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.

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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 the case of the He-pump it is therefore a common practice to switch off the pump for simultaneous fMRI/EEG measurements (Asseff 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, C5, C6, 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. EEG data analysis was performed offline using Matlab (The Mathworks Inc., Natick, USA). EEG recordings acquired during fMRI 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/OLS 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

<table>
<thead>
<tr>
<th>No.</th>
<th>Scanner</th>
<th>He-pump</th>
<th>Ventilation</th>
<th>EPI</th>
<th>Subject</th>
<th>Amplifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TRIO/VERIO</td>
<td>On</td>
<td>Off</td>
<td>Off</td>
<td>Inside</td>
<td>Inside</td>
</tr>
<tr>
<td>2</td>
<td>TRIO/VERIO</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Inside</td>
<td>Inside</td>
</tr>
<tr>
<td>3</td>
<td>TRIO/VERIO</td>
<td>Off</td>
<td>Level 1</td>
<td>Off</td>
<td>Inside</td>
<td>Inside</td>
</tr>
<tr>
<td>4</td>
<td>TRIO/VERIO</td>
<td>Off</td>
<td>Level 2</td>
<td>Off</td>
<td>Inside</td>
<td>Inside</td>
</tr>
<tr>
<td>5</td>
<td>TRIO/VERIO</td>
<td>Off</td>
<td>Level 3</td>
<td>Off</td>
<td>Inside</td>
<td>Inside</td>
</tr>
<tr>
<td>6</td>
<td>TRIO/VERIO</td>
<td>Off</td>
<td>Level 3</td>
<td>On</td>
<td>Inside</td>
<td>Inside</td>
</tr>
<tr>
<td>7</td>
<td>TRIO/VERIO</td>
<td>Off</td>
<td>Level 2</td>
<td>On</td>
<td>Inside</td>
<td>Inside</td>
</tr>
<tr>
<td>8</td>
<td>TRIO/VERIO</td>
<td>Off</td>
<td>Level 1</td>
<td>On</td>
<td>Inside</td>
<td>Inside</td>
</tr>
<tr>
<td>9</td>
<td>TRIO/VERIO</td>
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<td>Off</td>
<td>On</td>
<td>Inside</td>
<td>Inside</td>
</tr>
<tr>
<td>10</td>
<td>VERIO</td>
<td>Off</td>
<td>Level 2</td>
<td>Off</td>
<td>Inside</td>
<td>Outside</td>
</tr>
<tr>
<td>11</td>
<td>VERIO</td>
<td>Off</td>
<td>Level 2</td>
<td>Off</td>
<td>Outside</td>
<td>Inside</td>
</tr>
<tr>
<td>12</td>
<td>VERIO</td>
<td>Off</td>
<td>Level 2</td>
<td>Off</td>
<td>Outside</td>
<td>Outside</td>
</tr>
<tr>
<td>13</td>
<td>VERIO</td>
<td>Off</td>
<td>Level 1</td>
<td>Off</td>
<td>With contact</td>
<td>(EM-shielded)</td>
</tr>
<tr>
<td>14</td>
<td>VERIO</td>
<td>Off</td>
<td>Level 1</td>
<td>Off</td>
<td>With contact</td>
<td>(EM-shielded)</td>
</tr>
<tr>
<td>15</td>
<td>VERIO</td>
<td>Off</td>
<td>Level 1</td>
<td>Off</td>
<td>Without contact</td>
<td></td>
</tr>
</tbody>
</table>
electrodes for measurements 1–12) using the Fast-Fourier-Transform (FFT) implemented in the Matlab PSD command with a frequency resolution of 0.5 Hz. Scalp topographies of the artifact peaks are generated using the Matlab topoplot command. Since we found no differences in the artifact’s frequency between electrodes, the EEG results are presented by averaging the power spectra of all 31 scalp electrodes. A windowed FFT (window size = 10 s, no overlap) was applied to provide a temporal characterization of the artifact peak power with mean and standard deviation.

Finally, we compared the impact of the ventilation-related artifact with the gradient- and BCG-artifact. To this end, for each of the different artifacts, we computed the ratio “artifact-power/baseline-power” using the power spectrum of measurement 2 (He-pump off, ventilation off, EPI off) after BCG-correction as the baseline.

3. Results

3.1. He-pump artifact

The He-pump induced scanner specific artifacts in the frequency spectrum of the EEG with additional broad band frequency power starting from 20 Hz for the TRIO scanner and 30 Hz for the VERIO scanner. As mentioned by Ritter et al. (2010), switching off the pump eliminated the artifact, leaving only 50 Hz peaks of the line voltage and its higher harmonics (Fig. 1). Scalp topographies show no differences in the artifact’s frequency between electrodes but a modulation due to the position of the reference electrode (FCz). The time resolved FFT revealed a peak power fluctuation up to 10% for the TRIO scanner.

3.2. Ventilation artifact

The scanner’s internal ventilation system induced a specific peak and its higher harmonic in the frequency spectrum of the EEG data. Dependent on the ventilation level, this frequency peak was found at ~37 Hz, ~41 Hz, and ~50 Hz for ventilation levels 1, 2, and 3, respectively (Fig. 2, top row, measurements 3, 4 and 5). The peak frequency differed by about 1 Hz between the TRIO and the VERIO scanners. Scalp topographies indicated no differences between electrodes with respect to the contamination by the artifact but a modulation by the position of the reference electrode (FCz). The time resolved FFT revealed fluctuations in the peak power over time which were comparably low as for the artifact free measurement. In the TRIO scanner, all the three ventilation levels additionally induced broad-band noise in the frequency range between 80 and 95 Hz. Similar to the He-pump-artifact, switching off the ventilation eliminated all associated artifacts completely (Fig. 2, blue lines).

The fMRI settings with 30 slices, acquired within a TR of 2 s, induced a gradient artifact with an initial peak at 15 Hz in the EEG power spectrum, followed by its higher harmonics (30 Hz, 45 Hz, 60 Hz, etc.). The gradient artifact correction sufficiently eliminated the initial 15 Hz peak, leaving only residuals of the higher harmonics at 30 Hz, 45 Hz, 60 Hz, etc. (Fig. 2, bottom row). Additionally, as can be seen in the bottom row of Fig. 2, the frequency peaks of the ventilation artifact (at ~37 Hz, ~41 Hz, and ~50 Hz for level 1, 2, and 3, respectively) were clearly visible with an amplitude similar to (or even stronger than) the residuals of the gradient artifact. Scalp topographies again indicate no differences between electrodes with respect to the contamination by the artifact as shown for the residuals of the gradient artifact. For the VERIO scanner we found higher fluctuations in peak power over time during the EPI measurement. In the TRIO scanner, the EPI sequence induced additional broad-band noise (50–100 Hz) covering the ventilation induced high frequency noise which is visible in the measurement without EPI scanning (Fig. 2, upper plot).

Quantification of the ventilation artifact using the VERIO scanner for ventilation level 1 (level 2) revealed it to be two (three) times larger than the BCG-artifact, and compared to the gradient residual at 30 Hz the ventilation artifact at level 1 (level 2) was four (eight) times larger (Fig. 3 and Table 2). The ventilation artifact at level 3 overlapped with the 50 Hz line noise, which does not allow its valid quantification.

Fig. 4 shows the VERIO ventilation artifact (level 2) for different scenarios of the subject and the amplifier being located in- and outside the scanner. The artifact was maximal when the subject was located inside...
the tube on the patient table (Fig. 4, measurements 4 and 10, red and cyan lines) and it disappeared when the subject and the amplifier were located outside the bore, behind the scanner (Fig. 4, measurement 12, blue line). The amplifier alone in the scanner tube (not on the table) was less affected by the ventilation (Fig. 4, measurement 11, magenta line). Additionally, the 50 Hz line noise peak appeared only when the subject was inside the scanner tube. The antenna measurement in the VERIO scanner with direct contact between the antenna and the scanner, revealed the ventilation artifact for level 1 at 37 Hz (Figure 5, measurement 13, black line).
For measurement 14, a piece of wood (2 cm thick) served as an electromagnetic shield between the antenna and the scanner, and vibratory transmission was still possible. This setup only minimally reduced the artifact compared to measurement 15, where the antenna had no contact with the scanner and the artifact disappeared (Fig. 5).

4. Discussion

In this technical note, we describe a systematic artifact in the EEG signal, which is induced by the ventilation system within the MR scanner tube during simultaneous EEG-fMRI measurements. Our results show that the scanner's internal ventilation system causes vibrations of the scanner tube's internal coverage, interfering with EEG recordings and inducing a frequency peak in the power spectrum of the EEG. The different ventilation levels (i.e., 1, 2, and 3) induced a distinct frequency peak at ~37 Hz, ~41 Hz, and ~50 Hz, respectively. These frequency peaks are in the physiologically relevant gamma frequency range, and thus represent a crucial problem for studies specifically targeting this frequency range. Switching off the scanner's ventilation system eliminated the occurrence of the artifact and enabled reliable acquisition of gamma band oscillations together with BOLD signals.

We performed two sets of measurements using two different MR scanners (Siemens TRIO and VERIO) to depict the ventilation-induced artifact in different settings. Measurements 2–5 were conducted to exclusively illustrate the artifact for the different ventilation levels without disturbances of the MR scanning sequence. Besides the scanner specific frequency peaks, the TRIO scanner was more prone to high frequency vibrations between 50 and 100 Hz. This might be due to differences in the shielding of the almost 10 years younger VERIO scanner. A standard EPI sequence was used for measurements 6–9 to show that the ventilation induced artifact is still prominent, although disturbed by the considerably larger gradient artifact. These measurements allowed for a quantification of the different artifacts occurring in simultaneous EEG-fMRI settings. The ventilation induced artifact in the VERIO scanner was found to be 2–3 times larger than the BCG-artifact, and compared to the gradient artifact residual at 30 Hz (after applying a gradient artifact correction algorithm), it was even 4–8 times larger. This demonstrates that the ventilation artifact cannot be neglected.

With measurements 10–12 we tested different scenarios with the subject and the amplifier located in- and outside the VERIO scanner tube to identify at which site of the EEG system (EEG cap or amplifier) the artifact is mainly induced. Here, we showed that the ventilation dependent noise induction was most prominent on the electrodes placed directly on the subject’s head. The EEG amplifier alone in the scanner tube was less affected by the ventilation artifact. Thus, it is not sufficient to simply place the EEG’s amplifier outside the scanner tube because main artifact induction occurs directly at the EEG cap on the patient table.

Furthermore, we systematically tested two possible artifact sources: (1) the ventilation causes a vibration in the scanner, which is transferred to the EEG system placed inside the scanner tube. These transmitted vibrations probably cause movements of the EEG-equipment in the scanner static magnetic field, inducing electric fields that interfere with the EEG recordings. (2) The ventilation engine transmits an

![Artifact Quantification](image-url)

Fig. 3. Artifact quantification. Visualization of the BCG artifact (measurement 2, no ventilation, gradients off) and the gradient artifact (measurement 9, no ventilation, gradients on) before and after application of the artifact correction algorithms compared to the ventilation artifact of level 1 (measurement 3) and level 2 (measurement 4). For quantification, the power spectrum of the BCG-corrected measurement 2 (blue line) was used as a baseline. Ventilation level 3 is not quantified due to its overlap with the 50 Hz line noise.
The windowed FFT analysis revealed that the peak power was constant over time. Only the VERIO scanner showed higher fluctuations in peak power during EPI measurements. Also the He pump induced artifact of the MR systems we used was instable over time. These instabilities are an additional problem for offline correction methods such as the template subtraction. Furthermore, the He pump artifact highly differed between scanners. This is due to the fact that both scanners use the same ventilation system but different kinds of cryo cooling systems. Although it is a common practice to switch off the He pump when acquiring EEG during fMRI our measurements show that low frequencies are less affected when the He pump is not switched off. Thus EEG acquisition in the frequency range up to 30 Hz is possible even without switching off the He pump, especially with the VERIO scanner. Nevertheless, each EEG-fMRI user should assess the MR scanner specific noise characteristic. Especially when switching off the He pump is not possible, the frequency ranges of interest may not be affected or the noise characteristic shows a repetitive pattern so that post-hoc correction can be applied.

The ventilation-induced artifact can be eliminated most easily by switching off the ventilation during simultaneous EEG recordings. This, however, causes a temperature rise within the scanner tube. According to our experience short measurement blocks of ~10 min with short breaks for fresh air supply are still comfortable for the subjects we scanned so far. In cases of longer acquisition periods, an external ventilation system placed before or behind the scanner tube can replace the built-in ventilation of the scanner.

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References


The electromagnetic field that directly disturbs the EEG recording. To test these two hypotheses, we used a self-built antenna with a sensor resistor of 5 kΩ to directly measure the ventilation artifact independently from the EEG setup. Measurements 13–15 were performed with and without contact between antenna and scanner to allow for a differentiation between ventilation and electromagnetic fields as a possible artifact source. Without contact with the scanner bore (2 cm gap), the ventilation induced artifact disappeared, whereas with electromagnetically shielded contact, the artifact was only minimally reduced. This clearly points to vibration as the artifact source because the electromagnetic shield still allowed for vibratory transmission from the scanner to the antenna. This was supported by our observations after removal of the side cladding of the MR scanner, which clearly showed the vibrating elements of the ventilation system.

Comparing the two scanners, the peak frequencies of the ventilation artifact were almost similar, differing only by about 1 Hz. Since the artifact’s frequency for each scanner was highly reproducible on different days with different subjects and electrode caps, as well as in the different settings tested at the VERIO scanner (Figs. 4 and 5), these little differences in frequency spectra were most likely a scanner specific attribute.

Fig. 4. Artifact induction site. VERIO ventilation artifact with different combinations of subject and amplifier located in- and outside the VERIO scanner with ventilation set at level 2. The amplifier alone in the scanner is less affected by the ventilation artifact than the electrodes placed on the subject’s head. Note that the exact frequency peak of ventilation level 2 at the VERIO scanner (42 Hz) is highly reproducible.

Fig. 5. VERIO ventilation artifact (level 1) measured with an antenna. Electromagnetic shielding between antenna and scanner with a piece of wood (2 cm thickness) only minimally reduced the artifact (measurement 14, gray line) compared to the measurement with a 2 cm gap between antenna and scanner (measurement 15, no contact, dotted line). Note that the exact frequency peak of ventilation level 1 at the VERIO scanner (37 Hz) is highly reproducible.


