Journal of Neuroscience Methods 178 (2009) 120–127

Contents lists available at ScienceDirect

Journal of Neuroscience Methods

journal homepage: www.elsevier.com/locate/jneumeth

Effective electromagnetic noise cancellation with beamformers and synthetic gradiometry in shielded and partly shielded environments

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ARTICLE INFO

Article history:
Received 19 December 2007
Received in revised form
14 November 2008
Accepted 2 December 2008

Keywords:
MEG
Magnetic shielding
Synthetic gradiometers
Regularised and unregularised beamformers
SAM
ECD
CHEPS

ABSTRACT

The major challenge of MEG, the inverse problem, is to estimate the very weak primary neuronal currents from the measurements of extracranial magnetic fields. The non-uniqueness of this inverse solution is compounded by the fact that MEG signals contain large environmental and physiological noise that further complicates the problem. In this paper, we evaluate the effectiveness of magnetic noise cancellation by synthetic gradiometers and the beamformer analysis method of synthetic aperture magnetometry (SAM) for source localisation in the presence of large stimulus-generated noise. We demonstrate that activation of primary somatosensory cortex can be accurately identified using SAM despite the presence of significant stimulus-related magnetic interference. This interference was generated by a contact heat evoked potential stimulator (CHEPS), recently developed for thermal pain research, but which to date has not been used in a MEG environment. We also show that in a reduced shielding environment the use of higher order synthetic gradiometry is sufficient to obtain signal-to-noise ratios (SNRs) that allow for accurate localisation of cortical sensory function.

1. Introduction

Magnetoencephalography (MEG) is the non-invasive measurement of magnetic fields outside the head generated by the electrical activity of neurons within the brain. The aim of MEG is to increase the signal-to-noise ratio (SNR) of the recorded brain signals, and localise sources of these signals in the brain. This inverse problem is non-unique and ill defined because there are many current configurations that could have produced the same magnetic fields. The cortical magnetic fields of interest are typically in the femtoTesla range which is approximately 100 million times smaller than the earth's magnetic field and about 1 million times smaller than typical urban environmental noise (Hämäläinen et al., 1993; Vrba, 2002). In addition to environmental noise, the measured fields contain unwanted contributions from organs such as the heart, lungs and eyes, from muscle contractions, as well as from background brain activity arising from regions not being investigated. Therefore, inverse methods must ideally provide noise cancellation as well as source localisation.

As the ultimate aim of MEG is to determine the spatial and temporal patterns of the current sources from regions of interest within the brain, sensors must be protected from various artefacts that contaminate these signals from nearby and distant sources. Typically, the first defence against environmental noise is passive magnetic shielding (Hämäläinen et al., 1993). At the hardware level further noise reduction is achieved by using gradiometers to differentially sample the magnetic field around the head. This removes noise from distant sources where the magnetic interference is more or less uniform in space (Carelli and Leoni, 1986; Vrba, 2002). First-order gradiometers for example consist of two coils wound in opposite directions; but the effectiveness of gradiometer coils is a function of the balance, or similarity between coils. Typically the effective balance of a coil can be synthetically improved through the use of an array of reference channels. The reference channels are positioned far from the head such that they detect mainly environmental noise. Subsequently, a different linear combination of signals from the (noisy) reference channels is subtracted from each

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doi:10.1016/j.jneumeth.2008.12.006

of the sensor outputs. The weights of the coefficients can either be fixed (after calibration) or determined adaptively to create a high-order synthetic gradiometer (Vrba and Robinson, 2001). In comparison to hardware gradiometry, synthetic gradiometers are a cost efficient option since one array of reference channels can be used for any number of sensor channels.

On the other hand, there are linear and non-linear mathematical techniques that provide not only noise cancellation, but also source localisation. These methods include signal space separation (Taulu et al., 2004), beamformers such as synthetic aperture magnetometry (SAM) (Robinson and Vrba, 1999), dynamic imaging of coherent sources (Gross et al., 2001), linearly constrained minimum variance (Van Veen et al., 1997) or eigenspace beamformers (Sekihara et al., 1999), and multiple signal classification (Mosher et al., 1992). A discussion of each of these methods is beyond the scope of this paper. Barnes and Hillebrand (2003) and Hillebrand et al. (2005) provide a detailed description of the SAM beamformer method and its applications. Put simply, the beamformer is a spatial filter that estimates source strength on a voxel × voxel basis and is used to build up an image of source activity throughout the brain. Noise cancellation is attained through this spatial filter. Similar to traditional frequency filters that select signals within a specified temporal range, the spatial filter selects signals only from specified spatial locations. All other signals, such as those arising from environmental sources, heart beat (electrocardiogram, ECG) or adjacent brain areas are minimised by the action of the spatial filter. For each voxel, the output of the spatial filter is a weighted sum of all the MEG sensors, and is called a virtual electrode with the same millisecond time resolution as the original MEG signals. The virtual electrode time series can then be divided into active and passive epochs and power in preselected frequency bands can be calculated. The power difference between the two states can be calculated using all the epochs and then normalised by MEG sensor noise to obtain a statistical *pseudo-t* value (Vrba and Robinson, 2001). A three-dimensional image of source power is obtained when this process is applied sequentially to each voxel in the brain.

The two studies presented in this paper demonstrate the effectiveness of noise cancellation using a combination of methods outlined above. Firstly, we demonstrate the robustness of SAM in the localisation of thermal pain evoked potentials despite the presence of considerable stimulus-induced magnetic interference. Furthermore, by manipulating the regularisation parameter, we show how the magnetic interference is treated by the action of the beamformer. The cost of hardware magnetic shielding is significant, and even in well-shielded rooms environmental noise (such as tramlines) can still be a significant barrier to recording. In this paper we degrade the quality of our shielded environment by opening the door of the room to look at the efficacy of other noise cancellation methods. In a second experiment, we demonstrate the accuracy of source localisation with dipole analysis and SAM with and without high-order synthetic gradiometers on data collected in an 'open-door' environment.

2. Experiment 1

2.1. Methods

The contact heat evoked potential stimulator (CHEPS) (Medoc Ltd., Ramat-Yoshai, Israel) is a computerised thermal stimulator specifically designed to facilitate research investigating human sensory and nociceptive pathways. The present study was conducted to assess the suitability of this equipment in the MEG environment, as to date no study has combined the two. The CHEPS provides a rapid heating rate of 70 °C/s such that painful stimuli can be delivered from a skin temperature baseline of 32 °C up to a maximum of 55 °C in approximately 329 ms. This is achieved using a special 27 mm diameter probe that comprises two layers of stimulators, one external layer consisting of a very thin fast heating foil and one lower layer consisting of a Peltier element with heating and cooling capabilities. Although the probe has been designed for use in MR environment, and is suitable for EEG studies, the mechanism within the probe generates a significant magnetic field that produces a large artefact in the recorded MEG. This results in a shift in the range of the recorded MEG; activity in the absence of the stimulus is 950 fT (peak-to-peak), compared to 41 pT during stimulus presentation.

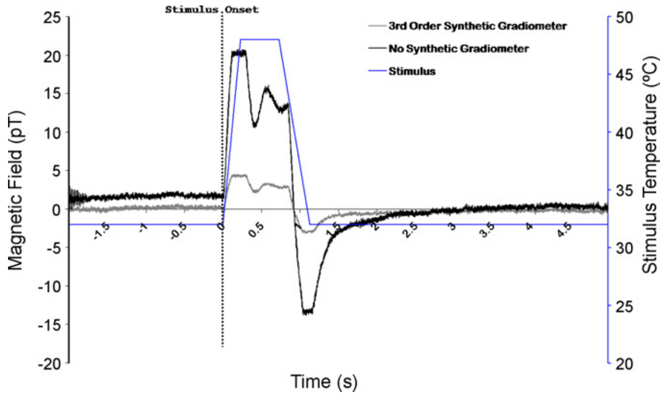

Fig. 1. Example of the magnetic artefact in a single MEG channel over the right central region produced by the CHEPS mechanism before (black trace) and after (grey trace) application of 3rd order synthetic gradiometer. The CHEPS trace (in blue) shows the temperature of the probe over the time-course of one trial rising from 32 to 48 °C at 70 °C/s in approximately 230 ms, sustained at 48 °C for 500 ms, then returning back to 32 °C at a rate of 40 °C/s. The vertical line indicates the onset of the stimulus. Note the duration of the artefact. Also note the attenuation of signal amplitude due to the 3rd order gradiometer (black vs. grey trace).

An example of the magnetic interference introduced by the CHEPS (coloured noise) in a single trial is shown by the black trace in Fig. 1. The rise in temperature of the CHEPS is represented by the blue trace, showing temporal correspondence with the artefact in the MEG trace. The interference has a frequency peak of 2 Hz and lasts for approximately 2 s. A similar level of noise was visible in all MEG channels across all trials. The grey trace illustrates the effect of applying a synthetic 3rd order gradiometer in reducing the level of the interference. Due to strength of the current produced by the CHEPS probe and the proximity of this to the MEG sensor array, the noise is not completely removed. Clearly, averaging the trials, therefore, would not remove the artefact from the traces and for this reason it is not possible to use equivalent current dipole (ECD) modelling for localisation of the masked electrophysiological evoked response. On the other hand, the beamformer spatial filter should act to minimise all magnetic sources bar those that arise from voxels near the target source location.

To assess whether accurate source localisation can be achieved with the SAM beamformer method despite the presence of this large magnetic artefact, MEG data was collected following 30 rapid painful heat stimulations to the dorsum of the non-dominant hand. Informed written consent was obtained and the local ethics committee approved the experimental protocol.

Data was recorded in shielded environment using a whole head CTF 275-channel scanner with 1st order hardware gradiometer coil configuration (VSM Medtech, Canada) at a sampling rate of 1200 Hz. The procedure was performed on eight participants for whom pain tolerance threshold was obtained. This was at an average level of 48.1 ± 1.5 °C across participants, and perceived to be strong pain; equivalent to a visual analogue scale (VAS) of 7 (on a 0–10 scale from no sensation to unbearable pain). Each of the 30 trials lasted 7 s with pre-stimulus time of 2 s and randomised inter-stimulus inter-