Coherent source and connectivity analysis on simultaneously measured EEG and MEG data during isometric contraction*

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Abstract— **The most well-known non-invasive electric and magnetic field measurement modalities are the electroencephalography (EEG) and magnetoencephalography (MEG). The first aim of the study was to implement the recently developed realistic head model which uses an integrative approach for both the modalities. The second aim of this study was to find the network of coherent sources and the modes of interactions within this network during isometric contraction (ISC) at (15-30 Hz) in healthy subjects. The third aim was to test the effective connectivity revealed by both the modalities analyzing them separately and combined. The Welch periodogram method was used to estimate the coherence spectrum between the EEG and the electromyography (EMG) signals followed by the realistic head modelling and source analysis method dynamic imaging of coherent sources (DICS) to find the network of coherent sources at the individual peak frequency within the beta band in healthy subjects. The last step was to identify the effective connectivity between the identified sources using the renormalized partial directed coherence method. The cortical and sub-cortical network comprised of the primary sensory motor cortex (PSMC), secondary motor area (SMA), and the cerebellum (C). The cortical and sub-cortical network responsible for the isometric contraction was similar in both the modalities when analysing them separately and combined. The SNR was not significantly different between the two modalities separately and combined. However, the coherence values were significantly higher in the combined modality in comparison to each of the modality separately. The effective connectivity analysis revealed plausible additional connections in the combined modality analysis.**

I. Introduction

The modalities EEG and MEG are the two neuronal activity recording techniques which has a high temporal resolution. In previous studies [1-2], the combination of both the modalities has shown substantial advantage over each of them alone. The implementation of the piece-wise approximation for the realistic head model has shown advantages over the simple boundary element method (BEM) when both modalities are measured simultaneously [3-4]. The central networks involved in the isometric contraction are well defined in EEG [5] and MEG [6] when analyzed separately. The beta rhythm seems to a play an important role in the information processing of the sensorimotor system for isometric contraction. It is principally located in the region of primary sensory motor cortex, supplementary motor areas and cerebellum [7]. The coherent source analysis approach has been clearly shown earlier that EEG is capable of detecting the oscillatory network of sources in the beta band [8]. However, the direct comparisons between the two modalities and the combination of the two are lacking in applying such coherent source analysis. The effective connectivity analyses have been tested for other hand movement tasks in one of the modalities separately [8]. To detect the coherent central network we first estimated the coherence between the simultaneously recorded 128-channel EEG with 306 MEG sensors and first dorsal interosseous (FDI) muscle and performed coherent source analysis (DICS) [9]. In the following step we estimated the effective connectivity using the renormalized partial directed coherence (RPDC) [10]. In the present study we could directly compare both the modalities separately and combined on three different factors namely the coherent network revealed, SNR and the effective connectivity.

II. Methods

A. Data Acquisition

In this study eight female and seven male healthy volunteers participated. The subjects were seated in a comfortable chair in a slightly reclined position. Both forearms were supported by firm arm rests up to the wrist joints. The subjects were asked to keep their eyes open and fixed on a point about 2 m away. Muscle activity was recorded by surface EMG from forearm extensors and above the first dorsal interosseus (FDI) muscle using silver chloride electrodes. MEG and EEG were recorded simultaneously with an Elekta Neuromag system. The EEG data was recorded with 128 electrodes, the MEG data from 306 sensors. Individual recordings were of 4 to 5 minutes duration. In this task, the subjects kept a constant medium-strength isometric contraction (ISC) of the FDI muscle.

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The simultaneous recording of MEG, EEG and EMG were sampled at 1000 Hz and band-pass filtered (EMG 30-200 Hz; EEG 0.05-200 Hz). EMG was full-wave rectified; the combination of band-pass filtering and rectification is the common demodulation procedure for tremor EMG [11]. Each record was segmented into a number of 1s - long high-quality epochs (L) discarding all those data sections with visible artifacts. For each task, depending on the length (N) of the recording and the quality of the data, between 250 to 260 1-s segments (M) were used for analysis such that N = LM.

B. Realistic head models

The realistic head models were implemented in this study based on the linear-collocation 3-layer boundary element method (BEM) model [12]. The main idea of this approach is developed based on the integrated analysis of both the modalities simultaneously [13]. The first step involved in implementing this model is to construct a realistic shaped BEM model for MEG. We localize then the neuronal source dipoles using non-linear optimization, and obtain the tangential components followed by the radial orientation of the source using MEG alone for different conductivity values. The second step is to implement a piece-wise homogeneous realistic shaped BEM model based on the individual MR images and the individual electrode locations. For MEG sensors the locations were recorded automatically by the Neuromag system and the EEG sensor positions were measured by a Polhemus system. By varying the $\rho_{brain}(= \rho_{scalp})$ and ρ_{skull} systematically and independently, we can estimate a set of conductivity-sensitive EEG forward gain matrices using the source location from step 1.

In the third step, we obtain the best fitting dipole moment parameters through a linear-fitting of the EEG data using the gain matrices from step2 for different conductivity values. In the fourth step, for each dipole we calculate the difference in tangential dipole moments between the ones obtained from EEG in step 3 for each particular combination of the $\rho_{brain}(= \rho_{scalp})$ and ρ_{skull}, and the tangential components obtained from the MEG in step1 to form a two-dimensional table. The goodness of the fit $(gfit) \times 100\%$ of the tangential component can be written as follows:

$$gfit = \left(1 - \frac{\sum_{x=1}^{2} \left(R_x^{EEG}\left(\rho_{scalp}, \rho_{skull}\right) - R_x^{MEG} \right)^2}{\sum_{x=1}^{2} \left(R_x^{MEG} \right)^2} \right) \quad (1)$$

where the summation in equation (1) is over the two tangential components. The final step is to identify the corresponding radial component from the EEG for which the optimal conductivity combinations were obtained in step 4 for each dipole. The full description of the BEM model for the combined approach is explained in these papers [5, 13].

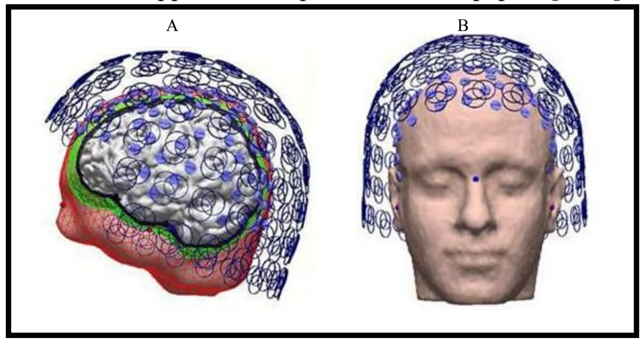

Figure 1. A. shows the realistic head model with the three layers, brain (white), skull (green) and scalp (red). B.shows the skin modelled till the neck with the EEG electrodes and the MEG sensors from one healthy subject.

C. Source analysis

DICS uses a spatial filter algorithm [14] and estimates the tomographic power and coherence maps which are based on the realistic head models shown in figure 1. Since the coherence between the identified areas with it is always 1, this region was considered as noise for the next run in the coherence matrix and further coherent areas were identified [15]. The spatial filter was applied to a large number of voxels covering the entire brain, assigning to each voxel a specific value of coherence to a given reference (EMG) signal for the individual beta frequency band. A voxel size of 5 mm was used in this study. In a further analysis, all the original source signals for each source with several activated voxels were combined by estimating the second order spectra and employing a weighting scheme depending on the analyzed frequency range to form a pooled source signal estimate for every source as previously described [16]. This analysis was performed for each subject separately, followed by a grand average across all subjects. The full description of the DICS for the combined approach is explained in this previous paper [5, 9].

D. Renormalized partial directed coherence (RPDC)

To find the effective causality between two signals, the method called renormalized partial directed coherence was used [10]. The pooled source signals were modelled using the autoregressive process to estimate the coefficients of the signals in the beta frequency band (15-30 Hz) with a multivariate approach. The estimation of the RPDC (R) values between two signals x and y at a specific frequency f can be written as:

$$\left| R_{x \leftarrow y}(f) \right| = \frac{A_{xy}(f)}{\sqrt{\sum_k \left| \hat{A}_{xy}(f) \right|^2}} \quad (2)$$

In order to obtain the coefficients A_{xy} the optimal order needs to be chosen which are estimated by minimizing the

Akaike information criterion (AIC) [17]. The bootstrapping method was used to calculate the significance level on the applied data after the estimation of the RPDC values. The full description of the DICS for the combined approach is explained in this previous paper [5, 10].

E. Statistical analysis

The significance of the sources were tested by a within subject surrogate analysis. The surrogates were estimated by a Monte Carlo random permutation 100 times shuffling of one second segments within each subject. Estimated the p-value for each of these 100 random permutations and the 99th percentile value of each source of all these permutations is taken as the final threshold. The voxel co-ordinates with the maximum coherence were compared within the same modality between the identified sources. A reference voxel for each of the identified sources were determined in the MNI co-ordinate system for the ISC task [primary sensory motor cortex - PSMC: (-59.0, -16.0, 40.0); supplementary motor area – SMA: (-9.0, -3.0, 42.0); Cerebellum – CER: (26.0, -58.0, -45.0)]. The Euclidean distance was estimated between the reference voxel and the maximum coherent voxel. In a further analysis, the Euclidean distance was estimated between the different modalities for each of the sources to identify the difference in location for each of these sources (e.g. EEG vs. MEG; EEG vs. EEG+MEG; MEG vs. EEG+MEG). The source coherence values (n=15, α = 0.01) for each of the modalities were tested for significance using the non-parametric Friedman two-way analysis of variance with two factors, the first factor being the sources (n=3 sources) and the second factor being the modalities (n=3: EEG, MEG, MEG+EEG). The RPDC values (n=15, α = 0.01) between the source signals were tested for significance using the non-parametric Friedman two-way analysis of variance with two factors, the first factor being the connections of the source signals (n=3 connections: EEG and MEG); (n=5 connections: MEG+EEG) and the second factor being the modalities (n=3: EEG, MEG, MEG+EEG). The Bonferroni correction was performed for all the post-hoc tests which involved multiple comparisons.

III. Results

A. Coherence and network of sources

Power spectral analysis on the EMG activity of all the subjects showed a dominant peak at the beta frequency (range 15-30 Hz; mean: 20.8±4.41) in this task. At this frequency all subjects exhibited significant coherence between FDI EMG electrode and EEG electrodes covering the region of the contralateral sensorimotor cortex.

For all the modalities EEG, MEG and combined the network for the beta frequency consisted of the PSMC, SMA and CER as shown in the group statistics maps of the healthy subjects (Figure 2). All the identified sources were statistically significant (p = 0.007) in a Monte Carlo random permutation test across all subjects within each modality. For the between subjects same modality test the Euclidean distance of the sources with the reference were not statistically different PSMC (EEG-p=0.56; MEG-p=0.22; MEG+EEG-p=0.34); SMA (EEG-p=0.75; MEG-p=0.45; MEG+EEG-p=0.62); CER (EEG-p=0.81; MEG-p=0.54; MEG+EEG-p=0.42). Thus, this test indicated the location of the identified sources were not significantly different between the subjects. In a further step, we tested the Euclidean distance for within subject's using different modalities. All the comparisons between the modalities showed no significant difference EEG vs. MEG (p=0.39); EEG vs. MEG+EEG (p=0.52); MEG vs. MEG+EEG (p=0.61). This test indicated the different modalities located the sources at the same location either when used separately or combined. The source coherence values for all the cortical and sub-cortical sources the combined (MEG+EEG) approach had significantly higher (p=0.005) coherence values compared to the other two modalities. In the comparison between EEG and MEG, EEG had significantly higher coherence values for the identified three sources (p=0.006). These results indicated all the approaches produces the optimum results except a significant difference in the coherence values.

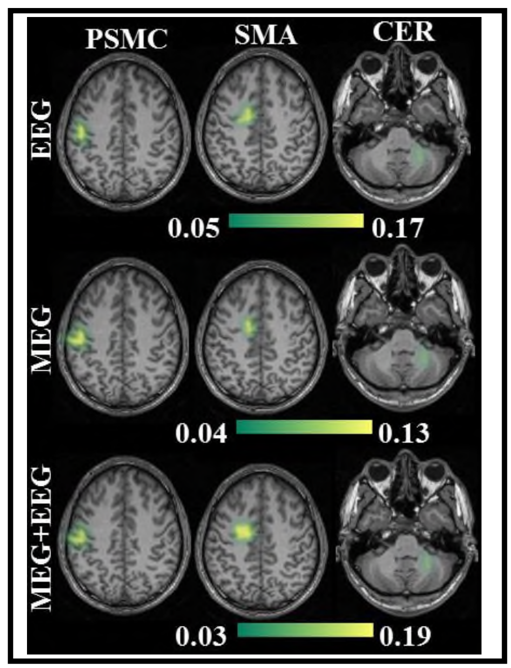

Figure 2. The grandaverage from all 15 healthy subjects. The network comprises of primary sesnory motor cortex (PSMC), supplementary motor area (SMA) and cerebellum(CER) for all the three modalities.The colorbar indicates the minimum and maximum coherence values in each modality.

B. Effective connectivity

All the modalities showed a similar interaction pattern of significant (p=0.004) bidirectional connection between the PSMC and CER. The interaction between PSMC and SMA was significant unidirectional information flow in the modalities EEG (p=0.003) (Figure 3) and MEG (p=0.006) (Figure 3). However, in the combined approach there existed an additional significant bi-directional connection between the CER and SMA. In the between subject factor analysis, the combined approach (MEG+EEG) (Figure 3) and EEG showed significantly higher RPDC values (p=0.008; p=0.007) in comparison to the MEG.

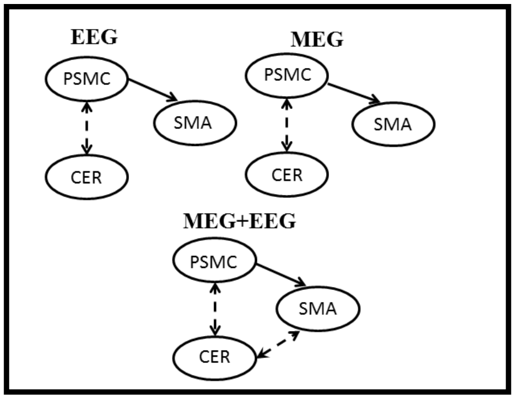

Figure 3. The effective connectivity from all 15 healthy subjects. The modalities EEG and MEG separately showed similar connections whereas the combined modality showed additional bi-directional connection between the CER and SMA.

IV. Discussion

In this task, the three modalities showed a similar network of activation with the involvement of PSMC, SMA and CER. In earlier EEG/MEG studies [6, 9] the 15-30 Hz coherence is found during isometric contraction and also represented in the primary sensorimotor cortex. In certain FMRI studies other areas like the cerebellum were also depicted during the isometric contraction [18-19]. In a combined EEG-FMRI study [20] all these areas in the brain were identified as part of the network. The network of information flow in the isometric task has not been well analyzed before using either of these modalities. The connections were similar between EEG and MEG, and the combined approach for the primary sensory motor cortex and CER. The only difference was the interaction between the SMA and the CER in the combined approach which showed a bidirectional connection which was not seen in either of the modalities alone. This connection has not been previously described but it can be hypothesized has to maintain a standard voluntary contraction the CER and the secondary motor centres constantly transform information between them, in order to withheld the strength of contraction.

In conclusion, the effective connectivity between the sources in the brain benefits from measuring simultaneously both these modalities. The combination of both these modalities and the usage of all the available electrodes/sensors give the optimum spatial resolution, and also indicated coherence could be a useful parameter for identifying the network of sources involved in an voluntary motor task.

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