Medical Engineering and Physics 000 (2016) 1–9

Contents lists available at ScienceDirect

Medical Engineering and Physics

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

A novel method for extraction of neural response from single channel cochlear implant auditory evoked potentials

Daniel Sinkiewicz[a], Lendra Friesen[b], Behnaz Ghoraani[c,*]

[a] Department of Electrical Engineering, Rochester Institute of Technology, United States
[b] Department of Speech, Language, and Hearing Sciences, University of Connecticut, United States
[c] Department of Computer and Electrical Engineering, Florida Atlantic University, 777 Glades Road, Boca Raton, FL, United States

ARTICLE INFO

Article history:
Received 19 February 2016
Revised 22 November 2016
Accepted 27 November 2016
Available online xxx

Keywords:
Time–frequency analysis
Auditory evoked potentials
Artifact suppression
Electroencephalography
Cochlear implant

ABSTRACT

Cortical auditory evoked potentials (CAEP) are used to evaluate cochlear implant (CI) patient auditory pathways, but the CI device produces an electrical artifact, which obscures the relevant information in the neural response. Currently there are multiple methods, which attempt to recover the neural response from the contaminated CAEP, but there is no gold standard, which can quantitatively confirm the effectiveness of these methods. To address this crucial shortcoming, we develop a wavelet-based method to quantify the amount of artifact energy in the neural response. In addition, a novel technique for extracting the neural response from single channel CAEPs is proposed. The new method uses matching pursuit (MP) based feature extraction to represent the contaminated CAEP in a feature space, and support vector machines (SVM) to classify the components as normal hearing (NH) or artifact. The NH components are combined to recover the neural response without artifact energy, as verified using the evaluation tool. Although it needs some further evaluation, this approach is a promising method of electrical artifact removal from CAEPs.

1. Introduction

Cochlear implants (CIs) are devices designed to help individuals with severe-to-profound hearing loss understand speech. However, relatively little is known regarding the neural basis of speech understanding improvements using these devices. Cortical auditory evoked potentials (CAEPs) provide a means of objectively evaluating the response to the stimulation provided through a CI on the adult central auditory system [1,2]. The analysis of CI patient CAEPs might provide a means of ensuring that CI devices are programmed appropriately and the patient's auditory pathways are receiving an adequate stimulus.

The P1 (positive), N1 (negative), and P2 (positive) waves of the late CAEP occur with peak latencies of 50 ms, 100 ms and 200 ms, respectively [3,4]. These waveforms, often referred to as the N1–P2 response, provide an index of stimulus detection at the level of the auditory cortex [3,5]. When a CI processes sound and stimulates spiral ganglion neurons, the device also generates an electrical artifact. This is particularly problematic with longer duration stimuli, such as speech stimuli (i.e., more than 25 ms) where the artifact can obscure the neural response evoked with the stimulus. With shorter duration stimuli, such as a tone-burst or click, the neural response follows the artifact at more than 50 ms and so the two can be more easily differentiated based on timing. When using longer duration stimuli, it is therefore important to use methods of artifact reduction in order to evaluate the N1–P2 response of CI patients.

A few techniques have been developed in an attempt to reduce the electrical artifact from the N1–P2 response in CI patients. One method, named the subtraction method [6], alters the inter-stimulus interval (ISI) between recording sessions to take advantage of the neural refractory period. The N1 and P2 waveforms evoked using a long ISI have larger amplitude than those evoked with a shorter ISI. The CI N1–P2 response evoked with the short ISI stimulus is dominated by the electrical artifact and is subtracted from the CI N1–P2 response evoked using the large ISI. The result should yield a relatively artifact-free response. A second method, named the polynomial method [7], takes advantage of the artifact shape to fit a polynomial to the electrical artifact. For tone stimuli, a polynomial can be fitted to both the stimulus envelope and the CI N1–P2 response to produce a good approximation of the artifact, which can be removed from the signal. Independent component analysis (ICA), a blind source separation technique, has also been applied to this problem in an attempt to separate the

* Corresponding author.
E-mail address: bghoraani@fau.edu (B. Ghoraani).

http://dx.doi.org/10.1016/j.medengphy.2016.11.009
1350-4533/

artifact from the N1–P2 response. This method assumes the two signals are independent sources and tries to recover the original N1–P2 response from the observed CI N1–P2 response [8]. One of the main challenges when ICA approach is used that the process has to rely on multi-channel data, which requires the usage of expensive multi-channel acquisition systems. Not knowing the exact characteristics of the artifact (or of the response) in multiple channels makes it difficult to determine which of the components derived from ICA are truly related to the implant artifact. It also relied on full EEG cap systems, which may add some level of difficulty when are used for CI patients with behind-the-ear processors and magnetic links.

The objective of the present work is twofold. (1) We develop a novel artifact evaluation tool to assess the amount of electrical artifact present at the N1–P2 response in CI patients. While the existing techniques are assumed to remove the artifact, there is no gold standard against which to compare their results. In order to judge the effectiveness of current artifact removal techniques, the electrical artifact must be separately identifiable from the normal N1–P2 response behavior. The N1–P2 response is a non-stationary process, so the continuous wavelet transform (CWT), can be used to analyze the artifact and N1–P2 response in the time–frequency (TF) domain [9], where the differences in their spectral content will be apparent. The proposed evaluation tool calculates the correlation coefficient between the CI N1–P2 response and the stimulus envelope in the TF domain before and after artifact removal to determine if the neural response has been successfully recovered. This work has been briefly introduced in our previous conference proceeding [10] and we extended its evaluation in the present work. (2) We also propose a novel N1–P2 response extraction technique that combines matching pursuit (MP) signal decomposition and support vector machines (SVMs) to recover the N1–P2 complex from a single channel EEG with combined CI artifact and neural response. We anticipate that these tools will reduce the CI artifact from the N1–P2 response in an efficient manner.

2. Materials and methods

2.1. Dataset preparation

Data was collected over three separate test sessions, each with a different stimulus as explained below.

2.1.1. Stimuli

The stimuli consisted of a short tone (Stimulus 1) and a long tone (Stimulus 2). The short duration tone served as a basic stimulus to generate the N1–P2 response, while the longer duration tone served as a more complex stimulus, which captured the full effect of artifact overlapping the neural response. Individual pulses for Stimulus 1 and 2 consisted of bi-phasic pulses and a pulse rate of 1000 pulses-per-second. Stimulus 1 was a 200 ms pulse train consisting of biphasic pulses with 57 μs per phase and was presented to CI subjects. Stimulus 2 consisted of a 656 ms biphasic current pulse train with pulse duration of 20 μs per phase. Pulses were directed to a medial electrode on the CI electrode array (generally electrode 8). Two homogeneous blocks of the stimuli with inter-stimulus intervals (ISI) of 500 ms or 3000 ms were presented directly to the subjects' CI at their most comfortable level. There were 200 stimulus presentations (epochs) for Stimulus 1 and 350 occurrences for Stimulus 2 in one block.

The stimuli presented to all CI subjects were generated by a computer-controlled interface unit, Bionic Ear Data Collection System (BEDCS, version 1.17; advanced Bionics Corporation, 2007), which bypassed the speech processor and controlled the stimulation of the implant directly.

For NH subjects, two similar homogeneous blocks were presented using a 1000 Hz 656 ms duration stimulus binaurally via ER-3A insert earphones at a level of 65 dB SPL(A), measured with a Larson Davis sound level meter. Stimuli were presented binaurally to all subjects with normal hearing because this is the manner in which they normally hear. Stimulus 1 involves the 500 ms ISA condition, while Stimulus 2 involves the 3000 ms ISI condition.

2.1.2. Subjects

All subjects were right-handed, native English speakers with no history of neurological disorders. Individuals provided written consent (using forms approved by the Toronto Academic Health Sciences Network at Baycrest or Sunnybrook Health Science Centre Institute Institutional Review Board) before participating in the experiment. The following experiments were performed for three groups of subjects:

- Five CI subjects were presented with Stimulus 1. The subjects ranged in age from 54 to 77 years of age and had the Advanced Bionics HiRes 90K.
- Four CI subjects were presented with Stimulus 2. The subjects ranged in age from 19 to 39 years of age and had the Advanced Bionics HiRes 90k implanted in their left side.
- Seven normal hearing (NH) subjects, who ranged in age from 50 to 53 years old. All NH participants had auditory thresholds within normal hearing limits bilaterally ($<$ 20 dB HL) across the frequencies of 250–8000 Hz, and had no history of hearing difficulty.

2.1.3. Electrophysiologic recordings and pre-processing

In this study, we recorded the electroencephalographic activities using a 64-channel Electrocap system with tin electrodes based on the International 10/20 system. During the recordings, we monitored eye-blink activities by placing electrodes superior and inferior to the eyes and at the outer canthim and kept the interelectrode impedances <5 kOhms. All EEG channels were amplified with a gain of 500 using a Neuroscan Synamps 2/RT 64-channel EEG recording system, sampled with a sampling frequency of 1 kHz, and filtered between 0.15 and 100 Hz. The recording window for Stimulus 1 and 2 was 600 ms and 1100 ms, respectively, beginning 100 ms before stimulus onset. Channel Cz was selected as a reference during all recordings.

Before and after the experiments, eye movements and blinks were recorded as separate recordings and used to derive ocular source components [11] that were removed from each recording in Brain Electrical Source Analysis (BESA) [12]. In addition, trials with electrical activity exceeding 200 μV were excluded for NH listeners. Overall, about 5% of the trials were excluded from further analysis due to movement and muscle activity.

Finally, all recordings were epoched, linear detrended, and baseline corrected to the pre-stimulus period. Any artifacts were manually rejected from the epochs. For each patient, the average of all the epochs were obtained, which were then passed through a band-pass filter with 1–50 Hz before any further analysis.

The stimulus envelope for Stimulus 1 and Stimulus 2 along with a NH and CI CAEP example are shown in Fig. 1(A) and (B), respectively.

2.2. Proposed artifact evaluation tool

We developed a new method based on the continuous wavelet transform (CWT) to evaluate how much electrical artifact exist in CI CAEPs. This is the first method proposed to deal with such an important question. It can be used to analyze the N1–P2 responses from before and after the artifact removal and quantify how well a technique removes the electrical artifact from CI CAEPs.