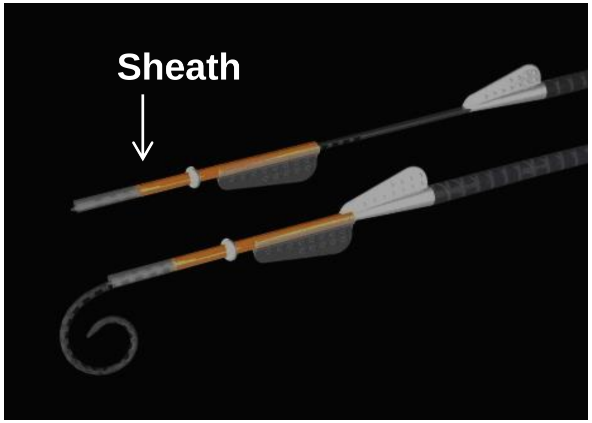
  - Easy insertion
  - Close to the outer wall



MED-EL, FLEX Electrode

- **Using External Sheath**

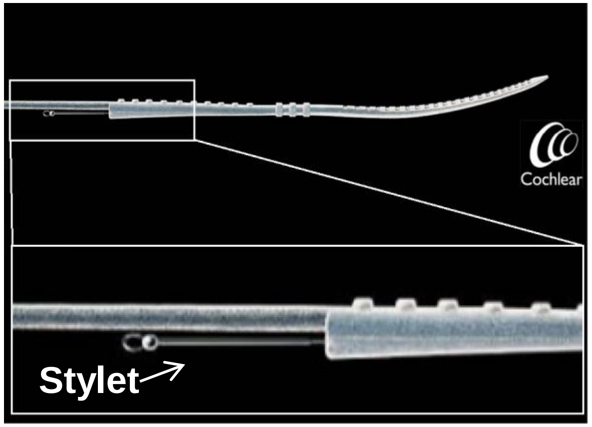
  - Precurved electrode
  - Held straight for insertion by sheath
  - Close to the inner wall



Briggs RJ, Tykocinski M, Development and evaluation of the modiolar research array-multi-centre collaborative study in human temporal bones, University of Melbourne and HEARing CRC, Cochlear Implant International:Volume 12, 2011

- **Using Internal Stylet**

  - Precurved electrode
  - Held straight for insertion by stylet
  - Close to the inner wall



Cochlear ™ Nucleus®, CI24RE Contou Advanced

Peri-modiolar Placement

- Positioning of electrodes in ST
  - Place close to inner wall of ST to minimize the distance between electrodes and SG
    - Maximize the number of largely non-overlapping populations of neurons
    - Improve spatial specificity of stimulation
    - Reduce threshold voltage
    - Increase battery life

Making entry to cochlea

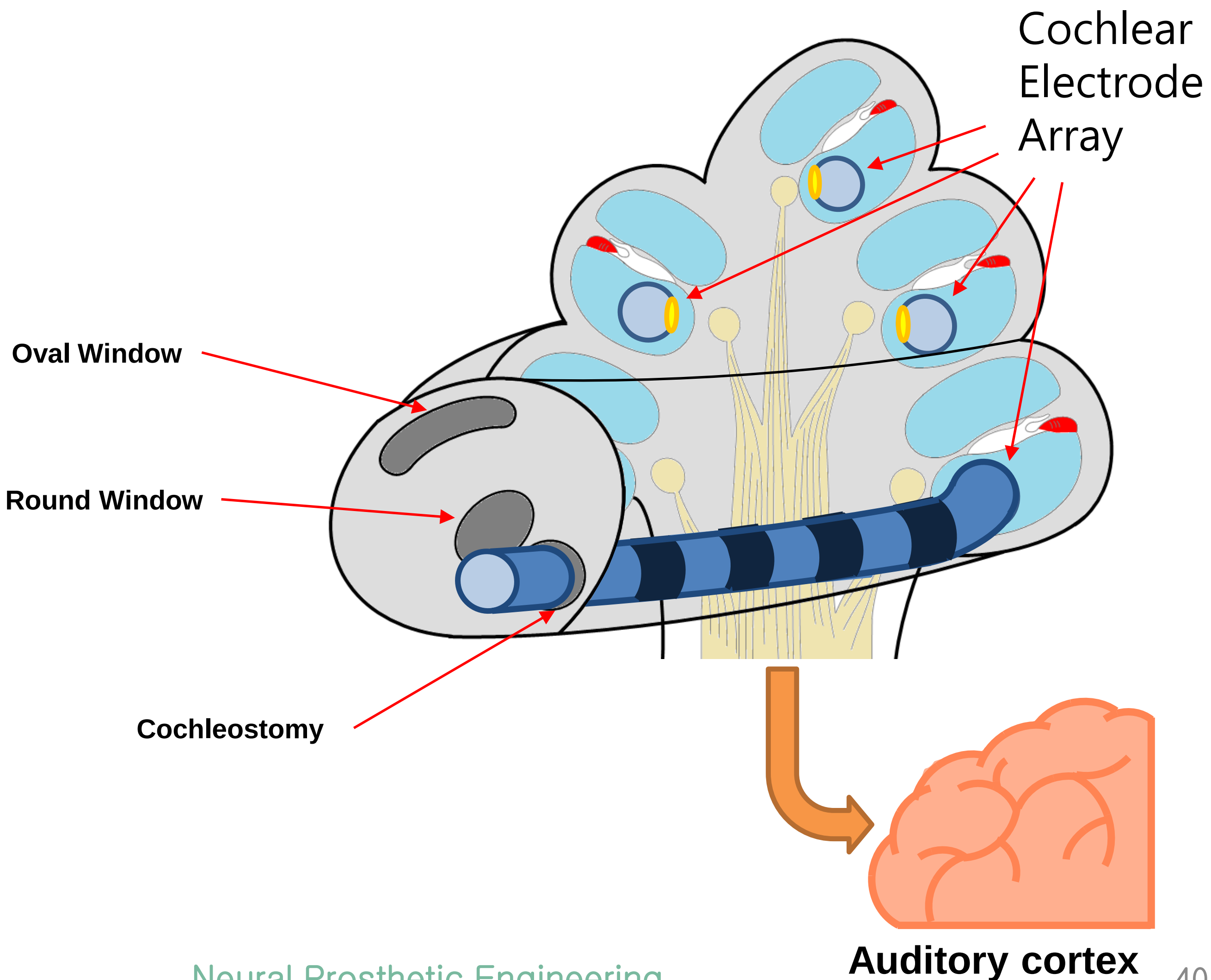
- **Cochleostomy Approach**

- Straight entry
-Relatively deep insertion depth
- Hard to drill
-damaging to HC

- **Round Window Approach**

- Using natural window
- Curved Entry
- Relatively shallow insertion depth
- Less drilling necessary
- saving residual HC's
- used in EAS (Combined electric and acoustic stimulation)

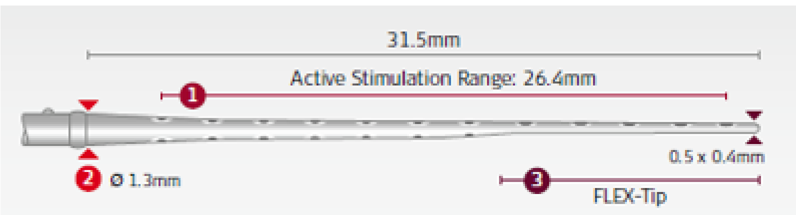
Cochleostomy and round window approach

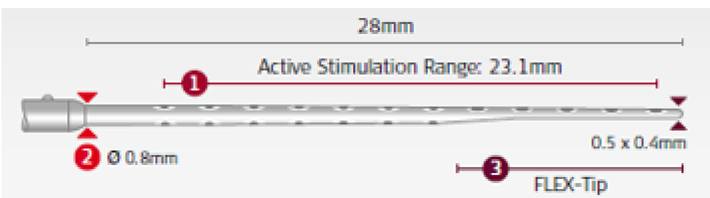


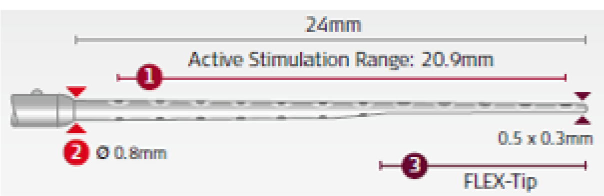
Electrode Length

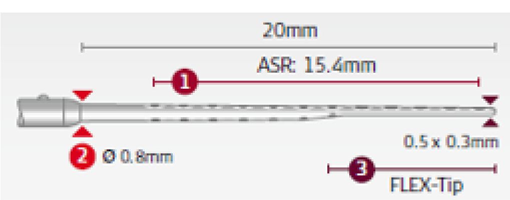
■ Length of cochlear electrode array

- **Electrical Only(long) vs Combined Electrical Acoustic Stimulation (short)**









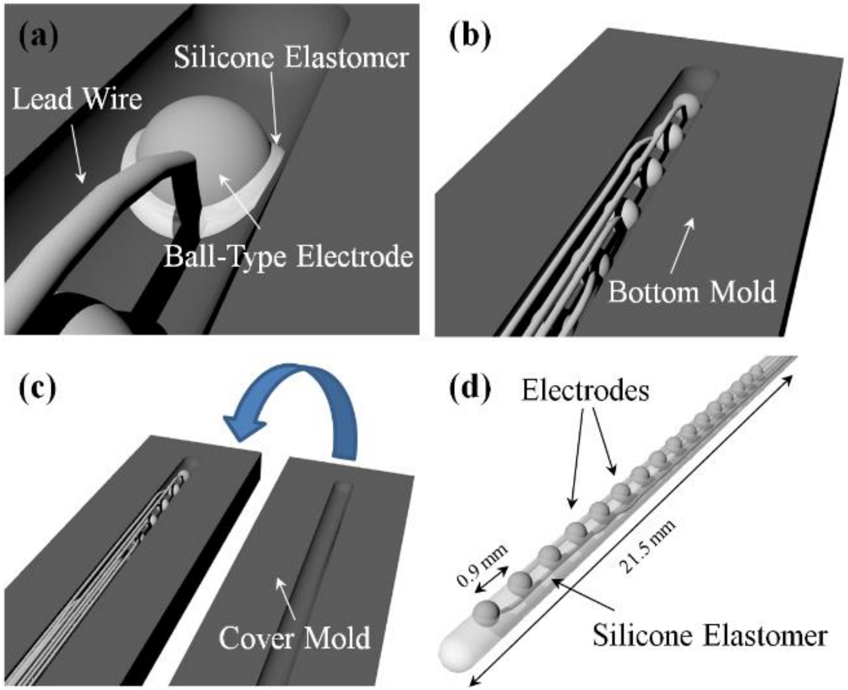
- Long electrode array
  - Deep insertion
  - Apex stimulation (low frequency)
  - High insertion trauma

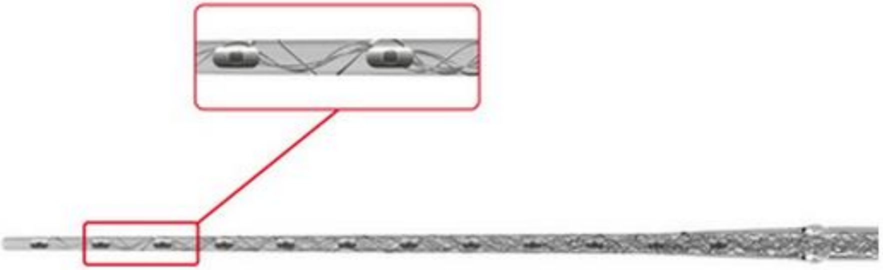
- Short electrode array
  - Acoustic + Electrical stimulation
  - Low insertion trauma

www.Medel.com

Conventional Electrode:
Pt-Ir wire/ Silicone Elastomer Body

- **Pt-Ir wire-based cochlear electrode array**



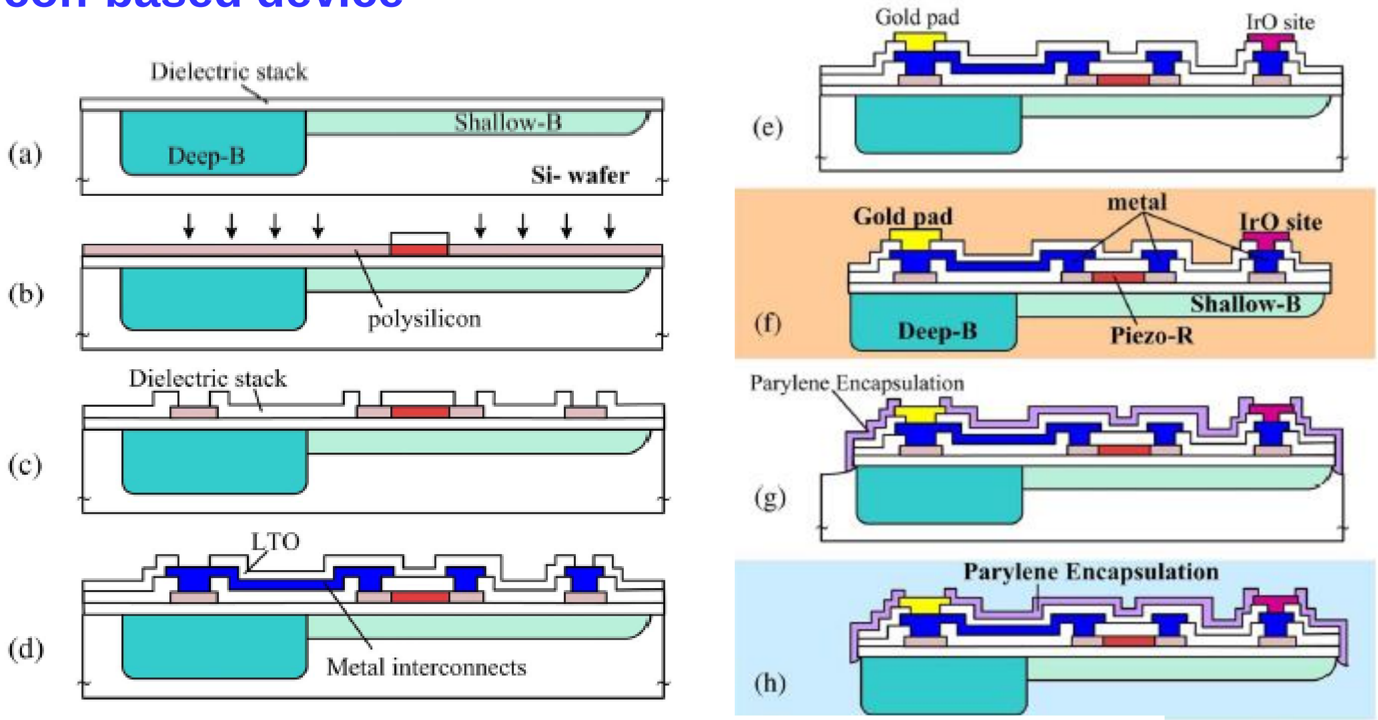


Many makers

Source	Manufacturing method/substrate	Number of contacts
Epic biosonics	automatic/silicon	16
Sonn (Raytheon)	automatic/silicon	37
Stanford	automatic/polymer	8
University of Michigan	automatic/silicon	128
Advanced Cochlear Systems	automatic/polymer	72
University of Utah	automatic/silicon	100
AllHear (House)	manual/wire	1
Med-El	manual/silicone	24
Cochlear Ltd.	manual/silicone	22
Advanced Bionics	manual/silicone	16
LAURA	manual/silicone	48
Seoul National University	automatic/polymer	16

MEMS based technology (U. Mich)

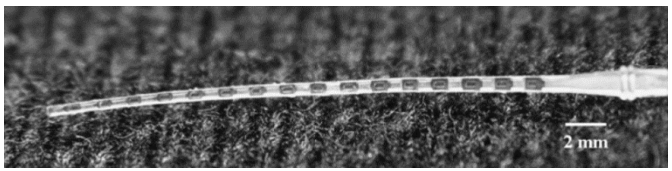
- Silicon-based device

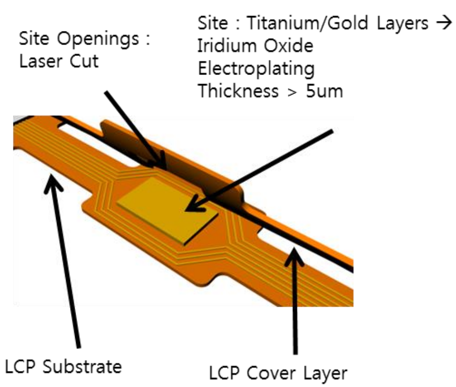


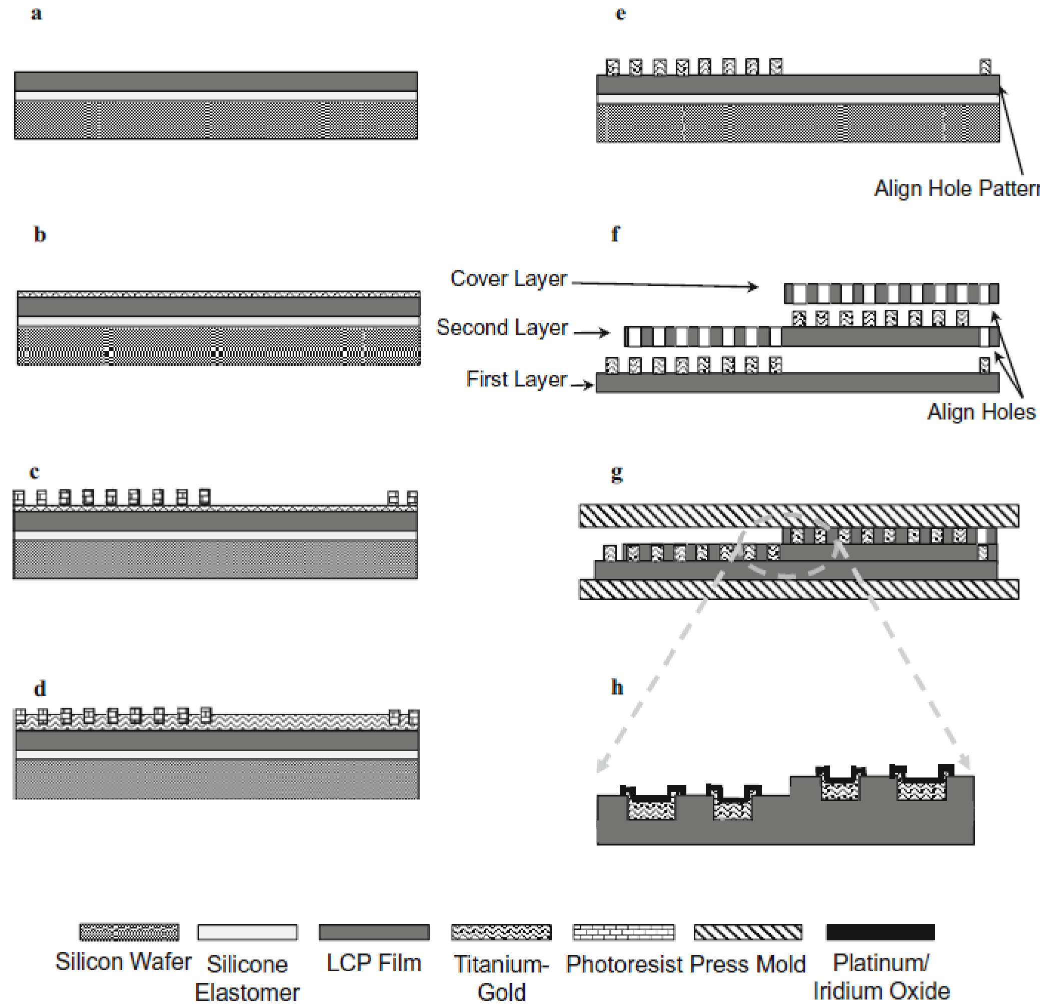
J.Wang et al., Journal of MEMS, 2009

Polymer (LCP) based Technology (SNU)

Polymer-based device







K.S.Min et al., Otology & Neurotology, 2014
T.M.Gwon et al., Biomedical Microdevices, 2015

Current Issues on Electrode Array

- Spatial selectivity (crosstalk) – beyond 8 effective channels- would more number of channels make difference?
- Removal of insertion trauma- how to minimize mechanical strain
- Straight or pre-curved? Is there a safety concern?
- Including other functionalities such as drug delivery, sensors etc.

Reference

- Berrang, Peter G., et al. "Modiolar hugging electrode array." U.S. Patent No. 6,374,143. 16 Apr. 2002.
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