Real-Time Electrocardiogram Artifact Correction using a Finite Impulse Response Filter Signal Processing Method and Computer System

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Introduction:

During MRI examinations, artifacts on electrophysiological waveforms (ECG, EEG, EMG...) are still a problem for both patient monitoring and triggering of acquisitions. These artifacts are mainly due to the magnetic field gradients, and can completely distort ECG signals (diffusion, black blood sequences), resulting in a wrong detection of the R-waves and difficulties in their interpretation (1-3). A Finite Impulse Response (FIR) filter signal processing method is applied to ECG artifact prediction from gradient waveforms. The predicted artifacts are able to be subtracted from the corrupted ECG in real-time. The method is implemented for real-time operation using a specially designed Signal Analyzer and Event Controller (SAEC) computer and electronics.

Methods:

Based on the assumption that artifact production by magnetic field gradient switching represents a Linear Time Invariant (LTI) process, artifacts $a_i(t)$ (on a given ECG channel i, i=1…N) can be determined by convolution of the gradient waveforms $[g_X(t)\ \ g_Y(t)\ g_Z(t)]^t$:

$$a_i = \sum_{j=X,Y,Z} h_{ij} \otimes g_j \ \ (i = 1...N)\,. \qquad [1]$$

The filtering equation can be rewritten in matrix form:

$$\mathbf{A} = \mathbf{H} \cdot \mathbf{G}\,, \qquad [2]$$

$$\text{with } \mathbf{H} = \begin{bmatrix} h_{1x}(1)\ldots h_{1x}(M) & h_{1y}(1)\ldots h_{1y}(M) & h_{1z}(1)\ldots h_{1z}(M) \\ h_{2x}(1)\ldots h_{2x}(M) & h_{2y}(1)\ldots h_{2y}(M) & h_{2z}(1)\ldots h_{2z}(M) \\ \vdots & \vdots & \vdots \\ h_{Nx}(1)\ldots h_{Nx}(M) & h_{Ny}(1)\ldots h_{Ny}(M) & h_{Nz}(1)\ldots h_{Nz}(M) \end{bmatrix}.$$

The digital FIR filter matrix H is computed employing ECG and gradient waveforms recorded during a training MRI scan, by inversion of the system [2]. The FIR filters are used during further scanning to predict artifacts according to Eq. [1]. The convolution products are computed in a point-by-point manner, in the time domain, resulting in a minimal delay introduced by the real-time filtering.
Validation of the method was performed both off-line, using pre-recorded signals (12 healthy subjects, 114 sequences), and under actual examination conditions (4 healthy subjects).

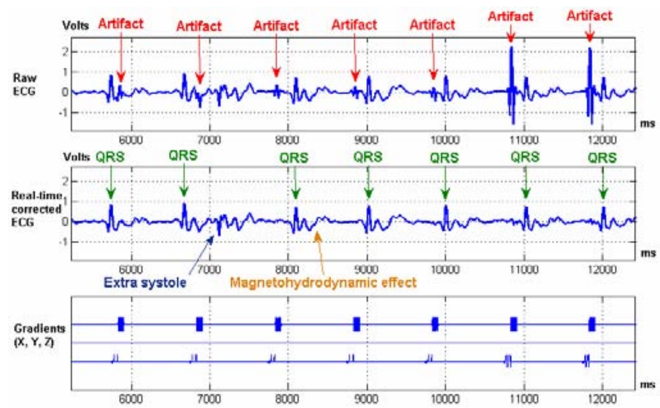

Fig. 1. Example of real-time corrected ECG signal with the proposed FIR filter-based method.

Real-time implementation:

The real-time implementation of our ECG artifact correction method requires specialized computer and electronics hardware for rapid and deterministic signal analysis and computation. Physiological signals collected by various sensors (such as ECG in this study) are transmitted outside the bore through optical fibers, and then are processed in real-time by the *Signal Analyzer and Event Controller* (SAEC), which consists in two modules: i) a PXI Embedded Controller (2.2 GHz Pentium 4, National Instruments) with a real-time OS and a data acquisition device (12-bit resolution, 1.25 MS/s sampling rate), for conditioning and analysis of physiological signals ; ii) a Host PC (Windows OS), for remote application control and user interface (100 Mbit Ethernet link).

Table 1. Mean artifact energy per cardiac cycle ($10^{-9}V^2$)

Group	Raw ECG	LMS correction	FIR correction
1	0.15	0.11	0.16
2	0.86	0.61	0.64
3	9.02	1.16	0.80
4	80.71	5.30	2.52

Results:

Table 1 shows the artifact reduction by the FIR filter method. The artifact energy was estimated by separating ECG cycles with gradients (corrupted ECG cycles) and without gradients (reference ECG cycles). Results were put into 4 groups according to the amount of artifacts that were created (Group 1: lowest artifact energy; Group 4: highest artifact energy). The artifact energy was estimated before (Raw ECG) and after correction, and results from a second correction method (LMS adaptive filter [3]) are given for comparison.

Conclusion:

Real-time operation was demonstrated at 1 kHz with a delay of only 1 ms introduced by the processing. This delay is short enough relative to the QRS complex (about 80 ms). The system is applicable for real-time processing of other physiological signals, such as EEG, EMG, and EOG, and opens the possibility of automatic monitoring algorithms in the MR environment. However, these algorithms would need special modification because the ECG signal still appears different when acquired inside the MR bore compared to external from the MRI scanner because of the magnetohydrodynamic effect.

References:

1.Felblinger et al. [1999] MRM. 41(4): 715-721.
2.Fischer et al. [1999] MRM. 42(2): 361-370.
3.Abächerli et al. [2005] Magma. 18: 41-50.