A method for real time artifact filtering during simultaneous EEG/fMRI acquisition: preliminary results

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ABSTRACT

A standard EEG equipment was modified in order to work properly during ultra fast MRI acquisitions. Changes include: amagnetic electrode cap, optical fiber link, shielding box for EEG amplifier, twisted low metal mass cable. The effects of the RF pulse and time varying magnetic fields were minimized by using a correct head cap wires locked environment montage and then removed with a simple subtraction algorithm during EEG/fMRI acquisition. Ballistocardiogram artifact was also minimized at suitable levels by using a comfortable head position and immobilization.

INTRODUCTION

Functional MRI allows to combine in one technique the high spatial resolution of MR imaging and the possibility to spatially detect changes of tissue oxygenation and perfusion induced by neuronal activation. Changes in blood oxygenation induce changes in MR signal (Blood Oxygen Level Dependent, BOLD technique) that can be detected with a resolution of few millimetres and a temporal resolution of few seconds; these characteristics are complementary to the electro physiologic characteristics (which recording systems are mainly EEG and MEG) that have a higher temporal resolution but a lower spatial resolution. It is therefore clear that the integration [1,2] of these two non invasive methods may provide an accurate investigation of brain function. An important application of the integration of these techniques in neurology is represented by the identification of the cortical area associated with neuronal activity.

Warach et al. (1996) [3] first demonstrated the clinical applicability of EEG-triggered fMRI by using EEG equipment specifically designed for recording during MR acquisition (Ives et al.,1993) [4]. However, they did not address the pulse artifact problem. They observed an artifact synchronised with cardiac activity (ballistocardiogram). According to Allen et al. (1998) [5], the pulse artifact is induced by

blood flow inside the head, normal to the static magnetic field. Initially this interaction was virtually impossible to eliminate, and the authors showed that a simple adaptive subtraction algorithm can partly solve the problem (Krakow et al., 1999)[6,7], instead it's possible to reduce this cardiac activity effect simply through a cable montage and patient head lock protocol (Allen et al. 2000,)[8].

Concerning EEG signal alterations due to the gradients (time-varying magnetic fields)[9], Ives et al. (1993)[4] and Huang-Hellinger et al. (1995)[10] observed that they induce an electromotive force (EMF) in each apparent wire loop perpendicular to the gradient field direction which is proportional to the cross sectional area of the wire loop and to the slew rate of the gradients.

When wires and electrodes of EEG device are placed inside the MR scanner, the fast varying gradient fields and the radio-frequency pulses during MRI scan induce a very intense electric noise that obscure the EEG signal.

MATERIALS AND METHODS

A standard portable 40-channel digital EEG amplifier (Mizar, EBNeuro S.p.A., Florence, Italy) was adapted to operate inside the MR room [11,12]. Conic Ag-AgCl electrodes pre-arranged into a cap of amagnetic material were filled with conductive gel [13]. The EEG apparatus (placed inside a shielded box to eliminate RF disturbance on the MR images) amplifies the signal, performs A/D conversion and multiplexing. The digital signal is then transferred, via an optical fibre connection, to an host computer (placed outside the magnet room) for demultiplexing, data acquisition, processing, and storage. Simultaneous EEG and EPI acquisitions were performed on whole body MR scanner Philips Intera 1.5 T (Dept. of Neurological Science, University of Rome, "La Sapienza").

Three healthy males volunteers (ages 25 to 30) were scanned. The approval of the local ethics committee was obtained for all EEG recordings during MRI. All subjects gave their informed, written consent for the study.

EPI images were acquired by single shot pulse sequence with the following parameters: TE 60 ms, FOV 24 cm, matrix 64x64, 18 contiguous slices with 5 mm thickness. Continuous fMRI acquisition methods was applied with 200 volumes (of 18 slices) each one with a repetition delay of 3 s for a total scan time of 10 min.

The EEG recorded features inside the MRI scanner during the EPI (Echo Planar Imaging) sequence were used in order to consider the whole magnetic artifact interferences on the EEG traces like evoked responses due to a specified "stimulation". For this reasons, the RF pulse and gradient field artifacts were detected, evaluated and then computed with a standard evoked potential methodic, considering **x(t)** as raw continuous signal acquired by the EEG amplifier.

Two fundamental hypothesis were used [14], the first one consider **x(t)** as a set of uncorrelated components : the EEG basal activity **eeg(t)**, the instrumental noise **n(t)** and the EPI evoked response **epi(t)**:

$$x(t) = eeg(t) + n(t) + epi(t) \tag{1.1}$$

The second one assume that **eeg(t)** and **n(t)** have zero mean. The EPI signal averaging procedure was briefly articulated in the following steps:

- Applying *M* EPI dynamic stimuli , and record resulting *M* responses;
- Aligning *M* responses to form an ensemble with each response EPI aligned in time;
- Averaging across all responses in the ensemble to get the EPI estimate;

We assume that each response (with **N** samples length corresponding to the duration of each EPI dynamic) was computed by **M** averages:

$$x_i(t) = [x_{i,1}(t), x_{i,2}(t), ..., x_{i,N}(t)] = eeg_i(t) + n_i(t) + epi_i(t) \ , \qquad \text{i=1,..,M} \tag{1.2}$$

$$x_{avg}(t) = \frac{1}{M}\sum_{i=1}^{M} x_i(t) \ , \qquad \frac{1}{M}\sum_{i=1}^{M} x_i(t) = \frac{1}{M}\left(\sum_{i=1}^{M} eeg_i(t) + \sum_{i=1}^{M} n_i(t) + \sum_{i=1}^{M} epi_i(t)\right) \tag{1.3}$$

$$x_{avg}(t) = eeg_{avg}(t) + n_{avg}(t) + epi_{avg}(t) \tag{1.4}$$

After M averages $eeg_{avg}(t) \to 0$ and $n_{avg}(t) \to 0$

$$x_{avg}(t) \cong epi_{avg}(t) \tag{1.5}$$

In this way the EPI synchronously averaged EEG is an estimate of the average waveform of the whole EPI interference (RF pulses and gradient fields) in the EEG channels. In other words, the overall computational process comprises the following basic operations:

1. evaluation of the EPI sequence informations into the EEG raw data and subsequently EPI event trigger detection;
2. computation of the artificial reference artifact model;
3. synchronized interference cancellation by zero-phase band pass filtering, subtraction and final appropriate windowing application.

The first step of the proposed algorithm essentially is based on an event trigger signal (S-detector) for temporal determination of the recurrent interference. Goldman (et al. 2000) [15] uses a trigger pulse (the duration of this trigger is related at the EPI sequence parameters) generated by the scanner in order to suppress gradient artifact in the EEG record; instead we use an internal peak detection algorithm that matches two discrimination criteria to evaluate MRI artifact peaks of the EEG signal: first and most simple criterion checks signal amplitude; the second one takes into account the timing. In detail, the first technique validates each sample of selected channels like a possible valid peak with amplitude threshold detection (performed during auto-calibration phase). The second step checks the matching between the peak and the known artifact time model: in this case each peak is associated with a specific EPI sequence event. Possible spikes and false events are simply ignored because they do not match correctly with the estimated time model.

The above described calibration sequence builds the artifact model by computing a user defined number of EPI sequences and also by updating built–in generic artifact model. The trigger points created by the dynamic detector are used for synchronous segmentation of the corrupted EEG raw data channels. Each channel is processed independently. The resulting temporal data segments are averaged in each channel. The so-obtained event synchronous average was considered as an estimate of the true interference and then stored in a reference memory. The reconstructed EPI artifact model was filtered (using a 10^{th} order zero-phase FIR band-pass Gaussian filter, 0.1 sec TC ,70 Hz LF) after its synchronization with the raw EEG recorded signal (also filtered by the same parameters), in order to remove the high frequency disturbances and the low artifacts modulations (mainly due to the Repetition Time of each volume of the EPI sequence) before the final subtraction. Such synchronous subtraction was shaped by standard numeric window (like Hanning or Kaiser), in order to attenuate edges interferences.

The result of this algorithm sequence is the quite cleaned EEG signal: synchronized interference cancellation by zero-phase band pass filtering, subtraction and final appropriate windowing application.

RESULTS

Good preliminary results were obtained by using our experimental EEG HW setup (Fig.1). For each patient a 3 minutes EEG recording were acquired outside the MR scanner (Fig.2) in order to monitor standard basal neuronal activations, then they were placed inside the scanner for another preliminary recording. It was interesting to note that the ballistocardiogram effect (Fig.3) was effectively attenuated (Fig.4) by our procedure and a residual amount was maintained just to have a physiological reference

pattern to control real time filtering action on signals shape. After these steps, a simultaneous EEG recording/continuous EPI sequence protocol was performed (Fig.5,7).

An noticeable result of our procedure is that the EPI images produced appear of good quality (Fig.7) without signal loss and induced noise from EEG devices, this is an important condition in fMRI activation maps processing. The dramatically obscured EEG recording (Fig.5) during EPI sequence was quite completely cleaned without distortion and loss of information. Our aim is to employ this procedure to perform an event related fMRI study in patients with drug refractory epilepsy and for this purpose we retain that real time monitoring of the EEG trace is necessary.

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Figure 1

Figure 2

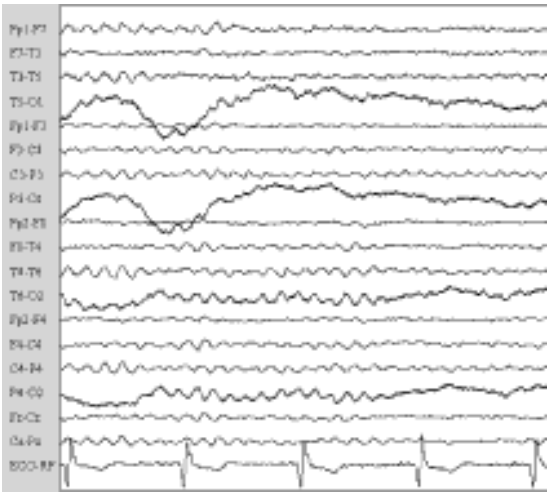

Figure 3

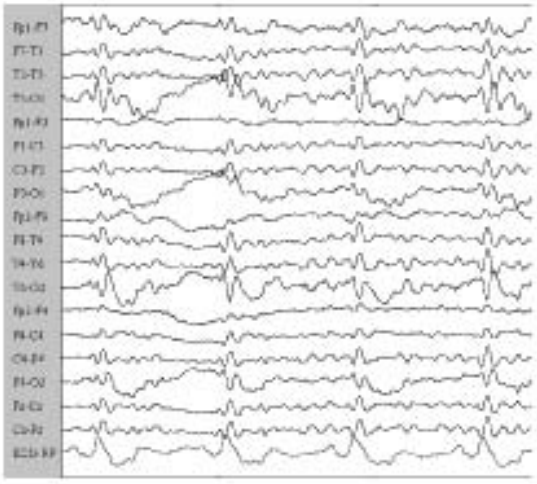

Figure 4

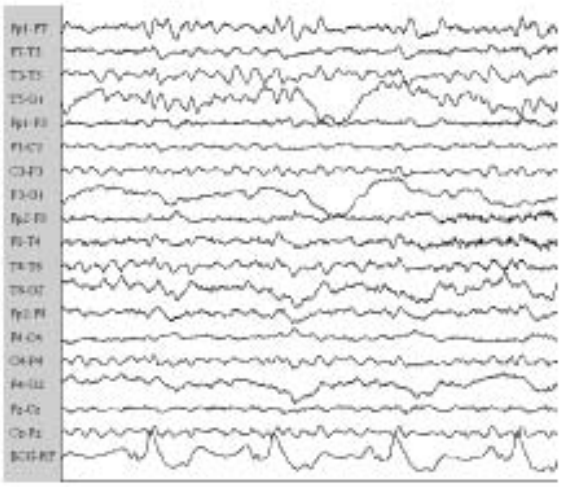

Figure 5

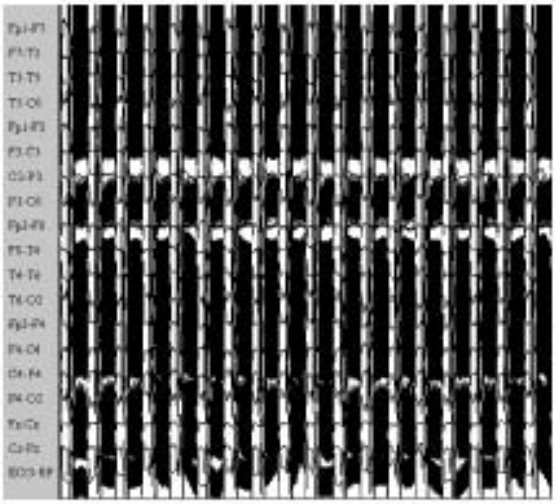

Figure 6

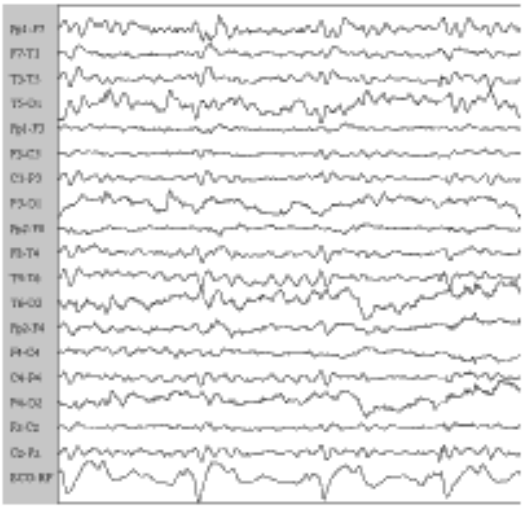

Figure 7

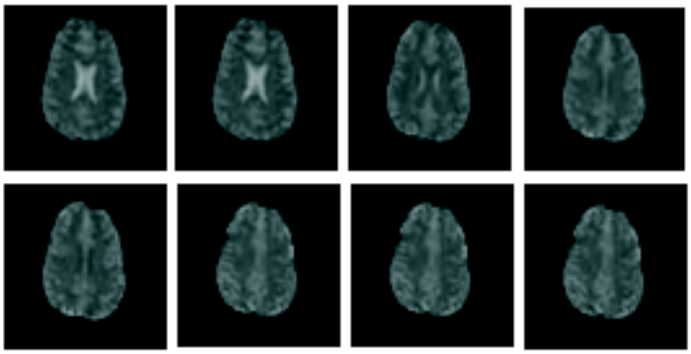

Figure Legends

Figure 1: EEG experimental HW setup

Figure 2: 3 seconds EEG trace recording of a health patient (age 30), outside the MRI scanner. Acquisition parameters: sampling rate = 4096 Hz, dynamic range: ±65.5 mVolts. EEG channels sensibility was 14.0 uV/mm; ECG channel sensibility was 140.0 uV/mm. Filtering: TC= 0.30 sec; HF= 60.0 Hz; Notch enabled (50 Hz).

Figure 3: 3 seconds EEG trace recording of a health patient (age 30), inside the MRI scanner. The evident ballistocardiogram artifact was caused by the inaccurate lock of a patient head for each EEG channel. Acquisition parameters: sampling rate = 4096 Hz, dynamic range: ±65.5

mVolts. EEG channels sensibility was 14.0 uV/mm; ECG channel sensibility was 140.0 uV/mm. Filtering: TC= 0.30 sec; HF= 60.0 Hz; Notch enabled (50 Hz).

Figure 4: 3 seconds EEG trace recording of a health patient (age 30), inside the MRI scanner. The evident ballistocardiogram artifact was attenuate for the whole trace by the comfortable and accurate lock of a patient head. Acquisition parameters: sampling rate = 4096 Hz, dynamic range: ±65.5 mVolts. EEG channels sensibility was 14.0 uV/mm; ECG channel sensibility was 140.0 uV/mm. Filtering: TC= 0.30 sec; HF= 60.0 Hz; Notch enabled (50 Hz).

Figure 5: 3 seconds EEG trace recording of a health patient (age 30), inside the MRI scanner during the EPI sequence before filtering. All recording was completely obscured by the RF pulse and gradient filed phases of the EPI scan. Acquisition parameters: sampling rate = 4096 Hz, dynamic range: ±65.5 mVolts. EEG channels sensibility was 14.0 uV/mm; ECG channel sensibility was 140.0 uV/mm. Filtering: TC= 0.30 sec; HF= 60.0 Hz; Notch enabled (50 Hz).

Figure 6: 3 seconds EEG trace recording of a health patient (age 30), inside the MRI scanner during the EPI sequence after filtering. Quite cleaned trace recording was obtained without loss signal information. Acquisition parameters: sampling rate = 4096 Hz, dynamic range: ±65.5 mVolts. EEG channels sensibility was 14.0 uV/mm; ECG channel sensibility was 140.0 uV/mm. Filtering: TC= 0.30 sec; HF= 60.0 Hz; Notch enabled (50 Hz). EPI sequence parameters: Time Repetition = 3 sec; 64x64 matrix dimension at 100%; 18 slices for dynamic, 100 dynamics, Time Echo = 60 msec.

Figure 7: EPI images of health patient (age 30), acquired simultaneously with on line EEG filtering recording