A Model for Removing Transcranial Current Stimulation Artifacts in Concurrently Measured EEG*

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Transcranial current stimulation (tCS) is a non-invasive brain stimulation technique that has shown promise for studying and improving brain function. It can be applied with low-amplitude direct (tDCS), alternating (tACS) or random noise (tRNS) currents. EEG, with its high temporal resolution, portability, and affordability, offers great advantages in investigating the effects of tCS on brain activity. However, concurrent EEG acquisition and tCS stimulation suffers from the drawback that injected current induces significant artifacts on simultaneously acquired EEG. Furthermore, stimulus-current-induced artifacts in measured voltages have powers that are large compared to that of EEG, in the frequency range of interest for EEG analysis. While simple high-pass filtering of the EEG would eliminate artifacts from tDCS, it is not suitable when stimulating with frequencies in the range of significant EEG activity (1-40 Hz). This occurs both in low-frequency tACS/tRNS and in high-pass filtered tRNS, as even in the latter case substantial power will remain at EEG frequencies. In such cases, attenuating tRNS artifacts in EEG requires a more comprehensive model, such as the one we present here.

The Neuroelectrics Starstim™, a wireless multi-channel stimulator system that provides different types of tCS waveforms and the ability to simultaneously measure EEG, was used in this study. Our model of current injection includes three parts: 1) a stimulation unit that estimates the actual currents delivered based on the desired current set in the control software, considering the hardware implementation of digital-to-analog converter (DAC) and voltage-controlled current source modules in the device; 2) a head model in the form of effective impedances between stimulating and sensing electrodes (that can be obtained using a spherical or realistic volume conduction model); and 3) an EEG measurement unit that incorporates the hardware implementation of the acquisition analog-to-digital converter (ADC). Given the knowledge of the desired current waveform, artifacts introduced in measured EEG due to tCS can then be estimated and removed.

The reliability of the proposed model was validated based on measurements of circuitry mimicking electrical current injection (tCS). The experimental set up included circuit analysis from voltage measurements from a phantom consisting of a simple resistive circuit using two stimulation electrodes and two measurement electrodes (For the frequency range considered, a purely resistive tissue model is supported by the literature). The measurements show that the proposed model can accurately estimate the voltages on the measurement electrodes, due to and based on the injected tRNS waveforms, despite the relatively high interference-to-signal ratio. The utility of the model was demonstrated by successful filtering of artifacts caused by 100-500 Hz tRNS from simulated EEG. The filtered EEG is an accurate estimate of the clean (simulated original) EEG.

Using this model, tCS-induced artifacts concurrently recorded with EEG can be estimated for any multi-channel stimulation and sensing montage. In future work, we will evaluate the utility of this model in filtering stimulation-induced artifacts from the experimental EEG data. While our resistive surrogate circuit only contains electrode-metal junctions, in real EEG subject recordings, highly-resistive and possibly capacitive skin-electrode junctions are present. For this reason, the scalp potential underneath an electrode is not necessarily equal to the potential on the electrode itself. We will investigate this phenomenon and develop a model for the impedance of this interface to improve our model.

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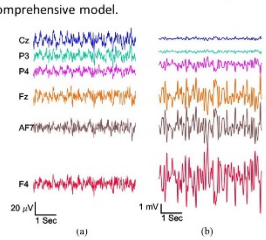
Abstract

Transcranial current stimulation (tCS) is a non-invasive brain stimulation technique that delivers low-amplitude currents to the head. It can be applied with low-amplitude direct (tDCS), alternating (tACS) or random noise (tRNS) currents. Since the underlying mechanisms of tCS are not well understood, simultaneous EEG acquisition with tCS can provide a better understanding of short term effects of tCS on brain activities. However, the acquired EEG is corrupted by significant artifacts generated by injected currents. Here, a new method is presented to estimate and remove tCS-induced artifacts for a combined tCS-EEG system.

Motivation

- EEG, with its high temporal resolution, portability, and affordability, offers great advantages in investigating the effects of tCS on brain activity.
- concurrent EEG acquisition and tCS stimulation suffers from the drawback that injected current induces significant artifacts on simultaneously acquired EEG.
- stimulus-current-induced artifacts in measured voltages have powers that are large compared to that of EEG, in the frequency range of interest for EEG analysis.
- High-pass filtering is not a suitable method when stimulating with frequencies in the range of significant EEG activity (1-40 Hz).
- Attenuating tRNS/tACS artifacts in EEG requires a more comprehensive model.

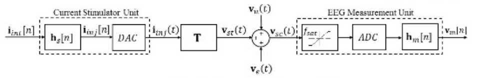


An example of EEG monitoring for six channels. (a) The real and clean EEG signals collected by the tCS-EEG system at eyes-opened rest state. (b) The corrupted EEG with the artifact generated by 250 mA white tRNS.

Method

The Neuroelectrics Starstim™, a wireless multi-channel stimulator system that provides different types of tCS waveforms and the ability to simultaneously measure EEG, was used in this study.

The proposed method was based on the characteristics of the tCS-EEG device and considering the head tissue. Our model of current injection includes three parts:



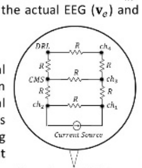
Block diagram of the model

1) A stimulation unit that estimates the actual currents delivered ($\mathbf{i}_{inj}$) based on the desired current ($\mathbf{i}_{int}$) set in the control software, considering the hardware implementation of digital-to-analog converter (DAC) and voltage-controlled current source modules in the device.
   The intended stimulation current generated by the device for each stimulating electrode can be expressed as:
   $$i_{int}[n] = A_{DC} + A_{AC}\sin[2\pi n f_{AC} + \theta] + A_{RN}\mathrm{RNS}[n]$$
   The injected stimulation current for all stim electrodes can be expressed as:
   $$\mathbf{i}_{inj}[n] = \mathbf{h}_s[n] * \mathbf{i}_{int}[n]$$
2) The effective impedances between stimulating and sensing electrodes (which can be obtained using a spherical or realistic volume conduction model).
   $$\mathbf{v}_{st}(t) = \mathbf{T}\,\mathbf{i}_{inj}(t)$$
3) An EEG measurement unit that incorporates the hardware implementation of the acquisition analog-to-digital converter (ADC).
   $$\mathbf{v}_{sc}(t) = \mathbf{v}_{st}(t) + \mathbf{v}_e(t) + \mathbf{v}_n(t)$$
   $$\mathbf{v}_m[n] = \mathbf{h}_m[n] * f_{sat}(\mathbf{v}_{sc}(nT_s))$$

Given the knowledge of $\mathbf{i}_{int}$ waveform, artifacts introduced in measured EEG ($\mathbf{v}_m$) due to tCS can then be estimated and removed, revealing the actual EEG ($\mathbf{v}_e$) and measurement noise ($\mathbf{v}_n$).

Experiments:

To identify filters characteristics, we conducted several series of measurements with Starstim and a phantom consisting of a simple resistive circuit. The experimental setup included circuit analysis from voltage measurements from a phantom consisting of a simple resistive circuit using two stimulation electrodes and two measurement electrodes.

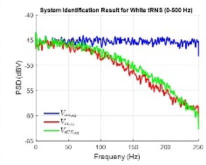


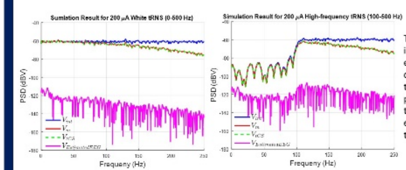
Experimental Setup

Results

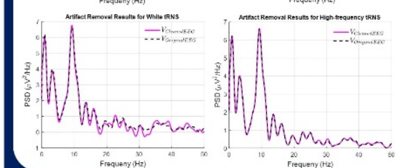
The frequency responses of filters in both stimulation and measurement unit have been characterized and were used to estimate the power spectrum of the voltage at the measurement unit.

Using the experimental results for system identification, we evaluated the performance of the model for a synthetic EEG signal during both white and high frequency tRNS. An EEG signal contaminated by a 200 μA tRNS and an additive white noise $N(0, \sigma^2)$ in which $\sigma = 1\,\mathrm{nA}$ (value based on measurement results from phantom) was simulated in the stimulation unit. The equivalent impedance between sensing electrode and stimulation electrodes was assumed 50 Ω (in the range of human head tissue).





The power spectrum of tCS-induced voltage at the sensing electrode, V_{tCS}, can be estimated due to the proposed model for tCS-EEG system. By subtracting power of V_{tCS} from the power of the contaminated EEG, we can estimate the power spectrum of the original EEG.



Simulation Results for Synthetic EEG shows that by having a correct estimation of equivalent impedance, the model can estimate the original EEG signal in the low frequency band.

Discussion

The measurements show that the proposed model can accurately estimate the voltages on the measurement electrodes. The reliability of the proposed model was validated based on measurements of circuitry mimicking electrical current injection (tCS) and having a correct estimation of **T**.

In real EEG recordings, highly-resistive and possibly capacitive skin-electrode junctions are present and the scalp potential underneath an electrode is not necessarily equal to the potential on the electrode itself and leading to incorrect estimations of **T**.

We will investigate this phenomenon and develop a model for the case in which we do not have an access to the correct values of the impedances.

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