INDEPENDENT COMPONENT ANALYSIS OF MAGNETOENCEPHALOGRAPHY DATA

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Abstract- **Independent Component Analysis (ICA) is applied to the Magnetoencephalography (MEG) data of a subject performing a yoga breathing exercise specific for the treatment of obsessive compulsive disorder. The spatio-temporal dynamics observed using a whole-head 148-channel MEG instrument are split into the fundamental modes, thus isolating separate brain activity signals. Experiments were performed on data from different brain regions. Spectral analysis of the more significant signals are presented. Moreover a new tool is developed as a Matlab toolbox to support the scientist both in the visualization and computation phases.**
***Keywords* – Magnetoencephalography, Independent Components Analysis, Spectral Analysis.**

I. INTRODUCTION

Various bioelectric signals are routinely recorded in modern clinical practice and new state-of-the-art monitoring equipment presents the engineer with new challenges for data analysis. This is especially true for the complex bioelectric and magnetic sources generated by the brain. The main advantages of using the magnetoencephalogram are that the brain and overlying tissue can be characterized as a single medium having constant magnetic permeability. Therefore the magnetic field (unlike the electric field) is not influenced by the shell-like anisotropic inhomogeneities surrounding the brain [1]. Moreover, the MEG measurement is indirect and does not require surface electrodes.

A major challenge for MEG data is the analysis and characterization of the spatio-temporal patterns [2,3,4]. Many different signals are simultaneously being generated from different brain regions and all interact in a complex manner. This suggests a need to be able to isolate and characterize both the stronger and weaker signals [3,4,5,6].

The focus of this paper is towards a more global understanding of the MEG data obtained using a 148-channel whole-head Magnes 2500 Biomagnetometer (4-D Neuroimaging, San Diego, California) located at The Scripps Research Institute (La Jolla, CA). MEG signals were recorded with a subject performing a yoga breathing exercise used for the specific treatment of patients with obsessive compulsive disorder [8].

The methodology adopted is based on two steps. The first employs ICA [5,6] with the idea that MEG signals can be thought of as having low dimensional components that can be isolated from the highly complex patterns to yield more fundamental components. This may allow for a second phase where each independent signal can then be better understood for its physical meaning.

Different experiments have been performed that show that ICA offers an interesting approach for reconstructing cortical neuronal activity. First a global analysis (including all the 148 signals) was conducted and then attention was directed to the various ICA modes. In the second step a Fourier analysis of the more significant components was performed, and several suitable filters were also applied.

Moreover a tool was developed to support the scientist in analyzing these signals using this approach. This tool provides an environment for the visualization of temporal series, frequency spectrum, spatio-temporal and Fourier maps, and ICA analyses.

II. A CASE STUDY

The magnitude of the magnetic field associated with the active cortex is extremely low; it is estimated that the magnetic field of the alpha wave is approximately 0.1 pT at a 5 cm distance from the scalp surface. The biomagnetic field associated with the magnetoencephalogram is roughly one hundred million times weaker than the magnetic field of the earth (50 μT). The recent technological advances employing a wide array of Superconducting Quantum Interference Device (SQUID) magnetometers have made measurements of these extremely low-strength magnetic fields possible.

In this application the SQUID magnetometer uses 148 channels. Each of the 148 pick-up coils in this instrument is a 2 cm diameter magnetometer, with a 2.2 cm distance between coils center-to-center. Each coil is connected to a SQUID that produces a voltage proportional to the magnetic field radial to the head, resulting in preferential sensitivity to neural electrical sources tangential to the surface of the scalp, sources emanating from cortical sulci. This MEG system has some advantages over previous instruments. Previous systems used gradiometers, which have the pickup and bucking coils in close proximity to eliminate the contribution of magnetic fields from more distant sources (e.g. heart, nearby electrical equipment).

The current system uses magnetometers with pick-up coils, and a separate noise detection and elimination scheme, which significantly increases the signal-to-noise ratio and improves the ability to detect deeper sources in the cortex. Trained MEG technicians positioned the subject, applied Electro-oculargram leads, and performed head-shape digitization. Only one subject was employed who is highly trained with yogic breathing meditation techniques and as a subject with MEG experimentation. Head-shape was digitized, based on known locations on the subject's head (tragus of left and right ears and nasion). Head shape data is for later co-registration between measurement coil locations, electrode locations, and scalp landmarks. Eye movements were recorded with electrodes placed above and below the right eye. Electrode impedances were set below 5 k-ohms. MEG data was recorded at 250 Hz, with an analog filter band pass of 1 to 100 Hz.

The subject was in a comfortable 45-degree reclining position, with the "helmet" of the MEG system placed around the head. The subject followed a well-practiced protocol [8] that involved 10 min of resting baseline recording, followed by 31 min of selectively breathing through the left nostril (using a plug for the right nostril) at a respiratory rate of one breath per minute (15 sec for each inspiration phase, 15 sec for breath retention, 15 sec for slow expiration, and 15 sec breath held out), again followed by 10 min of resting.

III. ANALYSIS METHODS

The complex nature of the MEG data requires an environment that allows for managing long data series with high sampling rates. This should include a procedure devoted to the visualization of the trends of the signals and for the comparison of multiple channels simultaneously. This can be useful for a first look at the data to establish the strategy to be followed and to separate the spurious parts of the signal that may be experimental artifacts in the data. Successive operations usually deal with frequency investigation. Power spectra are calculated in order to show the distribution of neural activity over different frequencies. Indeed, in some cases it is useful to distinguish the neural activity in the delta (0.1-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (12-20 Hz) or gamma (35-60 Hz) bands that reflect conscious or unconscious *internal processing* related to states as indicated in Table1.

BAND	RANGE	ACTIVITY
DELTA	0.1-4 Hz	DEEP-SLEEP
THETA	4-8 Hz	TOWARDS DEEP-SLEEP
ALPHA	8-12 Hz	AWAKE - RESTING
BETA	12-20 Hz	EMOTIONAL PROCESSING
GAMMA	35-60 Hz	“CONSCIOUS PROCESSING”

Table 1. Neural activity frequency bands.

The emergence of complex behavior in high dimensional systems can be represented by spatio-temporal maps [7] that reflect the temporal evolution of the variables of the system, and where amplitude is encoded with a color bar. Moreover, since the spatial distribution of the scalp channels, shown in Fig. 1, do not allow a mono-dimensional representation for each time instant, but rather invite a collection of two-dimensional frames, spatio-temporal maps have been considered as well as the possibility of building a movie showing frames in succession.

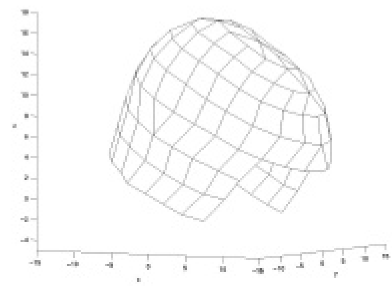

Fig. 1. The “helmet” for MEG recording. The sensors are located at the intersections of solid lines.

As discussed above the complexity of the system investigated does not allow an immediate understanding of the essential features of the neuromagnetic signals, especially when artifacts are present. When using ICA it is possible to estimate brain activity separated from artifacts [5,6]. This approach is based on the hypothesis of statistical independence of the signals, which arise from anatomically and physiologically separated processes.

The main idea underlying ICA is that given a collection of n measurements $x_1,\dots, x_n$ that are supposed linear combination of the n statistically independent non-gaussian original signals $s_1,\dots, s_n$, as follows:

$$x = As \tag{1}$$

it is possible to estimate the signals $s_1,\dots, s_n$ by the relation:

$$s = Wx \tag{2}$$

where W is an estimation of the inverse of the matrix A of unknown elements obtained by a recursive algorithm. Further details can be found in the tutorial [5] and review [6].

Usually two preprocessing techniques are used. First the *centering* is performed to make the x_i zero-mean variables. Then the *whitening* is performed to obtain uncorrelated components with unitary variance, by considering singular value decomposition of the covariance matrix of x. Discarding the singular values that are too small can reduce the dimension of the data.

Once the Independent Components (ICs) of the MEG signals are found, these can be analyzed: in the frequency domain in order to investigate their relations with particular activities, and in a series of experiments in order to illustrate their relations with particular scalp regions, or to investigate if the same ICs set are found starting from a reduced set of initial channels.

These features have been included in a tool developed as a MATLAB toolbox to support the scientist in data analyzes.

IV. RESULTS

In this section the results of the analysis methods described above are illustrated. The aim of these analyses is to find meaningful signals and to correlate them with the activity of the subject when performing the yoga exercise. Thus, the analyses have been repeated for the three exercise phases.

From an analysis of a time series it may be possible to distinguish faulty channels and to make a preliminary analysis showing that channels include artifact.

The time series showed high complex evolutions and a spatial correlation dependent on the distance between the considered coils.

The ICA analysis has been performed to characterize two different aspects, the first related to the spatial distribution of the channels and the second to evaluate the power spectra distribution of each IC to investigate its correlation with a particular human activity.

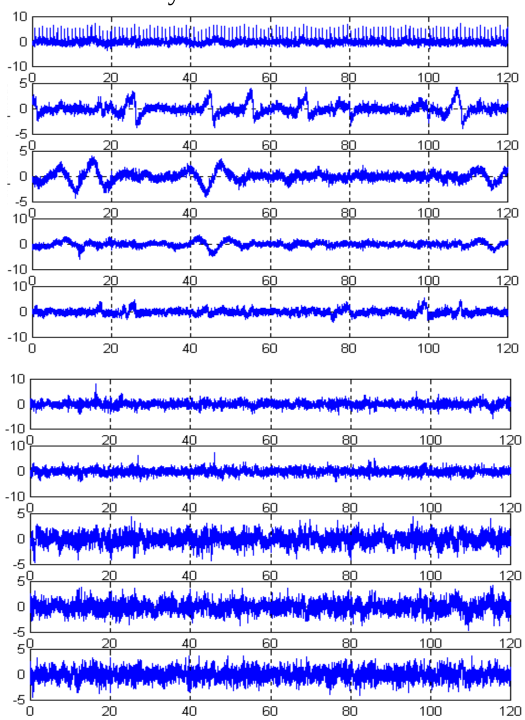

Fig. 2. Trends of two minutes of ICs (rest phase).

A. *Global behavior*

The whole scalp ICA demonstrates different time evolutions during each phase of the yoga exercise.

The criteria for dimension reduction in the whitening phase of the ICA algorithm is that the ratio between the maximum singular value and the smallest retained singular value is greater than 100. In the following, data from two minutes for each phase of the exercise have been analyzed as indicated in Table 2. This table also shows the reduced number of signals to be searched according to the criteria explained above. Since the algorithm does not always converge, the number of signals found can differ as shown in Table 2.

Phase	Minutes	Signals Searched	Signals found
Rest 1	**3°-4°**	**20**	**14**
Exercise	**25°-26°**	**22**	**19**
Rest 2	**45°-46°**	**18**	**14**

Table 2. Minutes analyzed for each phase to perform ICA.

Fig. 2 deals with the first phase of the exercise (3° and 4° minutes) and shows 10 of the 14 ICs.

It is quite difficult to attribute a physical meaning to each signal. The first signal of Fig. 2 has been recognized as cardiac activity with classical peaks at the heartbeat, while some of the other signals show a low frequency activity that could be evoked by artifacts.

The analysis of the time series of the second phase in Fig. 3 (25° and 26° minutes) shows a modulation of the cardiac rhythm as a result of the yoga breathing control exercise.

In order to investigate the physical meaning of the ICs three experiments have been considered:

- *I experiment.* The ICA has been applied to the various regions of the scalp in order to investigate the possible localization of an IC. As a result of such an analysis the IC related to the cardiac activity has been clearly revealed only in the neck region.
- *II experiment.* This second experiment deals with the possibility of considering a reduced set of starting channels. Namely, a high correlation has been observed between neighborhood channels. Thus, only some channels have been considered and the neighbors of these channels have been neglected. A comparison of the result of such an analysis and an ICA applied to the whole set of channels has been performed: some ICs are clearly identical.
- *III experiment.* Studying the complex behavior of high dimensional systems is fundamental for evaluating the invariant characteristics of the systems. In analyzing the ICA we observed that the weight matrix W, that gives the influence of each component related to the channel spatial distribution, are very similar during the exercise phases. The following experiment has been considered: once performed the ICA computations for a minute, the same ICA weight matrix is applied to other minutes to obtain the related ICs without again running the ICA algorithm. The signals obtained in this way are compared to the ones coming from the ICA application. No significant differences have been observed except when there are artifacts present in the data.

B. *Spectral analysis*

The study of the power distribution related to the frequency spectrum constitutes an important approach for characterizing brain activity. As explained previously some bands are more related to specific biological states.

A Fourier analysis was performed for each IC. Fig. 4 shows the Fourier analysis when performed on the IC related to the cardiac activity. The heart activity can be recognized as a peak in the delta band. The modulation of cardiac activity due to the breathing rate of one breath per min is evident in Fig. 3. The peak at 60 Hz is due to frequency of the US power grid.

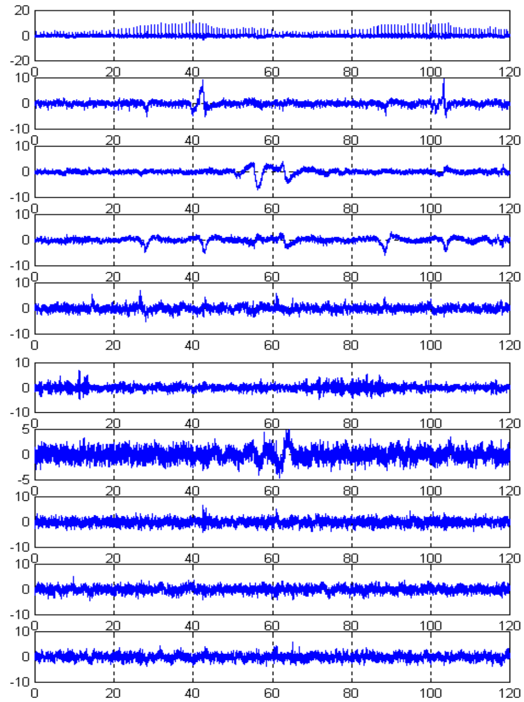

Fig. 3. Trends of two minutes of ICs (exercise phase).

V. Conclusions

The analysis of a recording of MEG data from a subject performing a yoga breathing exercise has been performed by using ICA. The spatio-temporal dynamics obtained from 148 channels has been split into the fundamental parts, thus isolating discrete brain activity signals. A physical meaning has been attributed to a signal showing peaks at the heartbeat frequency and modulated when the subject performs the yoga respiration. Different experiments have been performed in relationship to various brain regions, emphasizing that some ICs are localized in a given scalp region. Moreover a new tool has been developed as a Matlab toolbox to support the scientist both in the visualization of data and in the computation of ICA and other types of analyses.

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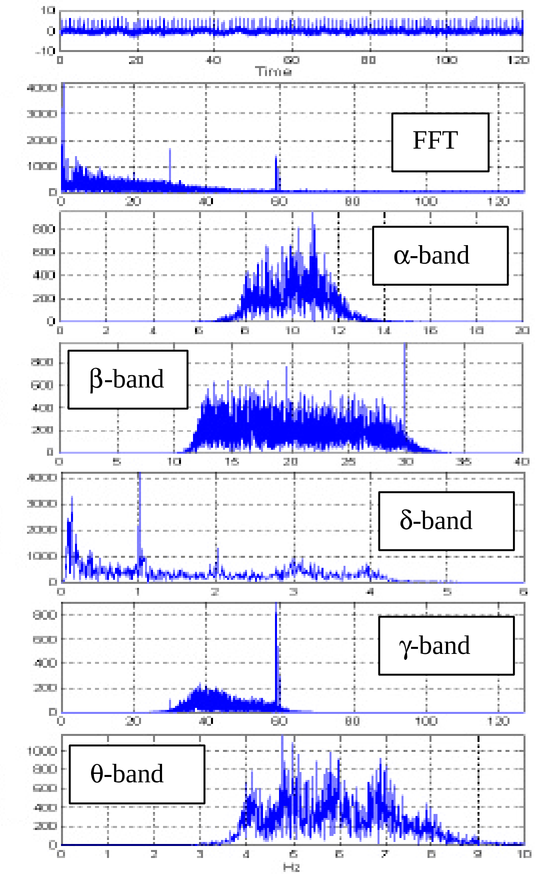

Fig. 4. Trend of the ICA signal modulated by the cardiac activity and Fourier analysis of the signal in the various bands.

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