Emulating Conventional Disc Electrode with the Outer Ring of the Tripolar Concentric Ring Electrode in Phantom and Human Electroencephalogram Data

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***Abstract*— Conventional electroencephalography (EEG) with disc electrodes has major drawbacks including poor spatial resolution, selectivity and low signal-to-noise ratio that critically limit its use. Concentric ring electrodes are a promising alternative with potential to improve all of the aforementioned aspects significantly. In our previous work, the tripolar concentric ring electrode (TCRE) was successfully used in a wide range of applications demonstrating its superiority to conventional disc electrodes, in particular, in accuracy of Laplacian estimation (tEEG). For applications that may benefit from simultaneous recording of EEG and tEEG in this paper we propose to use the signal from the outer ring of the TCRE as an emulation (eEEG) of EEG recorded using conventional disc electrodes. This will allow us to record EEG emulation 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 in phantom and human experiments suggesting the potential of eEEG as an emulation of EEG ($r \geq 0.99$).**

Keywords—neuronal signal synchrony; cross-correlation; 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].

EEG's poor spatial resolution is primarily due to (1) the blurring effects of the volume conductor with disc electrodes; and (2) EEG signals having reference electrode problems as idealized references are not available with EEG [2]. Interference on the reference electrode contaminates all other electrode signals [2]. The application of the surface Laplacian (the second spatial derivative of the potentials on the body surface) to EEG has been shown to alleviate the blurring effects enhancing the spatial resolution and selectivity [4]-[6], and reduce the reference problem.

While several methods were proposed for estimation of the surface Laplacian through interpolation of potentials on a surface and then estimating the Laplacian from an array of disc electrodes [5]-[9], concentric ring electrodes (CRE) have shown more promise. The CREs can resolve the reference electrode problems since they act like closely spaced bipolar recordings [2]. Moreover, CREs are symmetrical alleviating electrode orientation problems [10]. They also act as spatial filters enhancing the high spatial frequencies [10], [11]. Finally, bipolar CREs, consisting of just two elements including a single ring and the central disc, improve the radial attenuation of the conventional disc electrode from $1/r^3$ to $1/r^4$ with higher numbers of poles having the potential to enhance radial attenuation even further [12].

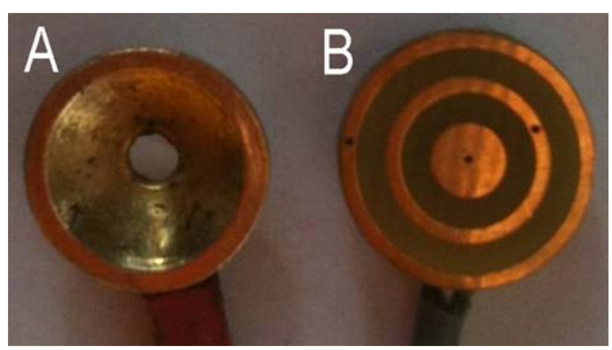

Fig. 1. Conventional disc electrode (A) and tripolar concentric ring electrode (B).

This work was supported in part by award number 1R21TW009384-01 from the Fogarty International Center of the National Institutes of Health as well as by awards number 0933596 and 1157882 from the National Science Foundation (all to WGB). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health or the National Science Foundation.

Tripolar CREs (TCRE), 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). TCREs have been shown to estimate the surface Laplacian directly through the nine-point method, an extension of the five-point method used for bipolar CREs, significantly better than other electrode systems including bipolar and quasi-bipolar CREs [13], [14]. The Laplacian algorithm is two-dimensional and weights the middle ring and central disc signal difference sixteen times greater than the outer ring and central disc signal difference [13], [14]. Compared to EEG with conventional disc electrodes Laplacian EEG using TCREs (tEEG) have been shown to have significantly better spatial selectivity (approximately 2.5 times higher), signal-to-noise ratio (approximately 3.7 times higher), and mutual information (approximately 12 times lower) [15]. TCREs also have very high common mode noise rejection providing automatic artifact attenuation, -100 dB one radius from the electrode [14]. Because of such unique capabilities TCREs have found numerous applications in a wide range of areas including brain-computer interface [16], seizure attenuation using transcranial focal stimulation applied via TCREs [17]-[20], seizure onset detection in animal models [21], [22] and, most recently, humans [23], etc.

Some current and future applications may require simultaneous recording of EEG using conventional disc electrodes and tEEG. For example, in [23] EEG and tEEG were recorded simultaneously from human patients with epilepsy to allow a direct comparison of seizure onset detection results for two sensor modalities. In [23] EEG and tEEG data were recorded by placing a set of TCREs directly behind the conventional disc electrodes that were in the standard 10-20 system locations but this approach has two disadvantages. First, EEG and tEEG are not being recorded at exactly the same locations. Second, this approach may require additional hardware as two recording systems may have to be used at the same time for EEG and tEEG data respectively (as was done in [23]) resulting in imperfect synchronization in time between EEG and tEEG.

In this preliminary study we propose to use the signal from the outer ring of TCRE as an emulation (eEEG) of EEG recorded using conventional disc electrodes. This will allow us to record 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 in phantom and human experiments to assess the potential of eEEG as an emulation of EEG. Moreover, in the phantom experiments, a shorted TCRE was also assessed as an alternative potential emulation of EEG. TCREs with diameter of 1.0cm (Fig. 1, B) were used in all of the experiments.

II. METHODS

A. Phantom Experiments

A diagram of the setup used for the phantom data collection is presented in Fig. 2. Three electrodes including the conventional disc electrode and two modified TCREs, one connected as the outer ring and the other one as shorted disc, were placed on a copper plate (Fig. 2, A) covered by a 3mm layer of Ten20 EEG conductive paste (Fig. 2, B) (Weaver and Company, Aurora, CO). The copper plate was made from a single sided copper cladded printed circuit board used as a cathode with a smaller round copper plate (Fig. 2, C) used as an anode and located in such a way that the three electrodes under test were located across two perpendicular diameters of the anode circle at a constant distance of 2mm from it (Fig. 2, D, E, and F). The cathode and anode were connected to a signal generator producing a sinusoidal wave with frequency of 30Hz and amplitude of 2.5V. Signals from three electrodes were digitized at 16-bit using a USB-2527 data acquisition card (Measurement Computing, Norton, MA) with sampling frequency of 1000Hz and duration of all the recordings equal to 30s.

We recorded a total of 10 series, each series consisting of 6 recordings corresponding to six possible combinations of positioning three electrodes at three different locations around the circular anode, to improve the statistical validity of the results. Using all possible positioning combinations at each series of recordings was meant to compensate for the variability due to location. For each series the order of recordings was randomized to balance out the potential effect of the temporal factor. Anode and cathode corrosion were cleaned after each series of recordings.

B. 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 total for this part of the study. 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

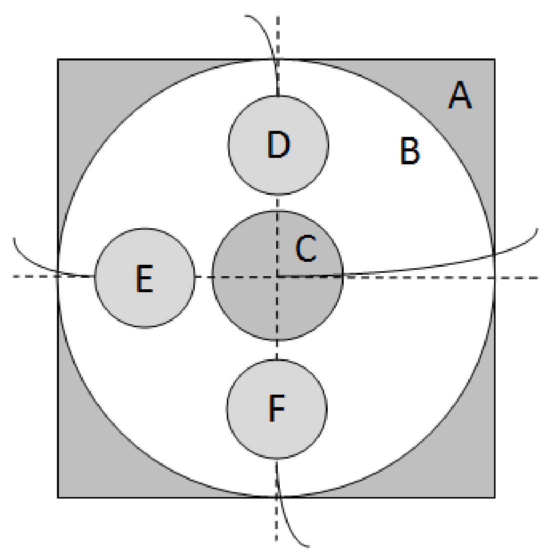

Fig. 2. Diagram of the setup used for the phantom data collection including: copper cathode plate (A), layer of Ten20 EEG conductive paste (B), copper anode plate (C), and three electrode locations (D, E, and F).

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).

C. *Signal Processing and Synchrony Measure*

All the signal processing was performed using Matlab (Mathworks, Natick, MA). Sixty 30s recording segments for the phantom data part of this study and 173 10s recording segments from 6 subjects for the human data part of this study 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, cross-correlation, a widely used linear measure of neuronal signal synchrony in the time domain was applied to all the respective pairs of signals from different electrode modalities [24]. For cross-correlation the signals were normalized to zero mean and unit variance. We calculated both the correlation coefficient at lag zero as well as the maximum correlation coefficient value corresponding to the optimal lag to account for possible time delay between the acquired signals.

D. *Statistical Analysis*

For the phantom data, statistical tests were used to assess significance of difference between the two proposed EEG emulation options: eEEG via the TCRE outer ring and shorted TCRE signals. First, we calculated average cross-correlation coefficients for each of 10 series of recordings averaging together coefficients for 6 recordings that comprised each series. Next, we applied unpaired or "independent samples" tests to samples of series cross-correlation coefficients ($n = 10$) between EEG vs. eEEG and EEG vs. shorted TCRE signal respectively: parametric two-sample Student's t-test (alternative hypothesis of sample means being not equal) and nonparametric Mann–Whitney test (alternative hypothesis of sample medians being not equal) [25]. The Ryan–Joiner (similar to Shapiro–Wilk) normality test was used for all the samples compared [26]. A parametric test was used only when both samples to be compared were normally distributed. Otherwise, a nonparametric test was used.

III. Results

A. *Phantom Data*

At lag zero the following cross-correlation coefficients (r) were obtained (average ± standard deviation) for 10 series of recordings: for EEG vs. eEEG, $r = 0.9744 \pm 0.0121$; for EEG vs. shorted TCRE signal, $r = 0.9445 \pm 0.0281$. There was a statistically significant difference between the two ($p = 0.009$).

Individual optimal lags varied between the recordings. Group average optimal lag was equal to one both for EEG vs. eEEG and for EEG vs. shorted TCRE signal. The maximum cross-correlation (r_{max}) corresponding to the unit optimal lag was higher than cross-correlation at lag zero (r) both for EEG vs. eEEG with $r_{max} = 0.9841 \pm 0.012$ ($p = 0.045$) and for EEG vs. shorted TCRE signal with $r_{max} = 0.9766 \pm 0.0195$ ($p = 0.013$). There was no statistically significant difference between the two maximum cross-correlations ($p = 0.385$).

B. *Human Data*

At lag zero the following cross-correlation coefficients were obtained (average ± standard deviation) for EEG vs. eEEG on data from 6 subjects $r = 0.9905 \pm 0.0065$. At optimal lag the maximum cross-correlation coefficients were equal to the zero lag coefficients suggesting that there was no time delay between the acquired signals.

IV. Discussion

Significance of difference between zero lag (r) and optimal lag cross-correlation (r_{max}) coefficients for both EEG vs. eEEG and EEG vs. shorted TCRE signal in phantom data suggests presence of a time delay between the acquired signals the source of which needs be determined. Difference between optimal lags for individual recordings suggests that this delay is variable so group optimal lag that was reported in this study provides a lower bound for the maximum correlation. For example, recalculating the maximum correlation allowing individual lags of up to one sample (that is, choosing either zero or unit lag for each recording) increases it both for EEG vs. eEEG with $r_{max} = 0.9921 \pm 0.012$ and for EEG vs. shorted TCRE signal with $r_{max} = 0.98 \pm 0.032$. Moreover, allowing optimal lags for individual recordings further increases the maximum correlation to $r_{max} = 0.9981 \pm 0.001$ for EEG vs. eEEG and $r_{max} = 0.9977 \pm 0.001$ for EEG vs. shorted TCRE signal. Taking into account these varying time delays between the acquired signals for the phantom data experiments, the results obtained on both phantom and human data confirm that signals from the outer ring of TCRE correlate well ($r \geq 0.99$) with the conventional disc electrode signals suggesting the potential of eEEG as an emulation of EEG via conventional disc electrodes. This 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).

The proposed EEG emulation alternative was to short all three recording surfaces of the TCRE. In the phantom experiments of this study the zero lag cross-correlation between the TCRE outer ring eEEG and conventional disc EEG was significantly higher ($p = 0.009$) than the corresponding cross-correlation for the shorted TCRE signal. This suggests that eEEG may be a closer approximation of disc electrode EEG than the signal from the shorted TCRE even though high maximum cross-correlation coefficients and lack of statistical significance between them suggests that both proposed EEG emulation options are valid. Another important consideration is that recording tEEG simultaneously with a shorted TCRE signal at the same location is difficult since constantly shorting and un-shorting of the three TCRE elements would require a complex multiplexer introducing additional switching noise. On the other hand, recording eEEG in parallel with tEEG using a single system does not require additional hardware providing researchers and clinicians with the best of both worlds.

This paper represents a first preliminary step toward emulating the conventional disc electrodes using concentric ring electrodes. Further investigation is needed for conclusive proof with short term directions of future work including determining the source of the varying time delay in the phantom data and conduction of a larger human data study. This study should include shorted TCRE (compared to just eEEG and EEG in the current preliminary study) as well as 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 its emulations is another issue that was not addressed in the current study that includes just the baseline activity. Most importantly, more measures of neuronal signal synchrony need to be added to the currently used time domain linear cross-correlation. Linear spectral coherence may be used to assess the synchrony in the frequency domain both in specific frequency bands and averaged across the spectra. Moreover, nonlinear neuronal signal synchrony measures are available including mutual information, transfer entropy, Granger causality, and nonlinear interdependence as well as different indices of phase synchronization such as the mean phase coherence [27].

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