Multi-Latency Electrophysiological Measures of Loudness in Cochlear-Implant Hearing

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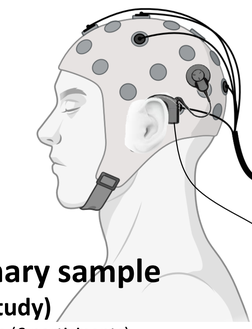
Introduction

Electrically-Evoked Compound Action Potentials (eCAPs) capture the synchronous response of the auditory nerve (AN) to electrical stimulation. They are sometimes used to fit cochlear-implant (CI) programming levels. However, evidence that they correlate with behavioural measures of loudness is mixed, and largely based on comparisons *between* listeners. Furthermore, measurements from the Panoramic eCAP Method (Garcia *et al.* 2021; 2024) show that eCAP amplitude can differ markedly between electrodes, within the same ear, despite being presented at similar (most-comfortable) loudness (MCL) and presentation rate.

In the absence of peripheral factors that explain across-electrode eCAP variation at the same loudness, we propose that there may be central gain varying idiosyncratically across both users *and* electrodes. To explore this question, we propose a framework for measuring multiple electrophysiological responses from different neural generators simultaneously, and exploring whether more-central responses predict better for perceived loudness. We therefore hypothesise that more-central measures will vary less across electrodes than more-peripheral ones when recorded at the same loudness.

Methods



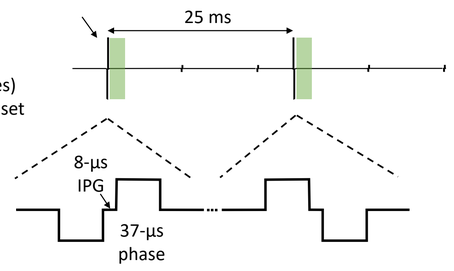
Preliminary sample
(ongoing study)
- 7 adult ears (6 participants)
- Cochlear® Nucleus devices

Direct electrical stimulation
(NIC 4.3 research software)

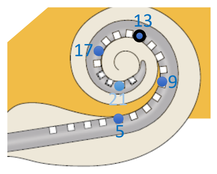
Intermittent pulse trains
- Total 4.7 – 5.8 minutes
  - 80-100 onsets/offsets
  - 11,200 -14,000 individual pulses

25-ms cycles (40 pulses per second, pps)
- Telemetry sequence after each pulse (1.8 ms, 20 kHz, 32 samples)
- Power-up pulses (0 current units) at 10 and 20 ms post pulse onset

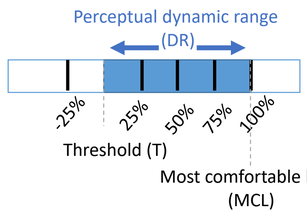
Electrical pulses
- Standard shape: symmetric, biphasic, rectangular
- Alternating polarity
- Monopolar mode



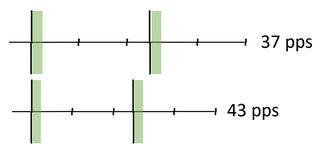
10 stimulation conditions to assess response variability with stimulation place and level (and response latency)



Multiple stimulating electrodes spanning the array (4 per ear) at loudness-balanced MCLs



Additional levels for one reference electrode (E13 or E17)



Additional rates at MCL for the reference electrode, (4.7 -minutes , continuous pulse trains) for apparent eASSR latency (group delay) estimation

Multi-latency response analysis

Onset and offset responses (~ 20-200 ms)
- Train onset/offset-locked epochs
- Epoch averaging
- Re-referencing to vertex (Iz)
- Interpolation around artefacts between -600 ms to 900 ms around pulse onsets
- Low-pass (200 Hz) and notch (40 Hz) filtering
- Automatic peak detection

eASSR (~ 40 ms) - electrically-evoked auditory steady-state response
- Train onset-locked epoch, 500 ms to 2,500 ms (exclude build-up in first 500 ms)
- Epoch averaging
- Re-referencing to vertex (Iz)
- Interpolation around artefacts between -600 ms to 900 ms around pulse onsets
- Amplitude measure in the spectral domain: modulus of 40-Hz (F0) Fast-Fourrier-Transform coefficient

eABR (<6 ms) - electrically-evoked auditory brainstem response
- Pulse onset-locked epochs, -10 ms to +30 ms
- Preprocessing and averaging
  - Baseline centering (-10 to 0 ms)
  - Rejection of outlier epochs
  - Epoch averaging with balanced polarity
  - Interpolation around artefacts
  - Band-pass filtering (300 - 3,000 Hz)
  - Re-referencing to vertex (Iz)
- Wave V peak (3-4.25 ms) and trough (4.25 – 5.25 ms) automatic detection, peak-to-trough amplitude measure

eCAP (<2 ms) - electrically-evoked compound action potential
- 960-1200-sweep eCAPs with standard recording electrode (recording electrode shift not shown here).
- Alternating polarity averaging + subtraction of artefact template (-25% DR condition)
- Standard N1 and P1 peak detection (visually confirmed) and N1-P1 amplitude measure
- Phase-locking value (PLV) computation as per He *et al.* 2024, averaged across 6x 26-point time window and 6 frequency bins. Notable residual artefact, so excluded.

Results: focus on eCAP, eABR, and eASSR amplitudes

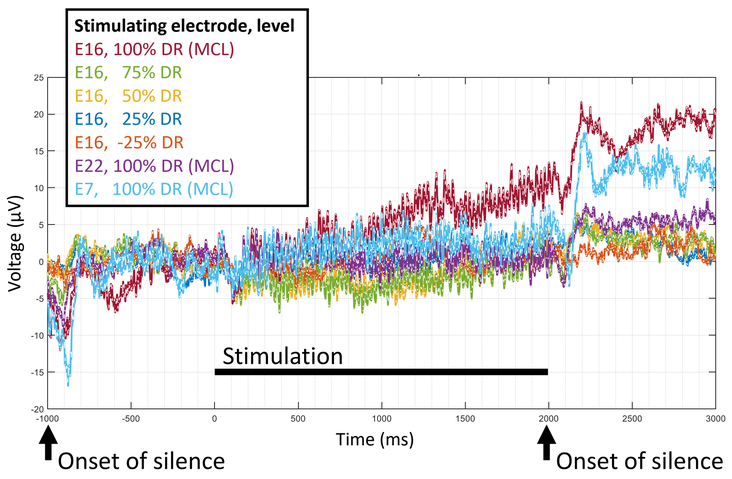


Figure 1: Train-onset-locked EEG epochs from pilot experiment (N = 1 ear)**.** Inion-vertex (Iz-Cz) montage, all pre-processing applied except notch. Note visible steady-state (stimulation segment) and offset responses (-1000 and 2000 ms).

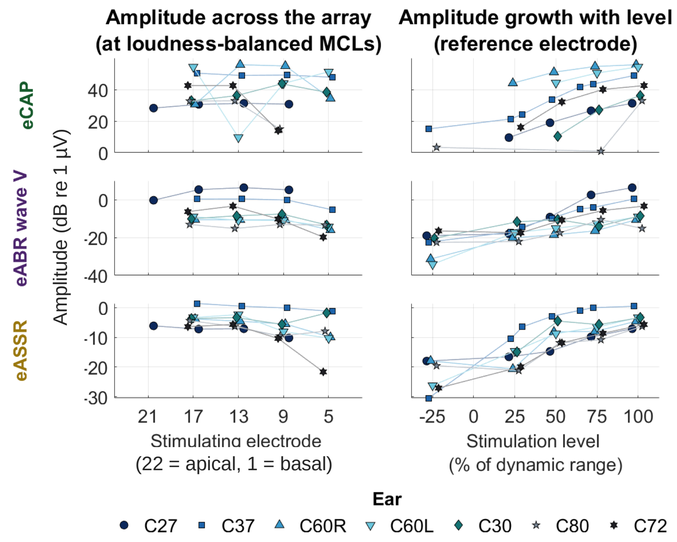


Figure 2: Stimulating electrode and level effects on multi-latency response amplitudes for N = 7 ears. Amplitude is measured at the inion (Iz, ref. Cz) for eABR and eASSR.

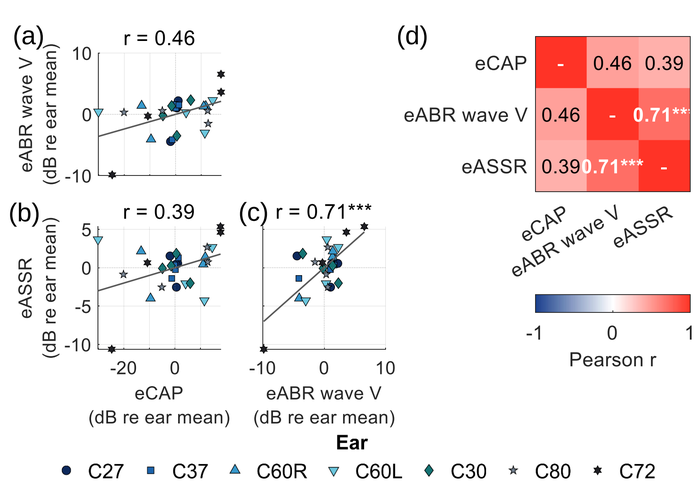


Figure 3: Co-variation of response amplitudes across stimulating electrodes. Amplitudes are expressed re the ear-level mean. (a) eABR versus eCAP. (b) eASSR versus eCAP. (c) eASSR versus eABR. (d) Heatmap of Pearson correlation coefficients (r). *p_{adj}<0.05, **p_{adj}<0.01, ***p_{adj}<0.001 (corrected for multiple comparisons with Holm-Bonferroni method)

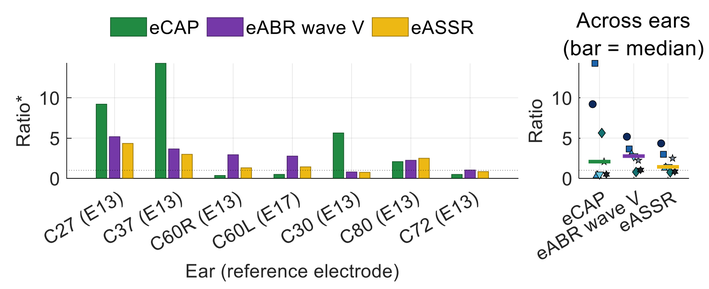


Figure 4: Ratio of level versus electrode effects.

***Ratio =** $\frac{X_{MCL,\,ref.electrode} - X_{50\%\,DR,\,ref.electrode}}{std(X_{MCL})_{across\ electrodes}}$,

with X the response amplitude

Discussion and conclusions

- All responses grow monotonically or almost with stimulation level.
- All responses also show more or less idiosyncratic variations between stimulating electrodes at equalized loudness (MCL).
- A good marker of perceptual dynamic range should show a large effect of input level relative to input electrode (large Ratio). Here, there is no clear winner between eCAP, eABR wave V, and eASSR, as no systematic pattern emerges beween participants for the Ratio.
- Co-variations of multi-latency response amplitudes across the electrode array at MCL suggest central auditory gain is relatively uniform along the tonotopy. Variations in amplitude along the array could result from residual errors or biases in loudness balancing (e.g. higher tolerance for apical stimulation).

Perspectives:
- More work is required to exploit other accessible measures (responses to pulse train onsets and offsets, eCAP phase-locking value) and may provide complementary information.
- More participants are to be tested to strengthen conclusions (study is ongoing).

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***References*:** Garcia *et al.* (2021): JARO 22(5) 567-589. DOI: 10.1007/s10162-021-00795-2;
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