HEARING AIDS AND AUDITORY IMPLANTS -
STATE OF THE ART AND FUTURE TRENDS

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CONTENT

- Introduction to hearing loss and diagnostics
- Indications to various hearing devices
- Functioning of modern hearing aids
- Future trends and developments in hearing aids and implantable auditory prostheses
- Cochlear implants
- Difficulties in speech recognition in noise

DEAFNESS AND HEARING LOSS
(WHO, 2019)

- 466 million people worldwide have disabling* hearing loss
- Hearing loss may be inherited, caused by complications at birth, certain infectious diseases, ototoxic drugs, exposure to excessive noise and aging
- People with hearing loss can benefit from hearing aids, assistive listening devices and cochlear implants
- Current production of hearing aids meets less than 10% of global need

[World Health Organization (2019)]
HEARING DIAGNOSTICS

- Localization / Speech-in-Noise / Binaural Tests
- Behavioral Observation Audiometry
- Sound Field Audiometry
- Tuning Fork / Whisper
- Electrophysiological Tests
- Pure-Tone / Speech Audiometry
- Event-Related
- Bone Conduction
- Cortical
- Impedance
- MLR
- ASSR
- ABR
- OAE
- ECOCHG
- Otoscopic Examination

EQUAL-LOUDNESS-LEVEL CONTOURS VS. PURE-TONE AUDI OGRAM

Graph showing equal-loudness-level contours and pure-tone audiogram.
ASPECTS OF HEARING LOSS

TYPE OF HEARING LOSS

- Conductive
- Sensorineural
- Mixed

ASPECTS OF HEARING LOSS

DEGREE OF HEARING LOSS (WHO)

<table>
<thead>
<tr>
<th>Grade of impairment</th>
<th>Corresponding audiometric ISO value</th>
<th>Performance</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - No impairment</td>
<td>25 dB HL or better (better ear)</td>
<td>No or very slight hearing problems. Able to hear whispers.</td>
<td></td>
</tr>
<tr>
<td>1 - Slight impairment</td>
<td>26-40 dB HL (better ear)</td>
<td>Able to hear and repeat words spoken in normal voice at 1 meter.</td>
<td>Counselling. Hearing aids may be needed.</td>
</tr>
<tr>
<td>2 - Moderate impairment</td>
<td>41-60 dB HL (better ear)</td>
<td>Able to hear and repeat words spoken in raised voice at 1 meter.</td>
<td>Hearing aids usually recommended.</td>
</tr>
<tr>
<td>3 - Severe impairment</td>
<td>61-80 dB HL (better ear)</td>
<td>Able to hear some words when shouted into better ear.</td>
<td>Hearing aids needed. If no hearing aids available, sign language.</td>
</tr>
<tr>
<td>4 - Profound impairment including deafness</td>
<td>81 dB HL or greater (better ear)</td>
<td>Unable to hear and understand even a shouted voice.</td>
<td>Hearing underdenta rehabilitation and sign language.</td>
</tr>
</tbody>
</table>

Grades 2, 3 and 4 are classified as disabling hearing impairment.

The audiometric ISO values are averages of values at 500, 1000, 2000, 4000 Hz.
CONFIGURATION OF HEARING LOSS

Unilateral, bilateral
Symmetrical, asymmetrical
Stable, progressive, sudden, fluctuating

OTHER ASPECTS OF HEARING LOSS
ALLEVIATING HEARING LOSS WITH HEARING DEVICES

1800s
The earliest hearing aids
Essentially nothing more than horn-style devices designed to capture more sound and direct it into the ear canal – first became popular in the 1800s.

1890s
The first electric hearing aid
In 1898, the first electric hearing aid was created by Miller Reese Hutchison. A portable carbon transmitter was used to amplify weak sounds using an electric current, based on the principle used in the telephone. Wearable and practical instruments were available from 1902, but were not in popular use until the 1940s. Even then, they only had the power to correct moderate hearing loss.
Carbon Microphone
HEARING DEVICES

HEARING-AID MANUFACTURERS

- Phonak (CH; Sonova): 24%
- Oticon (DK; William Demant Holding): 23%
- Siemens (GER): 17%
- GN Store Nord (DK; owner of ReSound): 16%
- Starkey Technologies (USA): 9%
- Widex (DK): 9%
COCHLEAR-IMPLANT MANUFACTURERS

- Cochlear (AU): 53%
- Med-El (AT): 28%
- Advanced Bionics (US/CH; Sonova)
- Neurelec (FR/DK; Oticon)
- Nurotron (CN)

WORLDWIDE IN 2012

- Hearing aids sold
  - 11 million hearing aids
  - 6 billion USD
  - 5% annual growth
- Cochlear implants sold
  - 50,000 cochlear implants
  - 1 billion USD
  - 10-15% annual growth
FUNCTIONING OF HEARING AIDS

LEVELS OF COMFORT AND HEARING LOSS

Dillon (2012) Hearing AIDS.
The growth of loudness is steeper in cochlear hearing loss compared to normal hearing.

Conductive hearing loss has a more linear effect on loudness perception.

Changes in loudness perception:
- Elevated threshold, abnormal loudness growth, discomfort level
- Frequency specificity

Decreased discrimination:
- Frequency, level and temporal changes
- Effect on speech perception

Binaural hearing:
- Degraded localization ability
- Degraded speech understanding in noise

Tinnitus
HEARING-AID TECHNOLOGY

- Multichannel amplification
  - Channel refers to a frequency band
- Compression
  - Knee points can be adjusted independently within each band
- Sufficient amplification
  - To avoid clipping
- Feedback suppression and elimination

HEARING-AID TECHNOLOGY

- Sufficient bandwidth and potential frequency lowering
- Bilateral fitting
- Preprocessing of sound
  - Directional microphones
  - Noise reduction algorithms
- Tinnitus maskers
The aim of a hearing aid is to restore loudness perception as close to normal as possible
  – Increasing loudness will increase speech discrimination

Hearing-aid gain prescription defines
  – Frequency and level-dependent amplification
  – Multichannel compression

Level of discomfort
  – Loudness discomfort level (LDL)
  – Uncomfortable (loudness) level (UCL, ULL)

The risk of hearing loss induced by amplified sound
  – Temporary threshold shift (TTS)
  – Permanent threshold shift (PTS)

The limits of the hearing-aid output
  – O90SPL, Rear-Ear Saturation Response
CALCULATING GAIN

- Gain is increased to maximize speech intelligibility index (SII)
- Loudness must not be more than for a normal-hearing person
- The left-hand side adjusts amplification channel by channel
- The right-hand side decreases total amplification based on a computational loudness model (Moore & Glasberg, 2004)

INNER AND OUTER HAIRCELL FUNCTION IN HEARING LOSS

- The anatomical and physiological basis of cochlear hearing loss (Halpin, 2002)

Hair-cell damage and the audiogram
0-65 dB HL: pure OHC dysfunction or a mixture of OHC and IHC dysfunction
> 65 dB HL: combination of OHC and IHC dysfunction
> 90 dB HL: likely a "dead region"
(Complete) destruction of the inner hair cells (IHCs)

When IHCs are non-functioning over a region of the cochlea, no transduction will occur

Commonly associated with
- Profound hearing loss (> 90 dB HL)
- Low-frequency hearing loss (near-normal at high frequencies)
- Steeply sloping hearing loss (> 50 dB/octave)

Audiogram can be misleading in IHC damage
- "Off-frequency listening"

How to apply hearing-aid gain at dead regions?

COCHLEAR DEAD REGION

- Provide amplification up to 1.7 times the lowest frequency of a dead region (Vickers et al., 2001)
- However, mixed results on whether amplification should be limited within a dead region (e.g., Cox, 2012)
- Frequency-lowering beneficial (transposition, frequency compression)
- Reliable and fast PTC measurement needed
  - TEN test (Moore et al., 2000)
  - Sweeping PTC (Malicka et al., 2009)
VERIFICATION AND VALIDATION OF HEARING AID GAIN

- Real-ear measurements / probe microphone measurements
- Taking into account the acoustic coupling of the hearing aid to an individual ear

State of the art technology

- Miniature hearing device
- 1 speaker, 2 microphones (BW = 10 kHz)
- Wireless communication
  - Binaural (ear to ear) communication
  - Connectivity to mobile phones, TV and other audio devices directly or via a relay
  - Supplied from a single Zink-Air battery (1 mW)
State of the art technology

- Sound processing
  - Gain 75 dB
  - Feedback cancellation
  - Multiple programs
  - Adaptive directionality
  - Numerous algorithms incl. frequency-dependent compression, noise reduction, sound environment classification
  - Binaural algorithms
SIZE, SIZE, SIZE

- Minimum size
- Maximum power
- Comfortable retention
- Flexible wearing options

AESTHETICS

- Partly or fully implantable hearing aids
- For conductive or mixed loss

Five weeks after surgery
WIRELESS CONNECTIVITY

- Remote control via a smart phone
  - "Made for iPhone"

WIRELESS CONNECTIVITY

- Managing wireless assistive listening devices
  - 2.4 GHz streaming technology
  - Adaptive directionality
  - QR codes
WIRELESS CONNECTIVITY AND FUTURE DEVELOPMENT

- Hands-free for mobile telephony
- Geotagging
  - Dedicated programs for different places
- Simultaneous speech translation
- Heart-rate monitoring

COCHLEAR IMPLANTS
COCHLEAR IMPLANTS

Deaf-born children
- Bilateral implantation
- With cochlear implants, they often meet age-appropriate verbal communication skills

Post-lingually deafened adults
- ~ > 70 dB HL
- < 60-70 % word scores in quiet
- Insufficient hearing-aid gain
- Difficulties in understanding speech in noisy, everyday environments

GLOBAL INDICATIONS VARY GREATLY

COCHLEAR-IMPLANT INDICATIONS
The number of implantees is increasing steadily.

HYKS: cochlear implantation 1994 - 2018
(750 implants, 692 new ears, 493 new patients)

Schematic: B. Nevison, Cochlear Corporation

Sound Processor Signal Path

1. Front End
   Acts on the whole signal

2. Filter Bank
   Acts on specific frequencies

3. Sound Coding

4. Amplitude Mapping

5. Gain/MPO Prescription

6. Radio Freq. Encoder

7. Combiner

Individual fitting parameters

Stimulation
SOUND CODING EXAMPLE (B. NEVISON, COCHLEAR CORPORATION)

Stimulation rate (e.g., 900 times per second)

TIME DOMAIN

FREQUENCY DOMAIN

ELECTRODE DOMAIN

Stimulation rate (250 Hz - 3500 Hz, typically about 1000 Hz)
SOUND SAMPLES

Strategy: F0/F2

"Hickory, dickory, dock;
The mouse ran up the clock.
The clock struck one,
The mouse ran down,
Hickory, dickory, dock."

Strategy: ACE

"Humpty, dumpty sat on a wall,
Humpty, dumpty had a great fall.
All the king’s horses and the king’s men,
Couldn’t put Humpty together again."

"(In)sensitivity to spatial distortion in natural scenes"
IMAGING IN INNER-EAR STRUCTURE PRESERVATION

Video courtesy of Ralf Greisiger & Greg Jablonski, Oslo University Hospital, Norway.

IMPLANT TELEMETRY AND COCHLEAR MONITORING

- Impedance telemetry
- Electrically-evoked compound action potentials
  - Responses from the spiral ganglion cells of the auditory nerve
- Intraoperative electrocochleography
  - Monitoring the cochlea during electrode insertion
  - Measuring the action and the summation potential (OCH/auditory nerve)
Figure 1. Three-stage model of mean expected auditory performance ranking over time for a hypothetical “average CI recipient”.


http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0048739
Table 1. Results from the 15 five-factor GLM analyses.

<table>
<thead>
<tr>
<th>Factor tested</th>
<th>F(d, df)</th>
<th>Significance p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>697(253)</td>
<td>0.325</td>
</tr>
<tr>
<td>Education level</td>
<td>4.245</td>
<td>0.245</td>
</tr>
<tr>
<td>Duration of moderate HL</td>
<td>7.215(15)</td>
<td>0.000*</td>
</tr>
<tr>
<td>Hearing aid use</td>
<td>690(283)</td>
<td>0.000*</td>
</tr>
<tr>
<td>PTA of the implantation ear</td>
<td>4.297(14)</td>
<td>0.007*</td>
</tr>
<tr>
<td>PTA of the better ear</td>
<td>3.300(3)</td>
<td>0.000*</td>
</tr>
<tr>
<td>HL at 500 Hz of the implanted ear</td>
<td>3.28(24)</td>
<td>0.000*</td>
</tr>
<tr>
<td>HL at 500 Hz of the better ear</td>
<td>2.98(7)</td>
<td>0.000*</td>
</tr>
<tr>
<td>Preoperative scores</td>
<td>4.289(7)</td>
<td>0.010*</td>
</tr>
<tr>
<td>Date at implantation</td>
<td>6.39(15)</td>
<td>0.006</td>
</tr>
<tr>
<td>Implantation or better ear</td>
<td>2.268(2)</td>
<td>0.073</td>
</tr>
<tr>
<td>Surgical approach</td>
<td>3.381(1)</td>
<td>0.031</td>
</tr>
<tr>
<td>Brand</td>
<td>3.29(5)</td>
<td>0.000*</td>
</tr>
<tr>
<td>Angle of insertion of the electrode array</td>
<td>2.46(1)</td>
<td>0.050</td>
</tr>
<tr>
<td>Percentage of active electrodes</td>
<td>2.32(7)</td>
<td>0.017</td>
</tr>
</tbody>
</table>


http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0048739

OUTCOMES AND TRENDS IN COCHLEAR IMPLANTATION

- Speech-reception-threshold in noise (50 % correct, in Finnish)
  - Normal-hearing -10 dB SNR
  - Cochlear implants -3…-4 dB SNR
  - ~15%/dB
- Benefits of preprocessing
- Cochlear implants in the elderly
- Bilateral implantation in the working-age population
- Significant residual hearing in the implanted ear
- Single-sided deafness
BINAURAL HEARING IN WORKING-AGE ADULTS

THE EFFECT OF BACKGROUND NOISE ON SPEECH UNDERSTANDING
SPEECH RECOGNITION AND SIGNAL-TO-NOISE RATIO

SIGNAL-TO-NOISE RATIO (DB SNR)

PSYCHOMETRIC FUNCTION AND SPEECH RECEPTION THRESHOLD IN NOISE (SRTN)

SPEECH RECEPTION THRESHOLD IN NOISE
(DB SNR FOR 50% CORRECT)
SNR AND SPEECH UNDERSTANDING


CLINICAL DATA
Hearing aids and cochlear implants increase first and foremost audibility
  – Deficiencies remain in dynamic, temporal, spectral and spatial resolution due to hearing loss

Alternatives to improve speech understanding
  – Moving closer to the sound source of interest
  – Moving to a less noisy environment
  – Connecting an assistive listening device (T, FM, digital wireless)
  – Improving the SNR of the incoming microphone signal
TECHNICAL SOLUTIONS TO IMPROVE SIGNAL-TO-NOISE RATIO

LISTENING ENVIRONMENTS

- All listening environments contain some amount of background noise
  - Spectral features
  - Temporal modulation
  - Location of sources

- One algorithm cannot effectively remove noise in all situations
DIRECTIONAL MICROPHONES

FIRST-ORDER SUBTRACTION MICROPHONE ARRAY

\[ \text{frontal direction} \xrightarrow{\text{d = microphone distance}} \] 

\[ \Sigma \]

\[ \text{digital delay} \]

\[ \tau \]

\[ \text{"null"} \]

output

omnidirectional

(\( \tau = 0 \mu s \))

figure-of-8

(\( \tau = 10 \mu s \))

hypercardioid

(\( \tau = 30 \mu s \))

cardioid

DILLON (2012)

IMPROVING SNR WITH DIRECTIONAL MICROPHONES

- Little reverberation, speaker in front and noise source behind at appr. 1 m distance
  - Benefit often 5 or up to 10 dB SNR
- More noise sources in the side and behind
  - Benefit between 2 – 5 dB SNR
- Normally-hearing listeners would also benefit from increased directivity
**DIRECTIONAL PATTERN, BEAMFORMING**

- **Static directivity**
  - The directivitional pattern is fixed,
  - The hearing device may switch between omnidirectional and directional mode *automatically*

- **Adaptive directivity**
  - The directional pattern changes its shape depending on the estimated location of the noise sources

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**DIRECTIONAL PATTERN, BEAMFORMING**

- **Static directivity**
  - The most beneficial in situations with multiple noise sources

- **Adaptive directivity**
  - The most beneficial in situations with (a) moving noise source(s)
ASSESSING SOUND PROCESSOR DIRECTIONALITY

DIRECTIONAL MICROPHONE TECHNOLOGY

- Integral part of modern hearing-aids and cochlear implant sound processors
- Immediate, well-documented improvement in SRTN
- Beneficial for all HA/CI users, including normal-hearing listeners
  - Subjective preference
  - Counseling
  - Binaural fitting/prescription
For the clinician, comparisons across brands are difficult.

<table>
<thead>
<tr>
<th>Directivity</th>
<th>Description</th>
<th>AB</th>
<th>Cochlear</th>
<th>Med-El</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dir 1</td>
<td>Omni or slightly forward facing</td>
<td>Processor microphone</td>
<td>Standard</td>
<td>Omni</td>
</tr>
<tr>
<td>Dir 2</td>
<td>(Slightly) forward facing</td>
<td>T-Mic</td>
<td>Fixed (Zoom)</td>
<td>Natural</td>
</tr>
<tr>
<td>Dir. 3</td>
<td>Adaptive directionality</td>
<td>UltraZoom</td>
<td>Adaptive (Beam)</td>
<td>Adaptive (always on)</td>
</tr>
</tbody>
</table>
TEST CONDITIONS AND PARTICIPANTS

<table>
<thead>
<tr>
<th>Test</th>
<th>Task</th>
<th>Speech</th>
<th>Noise</th>
<th>SD</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>Speech</td>
<td>Sono</td>
<td>SonoCI</td>
<td>Sono</td>
<td>Sono</td>
</tr>
</tbody>
</table>

Based on Directional Audio Coding (DirAC), Prof. V. Pulkki, Aalto University, Finland
Combining recorded real environments and anechoic speech
Perceptually accurate spatial auditory scenes
Playback setup independent of the recording setup

Koski, Sivonen, Pulkki (2013), Measuring speech intelligibility in noisy environments reproduced with parametric spatial audio, AES135, NY, USA.
Directional microphone: off on (forward focus)
reverberation 1 m distance
reverberation 2 m distance, SNR 0 dB

SUMMARY
SUMMARY

- A variety of hearing devices available
  - Aimed for different types of hearing loss
- Size and aesthetics continue to be important
- Breakthrough of wireless connectivity
- Auditory implants becoming "mainstream"

THANK YOU FOR YOUR ATTENTION!