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Reliable recording and analysis of MEG-based corticokinematic coherence in the presence of strong magnetic artifacts

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HIGHLIGHTS

- MEG-based corticokinematic coherence (CKC) reliably locates the primary sensorimotor (SM1) cortex.
- In subjects wearing magnetized material, temporal signal-space separation effectively cleans the MEG data.
- In the presence of such artifacts, CKC still locates the SM1 cortex with ~5 mm accuracy and allows reliable studies of proprioception.

ABSTRACT

Objective: Corticokinematic coherence (CKC) is the coupling between magnetoencephalographic (MEG) signals and limb kinematics during fast movements. Our objective was to assess the robustness of CKC-based identification of the primary sensorimotor (SM1) cortex of subjects producing strong magnetic artifacts when the MEG signals were cleaned with temporal signal space separation (tSSS).
Methods: We recorded MEG during active and passive forefinger movements and during median-nerve stimulation in the following conditions: (1) artifact-free, (2) a magnetic wire attached to the scalp at C3 location, and (3) a magnetic wire attached behind the lower central incisors. Data were pre-processed with tSSS and analyzed using standard CKC methods, somatosensory evoked fields (SEFs), and dipole modeling.
Result: Artifacts were effectively suppressed by tSSS, enabling successful identification of the SM1 cortex in all subjects based on CKC and SEFs. The sources were in artifact conditions ~5 mm away from the sources identified in artifact-free conditions.
Conclusion: tSSS suppressed artifacts strongly enough to enable reliable identification of the SM1 cortex on the basis of CKC mapping, with localization accuracy comparable to SEF-based mapping.
Significance: The results suggest that CKC can be used for SM1 cortex identification and for studies of proprioception even in patients implanted with magnetic material.

1. Introduction

Functional brain mapping is often performed as a part of pre-surgical planning for patients with lesions or abnormalities in the brain. Together with anatomical information, such mapping can pinpoint eloquent brain areas close to the resection area, so that the surgery can be optimally planned and those functionally important brain areas preserved (Atlas et al., 1996; Håberg et al., 2004; Majos et al., 2005). The pre-operative non-invasive brain mapping is often performed by means of functional magnetic resonance imaging (fMRI) (Atlas et al., 1996; Bartsch et al., 2006; Håberg et al., 2004; Majos et al., 2005). However, fMRI relies on the integrity of the neurovascular coupling that may be altered in various brain disorders (Bartsch et al., 2006; D'Esposito et al., 2003; Inoue et al., 1999; Korvenoja et al., 2006; Krings et al., 2001; Rossini et al., 2004). Magnetoencephalography (MEG) provides a complementary approach as it directly reflects neuronal

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activity, providing millisecond-range temporal resolution and reasonable spatial resolution (for a review of the MEG methods, see Hämäläinen et al., 1993). MEG is commonly used for time-resolved mapping of brain activity (Hämäläinen et al., 1993; Stufflebeam et al., 2009). However, one of the main challenges in measuring MEG is its sensitivity to magnetic artifacts. The magnetically shielded rooms in which MEG systems are located effectively help blocking *external* magnetic artifacts, whereas *internal* sources of interference (brought in by the subjects or patients; e.g. dental braces, cranial clips, implanted stimulators) may be more difficult to avoid.

Today, there are methods available to deal with such subject-generated artifacts. Many magnetic artifacts can be effectively suppressed with signal analysis. For instance, pre-processing of the MEG signals with temporal signal-space separation (tSSS) can suppress artifacts while preserving brain activity (Medvedovsky et al., 2009; Taulu and Hari, 2009; Taulu and Simola, 2006). The tSSS pre-processing method is a temporal extension of signal space separation (SSS; Taulu et al., 2004; Taulu and Hari, 2009; Taulu and Kajola, 2005), wherein brain signals are decomposed into internal and external SSS components (with respect to the brain), and only internal components are used to reconstruct the corresponding noise-free sensor signals (Taulu et al., 2004; Taulu and Kajola, 2005).

In tSSS, internal components are removed by orthogonal projection if their correlation with external components exceeds a pre-defined threshold (Taulu and Hari, 2009; Taulu and Simola, 2006). It has earlier been demonstrated that strong artifacts caused by dental braces can be effectively removed by tSSS, thus allowing accurate localization of neural sources of responses to median-nerve stimulation as well as of movement-induced 13–30 Hz modulations in the rolandic cortex (Hillebrand et al., 2013).

Similarly, it has been demonstrated that tSSS can effectively suppress strong magnetic artifacts generated *inside the body*, e.g. by vagus nerve stimulator (Carrette et al., 2011; Kakisaka et al., 2013; Song et al., 2009; Tanaka et al., 2009), or even by implanted electrodes used for deep brain stimulation (Mäkelä et al., 2007). However, it is not yet known whether artifacts that are generated close to the area that needs to be mapped can also be suppressed by tSSS. Such co-localization between artifacts and functional areas may occur in the clinical context, e.g. when a patient is in need of a second surgery near an area where cranial fixations (e.g. Craniofix; Aesculap, Inc., Center Valley, PA) have been inserted.

In patients with a lesion close to the rolandic area, the functional brain area that needs to be identified is the primary sensorimotor (SM1) cortex. One recently introduced method for such purpose is the corticokinematic coherence (CKC), the coupling between MEG signals and hand kinematics during fast repetitive active and passive hand movements (Bourguignon et al., 2011, 2013; Piitulainen et al., 2013a, 2013b). CKC peaks at movement frequency (and its first harmonic) and its main cortical sources lay in the primary sensorimotor (SM1) cortex, contralateral to the moved hand (Bourguignon et al., 2011, 2012). The high level of coherence typically obtained in CKC experiments is robust enough for reliable examination of the signal shape (to obtain information about proprioceptive afference to the cortex) and to successfully locate the SM1 cortex at the individual level with only ~3-min recordings (Bourguignon et al., 2011, 2013). The recording time can even be decreased to 1 minute, as was reported in a CKC study in which precisely timed passive movements were generated with a movement actuator based on pneumatic artificial muscle (PAM) (Piitulainen et al., 2015).

These results show that CKC is a fast and reliable tool to locate the SM1 cortex, worth considering as an addition to somatosensory evoked fields (SEFs) (Bourguignon et al., 2011, 2013), which, so far, constitute the 'gold standard' in MEG mapping of the SM1 cortex (Burgess et al., 2011; Hari and Forss, 1999; Korvenoja et al., 2006; Mäkelä et al., 2001). Besides allowing to locate the SM1 cortex, CKC provides a unique tool to quantify proprioceptive afference to the cortex (Bourguignon et al., 2015; Piitulainen et al., 2013b) with a potential for multiple clinical applications. However, it is not yet known how robustly CKC can be recorded in the presence of subject-generated artifacts. A potential challenge with CKC compared with other mapping procedures is that task-related head sways could generate artifacts that are coherent with brain responses, since both might contain signals time-locked to hand movements.

In this study, we explored how reliably CKC, in combination with tSSS preprocessing, could be recorded and used to locate the SM1 cortex in the presence of strong artifacts caused by nearby magnetic material. For this purpose, we adopted a well-controlled paradigm in which the participants performed repetitive movements in three conditions: (i) once without artifacts, (ii) once with artifacts originating from the teeth, and (iii) once with artifacts originating from the scalp. We also recorded SEFs to median nerve stimulation to compare the CKC results with the gold standard in SM1 cortex mapping.

2. Experimental procedures

2.1. Subjects

We studied four healthy males (ages 29, 35, 45, and 49 yrs) without any history of movement disorders; all were right-handed according to Edinburgh handedness inventory (Oldfield, 1971), with scores ranging from 63 to 90.

The study had a prior approval by the ethics committee of the Aalto University, and the subjects gave written informed consent before participation.

2.2. Experimental protocol

The experiment consisted of *active* and *passive* movements, median nerve stimulation, as well as *rest* in three artifact conditions (*control*, *scalp*, and *teeth*), resulting in a total of 12 recordings.

The *active* and *passive* movements involved fast repetitive flexion–extensions of the metacarpophalangeal joint of the right forefinger for 3 min. During *active* movements, subjects moved their right forefinger on their own at ~3 Hz without any contact with external surfaces. During *passive* movements, the subjects' right forefinger was passively moved by a PAM stimulator (Piitulainen et al., 2015), at a random inter-movement interval in the range 300–367 ms (i.e. ~3 Hz). *SEF*s were recorded in response to constant current pulses (0.2 ms) delivered to the median nerve at the wrist with a jittered 900–1100-ms inter-stimulus interval. A total of 300 stimuli were delivered during a ~5-min recording. We also recorded brain activity at *rest* for 3-min, during which the subjects were instructed to relax, not to move, and to gaze at a fixation cross located on the opposite wall of the magnetically shielded room. Ear inserts were used during all recordings to minimize responses to movement-related sounds.

In the *control* condition, no artifacts were experimentally introduced into the data. The *scalp* condition, however, aimed to simulate the situation in which artifacts are produced by patients having undergone brain surgery at the central scalp regions. For that purpose, a ~5-mm-long piece of Craniofix (Aesculap, Inc., Center Valley, PA), pre-magnetized at 3 T, was attached to the scalp at a location corresponding to C3 electrode in a standard 10–20 EEG montage (American Electroencephalographic Society guidelines for standard electrode position nomenclature, 1991). This location was chosen because it is located above the hand region of the left