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Off-line removal of TMS-induced artifacts on human electroencephalography by Kalman filter

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Abstract

In this paper we present an off-line Kalman filter approach to remove transcranial magnetic stimulation (TMS)-induced artifacts from electroencephalographic (EEG) recordings. Two dynamic models describing EEG and TMS signals generation are identified from data and the Kalman filter is applied to the linear system arising from their combination. The keystone of the approach is the use of time-varying covariance matrices suitably tuned on the physical parameters of the problem that allow to model the nonstationary components of the EEG–TMS signal. This guarantees an efficient deletion of TMS-induced artifacts while preserving the integrity of EEG signals around TMS impulses. Experimental results show that the Kalman filter is more effective than stationary filters (Wiener filter) for the problem under investigation.

Keywords: Electroencephalography; Transcranial magnetic stimulation; EEG–TMS combination; TMS-induced artifact; Kalman filter

1. Introduction

Transcranial magnetic stimulation (TMS) allows noninvasive brain stimulation of intact humans using rapidly time-varying magnetic fields generated by a coil positioned in contact with the scalp (Hallett, 2000; Kobayashi and Pascual-Leone, 2003). Besides the investigation of corticospinal motor pathways after stimulation of the motor cortex (Kobayashi and Pascual-Leone, 2003; Rossini and Rossi, 2007), TMS of nonmotor areas offered the unique opportunity to study several cognitive functions in a causal manner (Walsh and Cowey, 2000; Rossi and Rossini, 2004), since it is the only functional technique that allows to transiently interfere *in vivo* with the stimulated brain regions. Recently, TMS has been combined with other functional imaging techniques (Sack and Linden, 2003). This approach represents an important advance in cognitive neuroscience, since it permits the investigation of the local response to TMS at a neurophysiological level, thus enabling the determination of the cerebral areas directly or trans-synaptically affected by the magnetic stimulation.

TMS can be applied in combination with the following functional imaging techniques: positron emission tomography (PET; Paus et al., 1997), single photon emission computed tomography (SPECT; Okabe et al., 2002), functional magnetic resonance imaging (fMRI; Baudewig et al., 2001), electroencephalography (EEG; Thut et al., 2005) and with a different timing with respect to the functional scanning, thus providing different but complementary information about cortical activity. While the PET, SPECT and fMRI suffer from poor temporal discrimination (in terms of seconds fMRI, minutes PET), they are still the gold standard as to spatial resolution (Nikulin et al., 2003). However, brain responses occurring in the first tens of milliseconds following TMS are necessarily neglected, though such temporal window includes profound and function-related TMS-induced neural events which may have pathophysiological relevance and can help to causally elucidate neural substrates sustaining higher

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cognitive functions. Combined EEG–TMS may fill this gap, since it provides, together with high temporal resolution, unique information about the characteristics of cortical reactivity and connectivity (Ilmoniemi et al., 1997).

A technical deficiency of EEG–TMS coregistrations is that the TMS coil generates powerful rapidly changing magnetic fields that induce impulsive, high amplitude, long-lasting artifacts on the EEG trace (by artifact we mean any potential variation in the EEG signal not generated by the brain).

To solve this problem several *on-line* and *off-line* strategies (Ilmoniemi et al., 1997; Thut et al., 2005; Fuggetta et al., 2006) have been proposed in the literature so far. In the former, the artifacts are removed during the EEG–TMS coregistration using complex electrical circuits, while in the latter the filtering process starts only after the complete acquisition of the EEG–TMS trace. However, neither the on-line strategies (the EEG signal is irreparably cut during the TMS stimulus), nor the off-line approaches (present algorithms do not guarantee a complete artifacts suppression) provided satisfactory results up to now.

In the current work, we propose an original, low cost, off-line Kalman filter approach to remove TMS-induced artifacts from EEG recordings. It is well-known that EEG–TMS research can run up against several types of artifacts as auditory (due to the “coil click”), somatosensory (due to activation of trigeminal afferents) and muscular (especially occurring when TMS spread to facial nerve-supplied muscles). However, this study is particularly concerned with the suppression of the TMS artifact due to the induction of currents on the EEG electrodes.

After a preprocessing phase, two dynamic models describing EEG and TMS signals generation are identified from data and the Kalman filter is applied to the linear system arising from their combination. Suitable time-varying covariance matrices allow us to model the nonstationary components of the EEG–TMS signal. Experiments proved that the Kalman filter is more effective than stationary filters (Wiener filter) and it guarantees an efficient deletion of the electrical artifacts while preserving the integrity of the EEG signal around TMS impulses.

2. Materials and methods

2.1. Subjects

Experiments were carried out on 10 healthy volunteers (7 males) aged 22/43 years (average 28.5 years). All subjects gave their written informed consent for the study which was approved by the local ethical committee. The experiment was well tolerated by all subjects, none of whom reported side effects due to TMS.

2.2. TMS generation

Single-pulse TMS was generated using Magstim® Super Rapid biphasic stimulator and delivered through commercially available eight-shaped or circular coils (frequencies applied: 0.1 Hz and 10 Hz). The circular coil induces a more widely distributed electric field than the eight-shaped coil thus affecting larger regions of the cerebral cortex. The impulses generated by the equipment have the following characteristics: maximum discharge voltage 2 kV; maximum discharge current 7 kA; maximum magnetic field 2 T; rising time of the magnetic field 60 μs; length of the impulse 250 μs. Before starting the stimulation, individual threshold of TMS was determined for each subject according to standardized criteria (Rossini et al., 1994). The intensity of TMS pulses was set to 90%, 110% and 120% of the individual motor threshold.

2.3. EEG recording

EEG recording was carried out with Micromed® EEG equipment. The amplifier and the electrodes of the system are designed to work inside magnetic resonance scanners and therefore they also guarantee a correct acquisition of EEG signals in presence of high exogenous magnetic fields due to TMS. To assure a good temporal precision, a sampling frequency $f_s = 1024$ Hz has been chosen. The amplifier is optically connected to a PC with software Brain-Quick System Plus® and to a shielded cap containing the electrodes. The cap records 32 channels: 30 channels are dedicated to the electrodes disposed according to the international *10–20 EEG System*, while the last two channels are used for the electromyography (EMG) of hand muscles. The scalp region stimulated by TMS corresponded to the position of C3 electrode.

2.4. Database structure

The available database consists of seven records. A single record corresponds approximately to a 22 s acquisition on the 32 channels. Each record is divided into 15 data sets of 1500 samples. Each data set contains a single TMS impulse or stimulus having regular time spacing (see Fig. 1). The database was acquired at Department of Neuroscience, Section of Neurology, University of Siena.

2.5. Preliminaries

In spite of the electric shielding of EEG electrodes, power lines induce sinusoidal oscillations on EEG signals due to the 50 Hz carrier. These oscillations have been removed in a preprocessing phase preceding the application of the filtering procedures. Note that since scarce EEG activity is present at 50 Hz, the carrier can be removed without significant loss of information. Hereafter, the following notation will be used:

- $s_c(t)$ denotes the signal including the TMS-induced artifact, the EEG signal and the 50 Hz carrier;
- $s(t)$ denotes the signal including the TMS-induced artifact and the EEG signal, with the 50 Hz carrier suppressed.

Signal $s_c(t)$ can be written as a discrete Fourier series (Proakis and Manolakis, 1996),

$$s_c(t) = a_0 + \sum_{j=1}^{L} A_j \cos\left(\frac{2\pi jt}{f_s} + \theta_j\right)$$