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
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
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 20-20000 Hz

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

\[ \text{SPL} = 20 \times \log_{10} \left( \frac{P_x}{P_{\text{ref}}} \right) \]

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

## Degree of Hearing Loss

<table>
<thead>
<tr>
<th>Degree of Hearing Loss</th>
<th>Hearing Loss Range (dB SPL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>10 - 15</td>
</tr>
<tr>
<td>Slight</td>
<td>16 - 25</td>
</tr>
<tr>
<td>Mild</td>
<td>26 - 40</td>
</tr>
<tr>
<td>Moderate</td>
<td>41 - 55</td>
</tr>
<tr>
<td>Moderately Severe</td>
<td>56 - 70</td>
</tr>
<tr>
<td>Severe</td>
<td>71 - 90</td>
</tr>
<tr>
<td>Profound to total</td>
<td>91 and above</td>
</tr>
</tbody>
</table>

### 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

Middle Ear Implant

Floating mass transducer

Incus

FMT
Sensorineural hearing loss

- 'Hair cell' or 'auditory nerve' damage in inner ear
- 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 Yumors
- Medications: more than 200 medications and chemicals are ototoxic
Normal Haircells

IHCs

OHCs

Auditory cortex
Impaired Hearing Due to Damaged Haircells

Deafened (Damaged Hair cells)

IHCs

OHCs

Auditory cortex
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 tympani
- Target cell is spiral ganglion in modiolus

Cochlear Electrode Array

Auditory cortex
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.
Multiple devices available for hearing problems

Hearing Aids
Middle Ear Implant
Cochlear Implant
Auditory Brainstem Implant
Auditory Midbrain Implant
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
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)
In block diagram form,

- A brief conceptual block diagram

Speech

Microphone → Analog pre-processor → \( \sum \) → DSP hardware → Power Amplifier

External audio signal (phone, MP3 player)

Transmission Coil

External

Internal

Forward and backward telemetry

Intra-Cochlear electrode array → Receiver-stimulator Integrated circuit → Receiver Coil
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.
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


Multi-channel, it should be.

Single- vs. Multi-channel CI

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

3M/House single channel cochlear implant

- 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.

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)
Types of cochlear electrode array

- Straight vs Pre-curved

  • 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

- **Using External Sheath**
  - Precurved electrode
  - Held straight for insertion by sheath
  - Close to the inner wall

- **Using Internal Stylet**
  - Precurved electrode
  - Held straight for insertion by stylet
  - Close to the inner wall

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MED-EL, FLEX Electrode

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

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

[Images of cochlear electrode arrays showing different lengths and stimulation ranges.]
Conventional Electrode: Pt-Ir wire/ Silicone Elastomer Body

- Pt-Ir wire-based cochlear electrode array
## Many makers

<table>
<thead>
<tr>
<th>Source</th>
<th>Manufacturing method/substrate</th>
<th>Number of contacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epic biosonics</td>
<td>automatic/silicon</td>
<td>16</td>
</tr>
<tr>
<td>Sonn (Raytheon)</td>
<td>automatic/silicon</td>
<td>37</td>
</tr>
<tr>
<td>Stanford</td>
<td>automatic/polymer</td>
<td>8</td>
</tr>
<tr>
<td>University of Michigan</td>
<td>automatic/silicon</td>
<td>128</td>
</tr>
<tr>
<td>Advanced Cochlear Systems</td>
<td>automatic/polymer</td>
<td>72</td>
</tr>
<tr>
<td>University of Utah</td>
<td>automatic/silicon</td>
<td>100</td>
</tr>
<tr>
<td>AllHear (House)</td>
<td>manual/wire</td>
<td>1</td>
</tr>
<tr>
<td>Med-El</td>
<td>manual/silicone</td>
<td>24</td>
</tr>
<tr>
<td>Cochlear Ltd.</td>
<td>manual/silicone</td>
<td>22</td>
</tr>
<tr>
<td>Advanced Bionics</td>
<td>manual/silicone</td>
<td>16</td>
</tr>
<tr>
<td>LAURA</td>
<td>manual/silicone</td>
<td>48</td>
</tr>
<tr>
<td>Seoul National University</td>
<td>automatic/polymer</td>
<td>16</td>
</tr>
</tbody>
</table>
MEMS based technology (U. Mich)

- Silicon-based device

![Silicon-based device diagram](image)
Polymer (LCP) based Technology (SNU)

Polymer-based device

Site Openings: Laser Cut

LCP Substrate

LCP Cover Layer

Site: Titanium/Gold Layers →
Iridium Oxide
Electroplating
Thickness > Sum

Align Hole Pattern

Cover Layer

Second Layer

First Layer

Align Holes

Silicon Wafer
Silicone Elastomer
LCP Film
Titanium-Gold
Photosensitive Press Mold
Platinum/Indium Oxide
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.
• K.S.Min et al., Otology & Neurotology, 2014
• T.M.Gwon et al., Biomedical Microdevices, 2015
• J.Wang et al., Journal of MEMS, 2009
• F.A.Spelman, Audiology & Neurotology, 2006
• 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