Reduction of Electrocardiogram Interference from Diaphragmatic Electromyogram by Nonlinear Filtering

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Abstract-**We describe a method to suppress electrocardiogram (ECG) contaminations in the diaphragm electromyographic (EMG) signals obtained through intraoesophageal electrodes. A nonlinear filter technique originally developed for noise reduction in deterministically chaotic signals is used. The performance of the method was investigated using computer simulations. Multitaper spectral analysis was performed to assess quantitatively the difference between the simulated pure EMG signal and the processed EMG signal. The method is successfully applied to recordings from healthy subjects during deep inspiration.**
***Keywords* - ECG, EMG, Nonlinear Filtering, Diaphragm, PCA**

I. INTRODUCTION

Electromyographic analysis of a muscle can provide significant information regarding its physiological and pathophysiological behaviour. For example, a shift from high-frequency to low-frequency signal may indicate muscle fatigue [1]. A major obstacle encountered during analysis of the diaphragmatic electromyogram (EMG) signal is electrocardiogram (ECG) contamination. Generally the ECG interference is large in amplitude and overlapped with the frequency of the EMG. This causes an increase in the power content of the EMG signal and a distortion of its frequency content. Conventional highpass filtering essentially fails since the ECG has a frequency spectrum that overlaps markedly with that of the diaphragmatic EMG. The adaptive filter has been used to reduce the ECG artifacts but it needs the additional ECG recording as the reference input [2].

In the contribution, we present a nonlinear filtering technique to circumvent the above problems. We show that it is capable of removing ECG artifacts in the EMG signal while preserving essential features of the EMG signal.

II. METHODOLOGY

A. The Measurement of EMG

The recordings were obtained in six healthy volunteers. The EMG signals were recorded using electrodes placed on a manometric catheter. The manometric catheter was placed via the nose into the oesophagus and stomach. The EMG signal from these electrodes was fed into a Sensomedics (Anabeime, CA, USA) amplifier that was set to record a frequency band between 20 and 500 Hz [3 dB octave^{-1}]. The EMG signals related to crural diaphragmatic contractions were obtained in between the swallows while the subjects took deep inspiration. The data was on-line digitized using a 12-bit analog-digital converter with a sampling frequency of 1000 Hz and stored on the hard disk of a personal computer.

B. Nonlinear Filtering

The technique we describe below is an outcome of the theory of nonlinear dynamical systems. A fundamental idea in nonlinear analysis is that the dynamics of a system can be studied in a phase space (also called state space); a point in this space characterizes the state of the system at any moment of time. The phase space can be constructed by a procedure that starts from raw data and builds vectors by iterations of a time delay. Specifically, a scalar time series $\mathbf{x}_n, n=1,\cdots,N$ can be unfolded in a multidimensional phase space using time delay coordinates $\bar{\mathbf{x}}_n = (x_{n-(m-1)\tau},\cdots,x_n)$ (τ is a delay time and m is called embedding dimension). For deterministic dynamical system, the embedding theorem [3] guarantees that under certain conditions the reconstructed point set $\{\bar{\mathbf{x}}_n\}$ is a one-to-one map of the original attractor of the dynamical system. Based on the concept of an attractor in the phase space, a nonlinear filtering technique is designed to exploit the geometrical structure of the attractor where a multidimensional reconstruction of a signal can be approximated by a low dimensional manifold through local principal component analysis (PCA). The technique has been applied for fetal ECG extraction [4].

The nonlinear filtering algorithm may be divided into four steps: (1) Define a manifold of signal equivalent representation in the phase space. (2) Perform local weighted principal component analysis (PCA) in the phase space. (3) Project toward the subspace of several eigenvectors with the largest eigenvalues to get rid of the noisy components. (4) Convert projected vectors back into the original signal space to produce a cleaned time series $\hat{\mathbf{x}}_n$.

III. RESULTS

A. Performance Analysis

A series of computer simulations was conducted to evaluate the performance of the proposed algorithm. The simulated EMG corrupted by ECG artifacts (Fig. 1c) was generated by adding the simulated pure (free of artifacts) EMG (Fig. 1a) and real corrupting ECG signal (Fig. 1b). We can see from Fig. 1 that the simulated pure EMG is quite similar to the real EMG signal and the ECG is much stronger than the EMG. The processed EMG signal, recovered from the proposed algorithm, is shown in Fig. 1d, suggesting that the original pure EMG features are mostly preserved while the ECG interference is greatly suppressed.

The commonly used quantitative method for describing an EMG signal is the power spectral analysis, which is routinely performed by the periodogram method [1, 2]. To assess quantitatively the difference between the simulated pure EMG and the processed EMG signals, a relative error [2] is defined as

$$\delta = \frac{\sum_0^{250} (P(f) - P^{'}(f))^2}{\sum_0^{250} P^2(f)}$$

where *P(f)* and $P^{'}(f)$ are respectively the spectral densities of the simulated pure EMG and the processed EMG signals. A multitaper spectral analysis method was employed [5] to reduce the spectral leakage and windowing effects on the spectral estimate inherent in the periodogram method. Fig. 2 shows the power spectra of the original pure EMG signal (dashed line) and the processed EMG (thick solid line), together with that of the corrupted composite signal (thin solid line). The relative error is 0.11%, which is believed to be negligible. It is evident that the spectrum of the processed EMG matches very well with that of the original pure EMG signal.

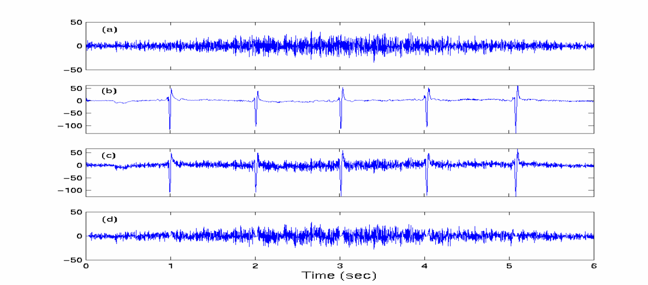

Fig. 1. A simulation example of suppression of ECG from EMG. (a) The simulated pure EMG signal. (b) The corrupting ECG signal. (c) The synthesized composite signal using (a) and (b). (d) The processed EMG signal.

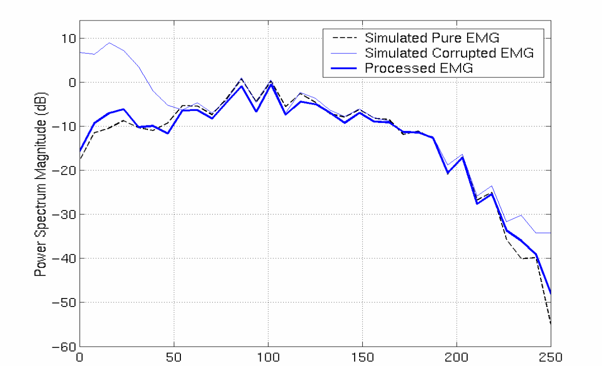

Fig. 2. Power spectra of signals shown in Fig. 1, as indicated in the figure legend.

B. Applications to Real EMG Recordings

The experimental EMG data described previously were used in this study. Substantial suppression of the ECG artifacts in the EMG signal was achieved. Two typical examples are presented in Fig. 3 (A and B) where the top tracing in each panel is the original EMG signal and the bottom one is the processed EMG signal.

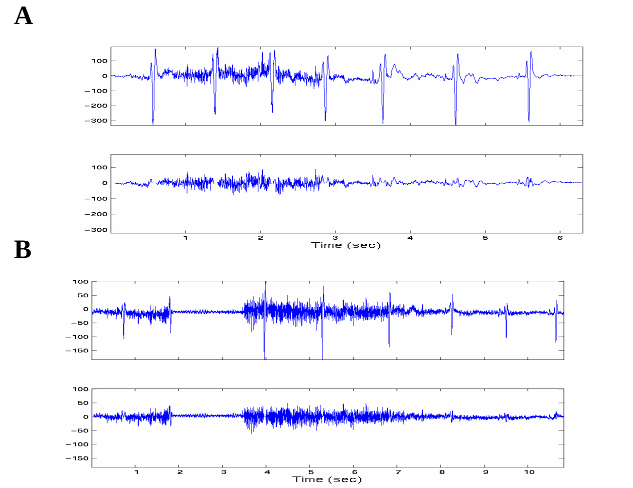

Fig. 3. Reduction of ECG artifacts in EMG signals during deep inspiration in two different subjects (A and B). In each panel, the top plot shows the original EMG recordings and the bottom plot is the processed EMG signal.

IV. DISCUSSION AND CONCLUSION

We have presented a nonlinear filtering technique for suppressing ECG contaminations in the surface diaphragmatic EMG signal. The performance of the algorithm was first evaluated on computer simulations. It was found that ECG artifacts could be successfully removed from EMG signal. Applications of the proposed method to real EMG signals obtained from six healthy subjects during deep inspiration were performed. Our results demonstrated the effectiveness of the proposed nonlinear filtering technique.

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