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Eliminating cardiac electrical artifacts from cardiac autonomic nervous signals using a combination of empirical mode decomposition and independent component analysis.

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Abstract— **Cardiac autonomic nervous (CAN) signals in ambulatory dogs can nowadays be measured by an implantable radio transmitter system. CAN signals are known to be related to heart failure. However, they are critically contaminated by cardiac electrical activities (CEA) which confound data analysis. We propose a method of analysis which combines empirical mode decomposition (EMD) and independent component analysis (ICA). This method composed of two steps: First, the EMD method decomposed a single channel recording into multichannel data, then we applied the ICA to these multichannel data. Using an ambulatory dog's CAN signal data from Seoul National University Hospital, we compared our approach with a commonly used high pass filter (HPF) method for various amplitudes of simulated CAN signals. Root-mean-squared errors between simulated CAN signals and CAN signals with CEA artifact were calculated for assessing the noise cancellation effect. Moreover, we observed changes in spectral content via power spectral density. Finally, we applied the proposed method to real data. Our method could not only extract and remove CEA artifact in CAN signals, but also preserved the spectral content of CAN signals.**

I. INTRODUCTION

The autonomic nervous system (ANS) organizes appropriate automatic behavioral responses. It includes a specialized group of neurons that regulate the cardiac muscles. The ANS interacts in the pathophysiology of heart failure such as cardiac arrhythmia [1]. Recent technological development has led to cardiac autonomic nervous (CAN) signal recordings in several ambulatory canine models [2]. CAN signals have been shown to be an invariable trigger of paroxysmal atrial tachyarrhythmia. Therefore, CAN signals may help us find the causes of heart diseases related to ANS. However, CAN signals are contaminated by the cardiac electric activity (CEA).

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Several studies have been proposed for quantifying nerve activities using high pass filters with a cutoff frequency greater than or equal to 100 Hz, which is a value normally used to eliminate CEA artifacts [3, 4]. However, these methods for eliminating CEA artifacts from CAN signals are only partially successful. The difficulty of CEA removal is mainly due to a large overlap between the CEA interference spectrum and the spectrum of CAN signals. The adaptive filtering method is also one of the procedures for removing CEA artifacts. In fact, this method requires a supplementary CEA recording as a reference signal. Therefore, we cannot remove the CEA artifacts from CAN signals without having a reference signal.

Recently, signal processing algorithms for biomedical signals including independent components analysis (ICA) [5] have been used for artifact removal in surface electromyography (EMG). These methods are applicable for analyzing biomedical signal without an extra recording of CEA signals. Nonetheless, multichannel data were required for the ICA. Several studies extended the ICA method for single channel data. Single channel ICA [6] technique chops the raw data into several signals with an equal length before applying the ICA. Although this algorithm can decompose acquired signals into independent components, this method requires stationary data.

Both Wavelet analysis and the empirical mode decomposition (EMD) are decomposition methods that were also widely used for denoising procedures. Wavelet breaks down a signal using a predefined linear time-invariant filter. Wavelet analysis provide more accurately localized temporal and frequency information. EMD can decompose any time series into a set of spectrally independent oscillatory modes [7]. However, Wavelet always requires a priori mother wavelet for denoising [8], while EMD decomposes a signal in a natural way without prior knowledge about the signal of interest embedded in the data series.

In this paper, we propose a method for removing CEA artifacts from CAN signals in an ambulatory dog using a combination of EMD and ICA [9]. This method is not new and has found an application in the EMG for removing electro- cardiography (ECG) [10]. Therefore, the purpose of this paper is to verify whether the combination of EMD and ICA is an appropriate method for quantifying nerve activity. Moreover, we compare its performance to that of HPF. Simulated signals were used to evaluate the efficiency of the method through root-mean-squared errors (RMSE) and Welch's power spectrum density.

II. METHODS

A. Algorithms

The idea follows two steps: First, single channel data are decomposed using Empirical Mode Decomposition (EMD) and then we apply Independent Component Analysis (ICA) [9].

EMD is a data driven time frequency technique which adaptively decomposes a signal, by means of the so-called sifting algorithm, into a finite set of amplitude and /or frequency-modulated (AM/FM) components, referred to as intrinsic mode functions (IMFs) [7]. An IMF is a function which satisfies two conditions: In the whole data set, the number of extremes and the number of zero crossings must either be equal or differ at most by one, and at any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero. The EMD algorithm decomposes the signal $s(t)$ as $s(t)=\sum_{i=1}^{K} D_i(t)+r(t)$, where the $D_i(t), i=1,...,K$ are the IMFs, and is $r(t)$ the residue. The EMD algorithm is briefly described as follows.

- Let $h(t)=x(t)$
- Find all local maxima and minima of $h(t)$
- All the local maxima $(e_{max}(t))$ are connected by a cubic spline as the upper envelope; follow the same procedure for the local minima $(e_{min}(t))$ to produce the lower envelope.
- Compute the local mean $m(t)=\frac{e_{min}(t)+e_{max}(t)}{2}$.
- Obtain the detail part of the signal $h_1(t)=h(t)-m(t)$.
- Let $h(t)=h_1(t)$ and repeat the process from Step 2 until $h_1(t)$ becomes an IMF.
- Compute the residue, $r(t)=s(t)-h_1(t)$, and go back to Step 2 with $h(t)=r(t)$, until a monotonic residue signal is left.

After the EMD method is used, independent component analysis (ICA) is applied using the derived IMF data. ICA is a multivariate statistical approach for blind source separation [11]. The basic ICA approach uses the following linear model such that $X = AS$, where A is called the mixing matrix, without prior knowledge. For ICA decomposition, we used the FastICA algorithm [12] (version 2.3, from http://reserach.ics. tkk.-fi/ica/fastica). FastICA is a highly efficient method for performing ICA estimation. The algorithm is based on a fixed-point iteration scheme maximizing non-Gaussianity as a measure of statistical independence. ICA is applied to the whole set of IMFs.

In a resulting ICA, the components related to the CEA artifact are set to zero before reconstruction of the cleaned CAN signals without the CEA artifact.

B. Data

The experiment data were obtained from Seoul National University Hospital. From an ambulatory dog, CAN signals were recorded with two pairs of bipolar wires. These bipolar wires recorded stellate ganglion nerve activity (SGNA) from the left stellate ganglion, and vagal nerve activity (VNA) from the superior cardiac branch of the left vagal nerve. The sampling rate of the two channels was 1 kHz.

III. SIMULATION AND EXPERIMENT

A. Simulation

The real value of CAN signals could not be measured due to CEA artifacts. Therefore, we simulated a CAN signal with an averaged CEA artifacts. We generated a uniformly distributed White Gaussian signal. Artificial CEA signals were generated from real data using a signal averaging technique, in which we averaged the amplitudes of CEA components in VNA and SGNA. Figure 1 illustrates that simulated CEAs and White Gaussian noise were mixed for 10 s. To assess the simulation data, we computed the root-mean square error (RMSE) to compare the different techniques. Moreover, spectral analysis of the combined EMD and ICA method and the HPF method was performed using Welch's power spectral density.

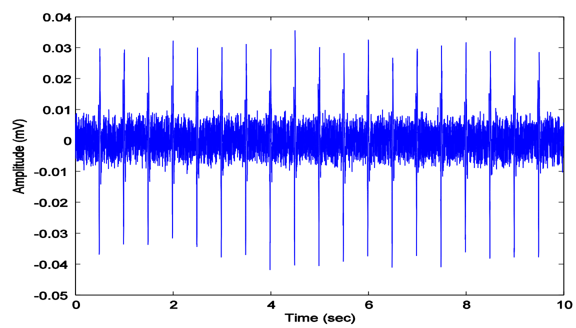

Figure 1. Simulated CAN signal with CEA.

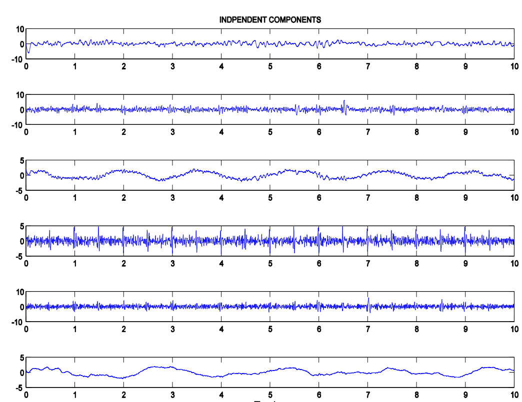

Figure 2. Independent sources after using ICA on the EMD decomposition. Component 4 is involved in CEAs.

Strings of independent components after using our proposed method are shown in Figure 2. The CEA matches Source 4. This source which corresponds to the CEA signal was set to zero and a contamination-free signal was rebuilt with other signals. Figure 3 shows the reconstructed signal without CEA artifacts. Red line illustrates the reconstructed signal and blue line illustrates simulated CAN signal with CEA. We could confirm that the peaks of CEA were removed. These figures show that the combined EMD and ICA method could extract CEA sources and remove CEA artifacts. As shown in Figure 3, HPF method was also able to eliminate the peaks of CEA. When looking at the Figure 4, however, HPF lost the spectral content, while the combined EMD and ICA algorithm better preserved the spectral content than HPF.

The performances of the proposed method on the data set were presented in Figure 5. Figure 5 shows root-mean-squared errors (RMSE) at varied amplitudes of the simulated CAN signals. At higher amplitudes, the amplitude of simulated CAN signal was higher than the amplitude of CEA. In this case, it was difficult to eliminate CEA artifact due to a high overlap between the two signals. However, the combined EMD and ICA method performed much better compared to the HPF with clearly lower RMSE at all observed amplitudes.

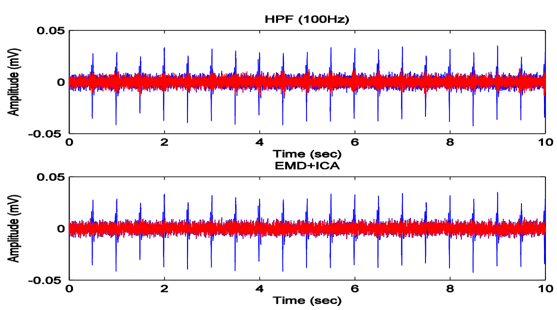

Figure 3. Reconstructed signal. (Top: HPF (100 Hz), Bottom: Combination of EMD and ICA).

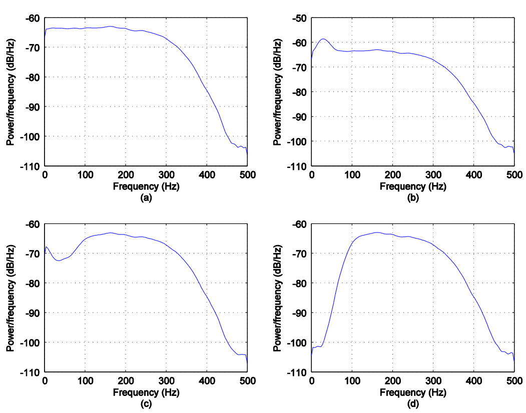

Figure 4. Power spectral density using Welch's method. (a)contamination-free simulated signal, (b) simulated signal with CEA, (c) EMD+ICA algorithm (d) HPF 100 Hz cutoff frequency.

B. Experiment

Now, the proposed method was applied to the real CAN signals including VNA and SGNA. Since CAN signals were recorded from an ambulatory dog, motion artifact was included in the signals. Motion artifact normally has frequencies between 2 and 20 Hz [13]. Therefore, we applied a third Butterworth high-pass filter with a 20 Hz cutoff frequency for removing motion artifact. Cleaned signals of VNA and SGNA are shown in Figure 6. The uppermost panel shows the cleaned VNA (Red line) and VNA with CEA artifact (Blue line). The bottom panel represents the cleaned SGNA (Red line) and SGNA contaminated with CEA (Blue line). After using the proposed method, we could confirm from real data that CEAs were removed. Figure 7 displays the power spectral density of real data. When compared with results from HPF, the combined EMD and ICA method performed much better than the HPF method.

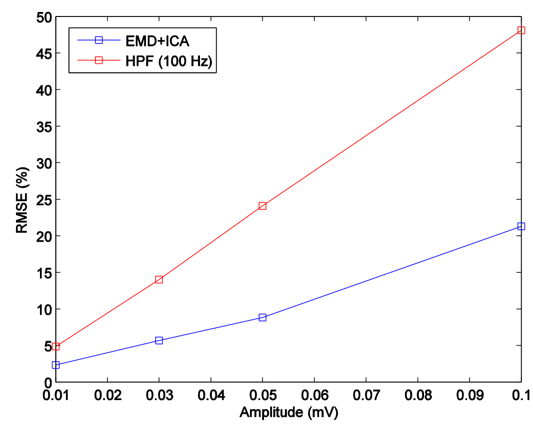

Figure 5. Comparison of performance of methods for root-mean-square errors (in %).

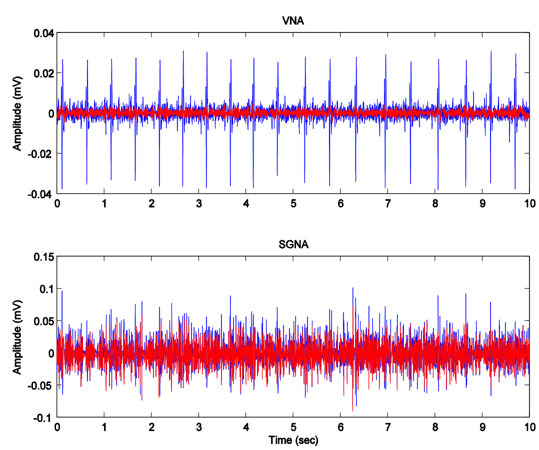

Figure 6. Real data of CEA removal by the combination of EMD and ICA.

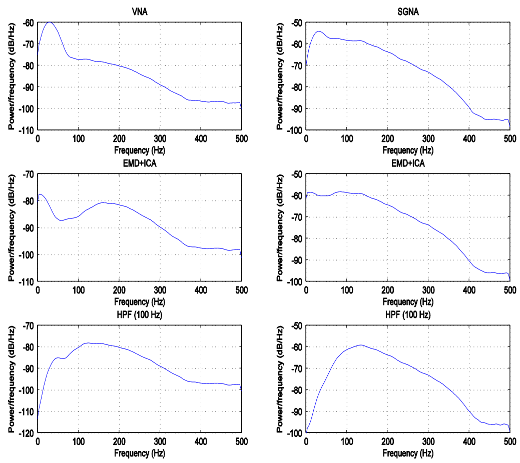

Figure 7. Power spectral density of real data. Top panel: Raw data, Middle: Using EMD+ICA, Bottom: HPF with 100 Hz cutoff frequency.

IV. DISCUSSTION AND CONCLUSION

In the present study, we proposed a combination of empirical mode decomposition (EMD) and independent component analysis (ICA) to eliminate cardiac electric activities (CEA) from the cardiac autonomic nervous (CAN) signals. The high pass filter (HPF) method has been usually applied for analyzing CAN signals and it to removes peaks of CEA from CAN signals. However, the HPF method was insufficient for preserving the inherent frequencies in CAN signals. Moreover, when the amplitude of CAN signals was increased, the HPF method could only partially remove the peaks of CEA in CAN signal. On the other hand, the combined EMD and ICA method could effectively extract and remove CEA artifacts without any other reference signal and multi- channels. Furthermore, the inherent frequencies in CAN signal were fairly preserved compared to the HPF method. The results of our method suggest that the combined EMD and ICA technique is a promising tool for removing CEA artifact in CAN signals. Therefore, the proposed method would help study the CAN signals.

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