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Evaluation of an artifact reduction strategy for electrically evoked auditory steady-state responses: Simulations and measurements

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HIGHLIGHTS

- It is feasible to record EASSRs with the described measurement setup including a biosignal amplifier, external sound card, Matlab software for stimulation and recording, and cochlear implants from the manufacturer MED-EL (Innsbruck, Austria).
- The analysis gave evidence that the artifact reduction method described by Hofmannand Wouters (2010) is successful in separating neural responses from artifacts induced by electrical stimulation.
- Neural responses at the stimulation rate can be clearly separated in the temporal domain from electrical stimulation artifact by averaging EEG epochs with alternating polarity stimulation, and linear interpolation of the residual artifact.
- Averaged responses within a stimulation period show identifiable EABR patterns.
- Amplitude growth functions and the latencies are in a physiological range.

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ABSTRACT

Background: Electrically evoked steady-state response (EASSR) recording is a measure of neuronal response strength after continuous electrical stimulation of the auditory system. In order to suppress the large electrical artifact generated by intracochlear electrical stimulation, a sophisticated artifact reduction processing strategy ("Hofmann procedure") has been proposed (Hofmann and Wouters, 2010). So far, EASSR recordings with artifact reduction procedures were reported only in cochlear implant (CI) users implanted with Cochlear devices (Macquarie, Australia).
New method: Here, we demonstrate the application of the Hofmann procedure in CI users implanted with MED-EL (Innsbruck, Austria) devices. To demonstrate potential limitations of the procedure, we calculated discrete time Fourier transformations (DTFT) of various pulse patterns which may be used for EASSR.
Results: EASSR recordings were obtained in three subjects and processed with the Hofmann procedure. Neural response amplitude growth functions and phase for modulated and unmodulated pulse trains at various stimulation rates could be assessed. Simulations of three different interpolation methods aimed to suppress the electrical artifact show that the interpolation of a sinusoidal signal in a temporal window between 0 and 1 ms has demonstrated negligible impact on the spectral amplitude of the signal with a superior performance of a spline interpolation.
Comparison with existing method: The Hofmann procedure, initially developed for recording EASSRs with CIs from the manufacturer Cochlear, was validated for MED-EL devices.
Conclusion: It is feasible to record EASSRs with the described measurement setup and CIs from the manufacturer MED-EL.

1. Introduction

1.1. Auditory steady-state response

The auditory steady-state response (ASSR) can be thought of as an electrophysiological response to an ongoing auditory stim-

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ulus. The ASSR enables automated analysis of evoked potentials by statistical evaluation to create an estimated audiogram. To generate ASSRs, continuous stimuli are presented leading to periodic neuronal responses. Amplitude-modulated (AM) pure tones may be used as stimuli. Neural generators, related to the depth and frequency of the AM, are triggered. AM frequencies of 20 Hz or less primarily trigger generators responsible for late cortical evoked potentials (primary auditory cortex and association areas). Response characteristics to 20–50 Hz modulation frequencies are similar to those found in the auditory midbrain, thalamus, and primary auditory cortex. With modulation rates above 50 Hz, responses are dominated by evoked potentials from the midbrain, including Jewett wave V. A continuous pure tone with AM frequency between 2 and 400 Hz evokes a steady-state response at the modulation frequency (Lins et al., 1996; Picton et al., 1987; Chambers et al., 1986; Kuwada et al., 1986; Rees et al., 1986), but it seems that the best range to assess hearing thresholds is between 75 and 110 Hz as at these rates the responses are not significantly affected by sleep (Lins et al., 1996). Evoked responses derived with continuously presented AM stimuli are analyzed in terms of both spectral energy and phase, and show, with sufficient response activity, a small amplitude at the frequency of modulation (Chambers et al., 1986; Kuwada et al., 1986; Picton et al., 1987). Statistical procedures determine whether a response is significant by comparing the response level at the particular modulation frequency to the noise level at adjacent frequencies or at the modulation frequency. The phase of the response can also be included in the statistical procedure.

In contrast to transient stimuli, such as clicks or tone pips used to assess frequency-specific responses, steady-state stimuli do not need masking noise (notched noise) to reduce the spread of energy into neighboring frequencies. ASSRs allow functional loss in different frequency regions of the cochlea to be assessed. Cost-efficient research platforms have been introduced using LabView or C/C++ (John and Picton, 2000; van Dun et al., 2008).

1.2. Electrically evoked auditory steady-state response (EASSR)

Electrically evoked auditory steady-state responses are continuous neural responses evoked by electrical stimulation by e.g. cochlear implants (CIs). CIs can provide functional hearing to people with severe or profound sensorineural hearing loss. EASSRs may enable automated threshold estimation as seen with ASSRs, provided that measurement is equivalently reliable. Therefore, EASSR recording is of potential interest in the assessment of CI function and automatic fitting for e.g. young children (Hofmann and Wouters, 2012).

The neuronal response from the auditory pathway is in the range of several 100 nV (Picton and Hillyard, 1974) whereas the remaining EEG signal is about 0.5–100 μV (Teplan, 2002). Therefore, in order to obtain a neuronal evoked response within an EEG recording, averaging of stimulation epochs is mandatory.

However, one of the greatest challenges in recording EASSRs is that the small neuronal response signal is compromised by the large electrical stimulation artifact. The electrical artifact is in the range of millivolts (here about 0.1 mV) which is about 1e5 times larger in amplitude compared to the neuronal response. Therefore, critical issues are the possible overdrive of the biosignal amplifier and how fast the amplifier is released from the overdrive in order to register the weak neuronal responses. The EEG recording is corrupted by this overdrive. In EASSR recordings which carry both the neuronal response and the artifact, a continuous recording is analyzed at the frequency of the stimulation. Therefore, sophisticated artifact reduction methods are required that suppress the artifact sufficiently.

One of the first EASSR recording setups for CI (manufacturer Digisonic MXM) was presented by Menard et al. (2004). The authors compared subjective thresholds in five subjects with those estimated using EASSR-based audiometry. The stimuli were pulse-width modulated pulse trains whereby the authors stated that inherent suppression of the artifact was present. They stated that "the non-linearity of response growth, as a function of (pulse) duration, provided the basis for teasing apart physiologic response and electrical artifact in the suprathreshold recorded responses" and found a good agreement between thresholds estimated with EASSRs and subjectively reported thresholds. Later, Menard (2008) (Figs. 53 and 54) showed a measurement of a CI stimulator in a tank using pulse-width modulated pulse trains (encoding the amplitude of the acoustic signal) and argued that the artifact amplitude does not depend on pulse width (but on stimulation amplitude).

Hofmann and Wouters (2010) presented an EASSR measurement setup which applied trains of low-rate unmodulated symmetric biphasic pulses (monopolar and bipolar mode, 40 pps) with a fixed phase width of 40 μs as stimuli. First results were published on recipients of Nucleus CIs (Cochlear CI24R (CS), CI24M, Macquarie, Australia). A customized software enabled the analysis of the EEG recordings. Artifact attenuation was achieved by the combination of three measures according to Hofmann and Wouters (2010): (1) alternating stimulation, (2) linear interpolation across the residual artifact transients, and (3) 100 Hz low-pass filtering. The linear interpolation was performed on a temporal window that spans over the artifact. Data points were interpolated between the two flanking points next to the window. The proposed EASSR artifact attenuation was validated by "recording on–off responses, determination of response latency across the measured pulse rates, and comparison of amplitude growth of stimulus artifact and response amplitude." The authors stated that "the electrophysiological thresholds determined from EASSR amplitude growth in the 40 Hz range correlate well with behaviorally determined threshold levels for pulse rates of 41 Hz."

Later, Hofmann and Wouters (2012) compared low rate (about 40 pps) and high rate pulse trains (900 pps, amplitude-modulated (AM) and pulse-width-modulated (PWM)) stimuli. High rate stimuli are applied in current coding strategies. They showed that behavioural thresholds correlated well with electrophysiologial thresholds for all three stimulus types (bipolar mode, low-rate, high-rate AM and PWM; $R = 0.96$). In this paper, we investigate whether it is in principle possible to record EASSRs with CIs from the manufacturer MED-EL with deeply inserted electrodes and different placing of external reference electrodes compared to other manufacturers. Therefore, this paper focuses on EASSR recordings with MED-EL implants and we evaluated the following:

- Whether or not modulated signals are useful for separation of artifact from neuronal response in EASSR recordings similar as for ASSR.
- The impact of alternative artifact interpolation strategies on the residual artifact amplitude.
- Whether or not the artifact reduction method proposed by Hofmann and Wouters (2010) is applicable for CIs from the manufacturer MED-EL (Innsbruck, Austria).
- Whether or not the neuronal response can be separated in the temporal domain after artifact reduction.

2. Methods

2.1. Stimuli and artifact reduction in EASSR recording

In the following, the limits in EASSR recordings are investigated by comparison of the spectral characteristics of simulated