A Versatile Approach to Detect Coherent Brain Areas with MEG

Belardinelli P.[1,2,3], Ciancetta L.[1,2], Del Gratta C.[1,2,3], Pizzella V.[1,2,3], Romani, G.L.[1,2,3]

[1] ITAB, Institute for Advanced Biomedical Technologies, University G. D'Annunzio, Chieti, Italy;
[2]Department of Clinical Sciences and Biomedical Imaging, University of Chieti;
[3]INFM– National Institute for the Physics of Matter, Coordinated group of Chieti

Abstract— **Understanding the functional connections among different brain areas represents an important challenge in modern neuroscience. The coherence of electric activity is considered to be a hallmark of functional connectivity. In this perspective, the study of coherence among different regions of the brain is an issue of ever growing importance. These studies are usually done in the frequency domain. MEG is a particularly well suited tool for this purpose because of its temporal resolution much higher than that of fMRI. Furthermore, its spatial resolution is better than that of EEG. Starting from the work of Gross et al. [1], LOCANTO (Localization and Coherence Analysis Tool) was conceived. LOCANTO is a new software which features different localization tools for different neurological landscapes. In this way, both localization and coherence results may not be biased by the correlation of multiple correlated sources.**

Keywords— **Localization, Coherence, Frequency Domain**

I. Introduction

A set of localization tools (Loreta and SAM) has been developed to detect the areas characterized by the strongest neural activity for a study on coherent areas which does not call for an external reference signal.
Our approach consists in using a complete tomography such as Loreta in a "blind" localization case (i.e.: if there is no cue about the number of correlated sources) or in the case that the number of correlated sources is known to be higher than two.

II. Methods

Beamformer techniques assume the source time courses to be orthogonal to each other. This implies that all source activities should be uncorrelated. It is known in fact that the spatial filter weight of an adaptive beamformer cannot perfectly block correlated signals. Such a problem causes two major disturbances on reconstruction results:

1) time course distortions
2) reductions in reconstructed signal intensities.

In general, cortical and subcortical activities are supposed to be correlated to a certain degree. Therefore, if we apply adaptive-beamformer techniques, it must be quantified how robust they are to the source correlation, and what kind of influences arise when they are used to reconstruct correlated sources.

Fortunately, if we focus on the case of neuromagnetic signals, it can be shown that, if the sources are only two, the reduction in signal intensity for sources with a medium degree of correlation is small. Also the time-course distortion for such sources may be discernible. The correlation coefficient between two correlated sources can be also estimated using the beamformer outputs. A method for retrieving the original time courses using estimated correlation coefficients has been developed by K. Sekihara [2].
However, when the sources happen to be more than two, it is not clear how much both source intensities reconstruction and time course estimations are affected by this situation.
If a tomography approach like Loreta is used in such cases, one can be sure that no reconstruction of any source will be affected by problems due to the activity of strongly correlated sources.
An isotropic 3D grid of constant step is placed inside a spherical model of the head. The sphere is fitted to reference points on the real head.
The following problem has to be solved at a precise instant in time and/or in the frequency domain (study of cross-spectral matrices):

$$\min_j \| \boldsymbol{BWJ} \|^2 \qquad \text{(I)}$$

under the constraints: (1) $\Phi = \boldsymbol{KJ}$ and (2) $\boldsymbol{RJ}=\mathbf{0}$
where Φ is an N-vector comprised of magnetic field measurements; $\boldsymbol{J} = (\boldsymbol{j}_1^T,...,\boldsymbol{j}_N^T)^T$ is a 3M vector comprised of the current densities **j** (3-vector) at M points with known locations within the brain volume; **K** is a transfer **N**x**3M**-matrix with α-th row $(\boldsymbol{k}_{\alpha 1}^T,...,\boldsymbol{k}_{\alpha M}^T)$, where **k** is the magnetic lead field potential (3-vector); **W** is a diagonal **3M**x**3M** matrix, defined as $\mathbf{W}=\boldsymbol{\Omega}\otimes\boldsymbol{I}$. **I** is the identity 3x3 matrix and Ω is a diagonal **M**x**M** matrix with $\Omega_{ii}=\sqrt{\sum_{\alpha=1}^{N}\boldsymbol{k}_{\alpha i}^T\boldsymbol{k}_{\alpha i}}$.
B represents the laplacian matrix.
Constraint (2) indicates that the radial component of the current density field is silent.

Such an approach holds both in time and frequency domain. The domains are actually dual. In the frequency domain, the source spectrum-reconstruction can also be determined by means of Loreta. This allows an approach similar to the Gross' one, using Loreta instead of Beamforming in the detection of coherent areas. It can be utilized in the most complicated cases. This procedure is much computation-demanding and, therefore, relevantly slower than the Beamformer application. In fact, in order to reconstruct the instantaneous activity power S_i on the *i-th* pont of our grid by means of the Beamformer, the coefficients of **H** minimizing the power have to be found:

$$\mathbf{S}^2_i = [\mathbf{H}_i^{\mathbf{T}}\mathbf{M}]^2 = \mathbf{H}_i^{\mathbf{T}}\,\mathbf{R}\mathbf{H}_i, \qquad \text{(II)}$$

where **R** is the measurement correlation matrix. In practice, the covariance matrix **C** is used instead of the correlation matrix.
The Beamformer coefficient solution is:

$$\boldsymbol{H}_i = \frac{[\boldsymbol{C}+\mu\boldsymbol{\Sigma}]^{-1}\boldsymbol{K}_i}{\boldsymbol{K}_i^T[\boldsymbol{C}+\mu\boldsymbol{\Sigma}]^{-1}\boldsymbol{K}_i} \qquad \text{(III)}$$

where μ is a Backus-Gilbert regularization parameter which is used as a tradeoff threshold between spatial selectivity and uncorrelated noise.
From (II) and (III) it is evident that the Beamformer, differently from Loreta, never uses the entire Leadfield matrix $\boldsymbol{K}$ in the calculations. Therefore it is less computationally demanding.
On the other hand, using Loreta, there is no risk of bias due to source correlation.
In the frequency domain, in order to reconstruct frequency spectra for a study on coherence between different brain areas, the problems to be solved are quiet similar. Using the Beamformer technique, the covariance matrix must be replaced with the cross spectrum density matrix of signals.

III. RESULTS

To test the localization algorithms on real data, 5 trials on right median nerve stimulation data sets were made.
As a result, we got the clear activations in S1 (see Fig. 2) and S2 at the well known latencies reported in literature.

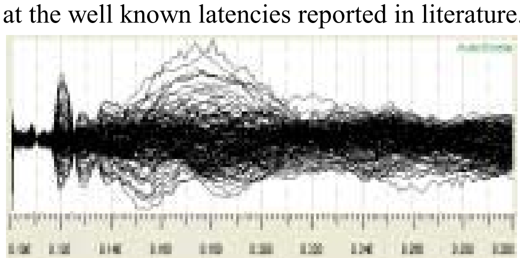

Fig 1: Time spectrum for the magnetic signal generated by the median nerve stimulation

Fig. 2: Localization by means of Loreta of S1 activation with right median nerve stimulation data

Fig. 3: Localization by means of SAM Beamformer of S1 activation with right median nerve stimulation data

As a test for the coherence detection procedure by means of a Beamformer, we calculated the coherence at around 40 Hz (the Piper rhythm) [3] during voluntary contraction of the right forearm in one female subject.
recorded MEG signals over the whole scalp simultaneously with an electromyogram (EMG). The EMG was recorded during repeated isometric contractions of the forearm extensor muscles. The contractions were 6 seconds long. For what concerns the strength, the efforts for the contractions were either maximal, moderate, or weak (with mean rectified EMG levels either 100, 60–80, or 20–40% of those during maximal contraction).
Cortical signals were recorded with the 153 channels helmet shaped neuromagnetometer at ITAB, Chieti.

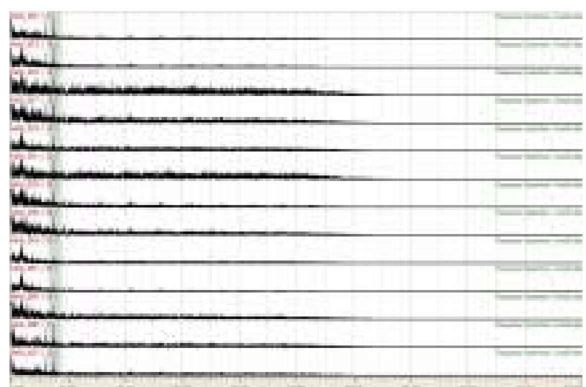

FIG. 4.: Frequency spectrum of magnetic signals detected by channels in correspondence with primary somatosensory cortex and SMA. The outlined frequency band shows that at about 40 Hz there is an amplitude peak as expected from the literature [3]

It is known in fact that the EMG of healthy humans demonstrates a tendency to rhythmic oscillations at around 40 Hz (the Piper rhythm) during strong voluntary contraction. We recorded whole scalp magnetoencephalographic (MEG) signals simultaneously with surface EMG. In the subject, coherence and time domain analyses demonstrated correspondence between the grid points in the contralateral motor cortex as well as in SMA, and the 35- to 45-Hz EMG recorded during repeated maximal isometric contractions of the contralateral forearm extensor muscles. It is concluded that the Piper rhythm in muscle may be driven by a comparable oscillatory activity in the contralateral motor cortex and SMA. This cortical rhythmicity can be picked up in several types of movement.

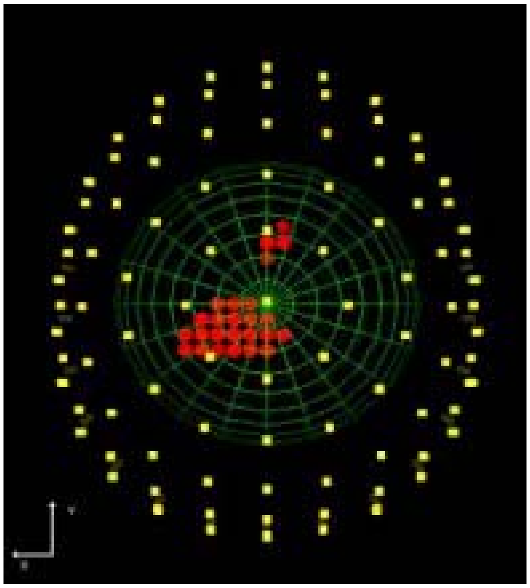

Fig. 5:: Coherence estimates in the 35-45 Hz band with a threshold of 0.7: OVERVIEW.

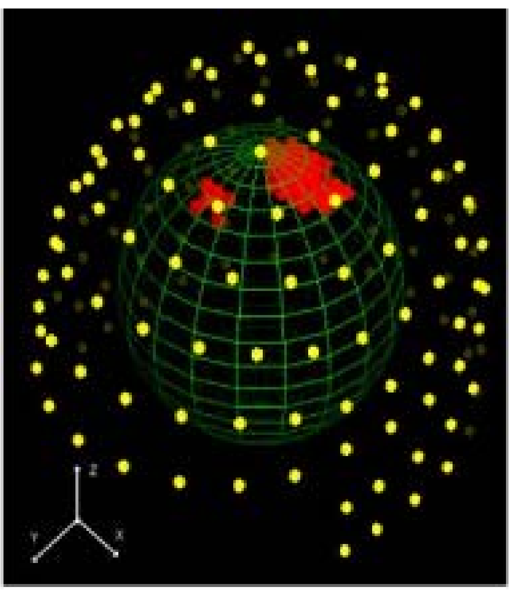

Fig.6: Coherence estimates in the 35-45 Hz band with a threshold of 0.7: HIGH SIDEVIEW

IV. DISCUSSION

Our idea behind the approach to LOCANTO is to use MEG at best where its best qualities lie.

This implied the development of a software which works mainly in the frequency domain to get a deeper view in the brain global dynamics. Since MEG temporal resolution is so good (1 ms), it is very convenient to study dynamic processes in the frequency domain with the help of an appropriate software. This does not mean that the localization part in the time–space domain has been overlooked. Since localization is practically always a starting point for a coherence analysis two different techniques (LORETA and Beamforming) were developed.

V. CONCLUSION

The originality of LOCANTO as a MEG analysis tool lies in its versatility. Both techniques are disposable by means of a selection change in a dialog box. The use of one rather than the other depends on the cues we possess about the neurological landscape we are going to analyze.

Theoretical proofs [2] and practical simulations show that each of the two techniques, in fact, works at best with different configurations of neurological sources. In particular, when more than two coherent sources are present there is no theoretical guarantee that the Beamforming should localize properly or give a correct spectrum reconstruction. Loreta, in this case, shows a much more reliable localization performance.

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