The Magic of Direct Drive:

What is it that makes the sound quality of direct drive hearing aids so good?

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Speaker & Disclosures

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- Research interest: Quantification of listener perceived benefit

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Learning Objectives

• Identify and define the various approaches to direct drive of the middle ear system.
• Identify advantages and disadvantages of middle ear implants and acoustic hearing aids.
Why bother with Direct Drive?

• Air conduction hearing aids (ACHA) have limitations that adversely impact the listening experience
• Severely limited low frequency response when vented
• Limited audibility and headroom in the high frequencies due to receiver roll off and feedback
• Users of direct drive hearing devices report:
  – Very natural and superior sound quality,
  – Superior performance in challenging listening situations,
  – Superior ability to hear soft sounds
  – Superior comfort for loud sounds

“It doesn’t sound natural”

- Air Conduction devices cause distortion in the output signal
  - Harmonic Distortion
  - Intermodulation distortion
  - Comb Filtering
  - Spectral Ripples
  - Signal processing purposely distorts the signal to create audibility of high frequency speech cues

- Limited audible bandwidth and dynamic range

- At high levels, the TM creates distortions in the signal at the stapes due to anisotropic properties
Relative Audible Bandwidth – Mild to Mod SNHL

Normal Hearing

Conventional Open Hearing Aid

Conventional Occluded Hearing Aid

20Hz  1 kHz  6 kHz  10 kHz

20 kHz
Increased Bandwidth Enhances Sound Quality

- If tolerable, extended high frequency amplification is beneficial
- Rated ‘Naturalness’
  - Increases with bandwidth
- Rated Preference
  - Increases with bandwidth

Moore and Tan, 2003; Ricketts et al, 2008; Brennan et al, 2014
High Frequency Audibility Is Not Enough

• Merely amplifying a narrow region can sound harsh and tinny

• If balanced with additional lows, providing MORE highs doesn’t sound tinny, it sounds more natural\textsuperscript{5}

Moore & Tan, 2003
Direct Drive Advantage

- Direct coupling to the ossicular chain overcomes the impedance mismatch that limits energy transfer from the air into the ear

ISO 226 Equal-Loudness-Level Contour
However...

- Implantable devices have limited audible bandwidth due to gain limitations, transducer drive efficiency (effective mass) and power budget considerations

Exception: Earlens

- Consistently produces 100-10,000Hz audible bandwidth
- Maximum output increases smoothly from 500-10KHz, allowing for exceptional audibility even with steeply sloping loss

*data on file at Earlens
High Gain Margin **without Trade-offs**

With direct vibration instead of acoustic transmission:

- High gain margin with open fit
- Sound quality preserved without use of feedback cancellation at all in some cases
- Broad spectrum audibility without the annoyance of feedback

![Graph showing insertion gain vs. frequency](image)

- **Mean RIC**
- **Mean RIC ± σ**
- **Earlens**

Insertion Gain [dB] vs. Frequency [Hz]

Struck & Prusick 2017
Relative Audible Bandwidth – Mild to Mod SNHL

- Normal Hearing
- Conventional Open Hearing Aid
- Conventional Occluded Hearing Aid
- Middle Ear Implant
- Earlens Contact Hearing Solution

Frequency bands:
- 20Hz
- 100Hz
- 1 kHz
- 6 kHz
- 10 kHz
- 20 kHz
Treatment of SNHL

ACHA vs. Direct Drive Approaches
Approaches

• Fully Implantable
  – e.g., Esteem (Med El)

• Partially Implantable
  – e.g., Soundbridge (Med El)
  – e.g., Maxum (Ototronics)

• Non-implantable
  – e.g., Earlens

• Conventional Acoustic Hearing Aids
How it works - Conventional HA

Acoustic Signal → Microphone → A/D → DSP → D/A → Amplified Acoustic Signal → Tympanic Membrane → Cochlea
How it works – Partially Implantable

Acoustic Signal → Microphone

Digital Signal Processor

A/D → DSP → D/A

Soundbridge

Maxum

Skin

Cochlea

Tympanic Membrane

Floating Mass Transducer

Driv e Coil

Magnet

Cochlea
How it works – Fully Implantable

Acoustic Signal → Tympanic Membrane → Sensor → Digital Signal Processor → D/A → DSP → A/D → Cochlea
How it works – Contact Drive

Acoustic Signal → Microphone → A/D → DSP → D/A → Motor

Transmitter
Receive Ring

Tympanic Membrane

Cochlea
Earlens Contact Hearing Solution

Contents are confidential and proprietary
Research Question

- Relative to acoustic stimulation, what is different about the signal transmitted to the stapes footplate via direct drive?
Experiment
Hypotheses

• Direct Drive of the ossicular chain generates a signal at the stapes footplate that is free of distortions to the input signal
• The calibration gain/damping effect of the direct drive mechanism prevents comb filtering
Methods

• In donated cadaver temporal bones:

• Compared stapes footplate responses achieved via:
  – Acoustic stimulation
  – Direct drive with Earlens Contact Hearing Solution

• Measured acceleration of stapes footplate using laser doppler vibrometry

• Derived frequency & phase responses to high level chirp signal
Experimental Setup
Experimental setup – Block Diagram
Measurement Setup

Probe Mic

Energy Source

3 mm

4.3 mm
Stimulus

- 50ms Chirp
- 24.4 - 25,000Hz
- Repeated and averaged 160-180x
Signal Capture and Analysis

- Hardware: NI USB-4431 data-acquisition module (National Instruments, Austin, TX) with a maximum sampling rate of 96 KHz.
- Software: LabVIEW based synchronous-averaging measurement software (Gottlieb et al., 2016).
  - Sampling rate: 48KHz,
  - Fast Fourier Transform (FFT) length: 4096
  - Runs averaged/temporal bone: 10

- From the measurements of stapes velocity (VST) and ear canal pressure (PEC), the following quantities are calculated:
  - The baseline sound-driven stapes transfer function without the Tympanic Lens on the TM.
  - The equivalent pressure output of the direct drive system
Results

• At the stapes footplate,
  – Acoustic drive condition demonstrated:
    • Minor comb filtering
    • Spectral Ripples
    • Phase shift with frequency
  – Contact direct drive demonstrated:
    • Smooth, flat spectral response
    • Consistent phase relationship
• Spectral ripples minimized with direct drive
• Superior audible bandwidth to both low and high frequencies
Results

• Phase relationship preserved with direct drive
Conclusions

• Substantial differences in transmitted signal quality are observed between acoustic and direct drive modalities

• Direct drive exhibits:
  – Superior effective bandwidth to both low and high frequencies
  – Smooth spectral shape and no induced ripples
  – Preserved phase relationship between input and output signals
  – Minimal group delay
  – Superior stable gain margin
Next Steps

- Investigation of direct/amplified path interaction effects on stapes signal with open fittings
  - Output SNR
  - Comb filtering effects
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References