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Reduction of ECG and gradient related artifacts in simultaneously recorded human EEG/MRI data

J. Sijbers[a,*], J. Van Audekerke[b], M. Verhoye[b], A. Van der Linden[b], D. Van Dyck[a]

[a]*Vision Lab, University of Antwerp, Groenenborgerlaan 171, B-2020 Antwerp, Belgium*
[b]*Bio-Imaging Lab, University of Antwerp, Belgium*

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Abstract

Nowadays, electroencephalography signals can be acquired from a patient lying in a magnetic resonance imaging system. It is even possible to acquire EEG signals during an MR imaging sequence. However, such EEG signals are severely distorted by artifacts originating from various effects (e.g., MR gradients, ECG). In this paper, a simple method is presented to reduce such artifacts. Thereby, special attention is focused on artifacts related to the patient's electrocardiogram. The method is shown to be effective, adaptive, and automatic.

Keywords: Restoration; Artifacts; Adaptive; Simultaneous EEG/MRI; ECG; Hall-effect

1. Introduction

Combination of electroencephalography (EEG) and magnetic resonance imaging (MRI) becomes increasingly popular due to their complementary virtues. Functional MRI (fMRI) is relatively accurate in spatially localizing functional active areas in the brain but lacks a good time resolution. On the other hand, opposite remarks can be made about EEG: its time resolution is quite good (of the order of 1 ms) but the resolution of spatial source allocation is generally low. Hence it is clear that combining these two imaging modalities can be helpful in the study of the brain [1,2,3,4].

It is not surprising, however, that EEG and MRI interfere severely during simultaneous acquisitions as both modalities are based on electromagnetism. The influence of the EEG recording system on the MR images acquired is quite small. On the other hand, EEG signals are heavily disturbed by various phenomena [1,5,6,7]:

- Static magnetic field interference: Movement in a magnetic field changes the electromagnetic flux through inter-electrode loops or loops within the subject from which electro-physiological readings are taken. This may result in unwanted contributions to the EEG recordings.
  Although it poses practical difficulties, the interference due to movement can quite effectively be avoided by fixing the patient and wires and avoiding loops in the wires.
- Magnetic gradient related interference: Obviously, the most important interference originates from switching magnetic field gradients during an MR imaging sequence. Gradient switching severely obscures the EEG. In fact, gradient related artifacts make the reading of the EEG signal almost impossible during the actual MR imaging. This problem can efficiently be solved by applying an adaptive filtering algorithm as described by Sijbers et al [8].
- Cardiac pulse interference: where it is hardly observed in animal data, this type of interference is much more pronounced in simultaneously acquired human EEG/MR data. ECG related artifacts are caused by a combination of:
  - small cardiac related movements of the body [7,9,10],
  - small but firm movement of the electrodes and scalp due to expansion and contraction of scalp arteries between systolic and diastolic phase [9]. Ives suggested these to originate from the accel-

* Corresponding author. Tel.: +32-0-3-218-0-452; fax: +32-0-3-218-0-318.
E-mail address: sijbers@ua.ac.be (J. Sijbers).

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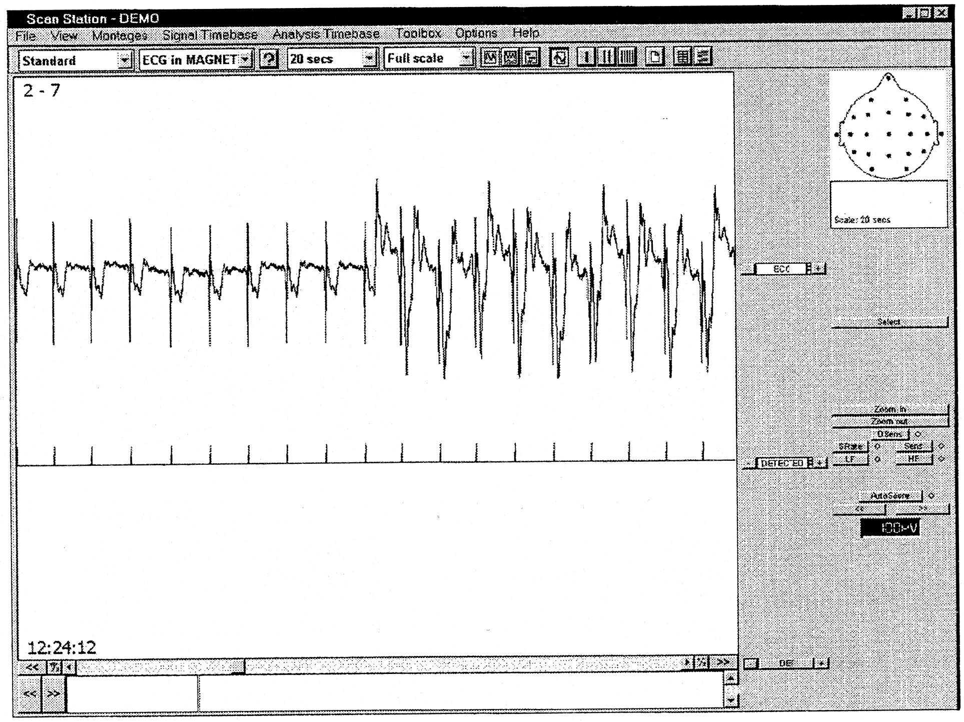

Fig. 1. The effect of the magnetic field on the ECG recording. The second channel shows the QRS onset detection outputs.

eration and abrupt directional change of blood flow in the aortic arch [1].

– fluctuation of the Hall-voltage due to the pulsating speed changes of the blood in the arteries [7,9].

Even with precautions taken, such as firmly fixing the electrodes to the scalp, cardiac pulses commonly generate artifacts with a standard deviation considerably larger than the EEG variations [7].

In this work, we focus on the last problem, namely reduction of cardiac related artifacts. This problem was previously discussed by Allen et al [9]. They proposed an algorithm based on extraction of an average artifact, which is then subtracted from the individual artifacts. In this work, a new method is proposed that is adaptive to changes of the cardiac pulse speed as well as to changes in ECG pulse response.

2. Adaptive artifact reduction

In this section, an adaptive approach is described for the reduction of ECG related artifacts. In the following, the raw EEG signal is denoted by $f(t)$. This signal is assumed to be constituted of:

- a term $s(t)$ containing the encephalographic information but also all non MR gradient related artifacts such as movement artifacts or static magnetic field artifacts. As explained above, the disturbances that are still present in $s(t)$ are generally much smaller and/or occur less frequent compared to MR gradient and ECG related artifacts and do not render the EEG signal unreadable. In the following, restoration refers to the restoration of $s(t)$.
- artifacts $\{a_g(t)\}$ due to the switching of magnetic field gradients. It has been postulated and experimentally verified by Felblinger et al. that the gradient impulse response functions can be modeled as a linear time invariant system [11]. Hence, it is reasonably assumed that these artifacts are additive, such that they can be removed independent from other artifacts. An effective method for the reduction of such MR gradient artifacts was recently published [8].
- artifacts $\{a_p(t)\}$ related to cardiac events. Similar to MR gradient related artifacts, it is reasonable to assume that these can be modeled as linear, additive, and uncorrelated with respect to all other contributions to the acquired signal. In this work, we concentrate only on the removal of these kinds of artifacts.
- a white, gaussian distributed, and hence additive noise term $n(t)$.

In summary, we have:

$$f(t) = s(t) + \sum_p a_p(t) + \sum_g a_g(t) + n(t) \tag{1}$$

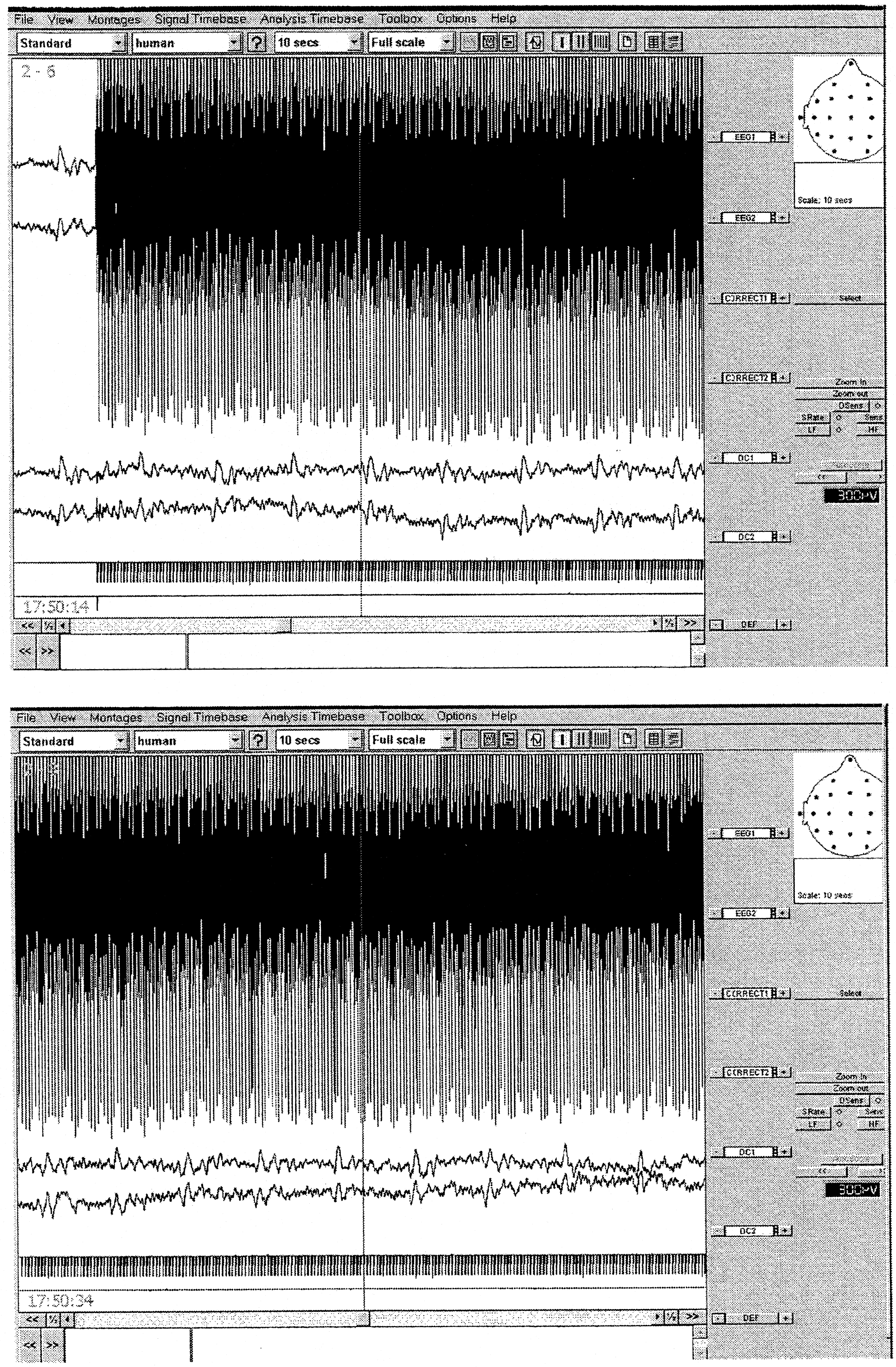

Fig. 2. Restoration results of MR gradient induced artifacts, where a fast gradient echo sequence was applied.

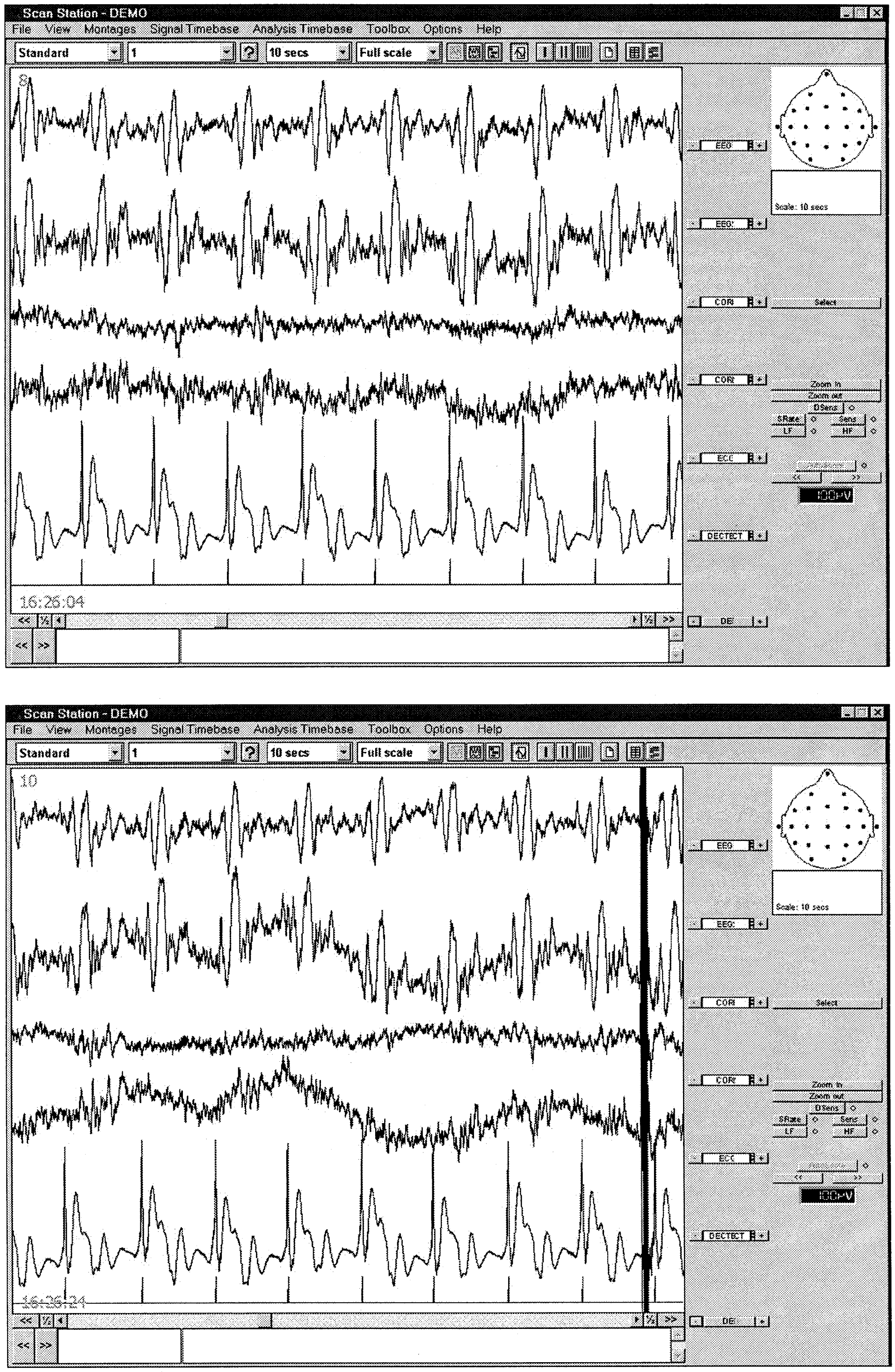

Fig. 3. Results of the ECG artifact reduction scheme.

The restoration scheme presented below consists of extraction of the artifacts, estimation of the artifact template, and adaptive filtering.

2.1. ECG detection

The artifacts that we want to extract from the EEG signals are response functions from the ECG. As the response is linear, the artifact rate equals the ECG pulse rate. Hence, in order to be able to extract a pulse artifact from the EEG signals, the onset of each ECG pulse must be detected.

Detection of QRS boundaries has been discussed extensively in the past [12,13,14]. However, in our experiments, we're not concerned with the full ECG characteristics; only the QRS onset is required. Moreover, the ECG is acquired in a strong magnetic field, which severely affects the appearance of the ECG response, as can be observed from Fig. 1.

To cope with this effect, we employed a modified version of a method described by Daskalov et al [12]. As we are only interested in detection of the QRS onset, we first remove, by means of a band-pass filter, information from the ECG that is irrelevant for such a detection. Next, the output is squared after which local maxima within an interval of 0.5 seconds are retained. A final selection is performed by applying constraints on the distance from one maximum to another. The second channel of Fig. 1 shows the detected QRS onsets.

2.2. Estimation of the artifact template

The goal is to select, from the QRS onsets detected in the previous step, L pulse artifacts from which an artifact template is extracted. This can be done by averaging the artifacts as described by Allen et al. [9]. However, the ECG is not quite stationary in the sense that the pulse rate is not always the same. Hence, simply averaging the artifacts would not lead to a satisfactory template, due to a lack of signal coherence. Therefore, prior to template extraction, the artifacts are scaled to a fixed time interval with size T.

After the selection the L artifact intervals, each artifact is normalized with respect to the mean and standard deviation. In addition, it is subjected to a wavelet-filter where the wavelet-coefficients of the highest frequencies are set to zero. Indeed, the ECG itself, and hence also its response is composed of frequencies that are generally smaller than 50 Hz. Hence, virtually all energy of the ECG artifact contribution within the selected interval is retained. Remark though that this low-pass operation will not affect the restored EEG signal as will become clear below.

Next, the scaled and filtered intervals are put in an $L \times T$ matrix after which each column (i.e., each time point) is median filtered. Median filtering was preferred above averaging as it is more insensitive to outliers and quickly adapts to changes in ECG response [8]. The resulting artifact template will be represented by $A(t)$. In our experimental setup, L ranged from 15 to 31 depending on the EEG signal-to-noise ratio.

2.3. Adaptive filtering

After computation of a primary template artifact $A(t)$, the filtering procedure proceeds as follows. Each time an artifact interval is selected using the QRS onset markers, it is preprocessed as described above and stored in the next row of the artifact matrix. Then, the template artifact $A(t)$ is updated and adapted to each artifact by minimizing the difference (MSE) with respect to the parameter b as given by:

$$\mathrm{MSE} = \sum_{t \in T} [s(t) - bA(t)]^2 \tag{2}$$

Using the optimized b-parameter, the template function is subtracted from the selected artifact. While processing the EEG channel, the artifact template $A(t)$ is updated adaptively. The whole procedure is repeated for each channel of the EEG data.

3. Materials and methods

Several tests were performed on human subjects. The experiments were done on a 4.7 T whole body MRI system (SMIS, London, UK) with a 900 mm aperture (the whole body clear bore was 640 mm). Images were taken with size 256×128, maximum gradient strengths, $G_r = 2$ mT/m, $G_p = 14$ mT/m, and $G_{sl} = 4$ mT/m, and ramp time 300 μs, FOV $= 30$ cm. The head insert clear bore was 380 mm.

The EEG data were collected with a nonmagnetic preamplifier (Schwarzer, Munich, Germany) through five Ag/AgCl sintered electrodes (Schwarzer, Munich, Germany) with a sample rate of 1 kHz. They were applied with electrode gel (Quik-Gel, neuromedical supplies, Inc, Herndon, VA 22070) and held on the skin by a headcap (Schwarzer, Munich, Germany). The electrode leads—0.9 mm thin and 85 cm long coax cables—were bundled together and firmly fixed. Precaution was taken not to put any loops in the leads. Next, they were attached to the inputs of the EEG preamplifier. Since the preamplifier is non-magnetic, and MR compatible, it can be positioned inside the magnets' bore as close as possible to the patient head. The amplified signal was then carried over a fiber-optic cable to the EEG-computer. The EEG-computer was equipped with special cards to operate with the EEG preamplifier (PTMS1 and PTMS3, Schwarzer, Munich, Germany).

The software used for measuring, displaying, and analyzing the signal was Brainlab (OSG, Rumst, Belgium). The software for filtering the data was written on site under

Visual C++ and has been integrated into the Brainlab software.

4. Results and discussion

It was already mentioned in the introduction that MR gradient artifacts can be treated independent from ECG pulse related artifacts. This can also be concluded from the Fig. 2, where the result of a previously published filtering scheme for MR gradient artifacts is shown, here applied to human MR/EEG data. The figure shows two EEG traces, corrupted during an MR sequence. Right below, the two restored EEG traces are shown. The last two traces denote the markers of the MR imaging sequence. Clearly, the effect of the gradients is strongly reduced, while all other signals (the relevant EEG as well as the ECG pulse artifacts) are retained. Hence, an additional ECG pulse artifact filtering scheme is required.

Fig. 3 shows typical results of the proposed ECG pulse artifact restoration scheme. The figure represents two original EEG channels. The lowest two channels show the ECG, along with the ECG onset detection. From these channels it is easily seen that the first two channels are polluted by ECG related artifacts which have a standard deviation that is significantly larger than the actual EEG. Channel 3 and 4 are the restored versions of the raw EEG channels. As can be observed, the artifacts induced by the ECG are strongly reduced while high frequency information is retained.

In summary, the proposed method is based on a simple experimental setup. Also, owing to the continuous updating of the artifact template, the method adapts itself to unforeseen changes of the ECG impulse response functions (e.g., when an electrode changes place, the appearance of the gradient artifact in the EEG recordings changes too).

In addition, the method has proved to be (relatively) computationally inexpensive. All data processing was performed on a 300 MHz PC. Finally, we remark that the filtering scheme as a whole is fully automatic, requiring no user-interaction at all.

5. Conclusions

Simultaneous EEG/MRI acquisitions suffer from severe pollution of EEG recordings, not only due to the switching of the magnetic field gradients but to ECG related artifacts as well. Without handling this problem, interpretation of the EEG signal is almost impossible. In this work, we described how ECG related artifacts can efficiently be reduced using an adaptive filtering scheme.

Acknowledgments

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