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Electrically evoked auditory steady-state response and stimulation artifact estimation using Kalman Filtering

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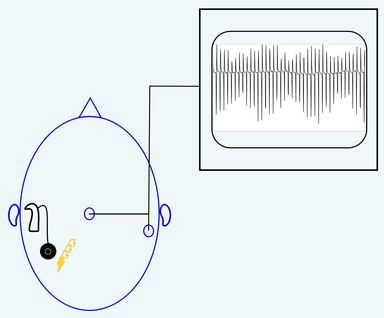
Introduction

Regular **Cochlear Implant (CI) fitting** is a crucial part of successful hearing restoration with Cochlear Implants. Unfortunately, the process is time consuming, difficult to perform and with variable outcomes, due to large variabilities across clinicians and CI recipients. **Electrically evoked auditory steady-state responses (EASSRs)** are neural auditory responses, resulting from neural phase-locking to continuous electrical stimuli. They can serve as objective measure to determine CI stimulation levels ([1, 2]) and are therefore a promising step towards fully **automated, objective fitting** of CIs.

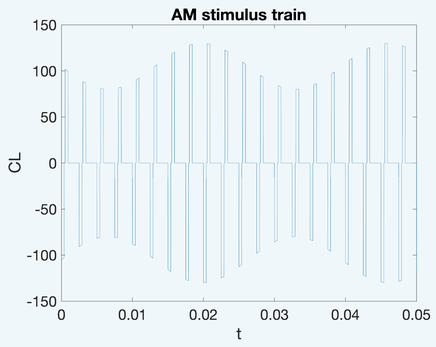


A major challenge when recording EASSRs are the **stimulation artifacts** of the implant, which make the neural response detection in **Electroencephalogram (EEG)** cumbersome. These artifacts are highly correlated with the EASSR and overlap the response in time as well as in the frequency domain. Existing **artifact removal** techniques such as Linear Interpolation (LI, [1, 2]), Template Subtraction (TS, [3]) and Independent Component Analysis (ICA, [4]) either fail to clearly separate artifact and response (ICA), require extra measurements (TS) or are unable to remove the artifact when it exceeds the inter-pulse interval (LI), e.g. for clinical stimulation settings of the CI. The goal of this work is hence to provide a method to **determine EASSRs in EEG measurements with clinical stimulation settings**. To do so, mathematical models for EASSR and stimulation artifact are fitted to the obtained EEG measurement. Through these models, the separation of neural response and artifact is possible and the existence of a neural response following the stimulation can objectively be determined.

Stimulation and Measurement setup

Stimulation

- Amplitude modulated pulse train
  - Symmetric biphasic, cathodic-first pulses
  - Phase width 25μs, IPG 8μs
  - **900pps**
  - E22 in **Monopolar mode**
  - Stimulation levels behaviorally determined per CI user
- 4 modulation frequencies to determine apparent latency
  - 34 - 43 Hz, equally spaced
- 300 epochs with 1.024s duration each



Example stimulus train to elicit EASSR

Recording

- 8-channel Biosemi ActiveTwo Hyper-Rate EEG
- Sample rate: 262.144kHz
- Reference electrode C_z

More details [5]

Participants information

- 10 adult CI users
- Average CI use: 4.3 years
- Cochlear Ltd. device

Model estimation using Kalman Filtering

- EASSR measurement modeled as linear dynamic system, represented in state-space form
- Observation (2), as linear combination of EASSR model and stimulation artifact model
  - EASSR model: Two sinusoids with modulation frequency of stimulus
  - Artifact model: Flexible length, depending on artifact duration
- Use of Kalman Filter to obtain optimal solution of time varying internal states $\mathbf{x_k}$

$$\mathbf{x_{k+1}} = \mathbf{F_k}\mathbf{x_k} + \mathbf{w_k} \quad (1)$$
$$\mathbf{z_k} = \mathbf{H_k}\mathbf{x_k} + v_k \quad (2)$$

$\mathbf{x_k}$ Unknown internal states
$\mathbf{F_k}$ State-transition model
$\mathbf{w_k}$ Process noise
z_k Observation (EEG measurement)
$\mathbf{H_k}$ Observation model
v_k Measurement noise

(3)

EASSR model

$$n[k] = A \cdot \cos(2\pi f_m k T_s - \phi) \quad (4)$$
$$= x_1 \cdot \cos(2\pi f_m k T_s) + x_2 \cdot \sin(2\pi f_m k T_s) \quad (5)$$

Artifact model

$$a[k] = x_1 \cdot a_1[k] + x_2 \cdot a_2[k] \cdots + x_N \cdot a_N[k] \quad (6)$$

Observation model Kalman Filter

$$z_k = \begin{bmatrix} cos(2\pi f_m k T_s) \\ sin(2\pi f_m k T_s) \\ a_1[k] \\ a_2[k] \\ \vdots \\ a_N[k] \\ 1 \end{bmatrix}^T \begin{bmatrix} x_{k,1} \\ x_{k,2} \\ x_{k,3} \\ x_{k,4} \\ \vdots \\ x_{k,N+2} \\ x_{k,N+3} \end{bmatrix} + v_k \quad (7)$$

Resulting amplitude and phase of EASSR

$$A_k = \sqrt{x_{1,k}^2 + x_{2,k}^2} \quad (8)$$
$$\phi_k = \arctan\frac{x_{2,k}}{x_{1,k}} \quad (9)$$

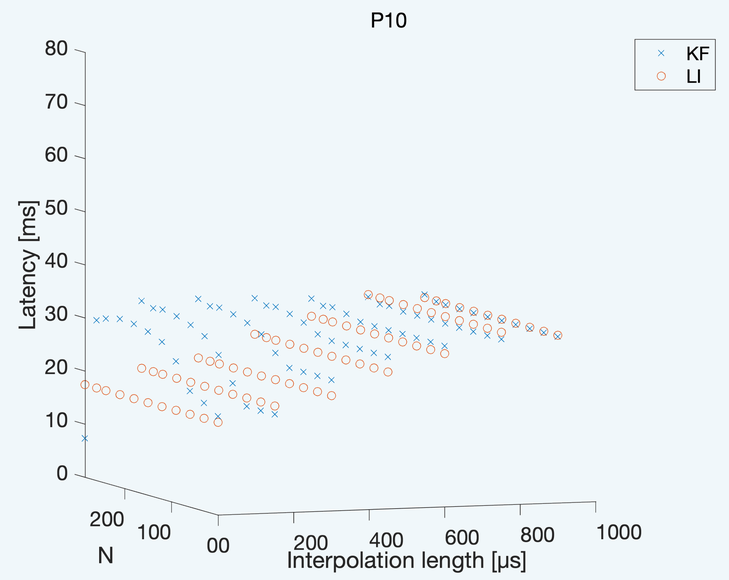
→ Determine apparent latency via group delay from EASSR phases over range of different modulation frequencies

Experiments and Results

Proof of viability of KF

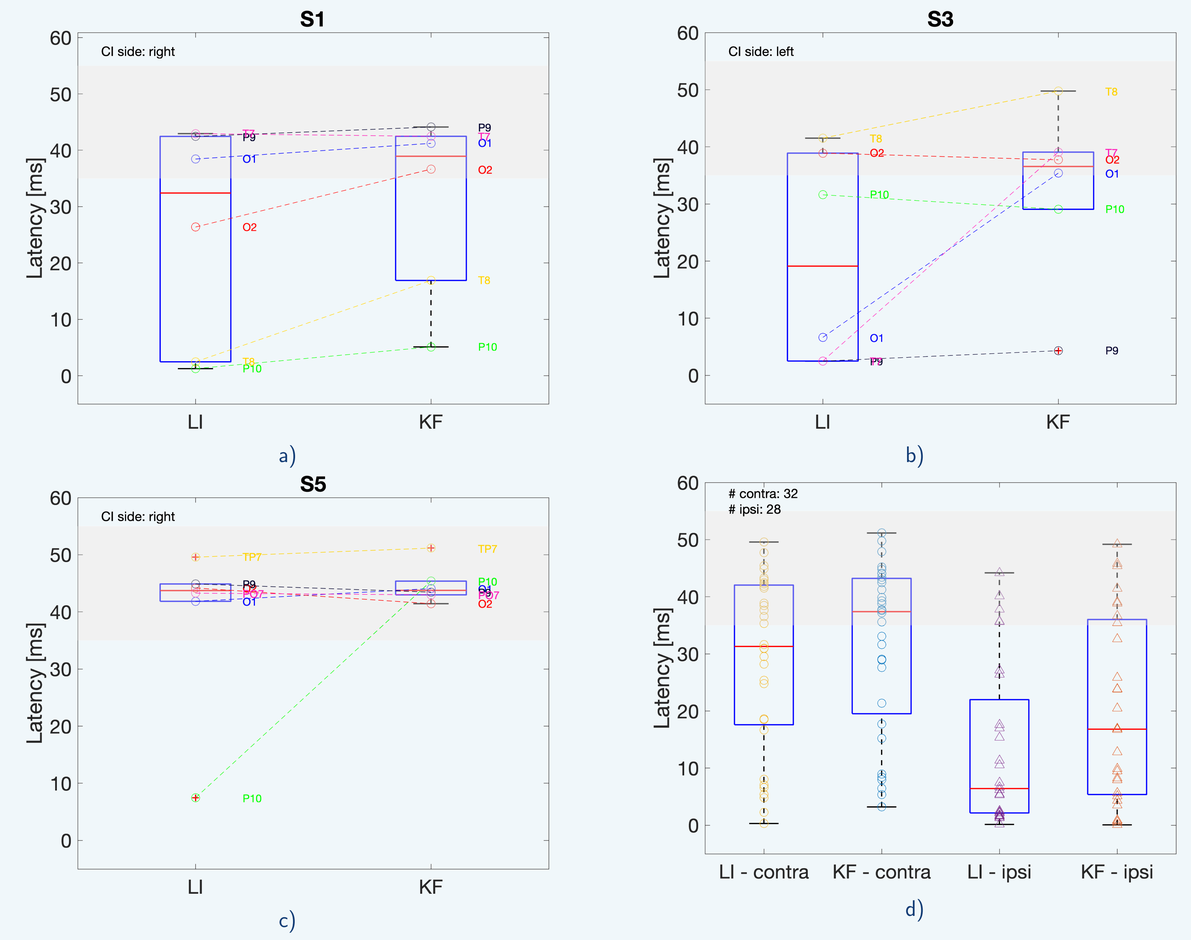
- Compare apparent latencies determined by LI and KF approach
- Vary interpolation length LI
- Vary number of used artifacts components N in KF

- ▶ Increasing interpolation length LI → more artifact being removed → latency converges towards expected values
- ▶ Increasing number artifact components in KF → better modeling of stimulation artifact → latency converges towards expected values
- ▶ Good latency values for KF, even without blanking, when N is sufficiently long
- ▶ Artifact model of KF is feasible to separate response and stimulation artifact → modeling of stimulation artifacts longer than inter-pulse interval should be possible → theoretical advantage over LI



Comparing apparent latencies, as determined by LI and KF for S3-P10. Varying interpolation length and number of artifact components N. Increasing latency values towards the expected range proves efficiency of artifact removal/ response detection.

Latency estimation for selected subjects



a) b) c) d)

Comparing latencies, determined by LI and KF. ■ = expected range. a) and b) Significant improvements in latencies for KF, especially in ipsilateral electrodes. c) Equal results for short artifacts d) Group comparison of all measured contralateral electrodes (32) and ipsilateral electrodes (28)

Conclusion

- ▶ Separation of response and artifact without additional artifact measurements (cfr. TS)
- ▶ Equal or better results of KF for short artifacts
- ▶ Advantage of KF over Linear Interpolation when artifact exceeds inter-pulse interval, e.g. clinical pulse rates and ipsilateral electrodes
- ▶ Potential response detection in ipsilateral electrodes with Kalman Filtering

Acknowledgements and References

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