Elimination of electrocardiogram contamination from vagus nerve recordings using ICA

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Abstract

Vagus nerve stimulation has become a recognized form of treatment for several conditions such as refractory epilepsy and depression. Vagus nerve signals have recently been recorded in rats in order to gain a better understanding of its exact mechanism of interference with these pathologies. For this purpose, nerve cuff electrodes offer many advantages but suffer from a low signal to noise ratio. In particular, cardiac artefacts represent a major burden to the subsequent extraction of information from the nerve signal. In this work, we show that these cardiac artefacts can be efficiently separated from the neural activity in multi-channel recordings by the ICA algorithm. The discarded source is highly correlated with a short time-delayed version of the ECG signal, which suggests that the artefact mainly results from volume conducted heart electrical activity.

Keywords – Vagus nerve recordings, cuff electrode, independent component analysis, ECG filtering.

1. Introduction

Vagus nerve stimulation is a recognized adjunctive treatment for certain types of intractable epilepsy and for major depression [1]. Nevertheless, the exact mechanisms involved with this treatment remain largely unknown. Experimental recordings of the vagus nerve activity aiming at a better understanding of those mechanisms have recently been achieved. For example, recent work investigated whether epileptic activity could be detected in vagus nerve recordings [2].

For this purpose, nerve cuff electrodes offer many advantages over standard electrodes [3]. Despite the many advantages offered, nerve cuff electrodes have a rather poor recording signal-to-noise ratio compared with nerve penetrating alternatives. This represents a major challenge for the subsequent extraction of accurate and useful information.

In particular, cardiac activities induce a major noise component in the signal [4]. A way to counteract this problem is to include more recording contacts in the cuff and make use of a blind source separation method. One of the most popular techniques for this purpose is independent component analysis (ICA) [5]. ICA solves the blind source separation problem by separating a multivariate signal into additive subcomponents, supposing that the source signals are statistically independent. The heart related artefacts can thus be isolated as one of the estimated sources and the clean vagus nerve signals can then be reconstructed by discarding it.

In the following work, this method of artefact filtering is applied to vagus nerve recordings obtained in rats using a spiral cuff electrode with 8 embedded recording contacts. The filtered artefact is compared to the simultaneously recorded ECG signal in order to identify the nature of these cardiac artefacts.

The following of this paper is structured as follows. Section 2 describes the experimental protocol for the recording of the data in rats. Section 3 gives a brief introduction to independent component analysis. Section 4 shows the results of the filtering, and Section 5 is the conclusion.

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. Adult albino rats (Wistar) were used 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 9 pieces of platinum foils of 1 by 1 mm contacts between them is used for recording [6]. Eight internal contacts made by opening in front of each piece of platinum a 500 µm diameter circular window in the inner silicone sheet. These are used for recording and one external (opening in the external silicone sheet) contact is the reference. The cuff is 17mm long and the distance between the centres of each contact is 2 mm. The sampling rate is 16384Hz. The impedance of the cuff is verified prior to recording as suggested in [7] (below 7 kOhms). The ECG signal is recorded from a silver wire electrode inserted subcutaneously.

3. Independent component analysis

Independent Component Analysis (ICA) [5] is a signal processing technique aiming at separating measured signals into their “source” components. Sources are considered as the basis components which are mixed to produce the measured signals. The general problem of recovering sources from the measured signals is called Blind Source Separation (BSS). It is blind because the mixture process (from the sources to the measured signals) is unknown and unobserved.

To be solved, this problem requires further hypotheses. The first one is that the sources are statistically independent; this leads to the so-called Independent Component Analysis (ICA). Another hypothesis must be made about the mixing. Among the possible alternatives, a linear and instantaneous mixing process has been considered here. Finally, it is assumed that the number of sources is equal to the number of observed mixed signals.

Let us define S the k×n matrix of source signals s_i, Z the k×n matrix of observed signals z_i, and A the k×k mixing matrix, where k is the number of independent sources, also equal to the number of observed signals, and n the number of observations (here time points) per signal. Then the model may be written as

$$Z = AS. \quad (1)$$

The ICA problem reduces to finding estimations S* of the sources by combining the observed signals Z:

$$S^* = WZ = WAS \quad (2)$$

where W is the separating matrix corresponding to the inverse of the mixing matrix A. Numerous methods based on some measurements of the independence between the estimated source signals S* are able to yield an valuable estimate of matrix A [5].

4. Experiments and results

The ICA algorithm is applied on a 5 seconds neural recording with 8 channels. Figure 1 shows one second of the recording. Cardiac contamination is obvious in the 8 channels.

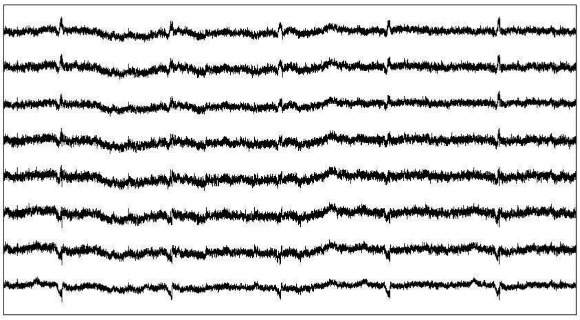

Fig. 1 The neural signal recorded by 8 distinct contacts, displaying 1 second. Cardiac artefacts are clearly visible.

Figure 2 shows the sources estimated by the ICA algorithm. The last source can visually be identified as an ECG signal, while no cardiac artefacts can be identified in the other estimated sources. The ICA model thus successfully separates and isolates the heart related artefacts from the neural activities.

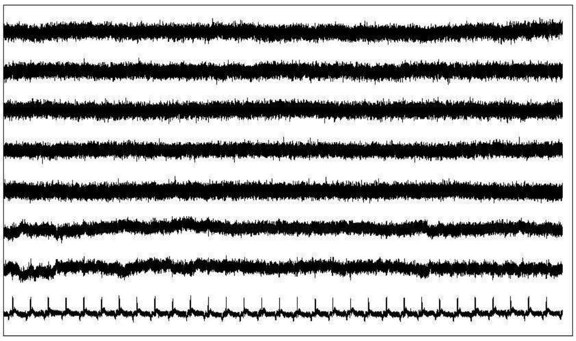

Fig. 2 The sources estimated by the ICA algorithm, displaying 5 seconds. The last source can visually be identified as an ECG signal.

The other estimated sources can be interpreted as neural activity and could correspond to the separation of the activity from fibres with different conduction velocities recorded at different locations. The rejected source appears to be highly correlated with a time-delayed version of the ECG signal that was recorded simultaneously. Figure 3 illustrates the delay between the estimated ECG source and the real ECG signal. The value of this delay is estimated to 2.5msec by maximal cross-correlation. Once the estimated ECG source is time shifted by this delay, the correlation value between the two signals is 0.83. The similarity between this rejected source and the ECG signal suggests that the artefact mainly results from volume conducted heart electrical activity. The delay can be explained by cardiac conduction times.

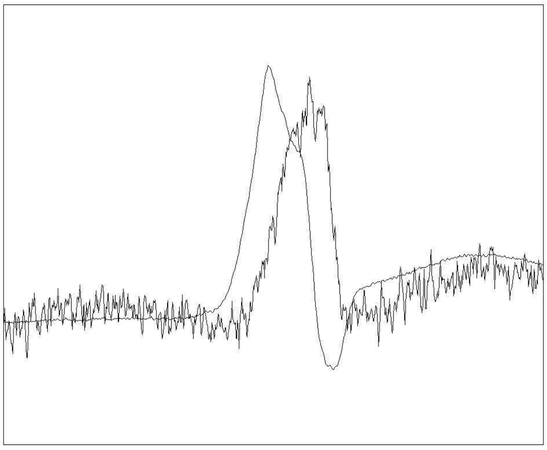

Fig. 3 Illustration of the delay between the estimated ECG source (sharped line) and the real ECG signal (smooth line), displaying 50msec.

The clean vagus nerve signals can then be reconstructed by discarding the associated unwanted source in Eq. 1. Figure 4 shows the clean reconstructed signals.

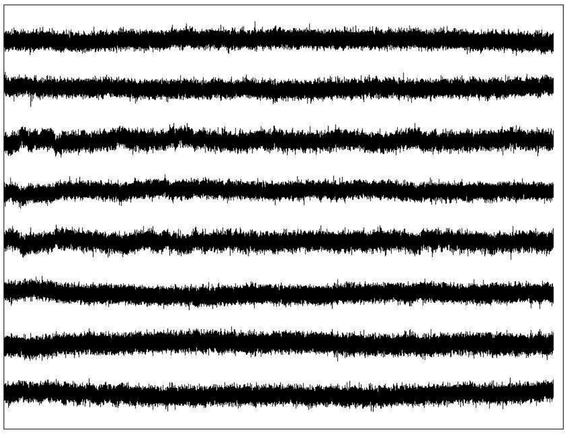

Fig. 4 Reconstructed neural signals after discarding the source corresponding to ECG artefacts, displaying 5 seconds.

4. Conclusion

Recordings from the vagus nerve suffer from a low signal to noise ratio. In particular, cardiac artefacts represent the major source of noise in the signal. In this work, we show that these cardiac artefacts can be efficiently separated from the neural activity in multi-channel recordings by the ICA algorithm. The discarded source is highly correlated with a short time-delayed version of the ECG signal, which suggests that the artefact mainly results from volume conducted heart electrical activity.

The other estimated sources could correspond to the separation of the activity from fibres with different conduction velocities recorded at different locations. However, as it can be seen by zooming on the estimated source corresponding to the ECG artefact (see Figure 3), the extraction is not totally perfect because the signal contains high frequency noise. This should be improved by the use of semi-blind source separation models which are more optimized for the extraction of temporal signals whose structure is known [8]. These models are based on second-order statistics and are able to integrate a priori knowledge about the time structure of the signals such as the period.

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Acknowledgements

G. de Lannoy is funded by a Belgian F.R.I.A. grant. This work was partly supported by EC project 'IMANE' IST-4-026602-STP, the Belgian ``Région Wallonne" ADVENS 4994 and DEEP projects.