Cancellation of Cardiac Interference in Diaphragm EMG Signals using an Estimate of ECG Reference Signal

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Abstract— **The analysis of the electromyographic signal of the diaphragm muscle (EMGdi) can provide important information in order to evaluate the respiratory muscular function. However, EMGdi signals are usually contaminated by the electrocardiographic (ECG) signal. An adaptive noise cancellation (ANC) based on event-synchronous cancellation can be used to reduce the ECG interference in the recorded EMGdi activity. In this paper, it is proposed an ANC scheme for cancelling the ECG interference in EMGdi signals using only the EMGdi signal (without acquiring the ECG signal). In this case the detection of the QRS complex has been performed directly in the EMGdi signal, and the ANC algorithm must be robust to false or missing QRS detections. Furthermore, an automatic criterion to select the adaptive constant of the LMS algorithm has been proposed (μ). The μ constant is selected automatically so that the canceling signal energy equals the energy of the reference signal (which is an estimation of the ECG interference present in the EMGdi signal). This approach optimizes the tradeoff between cancellation of ECG interference and attenuation of EMG component. A number of weights equivalent of a time window that contains several QRS complexes is selected in order to make the algorithm robust to QRS detection errors.**

Keywords— **Adaptive Canceller, EMG, Diaphragm muscle.**

I. Introduction

The electromyographic signal of the diaphragm muscle (EMGdi) can be used to monitor the contractile activity of the diaphragm muscle during respiration. The amplitude of the EMGdi signal is related with the number of active motor units of the muscle during contraction [1]. Also it has been shown that the fatigue of the diaphragm is preceded by shifts from high to low frequency in the EMGdi signal [2].

One of the major concerns in the EMGdi amplitude and frequency analysis is the electrocardiographic (ECG) interference. The ECG interference introduces a distortion in both EMGdi signal power and frequency content. The ECG interference is overlapped with the low frequency range of the EMGdi signal. A traditional method in order to eliminate the ECG interference is simply by means of the detection and removal of the segments of the EMGdi signal with presence of QRS complexes [3]. However, this method segments the signal and excludes portions of the signal that may contain important information. Adaptive filtering techniques have been applied successfully in order to isolate the cardiac component from EMG noise [4], and for heart activity cancellation in EMG signals from different respiratory muscles [5], and from the EMGdi signal [6,7]. The most important part of all these adaptive filtering techniques is the artificial construction of a reference signal that must be highly correlated with the ECG interference but uncorrelated with the EMGdi activity.

In this work, we present an adaptive noise canceler (ANC) based on event-synchronous cancellation scheme with an automatic criterion for selecting the appropriate parameters for the computation of the adaptive filter in order to remove the ECG interference while preserving the essential features of the EMGdi signal, even with the presence of false positives and false negatives in the ECG reference signal.

II. Methodology

A. Signals and instrumentation

A mongrel dog was surgically instrumented under general anesthesia via a femoral venous catheter with pentobarbital sodium (25 mg/kg). The EMGdi signal was measured via internal electrodes inserted into the costal diaphragm, as described in [8]. The dog was anesthetized and remained in supine position during the acquisition. The dog breathes against a constant inspiratory resistive load during the study. The EMGdi signal was amplified, analog filtered, digitized with 12 bit A/D system at a sampling rate of 4 kHz, and decimated at 1200 Hz. This protocol and study was approved by the Ethics Committee and performed in accordance with guidelines for Animal Research of the Hôpital Notre-Dame in Montreal (Canada).

Fig 1 shows an example of five respiratory cycles of an EMGdi signal with ECG noise. It can be observed that the cardiac signal overlaps in frequency with the EMG activity.

B. EMGdi adaptive noise canceller

The block diagram of the EMGdi ANC is shown in Fig 2. The utilized scheme is similar to the schemes proposed in [4] and [5]. The primary input to the noise canceller is the original EMGdi signal (corrupted with the ECG interference) filtered in the frequency band of the ECG interference (between 2 and 40 Hz) with a 4th order bidirectional Butterworth filter (d[n]). The reference input (x[n]) must be uncorrelated with the EMGdi activity but correlated with the ECG interference. This signal was artificially generated according to the method described in section C. The output of the adaptive filter is the cancellation signal (y[n]) which is subtracted from the original signal in order to produce the filtered output (EMGdi clean of ECG activity).

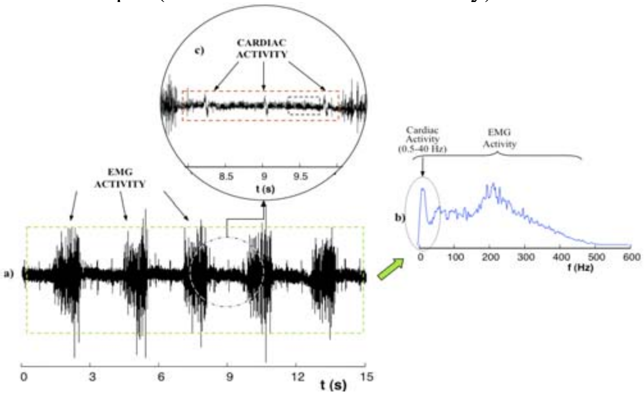

Fig 1 Example of five respiratory cycles of the EMGdi signal (a) EMGdi signal, (b) EMGdi Power Spectral Density, (c) detail of the cardiac interference present in the EMGdi signal

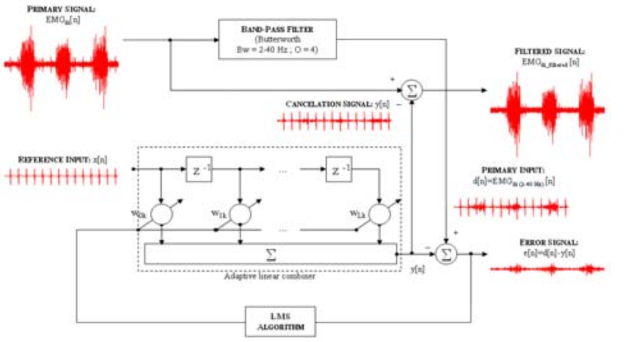

Fig 2 Block diagram of the EMGdi adaptive ECG noise canceller

C. Reference signal

Fig 3 shows a scheme of the algorithm used to generate the reference signal. As the main ECG frequencies are bounded in the range between 2 and 40 Hz [9], the original EMGdi signal (Fig 4A) was filtered with a 4th order Butterworth band-pass filter with this frequency range. Thus, a great part of the EMGdi activity was eliminated (Fig 4B). Then, the filtered signal is convolved with a manually selected ECG pattern (Fig 4C). The next step is a non-linear transformation based on squaring this convolution (Fig 4D). This transformation makes the signal positive and allows its integration. The local maxima of this signal determine the point of synchronism chosen for the detection of the cardiac beats. The detection of those local maxima is realized by means of two moving average windows on the convolved signal (with lengths of 0.1s and 1s, respectively) (Fig 4E). A train of unitary impulses is generated from those local maxima (Fig 4H). Next, the RMS value is calculated from the EMGdi signal (without filtering), with a window located between 0.3 and 0.1 s before the detection, and another window located between 0.1 and 0.3 s after the detection (Fig 4F). The QRS complexes whose RMS values do not overcome a certain threshold are used to generate an average ECG pattern (Fig 4G). Finally, the unitary train of impulses is convolved with the average ECG pattern in order to generate an estimation of the cardiac activity present in the EMGdi signal (Fig 4I). This signal is considered as the reference input of the adaptive filter.

D. Parameter Selection of the Adaptive Canceller

The scheme of adaptive cancellation (Fig 2) requires the selection of two parameters: the number of weights of the linear combiner (L) and the adjustment or adaptive constant (μ) of the LMS algorithm.

Since it was desired that the adaptive canceller was robust against false positives and false negatives in the detection of the QRS complexes, it has been selected a value of L equivalent to 4 seconds of reference signal. In that way, the reference input canceller will include a sequence of 4 to 10 QRS complexes, even though there were one or two detection errors.

If the adaptive constant μ is too high, the adaptive filtering will remove all the ECG interference in the signal, but it will also perform an undesired attenuation of the EMGdi signal. Furthermore the adaptive algorithm would become unstable. On the other hand, if the μ is too small, the adaptive filtering will not remove completely the ECG interference. Therefore, the choice of the constant μ is a compromise between the complete cancellation of the ECG activity and the preservation of the EMGdi signal. In this work, the constant of adaptation (μ) was chosen so that the energy of the output or cancellation signal matches with the energy of the reference input (that is an initial estimation of the ECG interference). The process of obtaining this value of μ is done through an iterative process. Based on two initial values (points 1 and 2 in Figure 5), we calculate the energy of the cancellation signal using an μ value corresponding to the intersection of the line joining these two points with the energy of the reference signal (point 3 in Figure 6). The following iterations are performed between the new calculated point and the point with nearest μ. The iterative process ends when the cancellation signal energy differs by less than 0.1% of the energy of the reference signal.

III. Results

Fig 6 shows an example of application of the proposed adaptive cancellation algorithm over a 4 s segment of an EMGdi signal. Fig 6A shows the 2-40 Hz band pass filtered EMGdi signal. Fig 6B0 shows the generated reference signal. In this example it has been added 3 QRS detection errors: a false negative (FN) and two false positives (FP). Fig 6C0 shows the direct cancellation of the ECG activity by subtraction. The distortion in the EMGdi signal produced by the QRS detection errors can be observed. Fig 6B1-C1, B2-C2 and B3-C3 show the cancellation signal for three different μ values: the optimal μ value (Fig 6B2-C2), a smaller μ value (Fig 6B1-C1), and a greater μ value (Fig 6B3-C3).

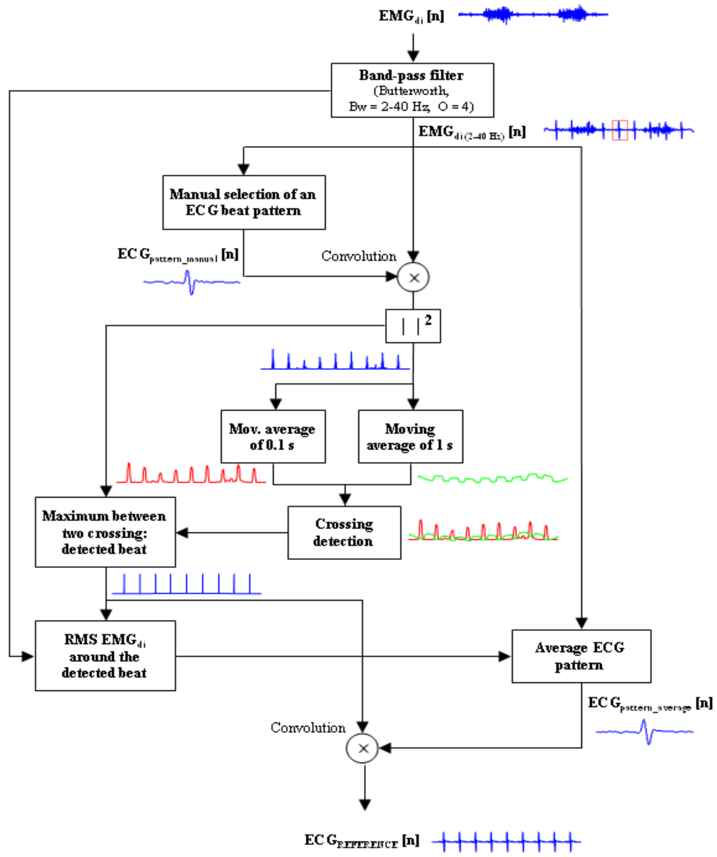

Fig 3 Block diagram of the algorithm for detection and estimation of the ECG activity present in the EMGdi signal (ECG reference)

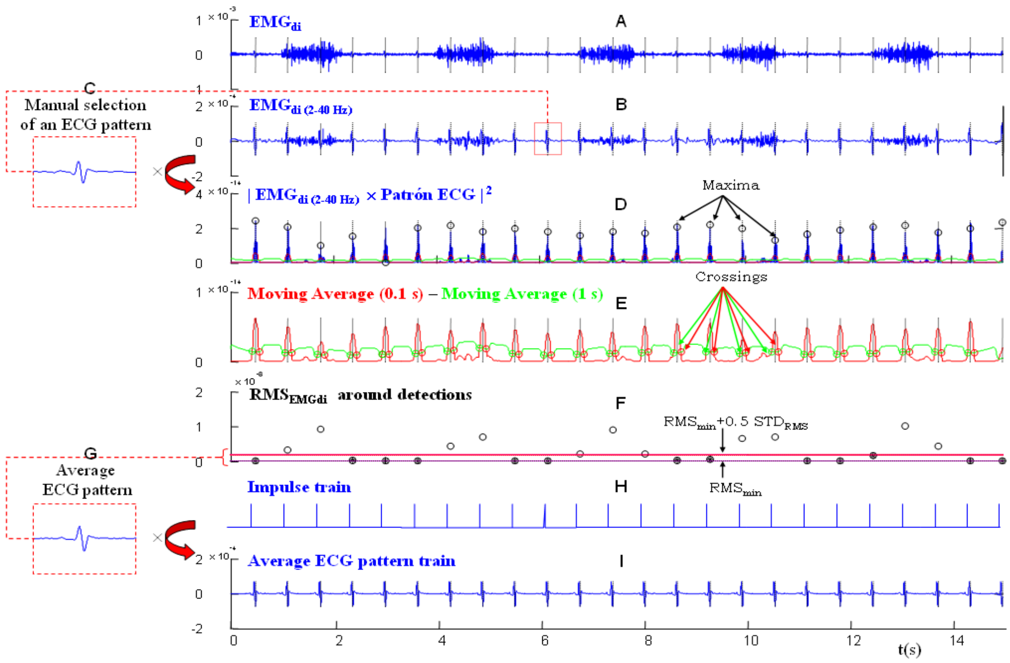

Fig 4 Example of estimation of the cardiac activity (ECG reference) in the EMGdi signal

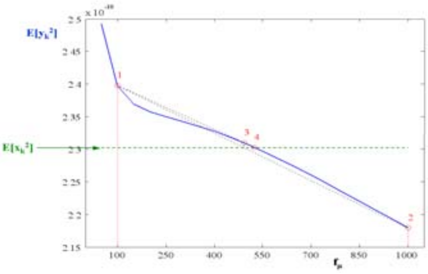

Fig 5 Energy of the reference signal and evolution of the energy of the canceling signal versus the factor μ

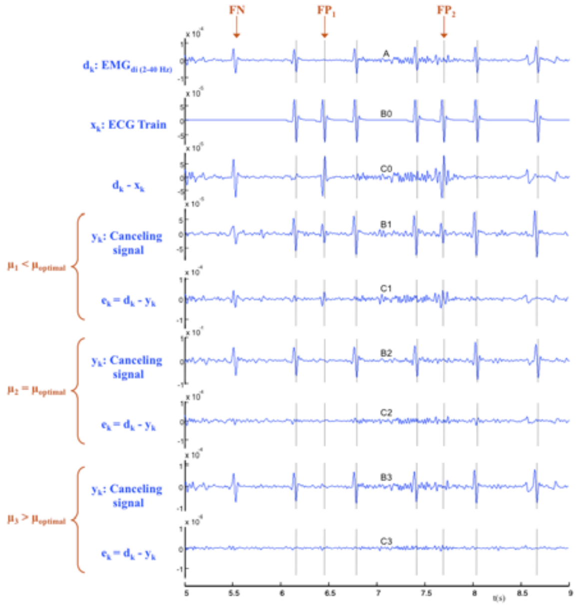

Fig 6 Example of application of the adaptive ECG interference canceller: primary input (A), reference input (B0), cancellation by direct subtraction (C0); and cancellation signals (B1-B2-B3) and error signals (C1-C2-C3), using, respectively a mu value that makes the power of the cancellation signal be less (1), equal (2) and greater (3) than the reference signal

IV. Conclusions

The reference input used in the proposed ECG interference adaptive cancellation algorithm is an initial estimation of ECG activity present in the EMGdi signal. These detection errors in the QRS complex use to be more frequent when there is presence of high electromyographic activity, and it is precisely in those cases in which it is more desired to cancel the ECG interference. In order to fix possible errors in QRS detector it has been selected a number of weights equivalent to 4 seconds, so that it is combined the information of more than one beat.

Furthermore we have designed an automatic criterion for the selection of the μ constant so that the canceling signal energy equals the energy of the reference signal. Starting from two initial μ values, the proposed automatic criterion reaches the recommended μ value in just 2 or 3 additional iterations. This approach optimizes the tradeoff between cancellation of ECG interference and eliminating EMGdi component.

The adaptive algorithm proposed has not been designed to work in real time. It has been used to eliminate the cardiac interference in the EMGdi of a signal database. It should be noted that, once fixed the number of weights, the algorithm cancels the ECG activity from the EMGdi signal automatically (without any additional input signal or parameter).

The outcomes of this work suggest that the methodology presented in this paper could improve the analysis and interpretation of EMGdi signal, in cases where it is not possible to have a recorded ECG reference signal.

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