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Comparison of the spatial resolution of source imaging techniques in high-density EEG and MEG

T. Hedrich[a,*], G. Pellegrino[a,b,g], E. Kobayashi[b], J.M. Lina[c,e,f], C. Grova[a,b,d,e]

[a] Multimodal Functional Imaging Lab, Biomedical Engineering Dpt., McGill University, Montreal, Canada
[b] Neurology and Neurosurgery Department, Montreal Neurological Institute (MNI), McGill University, Montreal, Canada
[c] Département de Génie Électrique, École de Technologie Supérieure, Canada
[d] Physics Dpt., PERFORM Centre, Concordia University, Canada
[e] Centre de recherches mathématiques, Université de Montréal, Montreal, Canada
[f] Center for Advanced Research on Sleep Medecine (CEAMS), hôpital du Sacré-Coeur, Montreal, Canada
[g] San Camillo Hospital IRCCS, Venice, Italy

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ABSTRACT

Background: The present study aims at evaluating and comparing electrical and magnetic distributed source imaging methods applied to high-density Electroencephalography (hdEEG) and Magnetoencephalography (MEG) data. We used resolution matrices to characterize spatial resolution properties of Minimum Norm Estimate (MNE), dynamic Statistical Parametric Mapping (dSPM), standardized Low-Resolution Electromagnetic Tomography (sLORETA) and coherent Maximum Entropy on the Mean (cMEM, an entropy-based technique). The resolution matrix provides information of the Point Spread Functions (PSF) and of the Crosstalk functions (CT), this latter being also called source leakage, as it reflects the influence of a source on its neighbors.

Methods: The spatial resolution of the inverse operators was first evaluated theoretically and then with real data acquired using electrical median nerve stimulation on five healthy participants. We evaluated the Dipole Localization Error (DLE) and the Spatial Dispersion (SD) of each PSF and CT map.

Results: cMEM showed the smallest spatial spread (SD) for both PSF and CT maps, whereas localization errors (DLE) were similar for all methods. Whereas cMEM SD values were lower in MEG compared to hdEEG, the other methods slightly favored hdEEG over MEG. In real data, cMEM provided similar localization error and significantly less spatial spread than other methods for both MEG and hdEEG. Whereas both MEG and hdEEG provided very accurate localizations, all the source imaging methods actually performed better in MEG compared to hdEEG according to all evaluation metrics, probably due to the higher signal-to-noise ratio of the data in MEG.

Conclusion: Our overall results show that all investigated methods provide similar localization errors, suggesting very accurate localization for both MEG and hdEEG when similar number of sensors are considered for both modalities. Intrinsic properties of source imaging methods as well as their behavior for well-controlled tasks, suggest an overall better performance of cMEM in regards to spatial resolution and spatial leakage for both hdEEG and MEG. This indicates that cMEM would be a good candidate for studying source localization of focal and extended generators as well as functional connectivity studies.

Introduction

High-density Electroencephalography (hdEEG), defined here as EEG with 256 electrodes, and Magnetoencephalography (MEG) are two complementary and non-invasive neurophysiology modalities used to depict electromagnetic brain activity (Stefan, 2009; Ebersole and Ebersole, 2010; Ahlfors et al., 2011). Electrical and magnetic source imaging consist in solving a so-called inverse problem, localizing the generators of scalp EEG or MEG signals into the brain (Darvas et al., 2004).

The inverse problem is ill-posed by nature and a unique solution can only be found if specific constraints are added for regularization (Panday et al., 2009). Multiple inverse solution approaches are nowadays available, including equivalent current dipole fitting, dipole

* Corresponding author.
E-mail address: tanguy.hedrich@mail.mcgill.ca (T. Hedrich).

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scanning approaches and distributed source models (see Wendel et al. (2009) and Klamer et al. (2014)).

The spatial accuracy of source imaging techniques is influenced by several factors, including the choice of modality (Pittau et al., 2014), the number of sensors (Sohrabpour et al., 2014), the orientation of the generator (Ahlfors et al., 2010), the conductivity of the biological tissues (Aydin et al., 2014) and the source imaging technique used to solve the inverse problem (Hauk et al., 2011).

The objective of this study was to compare the intrinsic spatial resolutions of different source imaging techniques applied to hdEEG and MEG signals, when considering these two modalities with approximately the same number of sensors. We analyzed the resolution matrix, whose application in the neuroimaging field was originally proposed by Menendez et al. (1997), to characterize the spatial properties of a linear inverse operator. The spatial resolution matrix is a square matrix, whose size is the number of dipolar sources, providing the following two features (Schoffelen and Gross, 2009):

1. The columns of the resolution matrix quantify the Point Spread Functions (PSF) of every dipolar source of the source space. Each PSF is assessing the solution of the source imaging method for the activation a single cortical dipole, when considering noise-free data. Analyzing the localization error and the spatial extent of the PSF provides information about the intrinsic spatial property of a source imaging technique.
2. The rows of the resolution matrix represent the crosstalk functions (CT) which reflect the influence a single dipolar source may have on the estimation of the generators in its neighborhood. Hence, the spatial extent of the CT informs on the amount of "source leakage" and the potential bias in the estimation of functional connectivity patterns leading to spurious local coherence (Schoffelen and Gross, 2009).

An ideal resolution matrix should be the identity matrix. In practice, any source estimate is subject to blurring (if large amplitude values are found in off-diagonal terms in the matrix) and mislocation (if off-diagonal values were higher amplitude than diagonal values).

Once PSF and CT maps are constructed for each dipolar source, one can assess their spatial properties through evaluation metrics such as Dipole Localization Error (DLE) and Spatial Dispersion (SD) (Liu et al., 2002; Molins et al., 2008). DLE measures the Euclidean distance between the maximum of the PSF or CT maps and the true source location, whereas SD quantifies the spatial spread around the true source location.

Beyond the theoretical analysis of the resolution matrix, a validation of the comparison between the intrinsic spatial resolution can be achieved by studying real data acquired under well-controlled paradigms, for which the location of generator is known a priori. To that motive, we measures somatosensory evoked responses measured after electrical stimulation of the median nerve. This paradigm is known to generate evoked response exhibiting the activation of the contralateral primary sensory hand region (Balzamo et al., 2004). In this context, for which the generator is located in a predefined focal brain region, properties of source imaging techniques and comparison between them could also be evaluated using DLE and SD metrics, as proposed by Molins et al. (2008).

We chose to evaluate and compare four distributed sources localization methods. Three of them are well-known linear operators: Minimum Norm Estimate (MNE) (Hämäläinen and Ilmoniemi, 1994), dynamic Statistical Parametric Mapping (dSPM) (Dale and Sereno, 1993) and standardized Low-Resolution Electromagnetic Tomography (sLORETA) (Pascual-Marqui, 2002). The fourth one is the coherent Maximum Entropy on the Mean (cMEM) (Amblard and Lapalme, 2004; Grova et al., 2006), which is a novel non-linear method specifically evaluated for its sensitivity to recover the spatial extent of the underlying cortical generators (Chowdhury et al., 2013; Heers et al., 2016; Grova et al., 2016). Whereas the calculation of the resolution matrix is straightforward for the linear methods (MNE, sLORETA and dSPM), specific estimation of the resolution matrix for the non-linear method cMEM was performed with the iterative reconstruction of the PSF of every dipolar source.

We proposed a systematic and quantitative assessment of these source imaging techniques based on two strategies: (i) theoretical analysis of the resolution matrix; (ii) study of the source estimated from hdEEG and MEG responses evoked by electrical median nerve stimulation, in the primary somatosensory cortex.

Material and methods

Subjects selection

Five right-handed healthy subjects (3 males, mean age $\pm$ standard deviation $=26.6 \pm 3.21$) were selected for this study. The study was approved by the Research Ethics Board of the Montreal Neurological Institute and Hospital and a written informed consent was signed by all participants prior to the procedures.

Electrical Median Nerve Stimulation

Electrical Median Nerve Stimulation (MNS) was performed using a Digitimer system (Digitimer DS7A, Letchworth Garden City, U.K). 600 stimuli were delivered to the left and right median nerves using electrodes placed on the wrist. A 12-min run was acquired for each stimulation side, using two different modalities, i.e. hdEEG and MEG. The stimulus duration was set to 0.2 ms, the inter stimulus interval was set to 500 ms, with an additional jitter between 0 ms and 500 ms. The stimulation intensity was set just above the motor threshold to cause a small thumb movement. During the whole recording, participants were instructed to focus on a fixation cross in the middle of a black screen.

MEG data acquisition

MEG data were acquired on a 275-gradiometer CTF system (VSM MedTech Systems Inc., Coquitlam, BC, Canada) in a magnetic shielded room at the McConnell Brain Imaging Centre of The Montreal Neurological Institute (McGill University, Montreal, Canada). Electrocardiogram (ECG) and electrooculogram (EOG) were acquired to record potential sources of artifacts contaminating MEG signals. The sampling rate was set to 1200 Hz. Continuous head localization was obtained using three localization coils attached to the nasion and left and right peri-auricular points on each subject. The exact position of the localization coils, as well as the shape of the head of the subject, were digitized with a 3D Polhemus localizer for subsequent coregistration with the anatomical MRI.

hdEEG data acquisition

hdEEG was recorded using a 256-electrode EGI system (Electrical Geodesics Inc., Eugene, Oregon) with a sampling rate of 1000 Hz. ECG was also recorded using additional electrodes. Since the EEG system we used for this study was actually an MRI-compatible EEG device, each electrode was equipped with an additional $10\ k\Omega$ resistance. Good data quality was achieved by maintaining the EEG impedances below $70\ k\Omega$.

The EEG sensor positions were estimated using the Geodesic Photogrammetry System (GPS, geodesic inc., Eugene, OR). The system consists in 11 cameras mounted in a geodesic structure. The electrodes were then manually labeled on the 11 pictures, and the coordinates were calculated using a triangulation algorithm (Russell et al., 2005).

Anatomical MRI

A high resolution T1-weighted MRI (MPRAGE 1 mm isotropic 3D