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Improvement of spatial selectivity and decrease of mutual information of tri-polar concentric ring electrodes

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Abstract

Electroencephalography (EEG) signals are spatio-temporal in nature. EEG has very good temporal resolution but typically does not possess high spatial resolution. The surface Laplacian enhances the spatial resolution and selectivity of the surface electrical activity recording. Concentric ring electrodes have been shown to estimate the surface Laplacian directly with significantly better spatial resolution than conventional electrodes.

For this report movement-related potentials (MRP) signals were analyzed. The signals were recorded using tri-polar ring electrodes in the original configuration as well as in bipolar and unipolar configurations achieved by excluding or shorting recording surfaces of the tri-polar version, respectively. The electrodes were placed in an array scheme of 35, encompassing the area between Fz-Cz-Pz-P3-T5-T3-F7-F3 centered on C3. Data were measured in five steps sequentially using only seven electrodes at a time, displaced after each step and aligned during evaluation later. Subjects were cued to press a micro-switch. The signal-to-noise ratio (SNR), spatial selectivity, and mutual information (MI) of the MRP signals recorded with the different electrode systems were compared.

The MRP signals recorded with the tri-polar concentric ring electrode system have significantly higher SNR than from bipolar concentric ring electrode and conventional disc electrode emulations. The tri-polar electrodes have also shown significantly higher spatial selectivity as well as significantly less mutual information between locations than the other two electrode configurations tested. These characteristics should make tri-polar concentric electrodes beneficial for EEG applications.

Keywords: EEG; Movement-related potentials (MRP); Electrode; Spatial selectivity

1. Introduction and background theory

Brain activity is a spatio-temporal process and it is imaged by the phenomenon of electrical potentials on the scalp surface, called electroencephalogram (EEG). Hans Berger recorded the first human EEG in 1924. Today, EEG is still an important non-invasive method for investigating activity of the brain and easier to use than the alternative magnetoencephalography (MEG). The EEG equipment is not very expensive and gives sufficient temporal resolution to study the functioning of the brain. However, EEG has limited spatial resolution and selectivity.

Recently, there has been some significant advance in the field of EEG, despite the increasing application of brain analysis with imaging methods like fMRI. One such advancement is the application of surface Laplacian to 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 (He, 1999; He et al., 2001). 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 (Besio et al., 2006a,b). Concentric ring electrodes also act as spatial filters which depend on the number of rings and weights (Farina and Cescon, 2001) given to the concentric rings and these spatial

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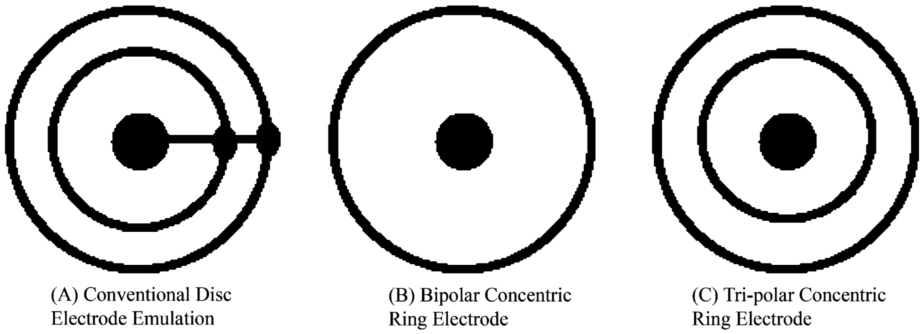

Fig. 1. Different electrode systems evaluated. (A) Conventional disc electrode emulation, (B) bipolar concentric ring electrode, and (C) tri-polar concentric ring electrode.

filtering characteristics increase the spatial selectivity (Klug et al., 1997).

The Laplacian potentials for bipolar and tri-polar concentric ring electrode systems (Fig. 1), Laplacian EEG (LEEG), were calculated by the formulas (1) and (2), respectively.

The formula used to calculate the Laplacian Δp_0 with the bipolar concentric ring electrode is

$$\Delta p_0 \cong V_\mathrm{o} - V_\mathrm{d} \qquad (1)$$

where V_o is the voltage on the outer ring and V_d is voltage on the center disc. Eq. (2) is the formula for calculating the Laplacian Δp_0 using the tri-polar concentric ring electrode (Besio et al., 2006a,b):

$$\Delta p_0 \cong 16(V_\mathrm{m} - V_\mathrm{d}) - (V_\mathrm{o} - V_\mathrm{d}) \qquad (2)$$

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

This paper discusses the use of the different electrode systems shown in Fig. 1, (A) conventional disc electrode emulation, concentric ring (B) bipolar and (C) tri-polar electrodes for recording movement-related potentials (MRP) signals. The MRP can be measured via EEG techniques when movements such as pressing a micro-switch are repeated. MRP are very helpful in analyzing motor control in basic research, neurological investigations, rehabilitation, sport sciences etc. because they reflect the central component of motor activity. The MRP signals were used to compare the spatial selectivity, signal-to-noise ratio (SNR), and mutual information (MI) for tri-polar and bipolar concentric ring electrodes, and conventional disc electrode emulation.

2. Methods

2.1. Data acquisition

2.1.1. MRP recording basic design

For each part of the study male subjects were volunteers who gave informed consent and the experiments were conducted in accordance with the IRB approved protocol. All five right-handed subjects involved in the experiment were free of any known neurological disorders and their age ranged from 24 to 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 as briskly as possible when a metronome was cued, and EEG signals were recorded continuously during the experiment. The subjects were asked to close their eyes to reduce the electroocculogram (EOG) artefact. These MRP recording methods followed previously disclosed methods for recording fast repetitive movement signals from the brain (Gerloff et al., 1997; Kopp et al., 2000).

The scalp of the subject was prepared once and the electrodes were placed and used consecutively for conventional disc electrode emulation, bipolar and tri-polar concentric ring electrodes. The order that the electrode configurations were recorded from was randomly assigned. Thirty-five locations were recorded using seven conventional disc electrode emulations placed over the left hemisphere of the brain in a 5 × 7 array encompassing the area bounded by Fz-Cz-Pz-P3-T5-T3-F7-F3. The placement of the electrodes was based on a 10/20 system as shown in Fig. 2. Due to the lack of instrumentation with ultra-low noise input and high input impedance for recording 35 locations, 70 channels at a time, the recordings were taken seven locations at a time and synchronized later with the time reference from the hardware-debounced micro-switch. The center of the array was positioned

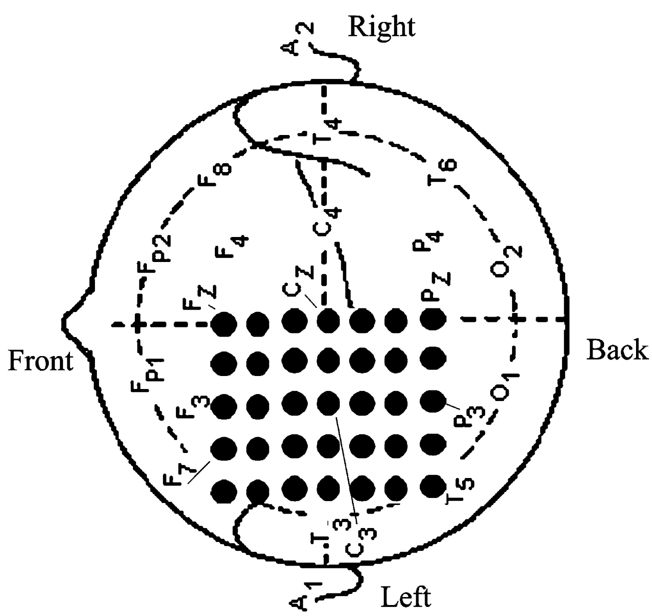

Fig. 2. Placement of electrodes shown on the left hemisphere of the head according to 10/20 international system.

on the line joining P3 and F3, and the inter-electrode distance was 2.0 cm. The reference electrode was placed near the earlobe on the contralateral side, i.e. right side compared to the electrodes. The recordings were taken by referencing each electrode to the reference electrode. The skin-to-electrode impedance was checked before each experiment and kept below 10 kΩ, usually around 2 kΩ.

Custom-built pre-amplifiers (gain 100) along with a Grass 15LT Bipolar Portable Physiodata Amplifier System with high performance P511 AC amplifiers were used for a total gain of 20 K. The filters were set from 0.3 to 30 Hz. This cascade was necessary, since the signals acquired from the tri-polar electrodes are on the order of 0.5 μV P–P which is too small for the available Grass 15LT Bipolar Portable Physiodata Amplifier System with high performance P511 AC amplifiers. The data were acquired using a data acquisition system (DataQ Instruments, Akron, Ohio, USA-44333) with a sampling rate of 250 samples/s per channel. One of the recording channels contained the micro-switch state as a reference of the movement instants.

2.1.2. MRP recording with conventional disc electrode emulation

For this part of the study, conventional disc electrodes were emulated by shorting the outer and middle rings to the center disc of the 1 cm diameter tri-polar concentric ring electrodes; those modified tri-polar electrodes were then used for recording MRP signals.

2.1.3. MRP recording with concentric ring electrodes

The concentric ring electrode recordings were acquired in differential mode, outer ring to center disc and middle ring to center disc for tri-polar and outer ring to center disc for bipolar. As with the emulated conventional disc electrode recordings, the recordings with concentric ring electrodes were also acquired using seven electrodes at a time.

2.2. Data processing

2.2.1. Pre-processing of MRP signals

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 60 Hz even though none could be seen. The EOG artefacts were removed with threshold detection. If the EEG recordings were greater than absolute 0.5 V (after amplification) then that window was neglected considering it an artefact. The micro-switch signal was used to find the time of movements using the rising edge of the 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 EEG and LEEG were divided into windows of 1 s (499 ms before, 500 ms after, and 1.0 ms for the instant the movement was detected). The offset in each signal window was removed by subtracting the mean of the signal window from the signal window. For each subject and electrode system, approximately 150 artefact-free trials were ensemble averaged for each location to form the MRPs.

2.2.2. Calculation of signal-to-noise ratio

The peak signal to noise signal ratio or SNR (Klug et al., 1997) was calculated using (3) for each electrode configuration. The peak signal period was determined as shown by the two vertical dashed lines in Fig. 3; the remainder of the window was considered the noise signal (Klug et al., 1997). The formula used to calculate SNR is

$$\mathrm{SNR} = \frac{E_{\mathrm{peak}}}{E_{\mathrm{noise}}} = \frac{(1/p)\sum_{i=1}^{p} x_i^2}{(1/n)\sum_{j=1}^{n} x_j^2} \qquad (3)$$

where E is the energy, x_i the amplitude of the signal, p the number of points in the peak, and n is the number of points in the noise.

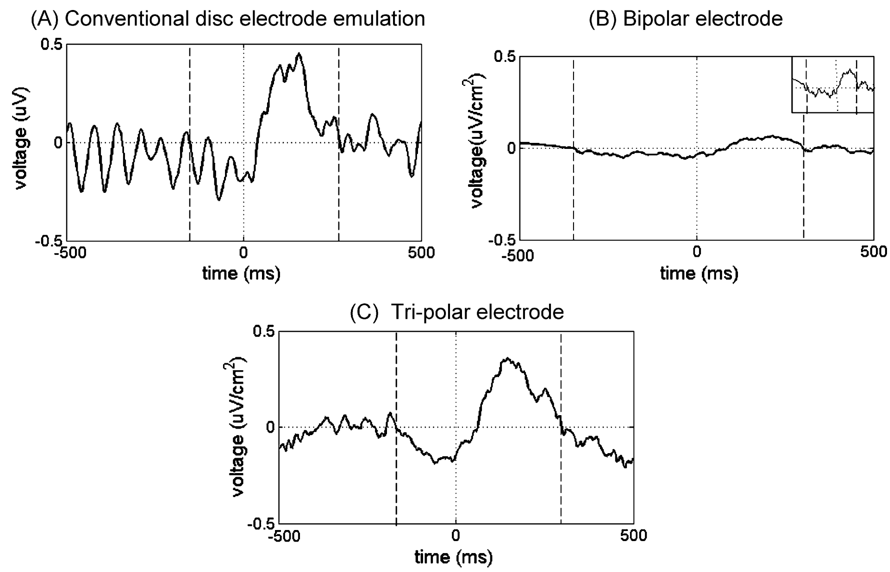

Fig. 3. MRP signals recorded from a single subject from (A) conventional disc electrode emulation, (B) bipolar, and (C) tri-polar electrodes at the CZ position.

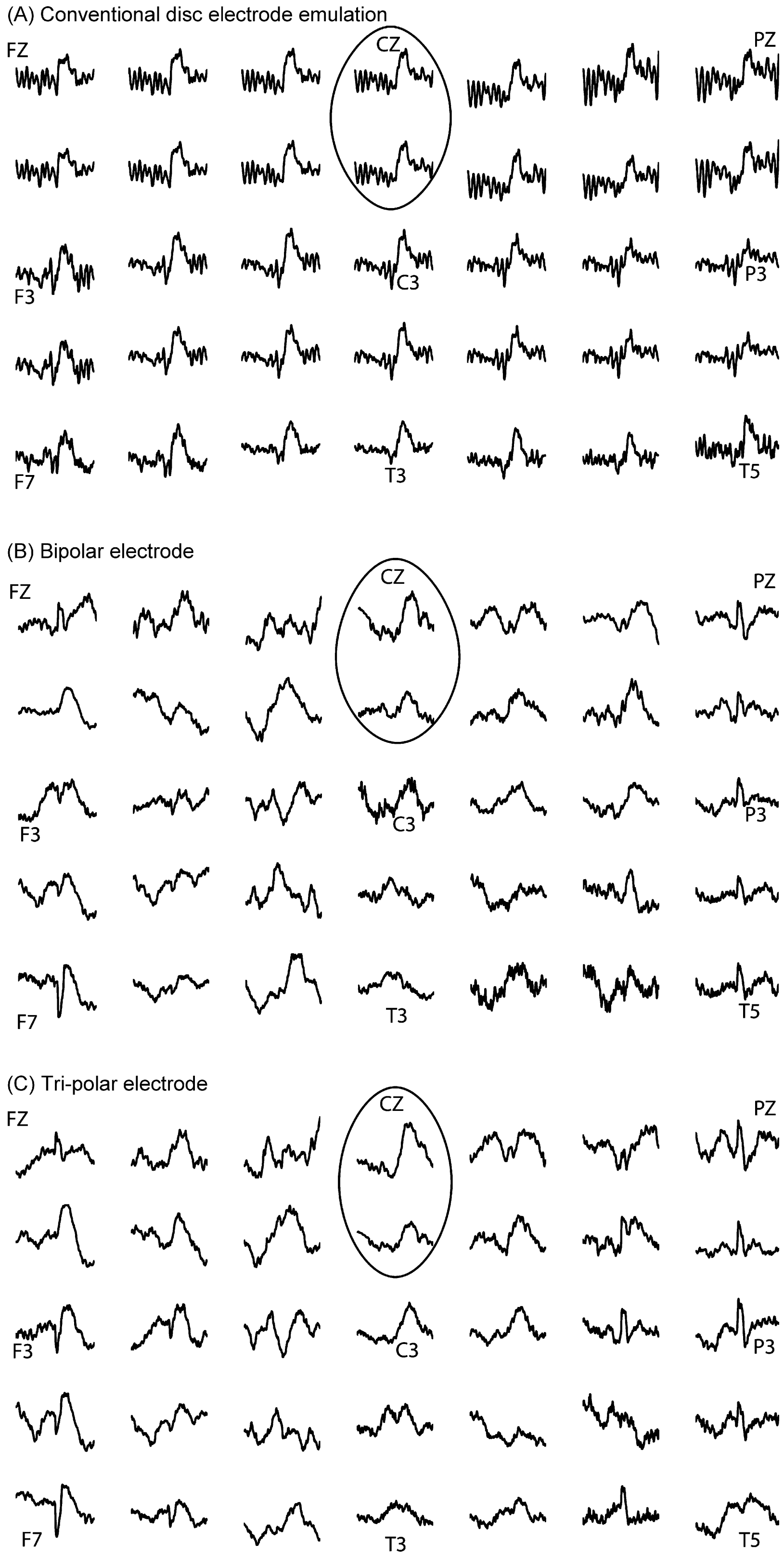

Fig. 4. (A) Two-dimensional map of MRP signals from their corresponding locations. MRP signals recorded from conventional disc electrode emulation. The vertical axis is normalized. (B) Two-dimensional map of MRP signals from their corresponding locations. MRP signals recorded from bipolar concentric ring electrodes. The vertical axis is normalized. (C) Two-dimensional map of MRP signals from their corresponding locations. MRP signals recorded from tri-polar concentric ring electrodes. The vertical axis is normalized.

The SNR of the three different electrode systems for each subject was calculated for the signals at each location, but only the SNRs for location CZ were tabulated. A single factor ANOVA and Bonferroni tests were conducted to compare the SNR of the three electrode systems.

2.2.3. Comparison of spatial selectivity of different electrode systems

The averaged MRP signals from the three electrode systems were plotted in a 2D map corresponding to their locations as shown in Fig. 4A–C. The peak-to-peak potentials of the signal component at each location for each electrode were also calculated. To compare the spatial selectivity, the ratios of the peak-to-peak potentials from each electrode location to each adjacent electrode location were calculated. These peak ratios between adjacent locations to CZ were used as a measure of the spatial attenuation of the electrodes, the spatial selectivity. The peak ratios were averaged for each subject. A single factor ANOVA and Bonferroni tests were conducted on the averaged peak ratios to compare the spatial selectivity of the three electrode systems.

2.2.4. Comparison of mutual information of different electrode systems

To compare the statistical dependence of conventional disc electrode emulation EEG, bipolar and tri-polar concentric ring electrode LEEG, the MI between the signals from each different location was computed. MI is not the same as the correlation coefficient (Kraskov et al., 2004), it is zero if and only if the two random variables are strictly independent. MI can be used on nonlinear data and calculates the level of independency between the channels. Pooling data from independent channels (Date, 2001) increases the total information from whole recordings.

The binned process technique (Kraskov et al., 2004) as calculated with (4) was used to calculate the MI between the signals from each location for each electrode system. Each signal from each location was partitioned into 16 bins:

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

where $p_{x_i}(k) = \int_k \mathrm{d}x_i \mu_{x_i}(x_i)$, $p_{x_j}(l) = \int_l \mathrm{d}x_j \mu_{x_j}(x_j)$, and $p(k,l) = \int_k \int_l \mathrm{d}x_i\, \mathrm{d}x_j \mu(x_i, x_j)$ 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):

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

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

$$p(k,l) = \frac{n(k,l)}{N} \quad (7)$$

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.

Table 1
Averaged SNR for conventional disc electrode emulation, concentric ring bipolar and tri-polar electrodes

	Disc	Bipolar	Tri-polar
Subject 1	1.661	2.086	5.899
Subject 2	1.808	2.961	5.793
Subject 3	2.073	2.602	4.136
Subject 4	1.299	3.537	5.534
Subject 5	0.430	2.961	5.793
Average	1.454	2.829	5.431

First, the MI between the seven locations recorded concurrently was calculated. This was performed five 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.

3. Results

3.1. Signal-to-noise ratio

The SNRs were calculated using (3) and are shown in Table 1 for the three electrode systems and all subjects. For a direct comparison the SNRs calculated for MRP signals recorded from the CZ location for all three electrode configurations were used. The MRP signals recorded from the CZ location for a typical subject are shown in Fig. 3. The signals from all three electrode systems are shown with the same Y axis to make the comparison between signals clearer. The inset is added for the bipolar signal since the magnitude is so small compared to the other signals. The time of the post movement peak was similar to what Gerloff et al. (1997) observed at approximately 150 ± 17 ms after the micro-switch closure for all subjects signifying the index finger movement. The SNR data was analyzed using a single factor ANOVA and Bonferroni tests. The SNR of the tri-polar concentric ring electrode signals showed significant improvement ($p = 1.58\text{E}{-6}$) over the SNR of bipolar concentric ring electrodes and conventional disc electrode emulation.

3.2. Comparison of spatial selectivity

The normalized MRP signals for conventional disc electrode emulation are plotted corresponding to their location as shown in Fig. 4A. The normalized MRP signals are shown in Fig. 4B for bipolar electrodes and in Fig. 4C for tri-polar electrodes. The average peak-to-peak ratio was 1.204 for conventional disc electrode emulation, 1.539 for bipolar concentric electrodes, and 3.091 for tri-polar concentric ring electrodes. The Bonferroni tests showed significant improvement ($p = 1\text{e}{-5}$) of the peak ratios obtained from tri-polar concentric ring electrodes over those obtained from conventional disc electrode emulation and bipolar concentric ring electrodes.

Table 2
Averaged MI for conventional disc electrode emulation, concentric ring bipolar and tri-polar electrodes

	Disc		Bipolar		Tri-polar	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Subject 1	0.2262	0.0092	0.0499	0.0019	0.0173	0.0012
Subject 2	0.3072	0.0140	0.0610	0.0027	0.0229	0.0024
Subject 3	0.2172	0.0116	0.0627	0.0030	0.0221	0.0017
Subject 4	0.3074	0.0172	0.0926	0.0035	0.0249	0.0028
Subject 5	0.2723	0.0128	0.0621	0.0024	0.0212	0.0019
Average	0.2661	0.0130	0.0656	0.0027	0.0217	0.0020

3.3. Comparison of MI

Mutual information 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 are shown in Table 2. The range of MI for MRP signals from conventional disc electrode emulation were similar to the MI reported by Date (2001). 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 ($p = 0.0104$) than the MI of bipolar concentric ring electrodes and conventional disc electrode emulation.

4. Discussion

The use of concentric ring electrodes has been shown to have enhanced characteristics over conventional disc electrodes in the past (He, 1999; Farina and Cescon, 2001). Besio et al. (2006a) have shown that tri-polar electrodes have higher spatial selectivity than quasi-bipolar, bipolar, and disc electrode configurations by computer modeling and phantom experiments conducted in a saltwater tank to verify the computer models. Both methods used single conductivity medium. Further comparisons were performed between tri-polar concentric ring electrodes and bipolar concentric ring electrodes as well as conventional disc electrode emulation. In each of the three measures of comparison used, SNR, spatial selectivity, and MI, the results from the tri-polar concentric ring electrodes were significantly better than the bipolar concentric ring electrodes and conventional disc electrode emulation.

The improvement in SNR was expected as the nine-point method and tri-polar concentric ring electrodes have higher attenuation of global signals, and this attenuation improves the spatial selectivity (Besio et al., 2006a,b). Improved spatial selectivity sharpens the peaks of the MRP signals (Klug et al., 1997). Even though only the SNRs at location CZ were shown in tabular form, the SNR at all locations were calculated and signals from tri-polar concentric ring electrodes had significantly higher SNR than the signals from the other electrodes at all other locations as well. The SNR measure used Eq. (3) (Klug et al., 1997) may be sensitive to offset not blocked by the 0.3 Hz high pass filter. If an electrode configuration that we tested was prone to high offset, the SNR measured would be low.

The increase in spatial selectivity can be observed by comparing the MRP signal maps of Fig. 4. The MRP signals recorded with tri-polar concentric ring electrodes have sharper peaks than the bipolar concentric ring electrode signals and conventional disc electrode emulation signals, in particular if you compare the CZ signals. The MRP signals obtained with tri-polar concentric ring electrodes show more spatial selectivity than the bipolar concentric ring electrodes and conventional disc electrodes emulation. This can be observed visually by comparing how sharply the magnitude of the signals recorded from the different electrode systems decreases compared to its neighbors. For the conventional disc electrode emulation there isn't much difference in magnitude noted through out the entire map of 35 locations. For signals recorded with bipolar concentric ring electrodes, the changes in the magnitudes of the MRP signal can be observed at location CZ and its neighbors which all have less magnitude. For the tri-polar concentric ring electrodes the changes are more evident. Comparing the magnitude of the peak at location CZ to its neighbors there is a large change.

The peak signals ratios were used to measure the sharp attenuation. The increased peak ratio shows the higher spatial attenuation for off-center signals for tri-polar concentric ring electrodes over bipolar concentric ring electrodes and conventional disc electrode emulation. The increased spatial attenuation of off-center signals or global signals will increase the spatial selectivity of the tri-polar concentric ring electrodes to sources below the center of the electrode.

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 improved further by increasing the number of channels recorded concurrently. Due to instrumentation limitations only seven locations could be recorded concurrently. With future improvement of the instrumentation, 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. An increase in information can be expected from the tri-polar concentric ring electrodes without increasing the number of electrodes and complexity of the system. By decreasing mutual information, classification should be improved with less electrodes. The decrease in electrodes should reduce the cost and complexity of EEG acquisition for ambulatory EEG based BCI systems (Lan et al., 2005).

To summarize our findings, the SNR, spatial selectivity, and MI were all found to be significantly better for signals from tri-polar concentric ring electrodes over signals from bipolar concentric and conventional disc electrode emulation. These improvements should be beneficial for the field of EEG.

5. Critical comments on experimental methods

The mechanical micro-switch onset signal was used as a reference to synchronize and ensemble average our EEG signals recorded in five different trial blocks. Fluctuating switch delays within a trial block will cause blurring of the MRP due to the averaging. Variations from block to block (maybe due to fatigue) in the sequential recording due to changing the recording sites of the seven electrodes will affect the time relations of the corresponding MRP in plots like those of Fig. 4A–C. Therefore, particular attention was paid to obtain this reference as accurate as possible. The output of the switch was electronically debounced using a latch circuit to prevent more than one pulse out of the micro-switch when the subject pressed it. Also, the subjects were asked to press the switch as briskly as possible when they heard the audio cue in an attempt to limit variability of the finger movement speed and, in turn, different response delays until switch closure (inevitably there must be some variation in these finger movements). When considering the possible effects of switch closure time variations, also the accuracy limit due to the sampling rate must be taken into account. This problem can be avoided by recording all EEG channels concurrently, which was not possible with the equipment available for this study.

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