Frequency Domain Synchrony Between Signals From the Conventional Disc Electrode and the Outer Ring of the Tripolar Concentric Ring Electrode in Human Electroencephalogram Data

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***Abstract*— For applications that may benefit from simultaneous recording of conventional electroencephalography (EEG) and tEEG, Laplacian EEG with tripolar concentric ring electrodes (TCREs), we proposed to use the signal from the outer ring of the TCRE as an emulation (eEEG) of EEG recorded using conventional disc electrodes. This allows recording EEG emulation from the exact same locations at the exact same time as the tEEG using a single recording system. In our previous work, time domain neuronal signal synchrony was assessed in phantom and human experiments suggesting the potential of eEEG as an emulation of EEG. In this paper, frequency domain neuronal signal synchrony was measured using coherence in human experiments further suggesting the potential of eEEG ($C \geq 0.98$).**

Keywords—neuronal signal synchrony; coherence; tripolar concentric ring electrode; tEEG; EEG.

I. Introduction

Electroencephalography (EEG) is an essential tool for brain and behavioral research and is used extensively in neuroscience, cognitive science, cognitive psychology, and psychophysiology. EEG is also one of the mainstays of hospital diagnostic procedures and pre-surgical planning. Despite scalp EEG's many advantages end users struggle with its poor spatial resolution, selectivity and low signal-to-noise ratio, which are EEG's biggest drawbacks and major hindrances in its effectiveness critically limiting the research discovery and diagnosis [1]-[3]. Tripolar concentric ring electrodes (TCREs), consisting of three elements including the outer ring, the middle ring, and the central disc (Fig. 1, B), are distinctively different from conventional disc electrodes that have a single element (Fig. 1, A) and have unique capabilities. They perform the second spatial derivative, the Laplacian, on the surface potentials. Previously, we have shown that tEEG, Laplacian EEG with TCRE configuration, is superior to conventional EEG with disc electrodes since tEEG has significantly better spatial selectivity, signal-to-noise ratio, localization, approximation of the analytical Laplacian, and lower mutual information [4]-[6]. Because of that, tEEG via TCREs has found applications in such areas as brain-computer interface [7] and seizure onset detection [8], [9] among others.

Some applications may require simultaneous recording of EEG using conventional disc electrodes and tEEG, for example, to allow a direct comparison of results for two sensor modalities, and placing two electrodes side-by-side has two disadvantages. First, EEG and tEEG are not being recorded at exactly the same locations. Second, additional hardware may be required as two recording systems may have to be used for EEG and tEEG data respectively resulting in imperfect synchronization in time between the two.

In [10] we proposed to use the signal from the outer ring of TCRE as an emulation (eEEG) of EEG recorded using conventional disc electrodes. This allows recording eEEG from the exact same locations at the exact same time as the tEEG using a single recording system. Time domain neuronal signal synchrony was measured using cross-correlation at different lags in phantom and human experiments with obtained results confirming that eEEG correlates well ($r \geq 0.99$) with the

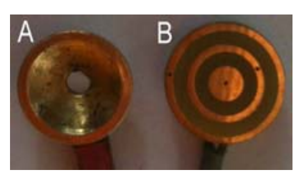

Fig. 1. Conventional disc electrode (A) and tripolar concentric ring electrode (B).

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conventional EEG [10]. In this paper, frequency domain neuronal signal synchrony was measured using coherence on human data from [10] to further assess the potential of eEEG as an emulation of EEG via conventional disc electrodes.

II. Methods

A. Human Experiments

The human data were collected from six healthy subjects (1-6, ages 24-40, one female). Baseline brain activity was recorded with the subjects seated in a chair and asked to remain motionless during the recording process to reduce movement induced artifacts. Durations of individual recordings ranged from 110s to 550s for a total duration of 1730s for 6 subjects which, when subdivided into non-overlapping segments of 10s resulted in 173 segments. The conventional disc electrode and a TCRE, recording both outer ring signal and Laplacian tEEG, were side-by-side at location P4 of the standard 10-20 system with reference and ground located on the right mastoid process. Skin-to-electrode impedances were maintained below 5kΩ. Signals from the TCRE were preamplified using a custom preamplifier with a gain of 6 after which both TCRE and conventional EEG signals were band pass filtered (0.1-100Hz) and digitized at 1200Hz using a gUSB amplifier with normalized unit gain (g.tec medical engineering GmbH, Schiedlberg, Austria).

B. Signal Processing and Synchrony Measure

All the signal processing was performed using Matlab (Mathworks, Natick, MA). Recording segments were digitally filtered (zero-phase fifth-order Butterworth) with band pass of 1-100Hz and 60Hz notch filter active since this frequency range is the current clinical standard for EEG recording and, therefore, is the primary goal for EEG emulation. Next, magnitude squared coherence estimate was calculated for EEG and eEEG signals of each segment using Welch's averaged modified periodogram method [11]. Hanning window of 1024 samples was used with 50% window overlap. Coherence coefficients corresponding to the 1-100Hz frequency range were averaged for each segment.

III. Results

Average coherence of $C = 0.9818 \pm 0.0133$ (average ± standard deviation) was obtained for EEG and eEEG on data from 6 subjects.

IV. Discussion

The results obtained in this study for frequency domain synchrony are consistent with the results for time domain synchrony obtained in [10]. It is an intuitive result since a conventional disc electrode is really a cup where there is an outer ring similar to the outer ring of the TCRE (Fig. 1). Cross-correlation analysis performed in [10] suggested presence of the varying time delay between the acquired signals of the phantom data set. Therefore, in this study we only used human data from [10] since for the human data maximum cross-correlation coefficients were obtained for zero lag suggesting that there was no time delay between the acquired signals.

Further investigation is needed for conclusive proof of potential of eEEG with short term directions of future work including determining the source of the varying time delay in the phantom data before using it to assess the frequency domain neuronal signal synchrony.

Moreover, a larger human data study needs to be conducted including a larger subject population with longer data durations for individual subjects (compared to short recordings from six subjects in the current study). Assessing the effect of subject's movement and induced artifacts on synchrony between EEG and eEEG is another issue that was not yet addressed. Most importantly, nonlinear neuronal signal synchrony measures need to be added to the currently used linear measures such as time domain cross-correlation in [10] and spectral coherence in this study. Potential nonlinear measures include mutual information, transfer entropy, Granger causality, and nonlinear interdependence as well as different indices of phase synchronization such as the mean phase coherence [12].

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