Moving GLM ballistocardiogram artifact reduction for EEG simultaneously acquired with fMRI

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Introduction

•EEG recording during MRI is challenging because of artifacts owing both to the static magnetic field and to switching of the imaging gradients.

•One particularly challenging artifact is the ballistocardiogram (BKG) generated by cardiac pulsations in the strong static field (Allen et al., 1998).

•BKG artifact is minimal outside a magnetic field but often exceeds 100 μV at 3 Tesla.

•BKG spectral components overlap physiologically relevant EEG bands of interest (e.g., alpha).

•The most commonly used method of BKG artifact reduction, moving average artifact subtraction (mAAS), computes a moving average phased to EKG triggers; this template is subtracted from the contaminated record (Allen et al., 1998). This method does not account for variability in the inter-heartbeat interval or overlapping BKG waveforms.

•Here we present an alternative method for removing BKG based on a moving general linear model (mGLM).

Theory - mGLM BKG reduction

•Assume the recorded EEG, $e(t)$, is composed of true encephalogram signal, $s(t)$, plus ballistocardiogram artifact, $b(t)$, where t is time relative to the start of the record.

$$e(t) = s(t) + b(t)$$

•Let t_j be the time of the j^{th} heart beat relative to start of the record.
•The ballistocardiogram waveform $\hat{b}(\tau)$ is modeled over a finite interval as a weighted sum of basis functions, $\{f_k(\tau)\}$.

$$\hat{b}(\tau) = \sum_k \phi_k f_k(\tau), \quad 0 \le \tau < T$$, where the ϕ_k are real scalars. N.B.: T may exceed the inter-beat interval.

•The BKG component of the recorded EEG then is given by

$$b(t) = \sum_j \hat{b}(t - t_j) = \sum_j \sum_k \phi_k f_k(t - t_j)$$

•Let $\{\phi_k\}$ and $\{f_k\}$ be represented as column vectors, $\vec{\phi}$ and $\vec{f}$.

•Ordinary least squares minimization of the error, $\left\langle (1/2)[b(t) - e(t)]^2 \right\rangle$, yields a linear system in $\vec{\phi}$:

the linear system

$$\boxed{A\vec{\phi} = (1/U)\int \sum_j \vec{f}(t - t_j)e(t)dt}$$

where A is the symmetric matrix:

$$a_{ik} = a_{ki} = (1/U)\int \left[\sum_j \sum_i f_i(t - t_j)\right]\left[\sum_j \sum_k f_k(t - t_j)\right] dt, \text{ and } \quad U = \int dt$$

•$\vec{\phi}$ can be recovered by left multiplication by A^{-1} of the linear system.

•We represent $\hat{b}(\tau)$ as a Fourier expansion. This representation will be complete because the recorded signals have been digitally low-pass filtered.

$$\left\{ \begin{array}{l} f_{2k}(\tau) = \cos(2\pi k\tau / T) \\ f_{2k+1}(\tau) = \sin(2\pi k\tau / T) \end{array} \right\}, \quad 0 \le \tau < T, \; f_k(\tau) = 0 \text{ otherwise.}$$

•A moving GLM strategy (multiple solutions computed over successive epochs) allows the model to adapt to slow temporal evolution of the BKG waveform.
•The present implementation computed one GLM for each beat over an interval of fixed duration, U = 10 sec.
•Time points containing artifact were excluded from the linear model and the integration limits then were extended on the right and/or left to maintain U constant.

Relationship of mGLM to mAAS

•mAAS estimates the EKG waveform on the interval, T, as the simple moving average of the recorded EEG over some number, N, of successive beats.

$$\hat{b}_j(\tau) = (1/N) \sum_{i=j-N/2}^{j+N/2-1} e(t_i + \tau)$$

•mGLM reduces to mAAS when successive heart beats are separated by intervals not less than T and the GLM integrals include no basis function fragments.
•In this circumstance A becomes the identity matrix (as the f_k are orthogonal).
•If beats overlap or the integrals include waveform fragments, then the off-diagonal terms of A become nonzero and mGLM no longer is equivalent to mAAS.

Experimental Methods

•9 subjects (ages 20-32 years)
•Multiple 5.5 minute EEG-fMRI runs per subject (11 total; eyes open, closed, or alternating between open and closed)
•Each fMRI run included 110 volumes; TR=3.013 sec (including a 1 sec pause)
•EEG data were recorded using a MagLink™ (Compumedics Neuroscan, El Paso, TX) system equipped with 24 bit Synamps/2™ DC amplifiers.
•The head cap contained MR compatible (sintered AgCl) electrodes attached to carbon fiber leads in series with a current limiting resistor.
•Electrode impedances were kept below 20 kΩ.
•Acquire 4.5™ software (Compumedics Neuroscan) was used to record standard, 21-channel 10/20 EEG plus VEOG, EKG, and two ear lobe channels, all referenced to an electrode between CZ and CPZ (20 KHz sampling rate).
•The EEG data were band pass filtered (1-30 Hz, 12 dB roll-off) using EDIT™ software (Compumedics Neuroscan).
•MR gradient artifact was effectively eliminated using Scan 4.5™. Data was decimated to 500 Hz and exported for further processing on Sun Solaris UNIX. Procedures were coded in C.

Experimental Design

•Beat onset times (t_j) were determined by analysis of EKG (custom procedure)
•Both mGLM and mAAS (similar to Allen et al., 1998) were run on all EEG channels.
•The mGLM template duration, T, was consistently set to 1.024 sec.
•The mAAS template duration was systematically varied to examine the effect of this parameter on performance.

Results

The Ballistocardiogram waveform

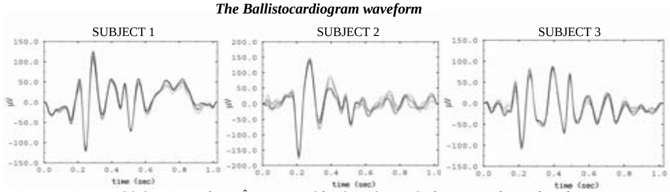

Figure 1: mGLM modeled BKG waveforms, $\hat{b}(\tau)$, computed for electrode O1. The first 18 waveforms of one fMRI run are shown superimposed for each of three subjects. Note characteristic waveform dominated by ~10 Hz periodicity.

Comparison of mGLM and mAAS BKG reduction

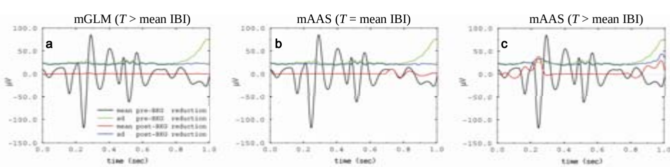

Figure 2: We assume that the BKG is additive and uncorrelated with all other contributions to the recorded signal. Therefore, averaging in phase with t_j should provide a good estimate of the BKG signal. Similarly averaging after BKG reduction provides a good estimate of the residual. Here, we plot the mean and standard deviation of signal in electrode O1 for a single subject after averaging in phase with the detected heart beat both before (mean: black, standard deviation: green) and after (mean: red, standard deviation: blue) BKG reduction by mGLM and mAAS. (**a**) mGLM BKG reduction using T = 1.024 sec. (**b**) mAAS BKG reduction with an averaging template of the mean inter-beat interval (IBI) (0.718 sec). (**c**) mAAS BKG reduction with an averaging template of 1.024 sec. Note that mAAS with a template length corresponding to the mean IBI does not completely remove the BKG artifact (red traces in b). Note also that the mGLM procedure performs better than the mAAS procedure when the averaging template length is increased beyond the mean IBI. The success of the mAAS procedure varies according to averaging template length (red traces in **b** and **c**) whereas the mGLM procedure performs well with T>mean IBI (flat red trace in **a**).

Effect of varying the mAAS averaging template length

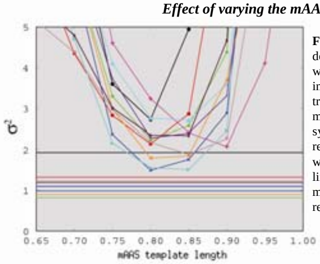

Figure 3: The mAAS BKG reduction procedure performance depends on the length of the averaging template. Residual artifact was quantitated as the variance (σ²) of the EEG waveform averaged in phase with t_j over a period of 1.5 sec *after BKG reduction* (red trace of figure 2). Residual variance was computed for eleven 5.5 minute runs from one subject as the mAAS template length was systematically varied in the range 0.6 sec to 1 sec. Each run is represented by a different color. The corresponding mGLM residuals were computed using T = 1.024 sec and are represented as straight lines. mAAS residuals were minimized at template lengths near the mean inter-beat interval (IBI) but were always greater than mGLM residuals.

Statistical Analysis

Procedure	Template length (T)	Mean σ² (μV²)	s.d. σ² (μV²)
mAAS	mean IBI	5.1	5.2
mAAS	1.024 sec	13.5	20.7
mGLM	1.024 sec	3.5	4.4

Across all subjects and runs residual BKG variance in electrode O1 was computed (as in Figure 3) following (1) mAAS using T = mean inter-beat interval (IBI), (2) mAAS using T = 1.024 sec, and (3) mGLM using T = 1.024 sec. Statistical significance was tested using Wilcoxon Signed Ranks. The mGLM method performed significantly better than the mAAS procedure when the mean IBI was chosen as the averaging template length (Z = -4.855, $p < 0.0001$) as well as when the template length was 1.024 sec (Z = -7.470, $p < 0.0001$).

Spectral analysis

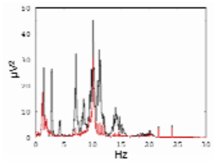

Figure 4: Power spectral density plot of electrode O1 (ref CPZ) from a single subject in an eyes closed run before (black trace) and after (red trace) mGLM BKG reduction. There is a substantial reduction of power in the fundamental frequency of the heart beat (1.1 Hz) and its harmonics, indicating successful BKG reduction. Additionally, there is substantial power reduction the 8 to 12 Hz (alpha) band, which is critical in EEG-BOLD correlation studies (see poster 454.21). Note normal appearance (including 10.5 Hz peak) of the post reduction power spectrum (red trace). Isolated peaks at 21.5 and 24 Hz correspond to residual gradient switching artifact.

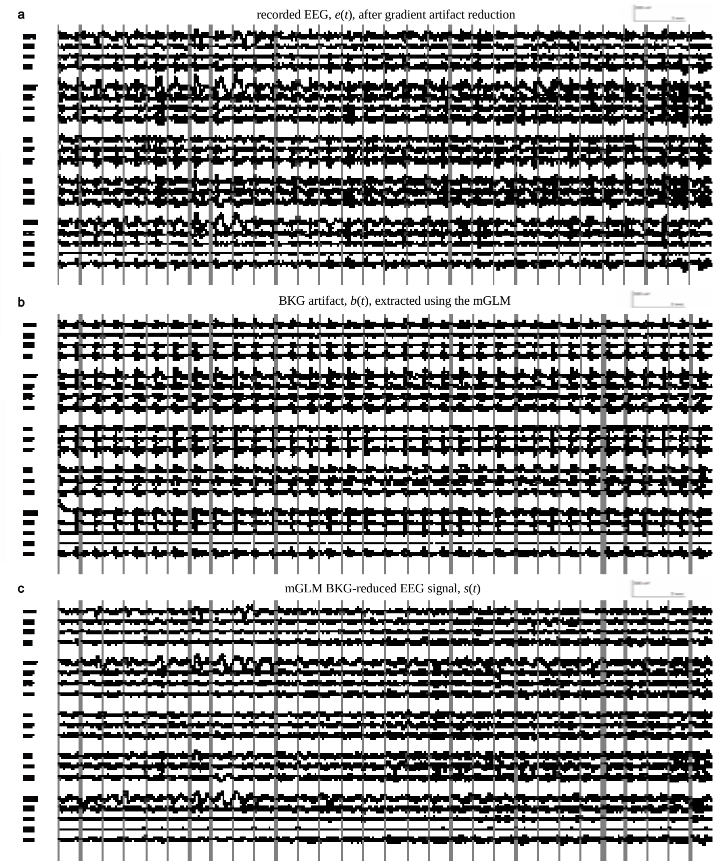

Figure 5: Thirty seconds of EEG data during the transition from eyes open to eyes closed. (**a**) the recorded EEG, $e(t)$. (**b**) the BKG artifact, $b(t)$, extracted using mGLM. (**c**) the BKG-reduced EEG signal, $s(t)$, demonstrating successful BKG reduction.

Conclusions

•BKG exceeds 100 μV peak to peak and contains significant power in electrophysiological bands of interest (alpha, theta, beta).
•mGLM reveals significant components of the BKG that outlast the inter-heartbeat interval (IBI).
•mGLM may be used to reduce BKG artifact including components outlasting the IBI.
•mGLM reduces BKG artifact more effectively than mAAS in the presence of IBI variability.

Reference

Allen PJ, Polizzi G, Krakow K, Fish DR, and Lemieux L. Identification of EEG events in the MR scanner: the problem of pulse artifact and a method for its subtraction. *NeuroImage*. 8: 229-239, 1998.

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