Cochlear Implants for Profound Hearing Loss – Signal Processing Considerations

Bernhard U. Seeber
Auditory Perception Lab
UC Berkeley
1966: “What is the likelihood that electrical stimulation of the auditory nerve can ever provide a uniquely useful means of communication?

The chances are small indeed, perhaps 5% or less as a laboratory exercise, certainly much smaller on a clinical scale."

Simmons, in an article on electrical stimulation

2004: More than 70,000 cochlear implants sold.
The auditory system
• Anatomy and function
• Link points for cochlear implants

Signal processing in cochlear implants
• Single channel CIs
• Feature extraction strategies: F0/F1/F2, MPEAK
• Waveform strategies: CA, CIS, SPEAK, ACE
• A current device

Future directions
• Stochastical nerve response
• Electro-acoustical stimulation
The Auditory System

Outer Ear  Middle Ear  Inner Ear

Drawing w. permission from “Promenade around the cochlea”, www.cochlea.org
The Auditory System – Cochlea

Round + Oval window

Helicotrema

Cochlear duct

Scala vestibuli

Nerve

Scala tympani

Pictures w. permission from “Promenade around the cochlea”, www.cochlea.org
The Auditory System – Organ of Corti

- Inner hair cells
- Outer hair cells
- Afferent pathway

Pictures w. permission from “Promenade around the cochlea”, www.cochlea.org
Candidacy for Cochlear Implantation

- **Profound hearing loss** >90 dB HL (now >70 dB HL)
  - Congenital disorders
  - Meningitis
  - Meniere’s disease
  - Drug treatment, e.g. Gentamycin
- **Sentence recognition** <30% (now <60%)
- **Auditory nerve** / spiral ganglion cells intact
- **Cochlea not ossified**
- **Influential factors**
  - Duration of deafness
  - Pre/post lingual onset of deafness
  - Age at implantation
Electrical Stimulation – Historical Introduction

- **Volta, ~1780**: Discovery of electrolytic cell, „boom within the head“ if 50V source is connected to electrodes in ear canal
- **Brenner, 1868**: studied effects of placement of electrodes, polarity, rate and intensity of stimulus
- **Wever and Gray, 1930**: Discovery that electrical responses in nerve of cat similar in frequency and amplitude to sound
- **50s, 60s**: Serious experiments on electrical stimulation, e.g. **Simmons (1966)**: in-depth studies, even multi-channel
- **Michaelson (1971), House (1976)**: first implantations of electrode with implantable receiver-stimulator - fail due to biocompatibility, but:
- **1972 to mid 80s**: 1000 House/3M single-electrode implants were implanted (FDA approval 1984!)
House/3M Single-Channel Cochlear Implant

The House/3M single-channel implant

House/3M device:

- Analog stimulation includes 16 kHz carrier
- Transcutaneous link through induction coil
- Small dynamic range on nerve lets output saturate/distort
- Majority of patients did not obtain open-set speech recognition
- Exceptional patients achieved 2-4% consonant recognition
Implant: here MED-EL Combi 40+ and Tempo+ Processor
The House/3M single-channel implant

House/3M device:
- Analog stimulation includes 16 kHz carrier
- Transcutaneous link through induction coil
- Small dynamic range on nerve lets output saturate/distort
- Majority of patients did not obtain open-set speech recognition
- Exceptional patients achieved 2-4% consonant recognition
Vienna/3M Single-Channel Cochlear Implant

Early 80s: Vienna/3M single-channel implant

Vienna/3M device:
- AGC: Better adaptation to small dynamic range on nerve
- EQ-filter: sinusoids 0.1 – 4 kHz adjusted to equal loudness
- Transcutaneous radio-frequency link, demodulated
- Some fine temporal information transmitted
- 15-85% word identification possible (Tyler, 1988)
Single-Channel Limitations

• Temporal coding in nerve fibers limited to <1 kHz
• Speech spectrum has fundamental frequency and formats:

/eh/ as in 'head'

Loizou, 1998
Frequency – to – Place Transformation in Cochlea

Mimick Processing of Cochlea:

Greenwood, 1961
Multi-Channel Cochlear Implants

- Cochlea: Frequency to place transformation
- Speech spectrum has fundamental frequency and formats

1984: First multi-channel implant (Nucleus)

### Multi-Channel Approaches

**Waveform Strategies**
- Compressed Analog
- Continuous Interleaved Sampling

**Feature-Extraction Strategies**
- F0/F2
- F0/F1/F2
- MPEAK
Compressed Analog Approach – Ineraid

- Ineraid device by Symbion, Inc., Utah (1980)
- UC San Francisco / Stortz device (1984)
- Advanced Bionics HiRes 90k Bionic Ear Implant (current)

Problem: Channel overlap – current spread in cochlea
Feature-Extraction Strategies: F0/F2

1984: First multi-channel CI uses F0/F2 strategy (Nucleus)
- 22 electrode array, only 1 electrode stimulated
- F0 coded in rate and formant F2 in place and amplitude
- Unvoiced intervals: quasi-random stimulation 100 pulses/s

- Clearly improved understanding of words
- Problems with consonants
Feature-Extraction Strategies: F0/F1/F2

1985: Advanced to F0/F1/F2 strategy (Nucleus)
- Improvement of vowel, but not consonant recognition
- Word scores from 30% (F0/F2) to 63% (Dowell et al., 1987)

Added for F1

- AGC
- 270 Hz LP
- 1-4 kHz BP
- Zero-Crossing
- Rectify + 35 Hz LP
- F0 rate
- A2
- A1
- 0.3-1 kHz BP
- Zero-Crossing
- Rectify + 35 Hz LP
- F1
- Pulse Generator
- 5 apical electrodes
- 15 basal electrodes
Feature-Extraction Strategies: MPEAK

~1990: MPEAK (multiple-peak) strategy (Nucleus)

Hf-Envelope

Voiced:
F1+F2 and E4+E7 @ F0

Unvoiced:
F2 and E1+E4+E7 @ ~250pps
**Waveform Strategies: Cont. Interleaved Sampling**

- 18000 pps CIS+, interpulse interval 56 μs overall / 667 μs channel
- All channels interleaved
- Deep electrode insertion up to 30mm
Waveform Strategies: Cont. Interleaved Sampling

300Hz

Envelope

Pulse-Mapping

12 electrodes

Clock

Time-Signal
Envelope

Amplitude

Time in sec

0 0.05 0.1 0.15 0.2 0.25

-3 -2 -1 0 1 2 3

x 10^{-3}

Med-El GmbH, Innsbruck
Waveform Strategies: Cont. Interleaved Sampling

1. Adjust Threshold +
2. Maximum Comfortable Level
3. Follows loudness growth function
4. All channels interleaved
5. Deep electrode insertion up to 30mm

Logarithmic Compression Function

Med-El GmbH, Innsbruck
Waveform Strategies: Cont. Interleaved Sampling

Electrode Design

**Monopolar:** Outside reference electrode
Larger current spread

**Bipolar:** Neighboring electrodes
More local current, more electrodes needed

Electrodes for specific applications: ossified cochlea, electro-acoustic stimulation…

- 56 µs overall / 367 µs channel
- All channels interleaved
- **Deep electrode insertion** up to 30mm

Med-El GmbH, Innsbruck
Waveform Strategies: Cont. Interleaved Sampling

- 18000 pps CIS+, interpulse interval 56 µs overall / 667 µs channel
- All channels **interleaved**
- Deep electrode insertion up to 30mm

Med-El GmbH, Innsbruck
Multi-Channel CIs – Auditory Simulation

Test speech reception with different pre-processing
Modulation of sinusoids or narrow-band noise

All channels, sinusoids: (12-ch CIS)
All channels, noise: (12-ch CIS)
**Waveform Strategies: SPEAK (n of m)**

**1995:** Nucleus CI24M implant – SPEAK:
- Blockwise channel picking strategy
- Adaptive stimulation rate 180-300 pps/ch
- Behind-the-ear device available
- Better performance than MPEAK (feature extraction)
Waveform Strategies: From SPEAK to ACE

2000: From SPEAK to ACE:
- Up to 2400 pps/ch and 14400 pps overall
- 8-16 ch used in clinical setting
- Subjective preference: 60% ACE, 23% SPEAK
- CUNY sentences in noise: 63% SPEAK, 71% ACE (Skinner, 2002)
Cochlear Implants – Current and Future

Manufacturers:

• Nucleus/Cochlear Corp., Lane Cove, Australia
• MedEl GmbH., Innsbruck, Austria
• Advanced Bionics/Clarion, Valencia, CA, USA:

HiRes 90K Implant:

• Higher stimulation rates: 83,000 pps
• Achieve natural, stochastical nerve response
• 16 channels, simultaneous, partially simultaneous and non-simultaneous operation: channel overlap
• Pulsatile or analog
• Monopolar, bipolar, or multi-polar
• Telemetry possibilities, MRI compatibility
Cochlear Implants – Future Outlook

• **Channel interaction – electrode design**
  - limit current spread: perimodiolar electrode placement
  - high-rate stimulation seems to allow better preservation of temporal information in nerve

• **Speech and music perception** – new algorithms
  - base on cochlea-preprocessing + compression
  - achieve natural, stochastical nerve response

• **Improve listening in noise**
  - Noise reduction algorithms
  - Directional microphones

• **Restoration of binaural abilities**
  - Improves speech perception especially in noise
  - Localization of sound sources
Cochlear Implants – Future Outlook

• **Electro-acoustic stimulation**
  • Preserve low-frequency hearing during surgery
  • Find CI-algorithms that add on to acoustic information

• **Reduce variability between subjects**
  • Find factors: channel interaction, age, time of implantation, training, …
  • Modeling, Prediction from psychophysics

• **Pre-surgery prediction**

• **Fitting parameters for the audiologist**
  • Efficient and accurate individual adjustments
  • Reduction of number of parameters
Summary

• **History** of electrical stimulation

• **Single-channel cochlear implants**
  • stimulate with analog, band-passed signal

• **Multi-channel cochlear implants**
  • Feature extraction strategies
    – F0/F2, F0/F1/F2, MPEAK
    – Features of speech coded
  • Waveform strategies:
    – CIS, SPEAK, ACE
    – Cochlear preprocessing mimicked by filterbank

• **Outlook**: Achieve natural response on nerve
Thank you!

Questions?