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Filtering Heart Related Activity from Vagus Nerve Recordings in Rats

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Abstract

Vagus nerve stimulation has become a recognized form of treatment for several conditions such as refractory epilepsy and depression. However, its exact mechanism of interference with these pathologies remains unknown. Vagus nerve signals have recently been recorded in rats in order to gain a better understanding of such situations. Due to the proximity of the recording site to the heart itself and beating arteries, the signal is contaminated by cardiac artifacts. These represent a major challenge to the subsequent extraction of accurate and useful information such as the frequency spectrum or the amplitude of the nerve signal. Efficient ECG contamination removal techniques have been introduced in the literature for the EMG signal. However, to our knowledge, the removal of cardiac activity contamination has never been investigated previously in neurograms. In this work, we investigate the application of these removal techniques on vagus nerve signals. The methods are evaluated on real experimental recordings from the vagus nerve in rats.

1 Introduction

The treatments of several refractory neurological or psychiatric diseases involve invasive stimulation of the vagus nerve. This has become a recognized procedure for epilepsy and severe depression [1]. Nevertheless, the exact mechanisms involved remain largely unknown. Recording of the neural activity in the vagus nerve have recently been achieved in order to gain a better insight in this field.

Due to the proximity of the recording sites to the heart and beating arteries, the vagus nerve recordings are typically contaminated with signals related to the cardiac activity, including the ECG. These artifacts can significantly distort the frequency spectrum and the amplitude of the global neural signal, thus presenting a major challenge to the subsequent extraction of accurate and useful information.

The same problem has been identified in electromyography (EMG) signals collected from the trunk muscles, where the proximity to the heart and the volume conduction characteristics induce a cross talk from the ECG through the torso. In recent years, several successful techniques have been reported to filter out ECG noise from the EMG signals [2,3,4]. However, to our knowledge, these methods have never been applied to neural signals. These are typically characterized by higher frequency contents but the heart related contamination is not only electrocardiographic in nature. It can contain plethysmographic and movement artifacts as well.

In this work, we investigate the application of three state-of-the-art EMG filtering techniques to vagus nerve signals. The pros and cons of each method are outlined. Real data obtained from acute recordings of the vagus nerve in rats are used in this study.

The remainder of the paper is structured as follows. After this introduction, Section 2 reports on the experimental nerve recording procedure. Section 3 introduces the signal processing methods exploited in this work. Section 4 describes and analyses the results of their application to our data.

2 Experimental Design

The experimental protocol for recording neural activity from the vagus nerve in rats has been approved by the Committee for Ethical use of Animals of the Faculty of Medicine of the Université catholique de Louvain. For these experiments, animals were anesthetized with intraperitoneal Xylazine (10 mg/kg body weight) and Ketamine (50 mg/kg body weight).

A 0.9 mm diameter self sizing spiral cuff made of two silicon rubber sheets carrying platinum contacts between them was used for recording. The cuff was 11 mm long. On its inner face, at 1.5 mm from each extremity, 0.5 mm diameter apertures were made in front of the recessed platinum contacts. Thus the distance between the centers of the two contacts was 8mm. The recording reference was a third contact placed outside the cuff halfway along its length. The sampling rate was 16384Hz. The impedance of the cuff was verified prior to recording as suggested in [5] (inferior to 7 kilo-ohms). A bipolar signal was obtained by subtraction of the signals from the two inner

zoomed extract corresponding to the first second of the signal in the upper trace. Cardiac contamination is obvious in either case.
This signal is the input to each of the three filtering algorithms. The MI value between the raw signal and the ECG signal is 0.22. Figure 2 shows the results on the total recording length.

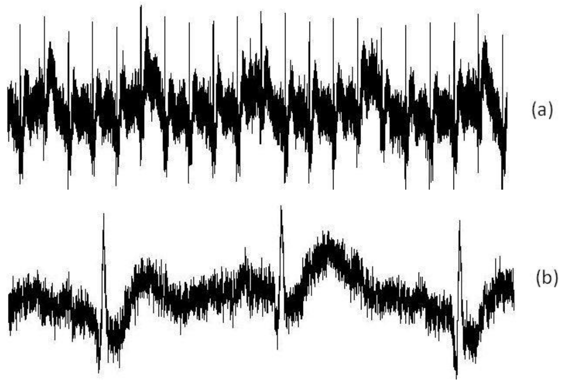

Fig. 1 (a) 5 seconds of nerve signal, (b) zoom on the first 600 milliseconds.

Fig. 2 Results of the removal algorithms: (a) FIR, (b) template subtraction, (c) DWT.

As revealed by these pictures, the FIR filter is not able to remove the QRS complex completely. The MI value of the FIR filter is in the 10^{-2} range. The template subtraction method performed better with a MI value in the 10^{-3} range, but still leaves some low frequency baseline wanderings probably corresponding to respiration artifacts. The DWT outperforms the other two methods, with a MI value in the 10^{-6} range and an almost perfect removal of the ECG contamination and of the baseline wanderings as can be judged visually.

5 Conclusion

Vagus nerve recordings in rats are contaminated with several sources of noise, the most important being the heart muscle signal. In this work, three methods designed for the removal of artifacts in EMG signals are applied to experimental neural data. These methods are high-pass FIR frequency filtering, a template subtraction algorithm and the discrete wavelet transform. The advantages and disadvantages of each method are outlined. The results are evaluated by visual inspection and by computing the mutual information between the filtered signal and the ECG signal. The FIR method, while being the simplest, is unable to completely remove the ECG noise in the signal. The template subtraction algorithm performs better, but still leaves artifacts from other sources unfiltered, such as baseline wanderings due to respiration. The DWT method outperforms the other two, and almost perfectly removes the artifacts. The mutual information is a suitable criterion for the unsupervised settings of the method parameters.

Acknowledgments

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6 References

[1] George M.S.; Nahas Z.; Bohning D.E.; Lomarev M.; Denslow S.; Osenbach R.; Ballenger J.C.: Vagus nerve stimulation: a new form of therapeutic brain stimulation. CNS Spectr., Vol 5, No 11, 2000, pp. 43-52

[2] Redfern M. S.; Hughes R. E.; Chaffin D. B.: High-pass filtering to remove electrocardiographic interference from torso EMG recordings. Clinical Biomechanics. Vol. 8, No. 1, 1993, pp. 44-48

[3] Bartolo A.; Roberts C.; Dzwonczyk R.; Goldman E.: Description and validation of a technique for the removal of ECG contamination from diaphragmatic EMG signal. Med. Biol. Eng. Comput., Vol. 34, 1996, pp. 76-81

[4] Azzerboni B.; Carpentieri M.; La Foresta F. ; Morabito F.C. : Neural-ICA and Wavelet Transform for artifacts removal in EMG. Proc. of the IEEE International Joint Conference on Neural Networks, Vol. 4, 2004, pp. 3223-3228

[5] Thil. M-A ; Gérard B.; Jarvis J. C. ; Delbeke J. : Two-way communication for programming and measurement in a miniature implantable stimulitor. Medical & Biological Engineering & computting, 2005, Vol. 43, pp. 524-534

[6] Moddemeijer, R.: On Estimation of Entropy and Mutual Information of Continuous Distributions. Signal Processing, 1989, Vol. 16, No. 3, pp. 233-246

[7] Mallat S.: A Wavelet Tour Of Signal Processing (Wavelet Analysis And Its Applications). IEEE Press, 1999, San Diego

[8] Liang H.; Lin Z.: Stimulus artifact cancellation in the Serosal Recordings of Gastric Myoelectric Activity Using Wavelet Transform. IEEE Trans. Biomed. Eng., Vol. 49, No. 7, 2002, pp. 681

contacts. Figure 1 shows 5 seconds of the bipolar signal that is used in this work.

3 Methodology

The following techniques for removal of ECG contamination from EMG signals have been reported in the literature: high pass filtering [2], template subtraction [3] and the discrete wavelet transform [4]. This section briefly introduces each of these methods and the performance metric used in this work.

3.1 Performance Metric

For the evaluation of EMG filtering techniques, a clean benchmark EMG signal is recorded at a location far away from the heart site. ECG contamination is then artificially added. In our situation, it is impossible to obtain a clean benchmark vagus nerve signal. Therefore, we choose to measure the mutual information (MI) between the ECG signal recorded from an additional channel and the filtered nerve signal as an estimation of performance [6].
The MI of two random variables is a quantity that measures the mutual dependence of the two variables [6]. Intuitively, it measures the information that the two variables share. Therefore, a low MI value between the filtered nerve signal and the ECG indicates that the filtering is very efficient.

3.2 High-pass Filtering

High-pass frequency filtering has been applied as a simple and potentially efficient method for the removal of artifacts in EMG signals [2]. The major advantages of this method are its simplicity and its very popular usage. On the other hand, the order of the filter must be chosen empirically while this parameter can significantly affect the results. Furthermore, this method is only effective if the artifact spectral content is limited and does not overlap with the signal spectrum.
The high-pass filter used in this work is a symmetric finite impulse response filter (FIR) with Hamming-window based linear-phase transfer function. A value of 500 for the filter order provides the best value for the performance metric. A cutoff frequency of 100Hz is used.

3.3 Template Subtraction

The template subtraction algorithm has shown a great potential for filtering EMG signals when the ECG signal can be recorded as supplemental data [3]. The global idea is that a template is subtracted from the nerve signal at each occurrence of a heart beat. The method thus makes use of the ECG signal and especially of the timing of the heart beats as sensed by a QRS detection algorithm [3]. The timing of QRS complexes thus identifies the occurrences of ECG contamination.
The template subtraction algorithm involves two steps. First, a template is created from the nerve signal at the contamination times. It is estimated by averaging neural recording samples corresponding to each QRS occurrence. In the second step, the template is subtracted from the neural signal at each contamination time.
The main advantage of this method is that it is not blind: it makes use of the information from the ECG signal. Also, because the template is estimated from the signal itself, any delay between the heart ECG signal and the ECG contamination is taken into account. However, the size of the template must be chosen carefully. It must be long enough to capture P and T waves but it must not overlap between successive heart beats. In this work, a template size of 2000 points is empirically chosen. Furthermore, the method is very dependent on the reliability of the QRS detection algorithm.

3.4 Wavelet Transform

The wavelet transform (WT) [7] is a time-frequency representation of a signal that was introduced to overcome the limitations in time and frequency resolution of classical frequency transforms such as the Fourier transform. The WT produces a time-frequency decomposition of a signal by the convolution of this signal with a so-called *wavelet function*. From a wavelet function $\psi(t)$, one can obtain a family of time-scale waveforms $\psi_{a,b}(t)$ by translation b and scaling a.
The continuous wavelet transform (CWT) of a function x(t) is a projection of this function on the wavelet basis $\psi_{a,b}$. The discrete wavelet transform (DWT) removes the redundancy of the CWT by using dyadic scales and discrete translations. Each DWT step produces two sets of coefficients: approximation coefficients (low frequency components) and detail coefficients (high frequency components), followed by a dyadic decimation (downsampling). The DWT has been used with success for artifact removal in EMG signals [4,8]. The main drawback of the WT is that the mother wavelet and the decomposition order must be empirically chosen. An order 6 *Daubechies* wavelet has been shown to be efficient for ECG filtering in EMG signals [4], and it has therefore been selected for this work as well. The decomposition level that provides the best value for the performance metric is chosen, which is in our experiments a = 5. The reconstructed and summed detail coefficients at previous levels thus correspond to nerve activity. The approximation coefficients correspond to the ECG signal.

4 Experiments and Results

The three ECG removal methods are compared on a 5 seconds neural recording. The raw nerve signal recording is shown in Figure 1. The lower trace is a