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A novel method for removal of deep brain stimulation artifact from electroencephalography

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HIGHLIGHTS

- DBS causes artifacts in EEG that preclude meaningful brain activity from being quantified.
- We modeled the DBS stimulation artifact as a series of narrow band components.
- We illustrated a technique for removing the stimulation artifact from EEG using matched filters.
- The technique was validated using synthetic DBS artifacts superimposed on EEG data.
- The technique successfully removed DBS artifacts for typical stimulation and recording setups.

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ABSTRACT

Background: Deep brain stimulation (DBS) has treatment efficacy in neurological and psychiatric disorders such as Parkinson's disease and major depression. Electroencephalography (EEG) is a versatile neurophysiological tool that can be used to better understand DBS treatment mechanisms. DBS causes artifacts in EEG recordings that preclude meaningful neurophysiological activity from being quantified during stimulation.

New method: In this study, we modeled the DBS stimulation artifact and illustrated a technique for removing the artifact using matched filters. The approach was validated using a synthetically generated DBS artifact superimposed on EEG data. Mean squared error (MSE) between the recovered signal and the artifact-free signal was used to quantify the effectiveness of the approach.

Results: The DBS artifact was characterized by a series of narrow band components at the harmonic frequencies of DBS stimulation. The filtering approach successfully removed the DBS artifact with MSE value being less than 2% of base signal power for the typical stimulation and recording setups. General guidelines on how to setup DBS EEG studies and configure the subsequent artifact removal process are described.

Comparison with previous method: To avoid stimulus artifacts, a number of EEG studies with DBS subjects have resorted to turning the stimulator off during recording, while other studies have used low pass filters to remove artifacts and look at frequencies well below 50 Hz.

Conclusions: This study establishes a method through which DBS artifact in EEG recordings can be reliably eliminated, thereby preserving a meaningful neurophysiological signal through which to better understand DBS treatment mechanisms.

1. Introduction

Deep brain stimulation (DBS) is becoming an effective treatment option for medication resistant neurological and psychiatric disorders. It is an approved treatment for late stage Parkinson's disease (Deuschl et al., 2006) and has shown therapeutic efficacy for treatment resistant depression (Holtzheimer et al., 2012; Kennedy et al.,

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2011). While clinical studies have established the efficacy of DBS, its treatment mechanisms are not yet understood. Electroencephalography (EEG) is a versatile neurophysiological tool that can be used to better understand DBS treatment mechanisms. However, DBS stimulation creates large amplitude artifact in the recorded EEG. To avoid this artifact, some clinical studies have resorted to turning the stimulator off during recording (Broadway et al., 2012; Kuhn et al., 2008), which is an approach that cannot assess the direct neurophysiological effects of DBS.

For removing DBS artifacts from EEG signals recorded with the DBS stimulator ON, several studies have applied filters online or offline with a low pass cutoff below the frequency of stimulation. For example, in one study, EEG data was recorded from subjects with their DBS stimulators set at frequencies ranging from 100 Hz to 185 Hz. To remove the artifacts, a 0.5–100 Hz bandpass filter was applied online during recording and a 50 Hz low pass filter was applied offline (Cavanagh et al., 2011). In another study, EEG data was recorded with DBS stimulators set at 130 Hz, 160 Hz or 185 Hz. No online bandpass filter was described, but a 50 Hz low pass filter was applied offline (Swann et al., 2011). In both cases, the assumption was that the artifact components generated by the DBS was entirely located in the high frequency range above the low pass filter cut off. As will be discussed in this paper, this assumption does not hold for all DBS stimulation setup and signal acquisition parameters. In fact, some DBS studies have reported artifact components in the recorded EEG below the frequency of stimulation, which is likely due to aliasing (Allen et al., 2010; Jech et al., 2006). Aliasing can occur if an appropriate low pass filter is not applied prior to data acquisition (Oppenheim and Schafer, 1999). Assuming that these studies did apply a low pass filter before sampling, the results suggest that the filters were not sufficient to remove artifact components prior to sampling.

Online low pass filters provided by many EEG systems are not configured to remove artifacts with narrow band components several times in amplitude higher than the background EEG. This is the challenge when dealing with EEG recordings with active DBS stimulation. Therefore, even if low pass filtering is adequate for examining neuronal activity in the theta or beta frequency range of previous studies, a more generalized artifact rejection approach would be necessary, especially for studies that are interested in brain oscillations up to 80 Hz or more. Successful attempts to extract DBS artifiacts have been done in magnetoencephalography studies looking at the effect of active DBS stimulation in Parkinson's patients (Airaksinen et al., 2011; Park et al., 2009).

In this study, we aimed to fully characterize the DBS stimulation artifact and develop a better method to remove it while preserving the underlying neurophysiological signal. Since DBS stimulation is periodic with a set frequency, the artifact waveform can be well approximated by a set of sinusoidal components located at predicted frequencies (Oppenheim and Schafer, 1999). Moreover, by knowing the signal acquisition parameters used in a study, the frequency of aliased components for the artifact can also be predicted. With our understanding of the DBS artifact waveform, we propose using the method of the matched filter to remove the narrow band components, which would not affect the underlying base signal that spans a broad frequency range. To evaluate the filtering approach, synthetic stimulator ON data with a known base signal is used. This can be done by adding a simulated DBS artifact to an existing EEG recording. After filtering the synthetic ON data, the recovered signal can then be compared with the original base signal to quantify the difference. To establish the general utility of the approach, simulation tests were run with DBS artifacts simulated in two different ways: (1) synthetically reconstructing the DBS artifact using a series of additive sinusoidal components at frequencies observed experimentally; (2) using the actual mathematical equation which describes the DBS pulse generated by the stimulator and filtering this signal. The precise methodology will be described later. These simulated artifacts were added to real EEG signals obtained from both a resting condition as well as a task condition to form the base signals used to evaluate our artifact removal algorithm.

2. Materials and methods

2.1. DBS artifact characterization

Given that DBS treatment involves repetitive stimulation, the artifact signal can be well approximated by a set of sinusoidal components. The frequencies of the sinusoidal components or natural harmonics (f_{harmonic}) are integer multiples of the stimulation frequency (f_{stim}) (see Eq. (1)). For example, if the stimulation is at 130 Hz, then sinusoidal components would be expected at 130 Hz, 260 Hz, 390 Hz, etc. (see Fig. 1).

$$f_{\text{harmonic}} = nf_{\text{stim}}, \quad n = 1, 2, 3, \ldots \tag{1}$$

In addition to the natural harmonics, frequencies of possible aliased artifacts in an EEG recording can be determined when given the sampling frequency (F_s). Frequencies of the aliased artifacts can be calculated by first taking integer multiples of the sampling frequency (F_s), then adding or subtracting integer multiples of the stimulation frequency (f_{stim}), and finally checking which of the resulting frequencies fall within the captured signal bandwidth from 0 to $F_s/2$ (see Eq. (2)). For example, if the stimulation frequency is set at 130 Hz and the data is sampled at 1000 Hz, then aliased components would be expected at 480, 350, 220, 90, 40, 170, 300, and 430, which are calculated from the first integer multiple of F_s. Likewise, aliased components at 440, 310, 180, 50, 80, 210, 340,

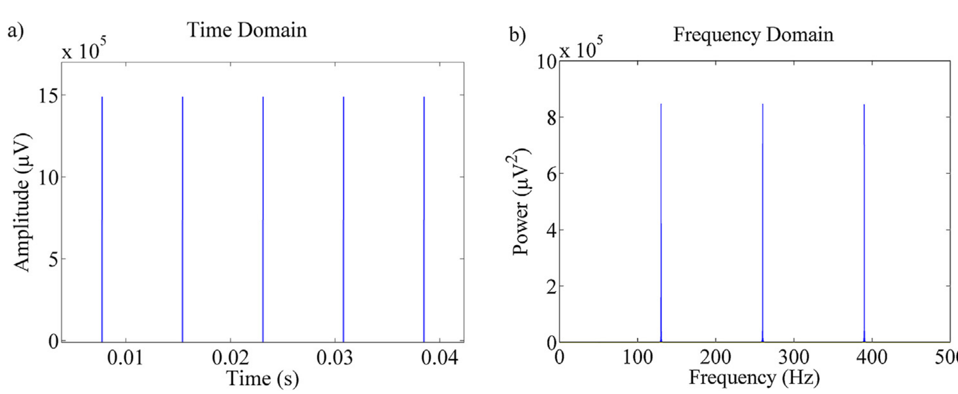

Fig. 1. Ideal DBS signal with frequency set at 130 Hz frequency, 1.5 V amplitude, and 60 μs square wave pulses plotted in (a) time domain, and (b) frequency domain.