

Equivalency Between Emulated Disc Electrodes and Conventional Disc Electrode Human Electroencephalography

Zhengan Zhu, James Brooks, Oleksandr Makevey, *IEEE Member*, Steven M. Kay, *IEEE Fellow*, and Walter G. Besio, *IEEE Senior Member*

Abstract— We have previously shown that tripolar concentric ring electrode (TCRE) Laplacian electroencephalography (tEEG) has significantly better signal-to-noise ratio, spatial resolution, and mutual information than disc electrode electroencephalography (EEG). This paper compares the EEG signals acquired simultaneously from the outer ring of the TCRE (oTCRE), shorting all three elements of the TCRE (sTCRE) and disc electrode (disc) concurrently from nearly the same location on the human scalp. We calculated the average correlation for the time series between each pair of signals and average coherence over the pass-band frequencies between all pairs of signals as well. All the correlations and coherences were above 0.99. The results suggest that the oTCRE can be used to record EEG concurrently with tEEG from the same sensor at the same location.

Keywords- Tripolar Concentric Ring Electrode, Conventional Disc Electrode, Cross-Correlation, Magnitude Squared Coherence, Canonical Correlation Analysis, Synchrony, Equivalency, EEG.

I. INTRODUCTION

The electroencephalogram (EEG) is used to study brain function that reflects the brain's electricity activity. To collect brain electrical signals electrodes are placed on the scalp and a conductive paste is used to conduct signals from the scalp to the electrodes. The EEG signal is typically on the scale of 10 to 100 microvolts. The EEG is one of the most common non-invasive methods for diagnosing brain related neurological disorders, such as epilepsy [1]. The EEG is also often used in brain computer interfaces [2]. The electrode serves to convert ionic currents in the body to electrical currents that can be processed by electrical circuits. The conventional disc electrodes (Fig. 1, A) have changed little since being introduced by Hans Berger [3]. Our group has developed the tripolar concentric ring electrode (TCRE) [4]. The TCRE consists of two rings (outer ring and middle ring) and central disc as shown in Fig. 1, B. Besio et al. found that TCREs approximate the Laplacian Δp_o using equation (1) [3],[8]:

$$\Delta p_o \cong 16(v_m - v_d) - (v_o - v_d) \quad (1)$$

where v_o , v_m and v_d are the voltages on the outer ring, middle ring and central disc of the TCRE respectively. The TCRE has benefits over conventional disc electrodes in: resolving the reference electrode problem since closely spaced bipolar differences are recorded from the TCREs [5] and alleviating electrode orientation problems since TCREs are symmetrical [6]. TCREs also act as spatial filters enhancing the high spatial frequencies [6]. 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 [7]. We have also found that EEG signals recorded with TCRE (tEEG) have significantly higher signal-to-noise ratio (SNR) over the EEG signal recorded with conventional disc electrodes [8]. Use of TCREs improved the accuracy of differentiating the motor imagery [9]. With such unique capabilities TCREs have been applied to seizure detection, focal electrical stimulation and other areas [10]-[11].

Typically, to compare the EEG to tEEG we place two sets of electrodes: conventional disc electrodes and TCREs. This means that the signals are not recorded from the same locations and may have contributions from different brain areas. Therefore, the electrodes would have to be put on the same locations in two separate experiments to record the activity from the same areas of the brain. This causes another problem since it is likely that the subject does not perform exactly the same from experiment to experiment and therefore the recorded brain activity varies. To overcome these limitations we hypothesize that the outer ring of the TCRE or shorted TCRE can serve as an emulation of a conventional disc electrode. In our previous work [12]-[13], we have preliminarily demonstrated this hypotheses. This paper serves as an extension to previous work and a stricter demonstration of the hypotheses.

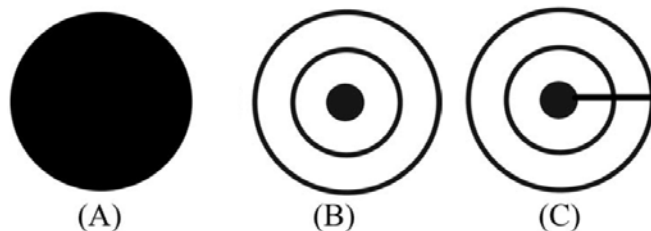


Figure 1. Different electrodes: (A) conventional disc electrode; (B) tripolar concentric ring electrode (TCRE); (C) shorted TCRE.

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II. METHODS

Human experiments were conducted in accordance with the University of Rhode Island IRB on six subjects. There are many methods available for calculating the synchrony between different EEG signals such as: cross-correlation coefficient, coherence, Granger causality, phase synchrony, state space based synchrony, information theoretic interdependence measures and stochastic event synchrony measures [14]. For this study EEG signals were recorded from three different types of electrodes. The signals were then used to calculate the correlation and coherence between each pair of electrodes. Also, canonical correlation analysis was applied to analyze the linear correlation between the groups of EEG signals. The correlation and coherence infer the synchrony between the signal pairs from the different types of electrodes. All the signal processing was performed using Matlab (Mathworks, Natick, MA).

A. Human Experiment Setup

A conventional disc electrode (disc1) was placed at O1 of the International 10-20 EEG Electrode System. A TCRE with only its outer ring used (oTCRE), another TCRE with its three rings shorted together (sTCRE), and a second conventional disc electrode (disc2) were all placed close to disc1 (see Fig. 2), the distance between the electrodes was approximately 2mm. A reference and a ground electrode were both located at the right mastoid process. All skin-to-electrode impedances were maintained below 5 KOhms. All the EEG signals were collected using a Comet AS40 Amplifier System (Natus Neurology, Warwick, RI, USA) with a sampling rate of 200 samples per second and band-pass filtered at 1~70Hz. Also, a 60 Hz notch filter was applied to the EEG signals. The EEG signals from the four electrodes were collected simultaneously at nearly the same location under the same conditions. In total, six healthy subjects, three males and three females, aged from 19 to 30, were involved in the experiment. Six trials were recorded for every subject. The subjects were asked to close their eyes for 30 seconds and open their eyes for 30 seconds. To account for the “variance” caused by the different positions of the electrodes, oTCRE, sTCRE and disc2 were selected randomly for each subject, see Fig. 2.B for all combinations of electrodes positions used.

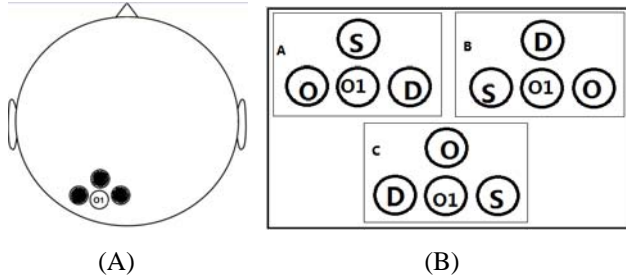


Figure 2. (A) Diagram of electrodes positions on the scalp. Disc1 is at location O1; (B) the three different configurations of oTCRE (O), sTCRE (S) and disc2 (D).

B. Cross-Correlation Coefficient

The cross-correlation coefficient is a well-known measure of linear interdependence between two signals. If

two signals are identical, then the cross-correlation coefficient is one, if they are opposite the cross correlation is -1. For every trial, the EEG signals were divided into segments of one second duration without overlap, assuming near stationarity as reported in [15]. The cross-correlations between pairs of EEG signals from oTCRE and disc1 were calculated according to equation (2). Similarly, cross-correlations were performed between disc1 and sTCRE, disc1 and disc2, disc2 and oTCRE, and disc2 and sTCRE.

The cross-correlation coefficient at lag zero estimator is given by equation (2), where two zero mean signals are $x[n]$, $y[n]$, $n=1,2,\dots,N$.

$$\hat{\rho}_{x,y} = \frac{\sum_{n=0}^{N-1} x[n]y[n]}{\sqrt{\sum_{n=0}^{N-1} x^2[n] \sum_{n=0}^{N-1} y^2[n]}} \quad (2)$$

C. Magnitude Squared Coherence

The magnitude squared coherence measures linear correlations in the frequency domain by means of the cross spectrum. It is especially useful in quantifying synchronization of the two signals in certain frequency bands including phase and amplitude synchronization of the two signals. The magnitude squared coherence between two signals x and y is the cross spectral density function normalized by their individual auto-spectral density functions [16], equation (3). We used the averaged periodogram method to estimate the spectrums [16].

$$|\gamma_{x,y}(f)|^2 = \frac{|P_{x,y}(f)|^2}{P_x(f)P_y(f)} \quad (3)$$

Where, $P_{x,y}(f)$ is the cross-spectrum of EEG signals x and y , $P_x(f)$ is the power spectral density of signal x , and $P_y(f)$ is the power spectral density of signal y .

D. Canonical Correlation Analysis

Canonical correlation analysis (CCA) measures the linear relationship between two groups of variables. The CCA is very helpful for analyzing multi-channels, multi-trials EEG signals. In general, CCA can be viewed as searching for two sets of basis vectors, one for groups of signals $X1$, say, it is of m channels of signals, and another second group of signals $X2$, say, it is of n channels of signals. Then the correlations between the projections of the variables onto these basis vectors are mutually maximized. Mathematically, let $X = \begin{bmatrix} X1 \\ X2 \end{bmatrix}$ and $\Sigma = \text{Var}(X) = \begin{bmatrix} \Sigma_{11} & \Sigma_{12} \\ \Sigma_{21} & \Sigma_{22} \end{bmatrix}$, where Σ is the variance of a new data matrix X and is a $m+n$ by $m+n$ matrix. The CCA considers linear combinations $u = a^T X_1$ and $v = b^T X_2$, and then extracts the variables a and b so that the correlation between u and v is at its maximum [17] equation (4)

$$\rho(u,v) = \frac{a^T \Sigma_{12} b}{\sqrt{a^T \Sigma_{11} a} \sqrt{b^T \Sigma_{22} b}} \quad (4)$$

The maximum of $\rho(u, v)$ with respect to \mathbf{a} and \mathbf{b} is the maximum canonical correlation. The solution is determined by calculating the eigenvalue and eigenvector of the matrix $\mathbf{M} = \Sigma_{11}^{-1} \Sigma_{12} \Sigma_{22}^{-1} \Sigma_{21}$. The matrix \mathbf{M} contains all the information about the linear correlation between the two groups of signals. The largest eigenvalue of \mathbf{M} is the maximum canonical correlation between the two groups of signals. Therefore, CCA provides a single scale measure of the linear correlation among a group of EEG signals from disc electrodes and a group of EEG signals from oTCRE. Also, CCA has an inherent relation with mutual information [18]. It can be shown that the mutual information between $\mathbf{x1}$ and $\mathbf{x2}$ can be given by

$$I(x1; x2) = \frac{1}{2} \sum_i \log\left(\frac{1}{1 - \rho_i^2}\right) \quad (5)$$

where the ρ_i are the eigenvalues of the matrix \mathbf{M} also equal to the CCAs. From equation (5), if the CCA is close to one the mutual information is high. The greater the correlation between the two groups of signals, then the more mutual information they have between each other. In our case, we mixed all six subjects' EEG from the disc1 electrodes as one group of EEG signals from disc1. Similarly, we did the same for oTCRE, sTCRE and disc2. The CCA was used to calculate the canonical correlation between the group disc1 EEG signals with the group of EEG signals from oTCRE. The procedure was repeated between all pairs of group EEG data.

III. RESULT

A. Raw EEG data

Figure 3 shows 2-second segments of raw EEG signals from the four electrodes. These segments are typical EEG alpha waves recorded when the subjects eyes were closed. By visual inspection, the EEG signals look very similar to each other.

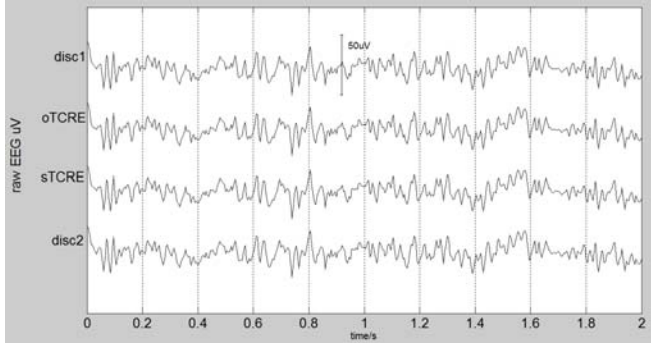


Figure 3. A randomly chosen 2-second segment of raw EEG data from all four electrodes while the subject's eyes are closed.

B. Cross-Correlation Coefficient

The cross-correlation was calculated in pairs, specifically, disc1 with oTCRE, disc1 with sTCRE, disc1 with disc2, disc2 with oTCRE, and disc2 with sTCRE. The cross-correlation between disc1 and disc2 served as a reference to compare the cross-correlations of the non-disc electrodes. The mean cross-correlation between the three pairs of electrodes over all six trials and the standard deviation are

shown in Table 1 for each subject. These results suggest that each electrode configuration is nearly identical since all of the mean disc1 cross-correlations are over 0.9900 with very low standard deviation (<0.0064). Since the correlations are all nearly one this indicates that there is a strong linear correlation between the EEG signals from the three electrode configurations, and thus they are all highly synchronized. To further analyze the signals we performed ANOVA analysis ($p > 0.7300$ for each combination of pairs) with post-hoc Bonferroni correction for multiple tests performed on the correlations. This multiple comparison suggests that there is no significant difference between the signals from each electrode configuration in the time domain.

TABLE I. CROSS-CORRELATION COEFFICIENTS.

Subject	Groups of Electrodes				
	Disc1 vs. Disc2	Disc1 vs. oTCRE	Disc1 vs. sTCRE	Disc2 vs. oTCRE	Disc2 vs. sTCRE
1	0.9967 ± 0.0028	0.9932 ± 0.0039	0.9983 ± 0.0007	0.9927 ± 0.0039	0.9890 ± 0.0056
2	0.9965 ± 0.0020	0.9972 ± 0.0043	0.9969 ± 0.0023	0.9957 ± 0.0025	0.9918 ± 0.0060
3	0.9983 ± 0.0006	0.9944 ± 0.0026	0.9965 ± 0.0012	0.9928 ± 0.0025	0.9963 ± 0.0020
4	0.9989 ± 0.0009	0.9981 ± 0.0006	0.9956 ± 0.0021	0.9921 ± 0.0038	0.9989 ± 0.0005
5	0.9948 ± 0.0037	0.9981 ± 0.0007	0.9985 ± 0.0023	0.9933 ± 0.0082	0.9952 ± 0.0031
6	0.9936 ± 0.0020	0.9964 ± 0.0019	0.9897 ± 0.0064	0.9672 ± 0.0109	0.9546 ± 0.0167
Mean	0.9965*	0.9962*	0.9959*	0.9889*	0.9876*

*. Average over subjects.

C. Magnitude Squared Coherence

Similarly, the EEG signals were divided into one-second duration segments to reduce the non-stationary nature of EEG signals [15]. The magnitude squared coherence of the three pairs of electrodes was calculated for each segment. Table 2 shows the average magnitude squared coherence over the frequency band 1~70Hz for each segment and over all the segments of EEG for each subject and each pair of electrodes.

TABLE II. MAGNITUDE SQUARED COHERENCE

Subject	Groups of Electrodes				
	Disc1 vs. Disc2	Disc1 vs. oTCRE	Disc1 vs. sTCRE	Disc2 vs. oTCRE	Disc2 vs. sTCRE
1	0.9919 ± 0.0033	0.9915 ± 0.0044	0.9956 ± 0.0012	0.9818 ± 0.0063	0.9821 ± 0.0071
2	0.9898 ± 0.0064	0.9897 ± 0.0087	0.9911 ± 0.0052	0.9895 ± 0.0039	0.9816 ± 0.0080
3	0.9951 ± 0.0015	0.9907 ± 0.0029	0.9891 ± 0.0030	0.9790 ± 0.0058	0.9973 ± 0.0020
4	0.9975 ± 0.0007	0.9961 ± 0.0010	0.9924 ± 0.0021	0.9872 ± 0.0035	0.9937 ± 0.0008
5	0.9863 ± 0.0056	0.9961 ± 0.0019	0.9960 ± 0.0023	0.9862 ± 0.0059	0.9903 ± 0.0042
6	0.9870 ± 0.0045	0.9894 ± 0.0039	0.9794 ± 0.0064	0.9656 ± 0.0127	0.9166 ± 0.0276
Mean	0.9912*	0.9922*	0.9906*	0.9800*	0.9769*

*. Average over subjects.

The mean magnitude squared coherence over subjects for each pair of electrodes is also given. From Table 2 we can see that the EEG signals from all four electrodes are strongly synchronized in the frequency domain with very high mean magnitude squared coherence values (>0.990 for disc1) and very low standard deviations (<0.0070). An ANOVA analysis ($p>0.7300$ for each combination of pairs) with post-hoc Bonferroni correction for multiple test was performed on the magnitude squared coherence. This multiple comparison suggests that there is no significant difference between the signals from each electrode configuration in the frequency domain.

D. Canonical Correlation Analysis

All trials of signals from all the subjects collected from disc1 electrodes were treated as a group of EEG signals. Similarly, there were three more groups of EEG signals from oTCRE, sTCRE and disc2, respectively. The CC coefficients between the three pairs of the groups of EEG signals are given in Table 3. These results suggest that groups of EEG signals from the four electrodes were highly correlated and synchronized with CC coefficients all higher than 0.9980.

TABLE III. CANONICAL CORRELATION COEFFICIENT

CCA	Groups of Electrodes				
	Disk1 vs. Disk2	Disk1 vs. oTCRE	Disk1 vs. sTCRE	Disc2 vs. oTCRE	Disc2 vs. sTCRE
ρ_{\max}	0.9990	0.9984	0.9984	0.9981	0.9967

IV. DISCUSSION

The results of the cross-correlation coefficients, magnitude squared coherence analysis, and CCA of the EEG signals from the five combinations of electrode pairs all support the hypothesis that the signals from all three electrode configurations are strongly correlated, synchronized, and nearly identical. The slight difference of mean cross-correlation, coherence, and CC of different pairs is likely due to the electrodes not being exactly at the same location on the scalp and the electrode-to-skin impedances are not exactly the same. It could be said that if the four electrodes could be used in exactly the same way concurrently, the signals from them would most likely be identical. All measures that we used for comparisons are linear. In the future nonlinear measures should be tested. In conclusion, with the minimal difference in all measures we calculated between the different electrode configurations it can be seen that the outer ring of the TCRE, and/or shorted TCRE is equivalent to the conventional disc electrode when needed.

The results of this study support the previous results from [11], using cross-correlation, and [12] using coherence. The data used for this study was different than what was used in [11 and 12]. We believe this is a sign of how robust the emulation of disc electrodes is when using the oTCRE or sTCRE.

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