Biomedical Signal Processing and Control 21 (2015) 74–81

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

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

Reduction of stimulation coherent artifacts in electrically evoked auditory brainstem responses

Hongmei Hu*, Birger Kollmeier, Mathias Dietz

Medizinische Physik, Universität Oldenburg and Cluster of Excellence "Hearing4all", D-26111 Oldenburg, Germany

ARTICLE INFO

Article history:
Received 19 February 2015
Received in revised form 5 May 2015
Accepted 26 May 2015
Available online 14 June 2015

Keywords:
Electrically evoked auditory brainstem response
Cochlear implant
Artifacts
Facial nerve stimulation
Principle component analysis

ABSTRACT

The electrically evoked auditory brainstem response (eABR) is one of the clinically employed objective evaluation tools for cochlear implant (CI) subjects. It is commonly obtained by averaging responses, but because of the electric CI stimulation, some artifacts are phase locked to the stimulus and do not average out by increasing repetitions. A series of artifact reduction methods, such as general post-processing procedures for all subjects and individual post-processing procedures for some subjects, were developed in this study, aiming at reducing CI stimulation coherent artifacts. Seven bilateral CI subjects were recruited, and both monaural and binaural multi-channel eABRs were recorded in this study. The results show that the CI stimulation pulse artifacts can be efficiently removed by the general post-processing procedure, using alternating polarity stimuli combined with linear interpolation. Recordings obtained with non-alternating polarity show a strong exponential decay. Exponential fitting and subtraction worked reasonably well in this case. For eABR recordings contaminated with facial nerve stimulation (FNS) artifacts, principle component analysis was introduced to minimize the FNS artifacts for potential clinic application in the future.

1. Introduction

A cochlear implant (CI) is an electrical device that helps to restore hearing to the profoundly deaf. The main principle of CI is to directly stimulate the auditory nerve via electrodes surgically inserted into the inner ear. With the development of new speech processors and algorithms, CI users benefit more and more from CIs [1]. However, average perception performance of CI users is still far below that of normal hearing (NH) listeners, especially in the presence of background noise. Bilateral cochlear implants (BiCIs) have provided some success in improving spatial hearing abilities to bilateral CI users, but with large variability in performance. One reason for the variability is that there may be a mismatch in the place-of-stimulation arising from electrode arrays being inserted at different depths in each cochlea. One promising objective way to optimize the interaural electrode pairing (IEP) is using the binaural interaction component (BIC) by recording the monaural and binaural electrically evoked auditory brainstem responses (eABRs) [2,3].

EABR is an objective measurement similar to acoustically evoked brainstem response (ABR). It is generated by delivering electrical pulses via an intra-cochlear electrode array of the cochlear implant and stimulating subsequent physiological structures. The morphology of an eABR is similar to a traditional ABR, but there are differences as well [4–6]: latencies for eABR are shorter than traditional ABR because the electrical stimulus directly activating the neural pathway, therefore avoiding the effects of the time delay associated with the acoustic travel time from the earphone to the neural pathway of the inner ear. The wave eV latency is approximately 1.5–2 ms shorter for eABR at high stimulus level. Wave eI and often, wave eII, will not be observed due to the stimulation pulse artifact from the implant. Amplitudes are larger than traditional ABR amplitudes. The morphology and the electrical artifacts of eABR depend on several factors such as stimulation mode, stimulus polarity, phase duration, stimulus rate, stimulus level, and stimulating electrode. The larger the pulse energy, the larger is the electrical artifact. EABR as well as ABR are commonly obtained by averaging responses to increase signal-to-noise ratio (SNR), but because of the electric CI stimulation, some artifacts are synchronous with stimulation and cannot be removed by ensemble averaging. These phase locked stimulus artifacts are the important sources of distortion in eABR recordings [7–12], they overlap with the evoked response in both the time and frequency domains, such that conventional time windowing and frequency filtering are incapable of removing stimulus artifacts without distorting the evoked response. There are several studies on how to remove some of the CI related artifacts, such as the strong artifact during the pulse and

* Corresponding author. Tel.: +49(0)4417983900.
E-mail address: hongmei.hu@uni-oldenburg.de (H. Hu).

http://dx.doi.org/10.1016/j.bspc.2015.05.015
1746-8094/

Table 1
Information of the seven BiCI participants.

ID	Sex	Age	Implant type/duration of CI experience (years)			
			Left		Right	
S1	F	27	SONATA	4	CONCERTO	3
S5	F	59	SONATA	5	SONATA	4
S6	F	47	SONATA	4	SONATA	0.75
S7	F	57	PULSAR	9	PULSAR	13

the exponentially decaying post pulse artifact [7–11]. This paper therefore focuses on another special CI related electrical artifact observed in some CI subjects' eABR data caused by the facial nerve stimulation (FNS). Unintended facial nerve stimulation is one of the most frequent complications in CI surgery and postsurgical fitting. There are several possible reasons accounting for the FNS following CI, such as the close proximity of the facial nerve to the lateral wall of the cochlea [13,14], a low impedance pathway, high stimulation levels [15]. Various methods have been proposed to eliminate FNS, such as changing the programming strategy and/or stimulation mode, turning off some electrodes, reducing the comfort levels under FNS thresholds and a re-implantation with a new device [16].

In some eABR recordings of CI participants, it was found that the CI electrodes stimulated not only the auditory nerve, but also some unexpected nerves, such as the facial nerve [16–18]. Thus, these nerves also elicited an EEG response. In cases of muscle-stimulating nerves, the evoked potential is expected to be much stronger than the eABR signal itself. The facial nerve response in eABR is triggered by the stimulus and does not average out with more repetitions. Its latency sometimes is also temporally overlapping with the wave eV latency regime. To our knowledge, no method has been described in the literature to suppress such artifacts in CI eABRs. Independent component analysis (ICA) [19] has been widely used in EEG signal processing in various applications, such as in attenuating the eye movement or eye blink [20–24]. It can be used to some extent to separate the EEG signals into statistically maximally independent components [25,26]. However the manual selection of CI artifact components requires expert-choices and is time consuming. Considering that our long-term goal is clinical usage, a computationally efficient principle component analysis (PCA) [27] based FNS artifact reduction method is proposed in this study.

The paper is organized in the following way: Section 2 describes the eABR recording setup. Section 3 introduces the typical features of the recorded eABRs and the general offline post-processing procedures to remove the common CI stimulation artifacts and to enhance the SNRs of eABRs in all CI subjects. Section 4 introduces the post-processing procedures for those data sets contaminated with either the exponential decay and/or FNS artifacts. In addition to the existing eABR artifact reduction methods, a new method based on PCA is proposed to remove the FNS artifact co-existing in multi-channel eABRs. Finally the discussions and the conclusions are presented in Section 5.

2. Experiment

2.1. Subjects

Seven BiCIs users took part in a parallel IEP study [2] and four BiCIs' (S1, S5, S6, and S7) data were presented as examples in this paper, because they show a FNS artifact in their eABR. Table 1 shows some information of these four participants.

All participants were severe-to-profound postlingually deaf and were using bilateral MED-EL CIs. The subjects ranged in age from 27 to 78 years. All subjects had a minimum of 9 months bilateral hearing experience with their CIs before joining in this study. All of them used both CIs daily. All subjects except S1 have no residual hearing. The compliance limit of the implants was checked before the experiment. Subjects were evaluated with an interview and questionnaires before the experiment. All participants gave informed consent after a full explanation of the experimental protocol. The voluntary informed written consent was obtained with the approval of the Ethics Committee of Oldenburg University.

2.2. Equipment

The stimulation and EEG setup is schematized in Fig. 1(a), which is part of our self-developed IEP research platform [2,28].

Stimuli were generated with the research interface box (RIB II, manufactured at University of Innsbruck, Austria) under the control of an on-line stimulation computer with a National Instruments (NI) I/O card. The monaural or bilaterally synchronized electrical pulses were applied to an external induction coil coupled to the MED-EL cochlear implants (without external processor). Prior to the experiment, the stimuli were verified using two detector boxes (the MED-EL CI simulators) and an oscilloscope. A graphical user interface (GUI) was used to input subject's information (e.g. implant type and implant ID) and experiment parameters (e.g. test electrode, pulse parameters), to execute the basic hearing tests (e.g., loudness estimation and loudness balancing), and to control the electrical stimulation via the stimulation computer. The participants' responses during the psychophysical testing were obtained using a touch screen monitor connected to the stimulation computer (For more details please refer to [2]).

A self-developed EEG cap for CI subjects (manufactured by Easycap, Herrsching, Germany) was used. Fig. 1(b) shows the scalp channel locations and labels of the EEG cap. Fig. 1(c) is a photo of the cap and the stimulation coil. Two electrodes (22 and 26) that were classically located at one of the CI coil positions were left unconnected (marked in red in Fig. 1(b)). The participant can switch between the CI telemetry coils and his or her standard coils during the preparation or pause, which is most convenient for communication and comfortable. Moreover, a dislocation of the coils when putting on the cap can be avoided. The position on the central anterior–posterior line is equivalent to 10%-electrode system (e.g. 31 = Fpz, Ref = Cz, 49 = lz, etc.). Channel 49, 56, 57, 59, 61, and 62 were the selected channels of primary interest, as these are the channels which pick up most of the brainstem potentials and are most typically used ABR recording sites.

2.3. Stimuli

All stimuli were constant amplitude pulse trains presented at a rate of 19.9 pulses per second (pps) to a single electrode. The rate of pulsatile stimulation was lower than typical stimulation rates used in clinical CI processors but optimal for the assessment of eABR [3]. The stimulus was a train of charge-balanced biphasic pulses, with 50 or 60 μs phase duration, and 2.1 μs interphase gap presented repeatedly via monopolar stimulation mode. A phase duration of 60 μs was used only when the subject could not reach the MCL with 50 μs. The trigger had a 5 ms duration and was sent 25 ms before the CI stimulation pulse (−25 ms) to the EEG recording computer as is shown in Fig. 2.

Alternating polarity stimulation was introduced in previous publications [7–11] for electric artifact suppression, especially for the rejection of post pulse artifact. However, alternating polarity is not an option for some investigations, for instance, at the most peripheral stages the response is polarity dependent [10]. If the desired eABR investigation requires a specific polarity, other means of artifact reduction are required. In subject S5, we therefore tested a biphasic pulse including a non-alternating stimulation: a positive (anodic) first phase followed by a negative (catholic) second phase. For the parallel IEP study, the reference electrode was the