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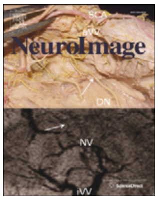

Technical Note

Internal ventilation system of MR scanners induces specific EEG artifact during simultaneous EEG-fMRI

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ABSTRACT

During simultaneous EEG-fMRI acquisition, the EEG signal suffers from tremendous artifacts caused by the scanner “environment”. Particularly, gradient artifacts and the ballistocardiogram have been well characterized, along with methods to eliminate them. Here, we describe another systematic artifact in the EEG signal, which is induced by the internal ventilation system of Siemens TRIO and VERIO MR scanners. A ventilation-level dependent vibration induces specific peaks in the frequency spectrum of the EEG. These frequency peaks are in the range of physiologically relevant brain rhythms (gamma frequency range), and thus interfere with their reliable acquisition. This ventilation dependent artifact was most prominent on the electrodes placed directly on the subject's head, so it is not sufficient to simply place the EEG's amplifier outside the scanner tube. Instead, the ventilator must be switched off to fully eliminate the ventilator's artificial manipulation of EEG recordings. Without the internal ventilator system being on, the temperature within the scanner tube may rise, thus requiring shorter scanning sessions or an additional external ventilation system.

1. Introduction

Despite several technical challenges, electroencephalography (EEG) acquisition during functional magnetic resonance imaging (fMRI) scanning is a widely established application for simultaneous investigation of neuronal and vascular brain responses (Ritter and Villringer, 2006). However, noise assessment and reduction are of special importance for EEG measurements within the magnetic field of the MR scanner, and strenuous effort must be made during experimental setup and data processing to reduce MR-related artifacts in the EEG. The most prominent EEG artifacts are: (1) *gradient artifacts* due to the rapidly alternating magnetic fields of the MR scanner, (2) the *ballistocardiogram* induced by cardiac-related body and electrode movements in the static magnetic field B0, and (3) vibration-related artifacts, e.g., those caused by the *helium pump* of the MR scanner. For gradient artifact- and ballistocardiogram-correction, several data processing methods have been developed that can be used for offline or online correction (Allen et al., 1998, 2000; Debener et al., 2007; Grouiller et al., 2007; Kim et al., 2004; Liu et al., 2012; de Munck et al., 2012, Niazy et al., 2005; Ritter et al., 2007). Post-hoc data correction for vibration related artifacts is still an unsolved problem. Template subtraction is often not applicable because in many MR systems the vibration related artifacts do not have a characteristic temporal shape as gradients or heart beat artifacts. And since all electrodes are similarly affected, correction algorithms using spatial filters (e.g. ICA) are not feasible. In case of the He-pump it is therefore a common practice to switch off the pump for simultaneous fMRI/EEG measurements (Assecondi et al., 2010; Bagshaw and Bénar, 2010; Bonmassar et al., 2002; Correa et al., 2010; Leicht et al., 2010; Ritter et al., 2010; Sammer et al., 2007, Wan et al., 2006).In this technical note we draw attention to another scanner induced artifact in the EEG. We show that the scanner's internal ventilation system for fresh air supply induces a frequency peak in the power spectrum of the EEG. The exact frequency of the peak is dependent on the ventilation level, but overall appears to be in the gamma frequency range of the EEG.

Yet, rhythmic EEG activity, such as gamma, is of special interest in the case of simultaneously acquired EEG and fMRI data because it can be related to many sensory and cognitive processes (Fries et al., 2001; Gray et al., 1989). Rhythmic EEG activity emerges from recurrent network interactions that are accompanied by changes in cerebral blood

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flow and oxygen consumption, which are reflected in the commonly used fMRI *blood oxygen level dependent* (BOLD) signal. A general way of analyzing simultaneously derived EEG and fMRI data is the correlation of the BOLD signal with the time course of the power spectrum of different EEG frequency ranges. Thus, EEG frequency band power can be used as a regressor in a general linear model that investigates how well fMRI data is explained by certain features of the EEG (for an overview of different ways of combining simultaneously measured EEG and fMRI data, see Huster et al., 2012). Most studies using simultaneous EEG-fMRI have reported an inverse correlation of the low-frequency EEG range (4–30 Hz) and the spontaneous BOLD signal fluctuations (for a review, see Nierhaus et al., 2009; Sadaghiani et al., 2010), whereas intracranial recordings reveal a close coupling between gamma-band (40–100 Hz) activity and the BOLD signal of sensory cortical regions (Lachaux et al., 2007; Mukamel et al., 2005). Since gamma band activity is a very weak signal in the EEG, combined EEG-fMRI recordings focusing on gamma activity are even more dependent on proper artifact reduction, and may therefore benefit greatly from the knowledge of potential artifact sources.

Here, we depict the ventilation-induced artifact recorded using two different MR scanners (Siemens TRIO and VERIO). By systematically combining different settings of ventilation strength with and without EPI scan, we were able to illustrate the ventilation artifact with and without disturbances of the MR scanning sequence. These measurements allowed for a quantification of the different artifacts occurring in simultaneous EEG/fMRI settings, and therefore the ventilation artifact could be reliably compared to the gradient artifact and the ballistocardiogram. Additionally, we investigated at which site in the EEG system (EEG cap or amplifier) the ventilation artifact is mainly induced in order to clarify if a simple setup change like “putting the amplifier outside the scanner bore” could reduce the artifact. Furthermore, we questioned how the ventilation interferes with the EEG recording. By measuring the artifact in the scanner room with a self-built antenna, we were able to differentiate between vibration and electromagnetic fields as the possible artifact source.

2. Material and methods

2.1. Data acquisition

Measurements were taken using two different 3-T SIEMENS Magnetom scanners (*Tim Trio* and *Verio*, Siemens, Erlangen, Germany) equipped with a standard head coil (12 channels). EEG recordings were acquired using an MRI-compatible EEG system(recorder settings: amplifier resolution = 0.5 μV, sampling frequency = 5.000 Hz, lowpass filter = 250 Hz) consisting of an MRI-compatible amplifier and a 32-channel EEG cap (Brain Products, Munich, Germany, Easy cap, Falk Minow Services, Herrsching-Breitbrunn, Germany). Thirty-one scalp electrodes were arranged according to the International 10–20 System (Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T7, T8, P7, P8, Fz, Cz, Pz, Oz, FC1, FC2, CP1, CP2, FC5, FC6, CP5, CP6, TP9, TP10, POz) with the reference located at electrode position FCz. An additional electrocardiogram channel was recorded for subsequent cardio-ballistic artifact removal. Impedances of all electrodes were kept below 5 kΩ. The EEG acquisition was synchronized to the gradient-switching clock of the MR-scanner using the Syncbox device (Brain Products, Munich, Germany).

A T2*-weighted echo-planar imaging (EPI) sequence (TR = 2000 ms, TE = 30 ms, flip angle = 90°, matrix 64 × 64, FOV = 19.2 cm, in-plane resolution = 3 mm × 3 mm, slice thickness = 4 mm, interslice gap = 1 mm) was used to induce the gradient switching artifacts in the EEG. 30 slices were acquired in an interleaved mode. The scanning planes were oriented according to the AC–PC convention. In one run, 60 volumes were acquired.

In each of the two MR-scanners, nine EEG measurements were taken with the subject at rest and the amplifier located inside the scanner bore. This represents the default setup for EEG-fMRI experiments; the cable connecting the subject's EEG cap with the amplifier is kept as short as possible, because it is prone to electromagnetic and vibration related artifacts. Different settings of He-pump, ventilation and EPI-scan were combined in order to systematically investigate artifacts caused by the scanner environment (see Table 1, Nos. 1–9). Moreover, we acquired three additional EEG recordings using the VERIO scanner with the ventilator running on level 2 and the amplifier and/or subject placed outside (i.e., behind) the scanner tube on a chair (Table 1, Nos. 10–12). Herewith, we aimed to find the artifact's main induction site (EEG cap or amplifier).

Next, we attempted to assess how the ventilation artifact is distributed: either via vibration or electromagnetic fields. For this purpose, we built an antenna with a sensor resistor of 5 kΩ connected to the EEG-amplifier via the ExG AUX input box (Brain Products, Munich, Germany). We performed three different tests with the ventilator running on level 1: (1) antenna in direct contact with the scanner, (2) antenna in contact with the scanner but electromagnetically shielded by a piece of wood (~2 cm thickness), and (3) antenna without contact with the scanner (gap ~2 cm). The amplifier was located outside the scanner bore (Table 1, Nos. 13–15).

Each measurement lasted approximately 1–2 min. During EEG measurement, the subject was instructed to lie still with their eyes open.

2.2. Data analysis

EEG data analysis was performed offline using Matlab (The Mathworks Inc., Natick, USA). EEG recordings acquired during MRI scanning (Nos. 6–9) were first corrected for gradient artifacts using a self-built template-based subtraction method. For this purpose, EEG data was segmented into epochs of 2 s (corresponding to the acquisition of each MRI volume, TR = 2 s) and high-pass filtered (cutoff 55 Hz). Then each segment was correlated with all other segments. Finally, the template for the subtraction of each segment was individually calculated from the unfiltered data by averaging the twenty most highly correlated segments. All EEG measurements (Nos. 1–12) were corrected for ballistocardiogram artifacts using the EEGLab (Delorme & Makeig, 2004) implemented BCG-correction routine (EEGLab, PCA/OBS approach). All measurements (Nos. 1–15) were downsampled to 500 Hz.

For further analysis, the first 5 s of each measurement was discarded and the following epoch of 50 s was selected for spectral analysis. Power spectral density was calculated for each channel (31 scalp

Table 1
Combinations of He-pump-, ventilation-, EPI-scan-, subject- and amplifier-setting used for the different measurements. Measurements 1–9 were performed using the TRIO and the VERIO scanner to show the ventilation level dependent artifact on two different MR systems. Measurements 10–15 were exemplarily performed using the VERIO with only one ventilation level, because the results are comparable for both scanners and all three ventilation levels. Antenna measurements (13–15) were performed with the amplifier always located outside the scanner bore. For measurement 14, a piece of wood was used for electromagnetic shielding between the scanner and the antenna.

No.	Scanner	He-pump	Ventilation	EPI	Subject	Amplifier
1	TRIO/VERIO	On	Off	Off	Inside	Inside
2	TRIO/VERIO	Off	Off	Off	Inside	Inside
3	TRIO/VERIO	Off	Level 1	Off	Inside	Inside
4	TRIO/VERIO	Off	Level 2	Off	Inside	Inside
5	TRIO/VERIO	Off	Level 3	Off	Inside	Inside
6	TRIO/VERIO	Off	Level 3	On	Inside	Inside
7	TRIO/VERIO	Off	Level 2	On	Inside	Inside
8	TRIO/VERIO	Off	Level 1	On	Inside	Inside
9	TRIO/VERIO	Off	Off	On	Inside	Inside
10	VERIO	Off	Level 2	Off	Inside	Outside
11	VERIO	Off	Level 2	Off	Outside	Inside
12	VERIO	Off	Level 2	Off	Outside	Outside
					Antenna	
13	VERIO	Off	Level 1	Off	With contact	
14	VERIO	Off	Level 1	Off	With contact (EM-shielded)	
15	VERIO	Off	Level 1	Off	Without contact	