Analysis of Cochlear Implant Artifact Removal Techniques Using the Continuous Wavelet Transform

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Abstract— **When patients with cochlear implants (CI) undergo cortical auditory evoked potential (CAEP) tests to evaluate their hearing, a large electrical artifact introduced by the CI obscures the relevant information in the signal. Several methods have been developed for the purpose of removing the CI artifact; however, there is no gold standard (i.e., patient's auditory response before the CI) to assess the effectiveness of these methods in terms of successful removal of artifact. To address this crucial shortcoming, we employ time-frequency (TF) signal representation (i.e., continuous wavelet transform (CWT)) to evaluate the effectiveness of two recent CI removal techniques, known as the subtraction and polynomial methods. Our results show that polynomial method consistently outperforms the subtraction method in the presence of tone stimulus. These results also indicate a possible CWT-based method for removing the CI artifact from a speech stimuli response, which the subtraction and polynomial methods cannot do.**

I. INTRODUCTION

Cochlear implant (CI) technology has allowed individuals suffering from hearing loss hear and comprehend speech. A means of objectively assessing speech perception in CI patients would help ensure the implants are programmed correctly and CI patients auditory pathways are developing properly. Cortical auditory evoked potentials (CAEPs) resulting from auditory stimuli passed through a CI have been successfully used to objectively assess both developing and mature auditory pathways [1], and may be useful in evaluating speech perception in CI patients [2]. Each CAEP consists of two peaks (i.e., the N1-P2 complex) that appear at 100ms and 200ms post-stimulus onset [3]. Their latencies and amplitudes reflect sound detection in the cortex [4]. When a CI processes a sound and stimulates the auditory nerve, it also generates an electrical artifact. When the sound stimuli last longer than a few hundred milliseconds, such as in speech, this artifact begins to overlap and obscure the N1-P2 complex. In order to use CAEPs to evaluate the auditory pathways of CI patients, this artifact must be removed [5].

Multiple techniques have been developed which attempt to remove the CI induced artifact from CAEPs with long stimuli. One well-known approach, proposed by Gilley et al. (2006), applies independent component analysis (ICA) to the recorded response to separate the neural response and artifact as independent sources. This technique is not ideal because ICA requires at least as many observation points as there are independent sources present, necessitating multi-channel data. In practice, CAEP evaluations are generally derived from artifact-free data from a single-channel [7], limiting the usefulness of a multi-channel approach. Recently, two methods have been developed which can remove the artifact from single-channel data: the subtraction method developed in Friesen and Picton [5] and the polynomial method developed in McLaughlin et al [7]. While both of these techniques have claimed to remove the artifact while leaving the N1-P2 complex intact, it is difficult to evaluate the resulting artifact-free responses without having the actual N1-P2 complex (without the CI artifact) for comparison. CAEP recordings vary between patients, and due to the circumstances requiring implants it is not possible to directly compare normal hearing (NH) and CI CAEPS for the same patient. Accurate results for the latency and amplitude of the N1-P2 complex are essential for evaluating CI patient hearing, so it important to determine whether these methods fully remove the artifact. The recorded CAEPs are also non-stationary processes, so frequency analysis will not provide any additional insight into the effectiveness of these methods. To identify the artifact in CAEP recordings it is important to know the time location of frequency content in the signal. Using the continuous wavelet transform (CWT), the recordings can be broken down into their time-frequency representations [8], where the artifact and neural response can be separately identified. The subtraction and polynomial methods can be evaluated in this domain by observing how much of the artifacts spectral energy is removed. Furthermore, if the artifact can be identified in the time-frequency domain it can be selectively removed, and the signal can be reconstructed in the time domain without the artifact. This method would be independent of the stimulus envelope, so it is possible the artifact can be removed from both tone and speech stimuli responses.

II. MATERIALS AND METHODS

A. Stimulus 1

1) Subjects: Subjects were 3 CI patients using the HiRes 90K Advanced Bionics, ranging in age from 54-77 years old. They were native English speakers and had no history of neurological disorders (same for all subjects in this paper).

2) Stimulus: The stimulus was a 200ms pulse train, with biphasic pulses having 57μs per phase, and was generated at 1000 Hz. Two homogeneous blocks containing 200 instances of the stimuli with ISIs of 500ms or 3000ms were presented directly to the subjects' CI at their most comfortable level (MCL), bypassing their speech processor, using the BEDCS research interface.

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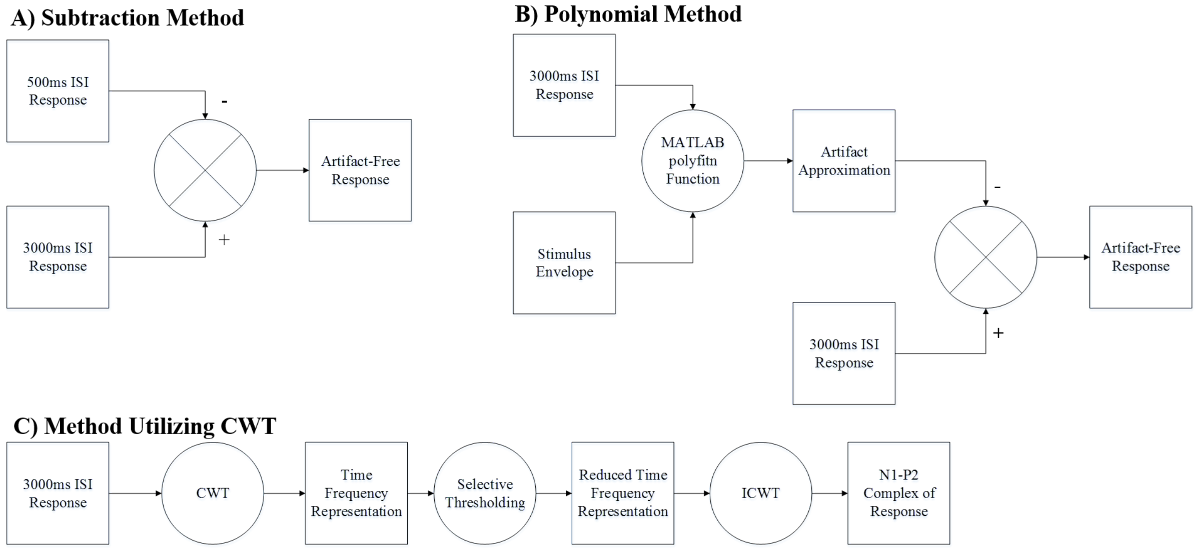

Fig. 1: Method Block Diagrams

3) Electrophysiological Testing: Recordings were made with a Neuroscan data collection system, using an electrode cap with 65 channels.

B. Stimulus 2

1) Subjects: Subjects were 4 NH individuals (23-31 years old) and 5 CI users (Nucleus-24 device) (37-57 years old). NH was defined as thresholds better than 25 dB HL across frequencies 250-8000 Hz (for all NH subjects in this paper).

2) Stimulus: The stimulus for all subjects was the syllable 'shi' (656 ms in duration), spoken by a female talker, taken from the 'Nonsense Syllable Test' [9], and presented in free field at 65 dB HL in 300 instances.

3) Electrophysiological Testing: Recordings were made with a Neuroscan data collection system, using an electrode cap with 32 channels.

C. Subtraction Method [5]

Pre-processing included ocular artifact rejection, filtering (1-25 Hz), and averaging for each tone stimulus CAEP response (same for all responses in this paper). The technique relies on varying the inter-stimulus intervals (ISI) of the stimuli to alter the magnitude of the N1-P2 complex. The N1-P2 complex increases in amplitude with increasing ISI up to a maximum amplitude at an ISI of 10s [10]. Friesen and Picton [5] assume the artifact amplitude is independent from ISI, so a CAEP with a short ISI can be subtracted from a CAEP with a long ISI to produce an artifact-free response. Therefore, as seen in Fig. 1A they remove the artifact by subtracting 500ms ISI response from the 3000ms ISI response.

D. Polynomial Method [7]

This method uses a bivariate polynomial to estimate and remove the artifact. CI signal processing strategies focus on using the temporal envelope of a stimulus to encode the stimulus pulse amplitudes [11], so it is reasonable to assume the artifact is related to the stimulus envelope. McLaughlin et al [7] determined a polynomial could be fitted to the CAEP response and its corresponding stimulus envelope to produce a good approximation of the artifact. This method is limited to tone stimuli though, because time-varying stimulus envelopes will allow the polynomial to fit and remove the neural response as well as the artifact. As shown in Fig. 1B, this method was applied to the 3000ms ISI responses for the tone stimulus. To preserve the neural response component, the polynomial was limited to the fourth order and the signal was randomized during the expected plateau of the stimulus envelope to preserve its statistical properties. After a polynomial approximation of the artifact was estimated, it was subtracted from the filtered response.

E. Wavelet Transform

CWT Introduction: The CWT is a process in which the desired signal is approximated by sums of scaled and shifted mother wavelet (MW) functions, which are centered on zero. The MW is shifted in position, b, along the signal to obtain coefficients representing the signal at that scale value. The MW is then dilated by a scaling factor a, and the coefficients are obtained in this fashion again [8]. This procedure is mathematically represented by the following equation:

$$T(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\psi^*(\frac{t-b}{a})\,\mathrm{d}t \tag{1}$$

The wavelet transforms scale factor allows the CWT to maintain resolution across the frequency spectrum [8]. In order to determine what scale (i.e. frequency) range to use, the recorded CAEPs were analyzed using the Fourier transform and found to have frequency content within 1Hz-50Hz. The scale values used in the CWT correspond to pseudo-frequency values based on the center frequency of

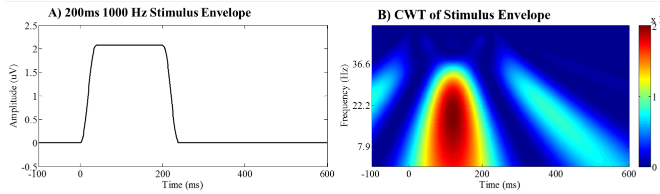

Fig. 2: 1000 Hz Tone Stimulus Envelope

the MW. In this analysis a range of 1Hz-50Hz was translated into scale values corresponding to the Coiflet4 MW.

Application of CWT on Stimulus and CAEP: In order to evaluate the two methods, the signals they used were subjected to the CWT. McLaughlin et al [7] determined the artifact is related to the stimulus envelope, so the 200ms tone stimulus envelope was transformed using the CWT. The resulting time-frequency representation can be seen in Fig. 2B. This representation shows the x-axis as time, the y-axis as frequency, and a color scale of the coefficient magnitudes. The time-frequency results are plotted in terms of energy, so they only contain positive values. For the subtraction method, the 500ms ISI response, 3000ms ISI response, and the artifact-free response were compared with the stimulus envelope in the time-frequency domain. For the polynomial method, the 3000ms ISI response, the artifact approximation, and the artifact-free response were compared with the stimulus envelope in the time-frequency domain.

III. RESULTS

A. Subtraction Results

The subtraction method produced clear N1-P2 complexes for tone stimuli in the time domain, which was expected given the results of Friesen and Picton [5]. The tone stimulus envelope can be seen in Fig. 2A, and the CWT analysis of the tone stimulus envelope can be seen in Fig. 2B. Fig. 3 shows the resulting CWT analysis of the subtraction technique on the recorded CAEP from one subject presented stimulus 1. Fig. 3A shows the 500ms ISI signal, the 3000ms ISI signal, and the difference signal in the time domain. Fig. 3B, Fig. 3C, and Fig. 3D show the CWT of the 3000ms ISI response, the 500ms ISI response, and the resulting artifact-free signal respectively. Fig. 3B and Fig. 3C clearly show spectral energy similar to the stimulus envelope in Fig. 2B, and its presence in the difference signal shown in Fig. 3D. Of the three subjects, the subtraction method completely removed the artifacts spectral energy from one. The other two subjects contained a remnant of the artifact, similar to that in Fig. 3B.

B. Polynomial Results

The polynomial method also produced clear N1-P2 complexes for both tone stimuli used, verifying the approach developed by McLoughlin et al [7]. The polynomial method was applied to the 3000ms ISI, because the larger ISI produces a larger N1-P2 amplitude. Fig 4 shows the results from the polynomial approach on the same response analyzed

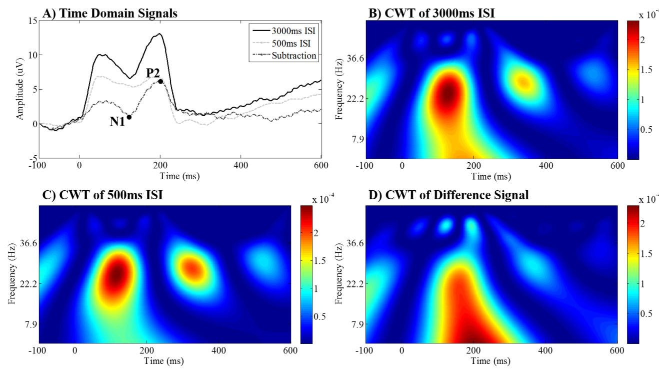

Fig. 3: Subtraction Method Results

in Fig. 3. Fig. 4A shows the three signals in the time domain. Fig. 4B, Fig. 4C, and Fig. 4D show the CWT of the 3000ms ISI signal, the approximated artifact, and the resulting artifact-free signal respectively. The artifact-free signal shown in Fig. 4D does not contain the remnant artifact energy displayed in the subtraction results shown in Fig. 3D. The polynomial method removes the majority of the artifacts spectral energy for all three subjects.

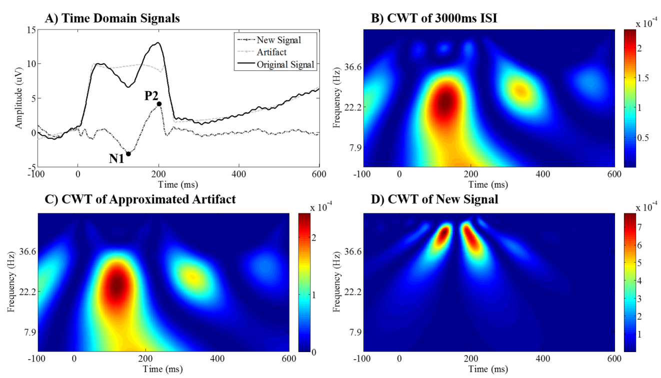

Fig. 4: Polynomial Method Results

C. Method Comparison

In order to compare the two methods, the time locations of the recovered N1 and P2 peaks and the amplitude between them were compiled in Table 1 for all three subjects. These results show the two methods had good agreement for the time locations of the peaks, but the amplitude difference values did not match well.

Table 1: Time Location and N1-P2 Amplitude Comparison

	Subtraction			Polynomial		
Patient	N1 Time (ms)	P2 Time (ms)	N1-P2 Amp. (µV)	N1 Time (ms)	P2 Time (ms)	N1-P2 Amp. (µV)
1	0.124	0.200	6.286	0.124	0.198	6.751
2	0.128	0.203	2.912	0.129	0.203	3.359
3	0.126	0.235	4.659	0.126	0.202	2.417
Mean	0.126	0.213	4.619	0.126	0.201	4.176
Std Dev	0.002	0.016	1.378	0.002	0.002	1.861

D. Continuous Wavelet Transform

The CWT analysis was extended to investigate the responses generated using speech stimulus 2, which contains a time-varying stimulus envelope and the subtraction and polynomial methods cannot be used to remove the CI artifact. The CWT of a CI subject can be seen in Fig. 5, while the CWT of an NH subject can be seen in Fig. 6. When comparing the two figures, the artifact and neural response are clearly identifiable in the CI results of Fig. 5. These results suggest the low frequency content of the artifact can be removed from the signal, leaving only the high frequency neural response components behind. By selectively applying a threshold to the neural response, as outlined in Fig. 1C, the artifact can be removed from the system.

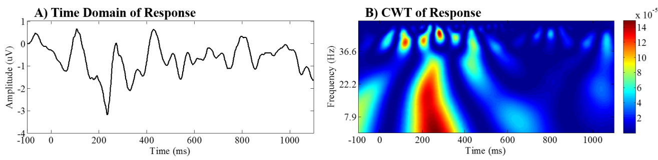

Fig. 5: CWT of CI response to 'shi' stimulus

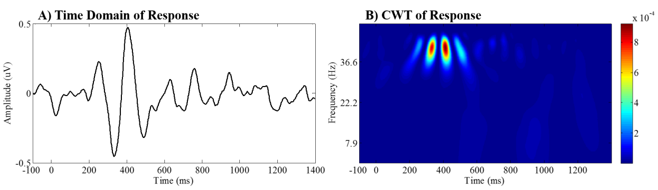

Fig. 6: CWT of NH response to 'shi' stimulus

IV. CONCLUSION

Utilizing time-frequency analysis to evaluate the subtraction and single-channel techniques has provided great insight into their ability to remove the CI artifact. CWT analysis has shown the artifact is caused by the stimulus envelope, and it is clearly visible in the time-frequency domain. While the subtraction technique appears to attenuate the artifact well in the time domain, the time-frequency domain shows spectral energy from the artifact often remains in the signal. The polynomial method also appeared to attenuate the artifact well in the time domain, which time-frequency analysis confirmed. Both the time location and amplitude of the N1-P2 complex are important in evaluating a subjects auditory perception, and remnant energy from the artifact can influence the amplitude of this complex after artifact removal. While the two methods showed agreement on the time locations of the N1-P2 peaks, both methods had different N1-P2 amplitude values (see Table 1). This difference is likely caused by the remnant artifact energy affecting the amplitude of the subtraction method results. The remnant energy can either be positive or negative, depending on which ISI had a larger artifact amplitude, which explains why the N1-P2 amplitude varied above and below the polynomial results.

The CWT analysis was also performed on CAEPs obtained by presenting the speech stimulus to the subjects. These results also show both the neural response and the artifact in the time-frequency domain. The time-frequency results can likely be used to selectively extract the relevant information or remove the artifacts spectral energy. This process would be independent of the stimulus envelope, so it would be able to remove the artifact for both tone and speech stimuli. The subtraction technique can remove the artifacts spectral energy, but its results are inconsistent. The polynomial method can successfully remove the artifact from tone stimuli responses, outperforming the subtraction results, but it cannot be applied to a response with a time-varying stimulus envelope. CWT analysis is effective in evaluating the removal of the CI artifact, and can possibly be used to extract the desired neural response peaks from responses to both tone and speech stimuli. In a future study, we are going to perform a comprehensive evaluation of the effectiveness of the proposed CWT technique for successful separation of the CI artifact from the CAEPs.

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