Biomedical Signal Processing and Control 31 (2017) 127–138

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

journal homepage: www.elsevier.com/locate/bspc

Characterization of cochlear implant artifacts in electrically evoked auditory steady-state responses

Hanne Deprez[a,b,*], Robin Gransier[a], Michael Hofmann[a], Astrid van Wieringen[a], Jan Wouters[a], Marc Moonen[b]

[a] KU Leuven, Experimental ORL, Dept. Neurosciences, Herestraat 49, 3000 Leuven, Belgium
[b] KU Leuven, STADIUS, Dept. Electrical Engineering (ESAT), Kasteelpark Arenberg 10, 3000 Leuven, Belgium

A R T I C L E I N F O

Article history:
Received 18 March 2016
Received in revised form 23 June 2016
Accepted 26 July 2016

Keywords:
Cochlear implant (CI)
CI stimulation artifacts
Electrically evoked auditory steady-state responses (EASSR)
Linear interpolation
Monopolar mode stimulation

A B S T R A C T

Objective: Electrically evoked auditory steady-state responses (EASSRs) are neural potentials measured in the electroencephalogram (EEG) in response to periodic pulse trains presented, for example, through a cochlear implant (CI). EASSRs could potentially be used for objective CI fitting. However, EEG signals are contaminated with electrical CI artifacts. In this paper, we characterized the CI artifacts for monopolar mode stimulation and evaluated at which pulse rate, linear interpolation over the signal part contaminated with CI artifact is successful.
Methods: CI artifacts were characterized by means of their amplitude growth functions and duration.
Results: CI artifact durations were between 0.7 and 1.7 ms, at contralateral recording electrodes. At ipsilateral recording electrodes, CI artifact durations are range from 0.7 to larger than 2 ms.
Conclusion: At contralateral recording electrodes, the artifact was shorter than the interpulse interval across subjects for 500 pps, which was not always the case for 900 pps.
Significance: CI artifact-free EASSRs are crucial for reliable CI fitting and neuroscience research. The CI artifact has been characterized and linear interpolation allows to remove it at contralateral recording electrodes for stimulation at 500 pps.

1. Introduction

A cochlear implant (CI) is an electronic device that can restore hearing in severely hearing impaired subjects. A CI system consists of three main parts: an external speech processor, the implant, and an electrode array inserted in the cochlea. The speech processor converts the incoming sound to an electrical stimulation pattern, which is transmitted to the implant via a radio frequency (RF) link. The electrodes stimulate the auditory nerve with biphasic charge-balanced pulses [1]. Two stimulation modes are often used, depending on the return electrode: bipolar mode for stimulation between intra-cochlear electrodes and monopolar mode for stimulation between intra- and extra-cochlear electrode(s). In clinical settings, pulses are often delivered at high rates in monopolar mode, which requires less battery power than stimulation in bipolar mode. Furthermore, threshold levels vary less over stimulation electrodes with stimulation in monopolar compared to bipolar mode, resulting in easier CI fitting.

Since early implantation is proven crucial for speech and language development (e.g. [2]), an increasing number of severely hearing impaired infants receive a CI within the first year of life. Prior to CI activation, the threshold (T) and maximum comfortable (C) stimulation levels are determined based on behavioral (verbal) feedback. This is particularly challenging in infants and subjects who cannot give reliable behavioral feedback. In such cases, objective CI fitting based on electrophysiological measurements could be used.

Objective CI fitting based on electrophysiological measurements is currently under investigation. Transient responses to low-rate stimuli measured at the electrode-nerve interface (ECAPs) and at the brainstem level (EABRs) have been investigated as objective measures for threshold estimation. However, the

Abbreviations: AGF, amplitude growth function; C, maximum comfortable stimulation level; CI, cochlear implant; d, interpolation duration; D, STIM artifact duration; EABR, electrically evoked auditory brainstem response; (E)ASSRs, (electrically evoked) auditory steady-state responses; ECAP, electrically evoked compound action potential; I, intercept of the CI artifact AGF; ICA, independent component analysis; PCA, principal component analysis; POD, programming device; RF, radio frequency; RF artifact, RF communication link artifact; STIM artifact, electrical stimulation artifact; T, threshold stimulation level; θ, slope of the CI artifact AGF.

* Corresponding author at: KU Leuven, STADIUS, Dept. of Electrical Engineering (ESAT), Kasteelpark Arenberg 10 bus 2446, 3001 Leuven, Belgium.
E-mail address: hanne.deprez@esat.kuleuven.be (H. Deprez).

http://dx.doi.org/10.1016/j.bspc.2016.07.013

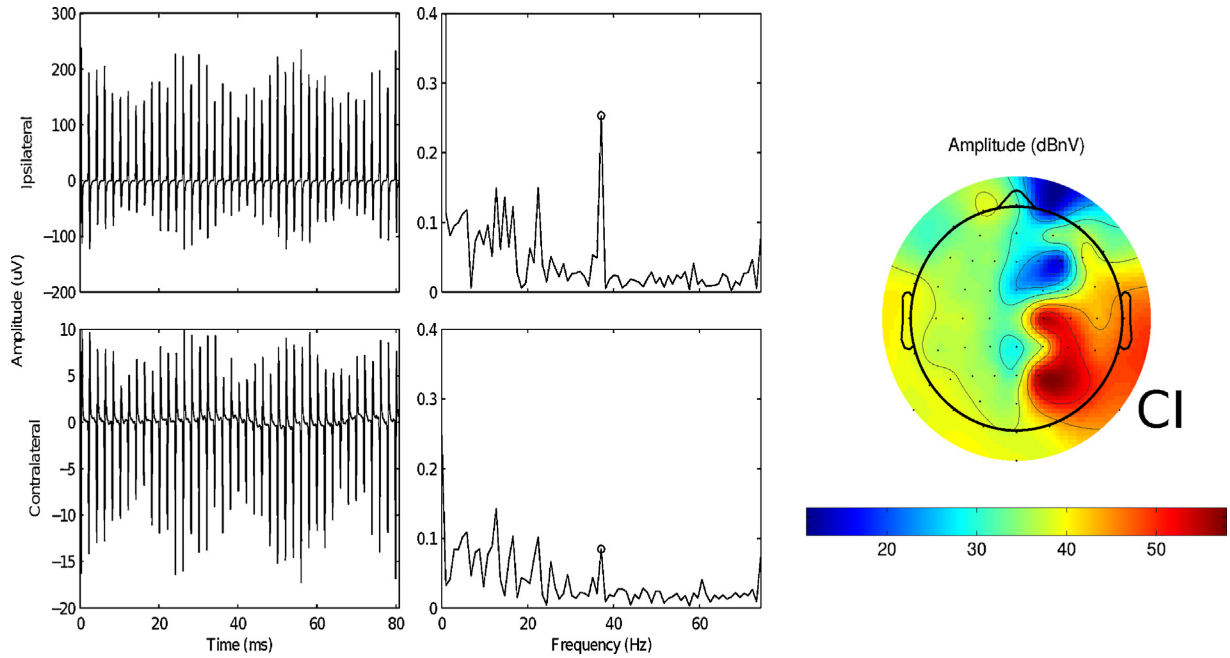

Fig. 1. Example of a CI artifact for S8, with a CI at the right side, measured with 37 Hz AM 900 pps pulse trains at a subthreshold stimulation amplitude. Left: time and frequency domain signals at recording electrodes TP_8 (ipsilateral) and TP_7 (contralateral), referenced to C_z. Right: spatial distribution of spectral power at the modulation frequency, referenced to C_z. The units of the topography plot are dBnV = 20 $\log_{10}$ nV, where 1 μV corresponds to 60 dBnV and 0.1 μV corresponds to 40 dBnV. No neural response is expected to be present, as subthreshold stimulation levels were used.

threshold values obtained with these methods that use low-rate stimuli are only moderately correlated with behavioral thresholds to high-rate pulse trains [3–6].

Objective CI fitting based on electrically evoked auditory steady-state responses (EASSRs) is also being researched. EASSRs are neural steady-state responses to electrical stimuli with a periodicity, such as a modulated pulse train. They are the electrical analogue of auditory steady-state responses (ASSRs), which are evoked acoustically, and can be recorded with head mounted scalp electrodes. ASSRs are the result of neural phase-locking to an auditory stimulus and the response is believed to result from different brain regions, depending on the repetition or modulation frequency of the stimulus (further called response frequency) [7,8]. (E)ASSRs can be detected in the frequency domain at the response frequency by means of a statistical test, e.g. an F-test or a Hotelling T^2 test [9,8].

EASSRs are corrupted by electrical stimulation artifacts, which can be caused by both the electrical stimulation pulses and the RF communication link between the external speech processor and the implant. The former can have a periodic component at the response frequency which may distort the neural response [12]. Fig. 1 shows the EEG signal recorded on two channels in time and frequency domain, for subthreshold stimulation. Both EEG signals have a component at the modulation frequency, which is caused by the electrical stimulation since no neural response is believed to be present. The spatial distribution of the spectral component at the modulation frequency is shown in the topography plot, indicating that the electrical stimulation artifact is present on all recording electrodes. The amount of distortion is highly subject-dependent, and is affected by the stimulation parameters and the recording electrode positions. Stimulation in monopolar mode results in larger CI artifacts than in bipolar mode [10,11].

It was recently demonstrated that EASSRs in response to high-rate stimuli result in electrophysiological thresholds that correlate well with behavioral thresholds for stimulation in bipolar mode [12]. The next step is to evaluate threshold estimation based on EASSRs for clinically used parameters, in particular for stimulation in monopolar mode.

Stimulation artifacts contaminating the EEG are a problem in various domains where electrical or magnetic stimulation is used, including deep brain stimulation, transcranial magnetic and current stimulation, somatosensory and cochlear implant stimulation.

Changes to the measurement set-up, such as maximum separation of stimulation and recording electrode leads, proper grounding of amplifier and subject, and careful skin preparation can help to reduce artifact amplitudes [10,13]. However, none of these measures can completely prevent the presence of excessive stimulation artifacts in the EEG. Optimal reference electrode placement has been investigated for transient responses to cochlear implant stimulation [14], but optimal selection of reference electrode has not yet been assessed for artifact removal in EASSR measurements. Stimulus design can also help to avoid stimulation artifacts: responses to alternating polarity pulses have been averaged in order to reduce the stimulation artifact [15,16], or short stimuli have been used such that the stimulation artifact has decayed before the response occurs [16]. Adjustments to the stimuli are not desirable in our case, because we aim to measure EASSRs to clinically used stimuli. Therefore, stimulation is restricted to cathodic-first, biphasic pulses, with fixed pulse width and interphase gap, presented at high rates and in monopolar mode.

Artifact elimination methods remove EEG channels or epochs that are contaminated with artifact. This is done for example with ocular artifacts in the EEG. However, all epochs are affected by stimulation artifacts in EASSR measurements because of the continuous stimulation. Furthermore, most recording channels are affected by stimulation artifact. Therefore, artifact elimination methods are not appropriate for artifact removal in EASSR measurements, since almost all data would be rejected.

Several methods have been proposed for stimulation artifact minimization. Single channel techniques include frequency [17], time–frequency [18–20], or adaptive filtering [21–26]. Template subtraction [27–30] has also been investigated. In the case of EASSR, frequency domain filtering is inappropriate because the stimulation artifact has a component at the response frequency. For adaptive filtering and template subtraction, assumptions