Mutual Information of Tri-polar Concentric Ring Electrodes

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Abstract— **Electroencephalography (EEG) signals are spatio-temporal. EEG has very good temporal resolution but typically doesn't possess high spatial resolution. The surface Laplacian enhances the spatial resolution and selectivity of the surface electrical activity. Concentric ring electrodes have been shown to estimate the surface Laplacian directly with significantly better spatial resolution than conventional electrodes and possess spatial filtering characteristics.**

Movement Related potentials (MRP) were recorded using tri-polar and bipolar concentric ring electrodes as well as conventional disc EEG electrodes while the subjects were pressing a micro-switch. The electrodes were placed in an array of 35 encompassing the area between Fz-Cz-Pz-P3-T5-T3-T7-F3. Mutual information (MI) of the MRP signals recorded with the different electrode systems was compared.

The MRP signals recorded with the tri-polar concentric ring electrode system have significantly less MI between locations than the other two electrode configurations tested. The decrease in MI should increase the total information available by pooling of information from independent tri-polar concentric ring electrodes. These characteristics should make tri-polar concentric electrodes beneficial for EEG applications.

Index Terms—**Electroencephalography, EEG, mutual information, concentric ring electrodes, Laplacian and tri-polar.**

I. Introduction

BRAIN activity is a spatio-temporal phenomenon. The brain electrical activity is distributed throughout the brain. Ions are associated with brain activity, and their flow creates electrical signals that can be detected on the scalp surface with electroencephalography (EEG). To our best knowledge, Hans Berger recorded the first human EEG from the scalp in 1924. Today, EEG is still one of the most important non-invasive methods for diagnosing many brain related neurological disorders. EEG gives sufficient temporal resolution to study the functioning of the brain and is the least expensive, easy to perform compared to many other imaging systems. However, EEG has limited spatial resolution.

Researchers have applied the surface Laplacian to EEG making it more useful for analyzing brain related problems by increasing the spatial resolution of EEG. Surface Laplacian mapping has been shown to enhance the high spatial frequency components and spatial selectivity of the electrical activity located close to the observation point [1-2]. These unique characteristics are based on the surface Laplacian being the second spatial derivative of the potentials. Tri-polar concentric ring electrodes have been found to estimate the surface Laplacian significantly better than other electrode systems [3-4]. Concentric ring electrodes also act as spatial filters which depend on the number of rings and weights [5] given to the concentric rings and these spatial filtering characteristics increase the spatial selectivity [6].

The tri-polar concentric ring electrodes, which were designed based on the nine-point-method (NPM), were shown to estimate the Laplacian significantly better than bipolar concentric ring electrodes based on the five-point-method which have been reported by Fattorusso [7] and He and Cohen [1-2]. The tri-polar electrodes were shown to have better attenuation of global signals than bipolar concentric ring electrodes [3-4].

Many researchers proposed MI as test of independence. The concept of mutual information (MI) was introduced by Shannon [8]. Information theory has an expanding role in interpreting data and in understanding the principles of representation and computation in the nervous system [10]. The MI is a measure of statistical dependence.

The amount of information gathered from EEG signals depends on the number of electrodes and MI or dependence between each electrode. The amount of information is increased by pooling of information from each location. Pooling of independent signals from individual sources has shown to provide more reliable information than from a single source [9-10]. Our hypothesis is that conventional disc electrodes have more mutual information; each location is interdependent on others and seems to be more correlated than concentric ring electrodes. The MI between locations causes the total amount of information from the pooling of information from different locations to be less. To increase the amount of information depends on the number of electrodes used for recording and to increase the information more electrodes are necessary. The number of locations is critical many cases for recording EEG signals [10]. The increasing number of channels increases the cost of the system and complexity of the system and preparation time. These are limitations of conventional disc electrodes for recording brainwaves.

For this research we recorded LEEG and analyzed MI between different locations for the three electrode systems shown in Fig.1 all with the same outer diameter.

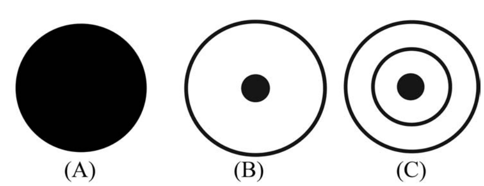

Figure 1 Different electrode systems used for MRP recordings; (A) conventional disc, (B) bipolar and (C) tri-polar concentric electrodes

II. METHODOLOGY

A. Data Acquisition:

Conventional disc electrodes (Grass F-E5GH, Grass Telefactor, West Warwick, RI, USA) of 1cm diameter were used for recording movement related potential (MRP) signals. Data was acquired from five right handed male subjects who were volunteers and gave informed consent. All the recordings were taken according to the IRB protocols. The subjects involved in the experiment were free of any known neurological disorders and their age ranged from 24-27 years. Subjects were seated in a comfortable chair with armrests and their right index finger was placed on a micro-switch. The subjects were asked to press the micro-switch when cued by a metronome, and EEG signals were recorded continuously during the experiment. The cue was given every three seconds. The subjects were asked to close their eyes to reduce the electrooculogram (EOG) artefact. MRP recording methods followed previously disclosed methods for recording fast repetitive movement signals from the brain [11-12].

Thirty-five electrodes were placed at locations over the left hemisphere of the brain with the electrodes arranged in a 5x7 array covering the area bounded by Fz-Cz-Pz-P3-T5-T3-F7-F3 were recorded. The placement of the electrodes was based on a 10/20 system as shown in Fig. 2. The recordings were performed in five groups of seven locations at a time along a straight line. These recordings were synchronized later with the time reference from the micro-switch. A 1cm inter-electrode distance was used. The common electrode was placed near the earlobe on the contra lateral side. The recordings were taken by referencing each electrode to the common electrode. The skin-to-electrode impedance was kept below 10KOhm for each experiment.

Custom built pre-amplifiers (gain 100) along with a Grass 15LT amplifier was used for a total gain of 20K. The filters were set from 0.3Hz to 30Hz. The data was acquired using a data acquisition system (DataQ Instruments, Akron, Ohio, USA-44333) with a sampling rate of 250S/S per channel. One of the recording channels contained the micro-switch state as a reference of movement instants.

The concentric ring electrodes were arranged at the same locations as the conventional disc electrodes for direct comparison. The recordings were taken in differential mode, outer ring to disc and middle ring to disc. As with the conventional disc electrode recordings, the recordings with concentric ring electrodes were also taken using seven electrodes at a time. Five movements of the seven electrodes were necessary to record from the 35 locations. The skin-to-electrode impedance was checked before each experiment and kept below 10KOhm. The same custom built pre-amplifiers and Grass 15LT amplifiers were used with the same filter settings as for the conventional disc electrodes. The gain of the amplifiers was set to 50K.

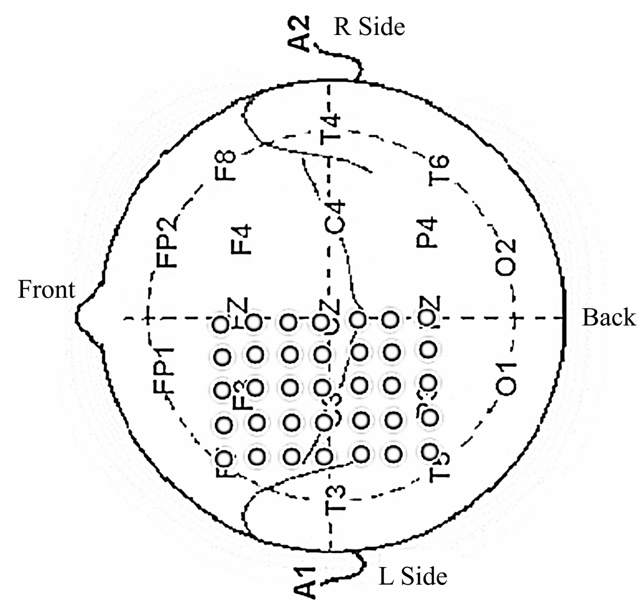

Figure 2 Placement of 35 electrodes for MRP recordings.

The MRP signals recorded with the different electrode systems were pre-processed using custom Matlab (Mathworks, Natick, MA, USA-01760) programs. The signals were pre-processed to remove 60Hz even though none could be seen. The EOG artefacts were removed with threshold detection. If the EEG recorded had potential greater than absolute 0.5V (after amplification) then that window was neglected considering it an artefact. The micro-switch signal was used as a time reference of the movements. Threshold detection was used to find the time of movements using the rising edge of the micro-switch signal. The signals recorded at different times were synchronized using the micro-switch pulses.

The recordings from concentric ring electrodes were used to calculate the Laplacian potentials for the different concentric ring electrode systems using (1) and (2) with the custom Matlab programs. The formula used to calculate the Laplacian Δp_0 with the bipolar concentric ring electrode is

$$\Delta p_0 \cong (V_o - V_d) \tag{1}$$

where V_o is the voltage on the outer ring and V_d is voltage on the disc. The formula used for calculating the Laplacian Δp_0 using the tri-polar concentric ring electrode [3-4].

$$\Delta p_0 \cong 16(V_m - V_d) - (V_o - V_d) \tag{2}$$

where V_o and V_d were previously defind and V_m is the voltage on the middle ring.

The EEG and LEEG were divided into windows of 1 sec (499 ms before and 500 ms after the movement). For each subject and electrode system, approximately 150 artefact free trials were ensemble averaged for each location to form the MRPs.

B. Mutual Information:

MI was used to measure the interdependency between different locations of each electrode systems analyzed. The signals at each location were normalized as it modulates between 0 and 1. $X_i(t)$ is the tth sample from ith channel. The i ranged from 1 to 7 and averaged from five sets of recordings. A binned process technique [13] was used for calculating MI with a custom Matlab programs. MI was calculated using (4) between the different locations of each electrode system. Each location was partitioned into 16 bins.

$$I(X_i,X_j) \approx I_{binned}(X_i,X_j) = \sum_{kl} p(k,l) \log \frac{p(k,l)}{p_{x_i}(k) p_{x_j}(l)} \quad (4)$$

where $p_{x_i}(k) = \int_k dx_i \mu_{x_i}(x_i)$, $p_{x_j}(l) = \int_l dx_j \mu_{x_j}(x_j)$, and $p(k,l) = \int_k \int_l dx_i dx_j \mu(x_i, x_j)$ and $\int_k$ means the integral over bin k. $p_{x_i}(k)$, $p_{x_j}(l)$ and $p(k,l)$ were calculated by (5), (6) and (7).

$$p_{x_i}(k) = n_{x_i}(k)/N \quad (5)$$

$$p_{x_j}(l) = n_{x_j}(l)/N \quad (6)$$

$$p(k,l) = n(k,l)/N \quad (7)$$

where $n_{x_i}(k)$ is the number of points falling into the kth bin of X_i, $n_{x_j}(l)$ is the number of points falling into the lth bin of X_j, $n(k,l)$ is the number of points within their intersection, and N is the total number of points in a window.

First, the MI between the seven locations recorded concurrently was calculated. This was performed 5 times since the 35 locations were recorded seven sites at a time. Then the grand MI average for each electrode system was calculated for each subject. The MI grand averages were tabulated for each electrode system and subject. The MI of the three electrode systems were then compared using a single factor ANOVA and Bonferroni tests.

III. Results

A. MRP signals:

The MRP signals recorded from the CZ location for a typical subject are shown in Fig 3. The time of the post movement peak was similar to what Gerloff et al. [11] observed at approximately 150±17ms after the micro-switch closure for all subjects. Time zero is the rising edge of the micro-switch signal.

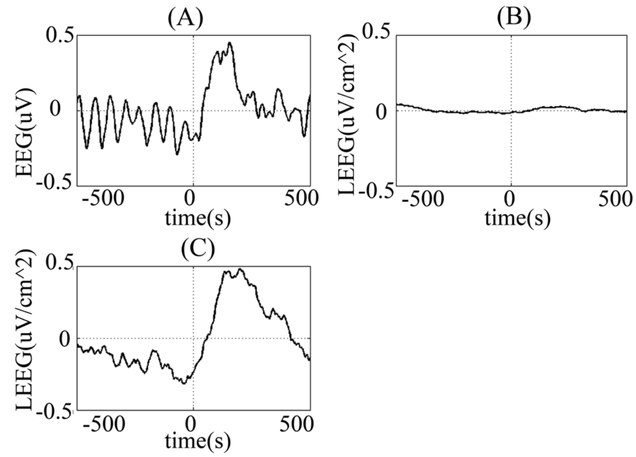

Figure 3. MRP signals recorded from CZ for different electrode systems. (A) Conventional disc, (B) bipolar and (C) tri-polar concentric electrodes.

B. Mutual Information:

The MI between each location for the three electrode systems were calculated with a custom Matlab program using (4). The grand averages of the MI for each electrode system were shown in Table 1. The range of MI for MRP signals from conventional disc electrodes are similar to the MI reported by Date [10]. The MI data were analyzed using a single factor ANOVA, and Bonferroni tests were also performed. The MI for tri-polar concentric ring electrodes was significantly less (p=0.0162) than the MI of bipolar concentric ring electrodes and, conventional disc electrodes (p=1E-5).

IV. Discussion

The Bonferroni statistical tests performed on the MI results showed a significant decrease in MI of MRP signals recorded with tri-polar concentric ring electrodes as compared to other electrode systems tested. The significance in the decrease of MI may be increased further by increasing the number of channels recorded concurrently. Due to instrumentation limitations only seven locations could be recorded concurrently. In the future improvement in the instrumentation for these tests could be repeated with more locations recorded concurrently. The decrease in MI increases the total information available by pooling of data from all independent electrodes. The increase in information from the tri-polar concentric ring electrodes can be achieved without increasing the number of electrodes and complexity of the system. By decreasing mutual information, classification should be improved, and brain computer interface (BCI) systems can be improved without a significant increase in cost.

TABLE I Mutual information (MI) for diferent electrode systems

	Disc	*Bipolar*	*Tri-polar*
Subject1	0.226	0.050	0.017
Subject2	0.307	0.061	0.022
Subject3	0.217	0.062	0.022
Subject4	0.307	0.093	0.024
Subject5	0.272	0.062	0.021
Average	*0.266*	*0.066*	*0.021*

V. Conclusion

The MI for the signals recorded from tri-polar concentric electrodes was significantly less than MI for the signals from bipolar concentric and conventional disc electrodes. These findings should be useful for the EEG field as well as BCI machines.

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