Suppression of Motion Artifacts in Optical Action Potential Records by Independent Component Analysis

Oto Janoušek[1], Jana Kolářová[1], Marina Ronzhina[1], Marie Nováková[2], Sridhar Krishnan[3]

[1]Department of Biomedical Engineering, Brno University of Technology, Brno, Czech Republic
[2]Department of Physiology, Faculty of Medicine, Masaryk University, Brno, Czech Republic
[3]Department of Electrical and Computer Engineering, Faculty of Engineering, Architecture, and Science, Ryerson University, Toronto, Canada

Abstract

Optical signals reflect electrical changes in the heart; however, the presence of motion artifact (MA) complicates the evaluation. Possibility of MA suppression by independent component analysis (ICA) method is presented in this article with an analysis of ICA efficiency and its limitations.

Suppression of MA by ICA method was compared with results obtained by state-of-the-art signal processing method, the ratio method. Based on this comparison, the ICA was found as highly precise and useful method for motion artifact removal. ICA seems to be a promising tool for analysis of optical signals recorded from the heart surface.

1. Introduction

Electrical activity of the heart can be recorded conventionally by the electrode technique or, newly, by the optical method [1]. Optical method is based on voltage sensitive dyes (VSD) utilization. VSD binds itself on the cell membrane and changes it's emission light according to action potential (AP) voltage. Although optical method has some significant advantages, it also has certain limitations in practice. Most important limitation is the presence of motion artifact (MA). MA interferes with the AP recordings.

MA origin can be described as follows: emission light collected by the photo-detector is modulated not only with transmembrane potential, but also with the movement of heart wall. The distance between photo-detector and light emitting cells of heart wall alters during heart contraction. Increasing distance produces decreasing intensity of the collected light. Moreover contraction of the heart produces deformation of heart wall. Deformation increases the total number of cells in the photo-detector field-of-view. It also changes total light intensity. These unwanted distortions of recorded optical AP are commonly termed as MA.

MA may significantly misrepresent useful information in AP records. There are three general approaches for its suppression in the literature: (a) chemical agents causing electro-mechanical uncoupling [2] (b) slight pressing of the heart wall against glass plate [3] and (c) offline signal processing techniques [4].

Signal processing techniques are superior to the other approaches, because they do not affect physiology of the heart. This article describes novel approach for suppression of MA in AP records, based on independent component analysis (ICA) [5]. Efficiency of ICA method assessed in this article is compared with state-of-the-art method, the ratio method.

2. Method

2.1. Experimental preparation

All measurements in this study were performed on rats. Experiments followed the guidelines for animal treatment approved by local authorities and conformed to the EU law. After premedication with benzodiazepines (Apaurin, 2mg, i.m., Krka, Slovenia), the rat was deeply anaesthetized by mixture of ketamin (60mg/kg of body mass, Narkamon, Spofa, Czech Republic) and xylazin (2mg/kg of b.m., Rometar, Spofa, Czech Republic), and the chest was opened. Then the heart was excised with a sufficiently long segment of ascending aorta. The aorta was then cannulated, the heart was mounted on the modified Langendorff apparatus [6] and placed in thermostat-controlled Plexiglas bath (37°C) filled with Krebs-Henseleit (K-H) solution of following composition (in mM): NaCl 118, $NaHCO_3$ 24, KCl 4.2, KH_2PO_4 1.2, $MgCl_2$ 1.2, glucose 5.5, Taurine 10, and $CaCl_2$ 1.2. The perfusate was oxygenated with 95% O_2 and 5% CO_2. The heart was perfused in the mode of constant perfusion pressure (85mmHg) and stabilized for 30 minutes. No chemical agents were used for contraction suppression.

2.2. Optical AP recording

The isolated heart was placed in the bath with K-H solution. Three-dimensional electrograms were recorded for heart function monitoring. The optical method was used for AP recording. Both electrograms and AP were recorded by touch-less methods. Isolated heart was beating freely without any mechanical restriction. For optical method, the isolated heart was slowly stained [13] with VSD di-4-ANEPPS, commonly used in cardiac studies [7]. It was diluted in K-H solution and retrogradely applied into coronary arteries. Fifteen minutes long staining procedure was followed by the washout, which removed redundant non-coupled VSD molecules from the cardiac tissue. Finally, the heart was kept without intervention for 30 minutes long period during which AP was recorded.

VSD emits the fluorescence light after excitation [3]. Spectral shift of emitted light reflects transmembrane potential of stained heart cells. Emitted light was collected by photo-detector, transformed by optical to voltage transducer to voltage signal, and saved to PC. Excitation was produced by laser ($\lambda = 488$nm) and transferred to the heart wall by optical probe (Avantes, Netherlands). The optical probe passed through Plexiglas bath wall and ended in proximity of the left ventricular wall. Micromanipulator allowed to set-up the probe in a position close to the heart wall but did not restrict movement of the beating heart [8]. The same optical probe was used for transfer of emitted light to the photo-detector (6 of 7 optical fibres in the multi-fibre probe were used for excitation light, 1 was used for light emission). The three-segment photodiode (RGB Color Sensor S9032-2, Hamamatsu Photonics, Japan) was used as a photo-detector. Light intensity in red, green and blue parts of emission spectra was recorded by corresponding segment of photodiode.

Signals with duration approximately 60 minutes were recorded with sample frequency 2kHz. The digital signals were stored on a hard disk for offline processing. Afterwards, signals were offline pre-processed and analyzed by ICA in Matlab R2007b (MathWorks, 2007).

2.3. Independent Component Analysis

Independent Component Analysis (ICA) [5] is a method for separating of the multivariate statistical data into its subcomponents. ICA can be also described as a statistical and computational technique for revealing hidden factors that underlie sets of random variables, measurements, or signals [9]. Generative model of ICA assumes that the mixed signals are the product of instantaneous linear combination of the independent sources. Such a model can be mathematically described as [5]:

$$x_i = a_{i1}s_1 + a_{i2}s_2 + \ldots a_{iM}s_M \qquad (1)$$

for all i = 1, ..., M, where x_1, ..., x_M are the observed random variables, s_1, ..., s_M are source random variables, and $a_{ij}, i,j = 1, \ldots M$ are real coefficients. Source random variables, s_i, must be statistically mutually independent.

Recorded optical signals in this study correspond to the ICA generative model. Optical signal is a mixture of optical action potential, motion artifact, and optical noise recorded by three-segment photodiode as:

$$\begin{aligned} R(t) &= a_R AP(t) + a_R MA(t) + a_R N \\ G(t) &= -a_G AP(t) + a_G MA(t) + a_G N \\ B(t) &= a_B MA(t) + a_B N \end{aligned} \qquad (2)$$

where *R(t), G(t)* and *B(t)* are recorded optical signals in three different ranges of fluorescence wavelengths (red, green, blue), *AP(t)* is AP, *MA(t)* represents MA and *N* is the optical noise, which is time invariant. Coefficients a_R, a_G, a_B represent amplification of red, green and blue segment of the photo-detector. Note that coefficient a_R and a_G must be opposite because of spectral shift of VSD during AP occurrence. AP was omitted in blue signal *B(t)* because VSD emitted light only at red and green parts of spectra.

AP can be extracted from optical signals by several ICA algorithms; in this article, WASOBI algorithm [10] was used.

2.4. Ratio method

Ratio method [11] was used for computing the AP template. Ratio of light from red and green parts of emission spectra was computed as follows:

$$AP_{ratio}(t) = \frac{R(t)}{G(t)} = \frac{a_R AP(t) + a_R MA(t) + a_R N}{-a_G AP(t) + a_G MA(t) + a_G N} \qquad (3)$$

where $AP_{ratio}(t)$ is a template of AP, *R(t), G(t)* are recorded optical signals (red, green), *AP(t)* is an action potential, *MA(t)* represent motion artifact and *N* is optical noise. Coefficients a_R, a_G, represent amplification of red and green segments of used photodiode. Ratio method is probably the most utilized signal processing technique for motion artifact suppression nowadays. Although this method is not ideal, it still remains state-of-the-art method for motion suppression. For this reason, it was chosen for comparison with ICA.

3. Results

3.1. Number of independent components

Number of independent components emerged from scree plot of eigenvalues of matrix composed from red, green and blue optical signals reveals (Figure 1). The line breaks at position number = 2; it suggests that there are two independent variables in the data set. This is in accordance with theoretical assumptions that optical signals are supposed to be mixture of two sources, AP and MA.

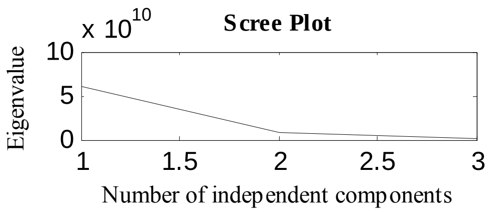

Figure 1. Plot of eigenvalues

3.2. ICA limitation

ICA, belonging to blind source separation methods group, performs source signals separation without a prior knowledge of original sources character. There is assumption of source signal character, however: source signals must be mutually independent.

Independency has been evaluated by comparison of the joint probability density function (pdf) of measured MA and modelled AP (Luo-Ruby [12]) with product of its marginal densities. Comparison of products of separate AP's and MA's pdfs (Fig. 2, part B) and its joint pdf (Fig. 2, part A) reveals that MA and AP are not fully statistically independent. Nevertheless dependency of MA and AP is really negligible, and ICA gives satisfactory results.

3.3. Efficiency of ICA

Efficiency of ICA was evaluated by comparison of AP obtained by ICA, $AP_{ICA}(t)$, with AP obtained by ratio method, $AP_{ICA}(t)$. Both results are almost identical, as can be seen in Fig. 3, part A and part B. Correlation coefficient between $AP_{ratio}(t)$ and $AP_{ICA}(t)$ is 0.995. Source signal for both methods was the same.

Both signals $AP_{ratio}(t)$ and $AP_{ICA}(t)$ are shown at the same scale in left part of Fig. 3. APs from both methods are almost completely overlapping, indicating that ICA results are the same as ratio method results. MA obtained by ICA is also almost completely overlapping with blue part of emitted light $B(t)$, where only movement of the heart contributed to recorded light intensity.

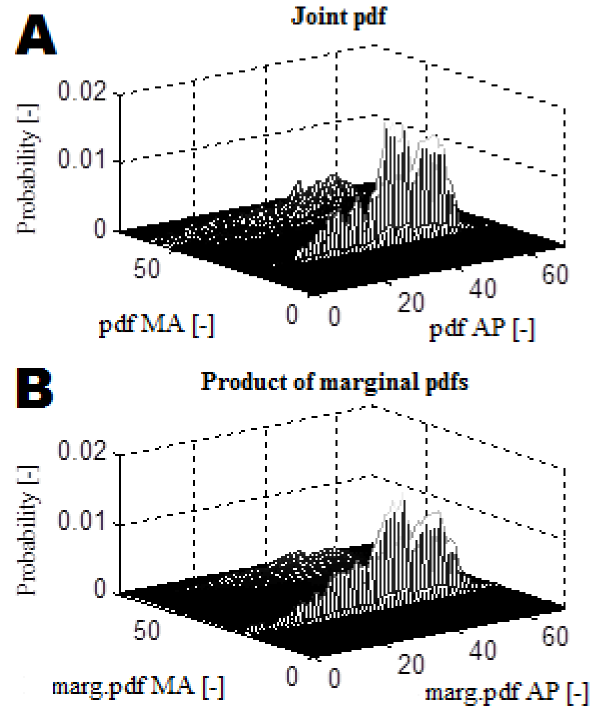

Figure 2. Joint probability density function of AP and MA (part A) and product of it's marginal densities (part B)

4. Conclusions

ICA can be used for MA suppression in simultaneously recorded optical signals. Both requirements on ICA input signals (independency, non-Gaussianity) are fulfilled. ICA can reveal AP and MA with very good accuracy.

Results showed that ICA is comparable with ratio method, which is state-of-the-art signal processing method for moving artifact restriction.

Although both methods give comparable results, there are some advantages and disadvantages of ICA, when compared with ratio method. ICA is superior over ratio method in case of different amplification of input sensors – i.e. segments of photodiode in this article – because ICA transforms scales of input data in a pre-processing steps. The shape of AP is therefore independent on input sensors amplification. On the other hand, ICA is more computationally demanding, and for this reason it may be more time-consuming and has more enormous memory requirements than ratio method. It may limit usage of ICA especially in on-line MA removal approaches.

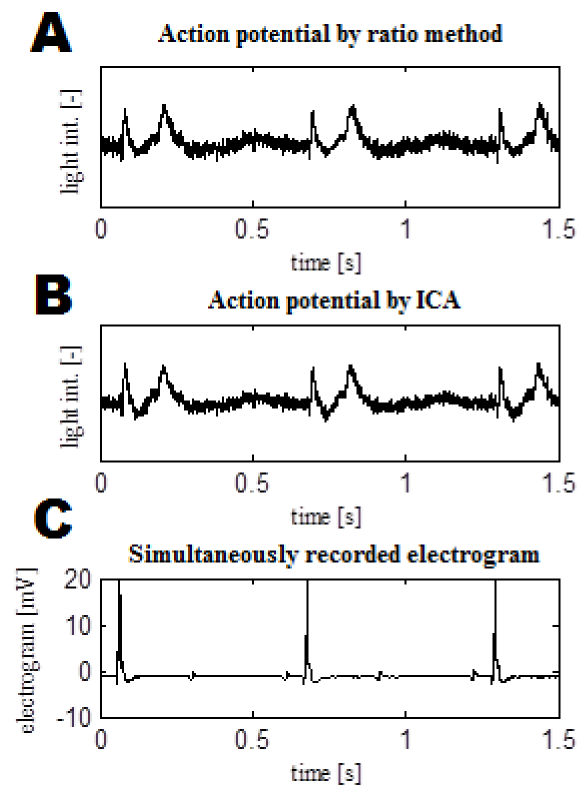

Figure 3. AP obtained by ratio method (part A), by ICA (part B) and corresponding electrogram (part C)

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Address for correspondence.

Oto Janoušek
Kolejní 4, Brno, 60200, Czech Republic
janouseko@feec.vutbr.cz