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Frequency-spatial beamformer for MEG source localization

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ABSTRACT

This article introduces a unique and powerful new method for spatial localization of neuronal sources that exploit the high temporal resolution of magnetoencephalography (MEG) data to locate the originating sources within the brain. A traditional frequency beamforming algorithm was adapted from its conventional application to yield information on the spatial location of simulated neuronal signals. The concept is similar to that used in signal source localization in magnetic resonance imaging (MRI) in which spatial location is determined by the frequency of oscillation of the MR signal. Whereas a traditional frequency beamformer uses the time course values of all sensors in the dataset to assign a power value for each possible frequency in the signal, it provides no information on the spatial location of those frequencies. Our approach assigns a power value to each location in the three-dimensional head volume. To compute this power value, the time courses of a subset of sensors closest to that location in space are used rather than all the time courses in the dataset. Our novel technique incorporates actual MEG sensor locations of the closest sensors at each location in space. The approach is relatively simple to implement, yields good spatial resolution, and accurately spatially locates a simulated source in low signal-to-noise environments. In this work, its performance is compared to that of the synthetic aperture magnetometry (SAM) beamformer and shown to exhibit improved spatial resolution.

1. Introduction

Magnetoencephalography (MEG) measures the extracranial magnetic field generated by the brain's electrical activity in an attempt to obtain information on the underlying neural activity [1]. It is a brain imaging technology of unsurpassed temporal resolution which produces high resolution (order of milliseconds) one-dimensional time course data at, typically, 275 locations around the surface of the head. The locations of these 275 sensors are shown in Fig. 1. Utilizing this data to deduce the spatial location of underlying neuronal sources has proven to be challenging. In Fig. 1, the source of brain activation is depicted as the red mass inside the sensors. The group of circles around the perimeter represent the MEG sensor array of the CTF MEG system. The colors of these sensors indicate the signal strength projected from the source. The red and yellow sensors indicate strong detectable signals, while gray indicates a weak or no signal detected at that location.

Recently, a novel MEG source localization technique was introduced that adapts a traditional frequency beamforming algorithm to yield information on the spatial location of simulated MEG sources [2]. A traditional frequency beamformer computes the frequencies present in a signal. It does so by computing a power value for each possible frequency in the signal and plotting this power value as a function of frequency. In computing this power value, the traditional frequency beamformere uses the time course values of all sensors in the dataset. Thus, it yields information on the frequencies present in the signal but provides no information on the spatial location of those frequencies. Our novel localization approach adapts this method by assigning a frequency power value to each location in a three-dimensional (3D) head volume. That is, at each location in the 3D head volume, the time course values of only the closest 21 sensors are extracted and used to compute a power value for a given frequency of interest. In this way, our approach provides a means of quantifying the strength

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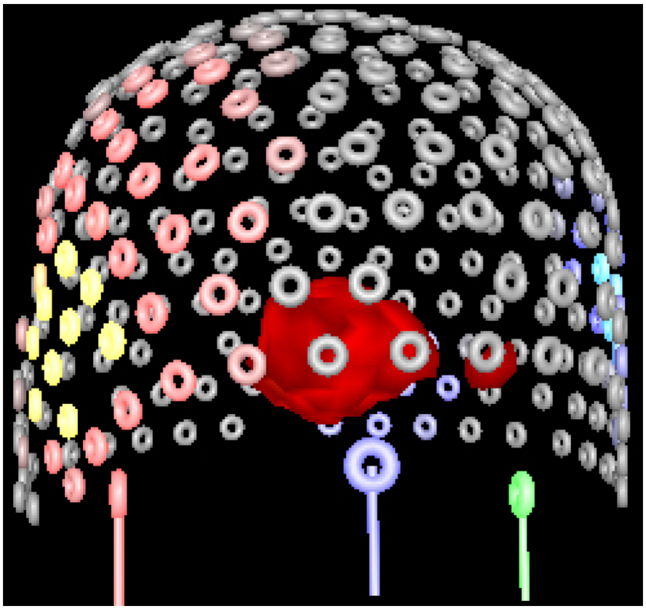

Fig. 1. Locations of 275 MEG sensors in the CTF MEG system. The colors of these sensors indicate the signal strength projected from the source. The red and yellow sensors indicate strong detectable signals, while gray indicates a weak or no signal detected at that location. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of the frequency content of the signal as a function of its spatial location. In this research, we more fully develop the approach and compare its performance to that of the widely recognized synthetic aperture magnetometry (SAM) beamformer in accurately locating simulated MEG sources. In addition, in this approach we revise the method of inserting simulated activations to the traditional current dipole.

1.1. Background

Whereas functional magnetic resonance imaging (fMRI) [3,4], provides unparalleled spatial resolution, yielding detailed information on the anatomical structures of the human brain, it relies on changes in cerebral blood flow and blood volume, referred to as the BOLD (blood-oxygen-level-dependent) effect, which is an indirect measure of brain functionality and limits its temporal resolution to about one second [5].

On the other hand, MEG and its electrical counterpart, electroencephalography (EEG), record direct responses from neuron activity. Thus, MEG and EEG are capable of tracking brain dynamics with millisecond temporal resolution [5]. This unsurpassed temporal resolution has led to the widespread use of EEG and MEG by clinicians and scientists investigating physiologic and pathologic brain function [6]. While EEG and MEG are superior to all other functional imaging methods with regard to temporal resolution, spatial localization is impaired by the ill-posedness and non-uniqueness of the EEG/MEG inverse problem [5].

1.1.1. Sensor time course data techniques

To extract information from MEG data regarding interactions between spatially disparate brain regions, some current popular techniques rely on the analysis of the sensor time course data [7–10]. Standard methods include coherence analysis and event-related synchronization/desynchronization (ERS/ERD). ERD and ERS have been demonstrated using a variety of different sensory-motor and cognitive paradigms and at a variety of frequencies [11,12]. Activity has been reported in the alpha [13–16] (8–15 Hz), beta [17–20] (15–30 Hz), gamma [21–23] (30–50 Hz), and theta [24–26] (6–10 Hz) bands. Several researchers [8] have used time course data in conjunction with wavelet-based techniques.

However, these techniques do not fully exploit the capability of MEG to localize sources of neuronal activity. Thus, many researchers are attempting to use the MEG time course data to deduce the origin of the underlying sources of brain activity. Task-related changes in spectral power in specific frequency bands are localized using conventional dipole source modeling [27–31], sometimes used in conjunction with contour maps, and beamformers [32–37], to place brain activity in the context of anatomy.

1.1.2. Dipole source models

Postsynaptic activity is often modeled as a single current dipole, which represents an idealized point source [38]. In this case to estimate the neural sources, the forward problem must be solved which maps a dipole source of known location, strength, and orientation, to an array of MEG sensors [39].

Given a forward model, that is, an assumed shape and conductivity of the head, and a set of MEG sensor time course measurements, the inverse problem is to find the current density distribution that generated the observed measurements. The solution to the inverse problem is an estimate of the number, location, and time series of each of the dipole sources. Solving the inverse problem involves making inferences regarding the distribution of underlying neuronal sources based on the observed MEG values at the surface, and there is no unique result [40].

Since the human evoked response is generated by multiple simultaneously active brain sources producing fields that overlap both in space and time, modeling this activity with a single current dipole can result in erroneous conclusions concerning its neuronal generation [41]. Thus, multiple current dipoles have also been applied to spatiotemporal analysis [40]. Dipole fitting [42,43] is a variant used to solve the inverse problem. Imaging methods using the Bayesian perspective have also been used to solve the inverse problem [44–46]. Nonparametric distributed source modeling is an alternative, non-dipole approach to deal with the indeterminacy of the inverse problem [47]. Magnetic Field Tomography (MFT) uses continuous probabilistic estimates of the primary current density to construct tomographic displays of brain activity. It solves the inverse problem using arbitrarily distributed non-dipole sources [48].

1.1.3. Beamformers

A beamformer is a processor used in conjunction with an array of sensors to provide a form of spatial filtering [49]. Spatial filtering refers to discrimination of signals on the basis of their spatial location. This concept is analogous to the more familiar temporal filtering, where one discriminates between signals based on their temporal frequency content [37]. The beamformer sensor array is designed to receive signals radiating from a specific location and attenuate those from other locations. The MEG beamformers developed to date rely on a lead field matrix which contains the computed MEG sensor values (forward solution) that would result for all possible locations and orientations of potential sources of neuronal activity. Furthermore, most of the MEG beamforming literature uses a dipole as the source model in calculating this lead field matrix.

The most common MEG beamformers are the linearly constrained minimum variance (LCMV) [49] beamformer and multiple signal classification (MUSIC) [35,42,50] and variations thereof. A limitation of the beamforming approach using dipole source models is that they are highly dependent on the underlying assumptions forming the basis of the lead field matrix.