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Gradient induced artifacts in simultaneous EEG-fMRI: Effect of synchronization on spiral and EPI k-space trajectories

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ABSTRACT

The nature of the gradient induced electroencephalography (EEG) artifact is analyzed and compared for two functional magnetic resonance imaging (fMRI) pulse sequences with different k-space trajectories: echo planar imaging (EPI) and spiral. Furthermore, the performance of the average artifact subtraction algorithm (AAS) to remove the gradient artifact for both sequences is evaluated. The results show that the EEG gradient artifact for spiral sequences is one order of magnitude higher than for EPI sequences due to the chirping spectrum of the spiral sequence and the dB/dt of its crusher gradients. However, in the presence of accurate synchronization, the use of AAS yields the same artifact suppression efficiency for both pulse sequences below 80 Hz. The quality of EEG signal after AAS is demonstrated for phantom and human data. EEG spectrogram and visual evoked potential (VEP) are compared outside the scanner and use both EPI and spiral pulse sequences. MR related artifact residues affect the spectra over 40 Hz (less than 0.2 μV up to 120 Hz) and modify the amplitude of P1, N2 and P300 in the VEP. These modifications in the EEG signal have to be taken into account when interpreting EEG data acquired in simultaneous EEG-fMRI experiments.

1. Introduction

Most functional magnetic resonance imaging (fMRI) studies are based on gradient-echo echo planar imaging (GE-EPI). However, GE-EPI is highly affected by magnetic field inhomogeneities causing both local image distortion and signal dropout, mainly in brain areas near air-tissue interfaces [1]. Spiral in-out techniques are a promising alternative as they provide advantages in the study of those brain areas [2]. However, spiral imaging is hardware demanding, and its k-space trajectories incorporate slew rate-limited and amplitude-limited regimes [2,3]. These hardware constraints in the spiral pulse sequence profiles affect the gradient induced artifact [4–6] features that are commonly observed in simultaneous electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) acquisition [7], increasing the amplitude of the artifact in some instances by up to one order of magnitude higher than when EPI sequence is used [8].

As it has been reported in recent publications [9,10], synchronization of both the EEG system and the MR scanner is necessary to achieve an optimal removal of the gradient artifact using artifact average subtraction (AAS) techniques, developed originally by Allen et al. [4]. These reports showed that the performance of the algorithm is maximized when the clocks of the MR and EEG systems are synchronized, (phase-locked clocks) and when repetition time (TR) is a multiple of the EEG sampling interval.

The primary aims of this article are, first, to provide a comprehensive characterization of the EEG gradient artifact depending on the fMRI pulse sequence and, second, to demonstrate the impact of synchronization and pulse sequence in its subsequent elimination. A conventional GE-EPI sequence and a spiral K-space filling fMRI sequence (GE-SPRLIO) [2] were used for phantom and human data. To our knowledge, this is the first work that analyzes the impact of using non-EPI sequences in EEG signal quality in non-simulated data and in presence of synchronization schemes for simultaneous EEG-fMRI.

2. Materials and methods

2.1. EEG data acquisition

EEG data were recorded using a brain products MR compatible EEG system with characteristics: sampling frequency (fs) = 5 KHz, band-pass filter (BPF) = 0.016–250 Hz-, 5th order 30 dB/oct and 32 channels EEG cap. Tests were made with and without a synchronization scheme [9,10].

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Five phantom sessions were repeated with the same MR protocol including an EEG acquisition of 6 minutes inside the scanner without any pulse sequence running. For the phantom data, the EEG cap was fitted to a water spherical MR phantom previously covered with Abralyt 2000 electrolyte paste in order to capture a pure gradient artifact. For simplicity, the induced EEG signals in the phantom experiment will be called 'EEG' to make easier to understand the applied methodology, equivalent to the one applied with a human subject.

Data from the human volunteers were obtained with eyes closed and during a visual task.

The visual task was repeated inside and outside the MR scanner in order to recover the visual evoked potential (VEP) as a measurement of EEG quality across trials. The design was thought to be valid for both techniques, EEG and fMRI, so it was designed as a mixed event-block paradigm described as follows:

- The paradigm consisted of the presentation of photos of objects with the same background color and with neutral emotional content.
- The task lasted 5 minutes and 30 seconds and was divided in 5 cycles of 20 seconds rest and 42 seconds of image presentation (one block). Each block consisted of 12 images.
- Each image was present on the screen during 1 second, and the interstimulus time was randomized to be 2 seconds, 2.5 seconds or 3 seconds. Each of these interstimulus times appeared 4 times per block. During rest and during the interstimulus time, a fixation-cross appeared on the screen.
- To maintain the attention during the task and to obtain a VEP with P300 wave, the subjects were instructed to store the images in their memories.
- Three versions of the task were available to be done to the same person (one of them outside the scanner, and two inside the scanner with two different MR pulse sequences or parameters.)

A Visuastim digital system (Resonance Technology Inc.) was used to show the images to the subject inside the scanner using MR compatible goggles. Superlab 4.5 was used to program the visual task. The system was synchronized with the MR scanner using the TTL trigger pulse. The first MR trigger pulse that was sent after the MR dummy volumes began the task. Additionally, a National Instruments USB-6009 digital card was attached to the computer where Superlab 4.5 was running. This card was used to send a mark to the EEG recording software program immediately before each new image stimulus presentation happened.

The local ethics committee approved these experiments, and informed consent was obtained from the volunteers.

2.2. MRI data acquisition

MRI data were collected with a 3.0 T HDxt General Electric MR scanner using a whole-body radiofrequency coil for signal excitation and an 8-channel brain coil for reception.

Single-shot GE-EPI and GE-SPRLIO spiral in-out [2] fMRI acquisition parameters were: acquisition matrix: 64×64, voxel dimension: $3.75 \times 3.75 \times 4$-mm, 100 whole brain volumes consisting of 36 near-axial slices with TE = 28 ms/TR2880 ms were acquired (TR = 2880.72 ms for the non-synchronization scheme).

The simultaneous EEG-fMRI acquisition for the phantom data was repeated for the following conditions: (i) in the absence of any pulse sequence (background noise inside the scanner); (ii) GE-EPI without synchronization (iii) GE-SPRLIO without synchronization; (iv) GE-EPI with synchronization; and, (v) GE-SPRLIO with synchronization. The human data were acquired in the following conditions: (i) in the absence of sequences, (vi) GE-EPI with synchronization and (vii) GE-SPRLIO with synchronization.

2.3. Data analysis: gradient artifact and pulse sequence

MATLAB R2009a was used to plot the pulse sequence X, Y and Z gradients and the EEG signal of one of the individual channels located in the left central cortex (channel C3), during the acquisition of one image slice from the phantom data for each type of sequence, GE-EPI and GE-SPRLIO.

2.4. Data analysis: EEG signal quality assessment (phantom data)

Since the removal of the gradient artifact using AAS [4] depends on the repeatability of the waveform across volumes [8,9], a preliminary analysis of the performance of AAS was made for both kinds of sequences with and without synchronization. EEG signal (100 volumes) was segmented in TR periods taking the MR trigger marker signal as reference for the EEG segmentation. A realignment procedure was used prior to this preliminary analysis and to the application of the AAS for the cases without synchronization to minimize the variability across successive volumes. Then, the mean and the standard deviation per time point (taking EEG channel C3 as representative channel) were computed for all the segments in each condition.

We applied the AAS algorithm [4] as implemented in Brain Vision Analyzer 2.0, using a sliding window of 21 volumes to compute the artifact template. After AAS, EEG signal was subsampled to 500 Hz.

Finally, the spectral content of EEG signals between 0.5–125 Hz was measured using the average voltage density (VSD; μV/Hz) with a Welch spectral estimation of 1024 windowed samples (2.048 seconds) in MATLAB R2009a [11]. Two quantitative measurements were extracted from the obtained voltage density spectra. First, the effectiveness of the AAS was calculated as the attenuation of signal amplitude Eq. (1) due to the AAS and compared with the background noise Eq. (2) at the slice frequency and harmonics [10]. The previous metric is a local measurement as it is calculated for specific affected frequencies; a local better AAS performance is obtained when the attenuation from Eq. (2) is equal to the attenuation calculated in Eq. (1). Second, the Euclidean distance was calculated as a global measure of the similarity between the background spectrum and each corrected spectrum for each pulse sequence as indicated in Eq. (3) for the range of frequencies defined by f_0–f_{max} (1–125Hz in the phantom case).

$$Att_{corrected}(f) = -20 \cdot log_{10}\left({}^{VSDcorrected}\!\big/_{VSDuncorrected} \right) \quad (1)$$

$$Att_{background}(f) = -20 \cdot log_{10}\left({}^{VSDbackground}\!\big/_{VSDuncorrected} \right) \quad (2)$$

$$Euclidean\ Distance = \sqrt{\sum_{i=f_0}^{f_{max}} (VSDcorrected_i - VSDbackground_i)^2} \quad (3)$$

2.5. Data analysis: EEG signal quality assessment (human data)

For both, the resting fMRI with closed eyes and the visual task series EEG epochs, after the removal of gradient artifact with AAS, the pulse-related artifact (PA) was removed using an independent components analysis (ICA) approach [12]. The same ICA was used to remove blinks from visual task series.

For the visual task EEG epochs, EEG signal was segmented channel-by-channel from −100 ms to 900 ms after each event marker sent by the stimulation program for each image presentation. Low or too high activity (less than 0.5 μV or greater than 100 μV between maximum and minimum segment values) or sharp changing activity (maximum allowed change of 25 μV/ms) EEG segments were discarded. The rest of the segments were baseline level corrected using the −100 ms to 0 s interval for each segment.