Resuscitation 81 (2010) 1087–1094

Contents lists available at ScienceDirect

Resuscitation

journal homepage: www.elsevier.com/locate/resuscitation

Clinical paper

Cardiopulmonary resuscitation artefact suppression using a Kalman filter and the frequency of chest compressions as the reference signal☆

Jesus Ruiz[a], Unai Irusta[a], Sofia Ruiz de Gauna[a,*], Trygve Eftestøl[b]

[a] Department of Electronics and Telecommunications, University of the Basque Country, Alameda de Urquijo s/n, 48013 Bilbao, Vizcaya, Spain
[b] Department of Electrical Engineering and Computer Science, University of Stavanger, 4036 Stavanger, Norway

ARTICLE INFO

Article history:
Received 5 October 2009
Received in revised form
24 December 2009
Accepted 22 February 2010

Keywords:
Cardiopulmonary resuscitation (CPR)
Automated external defibrillator (AED)
Sudden cardiac arrest (SCA)
CPR artefact suppression
Kalman filter

ABSTRACT

Aim: To develop a new method to suppress the artefact generated by chest compressions during cardiopulmonary resuscitation (CPR) using only the frequency of the compressions as additional information.
Materials and methods: The CPR artefact suppression method was developed and tested using a database of 381 ECG records (89 shockable and 292 non-shockable) from 299 patients. All records were extracted from real out-of-hospital cardiac arrest episodes. The suppression method consists of a Kalman filter that uses the frequency of the measured compressions to estimate the artefact and to remove it from the ECG. The performance of the filter was evaluated by comparing the sensitivity and specificity of an automated external defibrillator before and after the artefact suppression.
Results: For the test database, the sensitivity improved from 57.8% (95% confidence interval, 43.3–71.0%) to 93.3% (81.5–98.4%) and the specificity decreased from 92.5% (87.0–95.9%) to 89.1% (83.0–93.3%).
Conclusion: For a similar sensitivity, we obtained better specificity than that reported for other methods, although still short of the values recommended by the American Heart Association. The results suggest that the CPR artefact can be accurately modelled using only the frequency of the compressions. This information could be easily acquired through the defibrillator's CPR help pads, with minimal hardware modifications.

1. Introduction

The treatment for out-of-hospital sudden cardiac arrest (SCA) is immediate bystander cardiopulmonary resuscitation (CPR) and early electrical defibrillation if a malignant ventricular arrhythmia is observed.[1,2] However, chest compressions during CPR may cause rhythmic artefacts in the ECG, compromising the reliability of the shock/no-shock decision.[3] In current automated external defibrillator (AED) operation, CPR must therefore be discontinued during the rhythm analysis interval. Unfortunately, these hands-off intervals reduce the probability of restoration of spontaneous circulation (ROSC) after the delivery of the shock.[4–6] Some recently released defibrillators (ZOLL R series ALS and Plus) already incorporate CPR artefact filtering thus minimizing the hands-off interval in manual operation. However, the diagnosis based on the filtered ECG is not reliable enough for its use in automatic operation. The suppression of the CPR artefact would allow a reliable diagnosis by the AED during chest compressions, therefore, eliminating the hands-off intervals and increasing the probability of resuscitation success.

Strohmenger et al. first reported the spectral overlap between the CPR artefact and the dominant frequencies of human ventricular fibrillation (VF).[7] This overlap depends mainly on the rate and depth of the chest compressions, which may vary throughout the resuscitation intervention. Consequently, adaptive filters are more efficient than fixed coefficient filters in suppressing the CPR artefact.[7–9] The first adaptive filters were tested using artificial mixtures of human VF and CPR artefact samples collected from pigs in asystole.[8,10–12] The artefact was added to the ECG at several signal-to-noise ratios (SNRs) to assess the performance of the filter under different levels of corruption. The authors reported good theoretical results in terms of the improvement in SNR after the filtering process.

In 2004, Eilevstjønn et al. tested for the first time a CPR suppression method using real out-of-hospital SCA episodes, reporting results for the sensitivity (the ability to detect shockable rhythms) and the specificity (the ability to detect non-shockable rhythms).[13] Apart from the ECG registered from the defibrillation pads, Eilevstjønn et al. used up to four additional reference signals to estimate the CPR artefact. However, the acquisition of any reference signal implies profound hardware modifications for current AEDs. Therefore, efforts were focused on the simplification of the sup-

☆ A Spanish translated version of the abstract of this article appears as Appendix in the final online version at doi:10.1016/j.resuscitation.2010.02.031.

* Corresponding author. Tel.: +34 94 601 7341; fax: +34 94 601 4259.
E-mail address: sofia.ruizdegauna@ehu.es (S. Ruiz de Gauna).

0300-9572/$ – see front matter © 2010 Elsevier Ireland Ltd. All rights reserved.
doi:10.1016/j.resuscitation.2010.02.031

pression methods. Recently, two contributions presented adaptive filters based solely on the analysis of the surface ECG.[9,14] Sensitivity and specificity results were not as good, revealing the limitations of the method if the CPR artefact is directly estimated from the corrupted ECG. In 2009, Irusta et al. presented an intermediate solution, that only requires recording the instants when the chest compressions are given (e.g., through the CPR aid pads).[15] These instants were used to calculate the instantaneous frequency of the compressions, which served to accurately model the CPR artefact. A least mean square (LMS) filter estimated the artefact and then subtracted it from the corrupted ECG. The sensitivity and the specificity were comparable to those presented by Eilevstjønn et al., thus demonstrating the validity of the approach.

In the current paper, we describe a new CPR artefact suppression method based on the same hypothesis; that is, the CPR artefact can be accurately estimated and suppressed using the instants when the chest compressions are delivered. In this paper we propose a Kalman filter to estimate the CPR artefact using only this reference signal. The Kalman filter was adjusted and tested using the sensitivity and specificity of a commercial AED algorithm.

2. Materials and methods

2.1. Data collection

Irusta et al. fully describe the ECG database used in this study.[15] It consists of ECG records extracted from real out-of-hospital SCA interventions registered using the Laerdal's HeartStart 4000 AED, which was modified to acquire additional reference channels besides the surface ECG through an additional chest pad.[16,17] One of these reference signals was the compression depth which was used in our study to estimate the instantaneous frequency of the chest compressions.

The records were classified into five rhythm classes and labelled as shock or no-shock by expert reviewers: VF and pulseless fast ventricular tachycardia (VT, rate > 150 beats per minute) in the shockable category, and asystole (ASY), pulseless electrical activity (PEA), and pulse-generating rhythm (PR) in the non-shockable category.

The dataset is composed of 381 ECG records from 299 patients: 89 shockable (84 VF and 5 VT) and 292 non-shockable records (88 ASY, 166 PEA, and 38 PR). Each record in a class corresponded to a different patient. For training and testing purposes, we randomly generated two equal sized groups.

The records were 31 s long: in the first 15.5 s a CPR artefact corrupted the ECG, whereas in the last 15.5 s, CPR was stopped, so the ECG was free-of-artefacts (see Figs. 4 and 5). We could compare the AED diagnosis in the two intervals and evaluate the influence of the CPR artefact in the shock/no-shock decision because the underlying rhythm annotated by the reviewers was the same in both intervals.

The records were down-sampled from 500 to 250 Hz and stored with a resolution of 1.031 μV per least significant beat. They were pre-processed with an order-four Butterworth band pass filter (0.7–30 Hz).

2.2. Spectral analysis

The spectral analysis of the ECG records has been used as a preliminary tool for the design of efficient artefact filtering methods. We defined three types of data for the study: free-of-artefact shockable segments (last 15.5 s of the VF/VT records), free-of-artefact non-shockable segments (last 15.5 s of the PEA/PR records) and isolated CPR artefact segments (first 15.5 s of the ASY records). We estimated the power spectral density (PSD) of each segment using the Welch method with a Hanning window of 4.8 s.

First we analysed the mean compression rate using the isolated CPR artefact segments. The mean frequency was 121 cpm although the variability between records was very high with compression rates ranging from 73 to 170 cpm.

Fig. 1 plots the normalized average PSD of each type of data. The well-known overlap between the CPR artefact and the shockable records is clearly observable in Fig. 1a, and is reflected by the proximity of the dominant frequencies of the shockable segments to the average fundamental frequency of the CPR artefact. Furthermore, the overlap is higher with the PEA/PR segments, whose dominant frequencies are closer to the CPR artefact (Fig. 1b). As expected, the spectral analysis anticipates the challenge of artefact removal from corrupted non-shockable records.

2.3. CPR artefact suppression filter

The corrupted ECG acquired through the defibrillation pads can be considered as the sum of the underlying ECG and the CPR artefact:[8–15]

$$s_{in}[n] = \hat{s}_{ECG}[n] + \hat{s}_{CPR}[n]$$

We define a signal model of the artefact based on the instantaneous frequency of the compressions. The Kalman filter obtains an estimate of the artefact at each instant $\hat{s}_{CPR}[n]$, using the corrupted ECG $s_{in}[n]$ and the instantaneous frequency of the compressions. Thus,

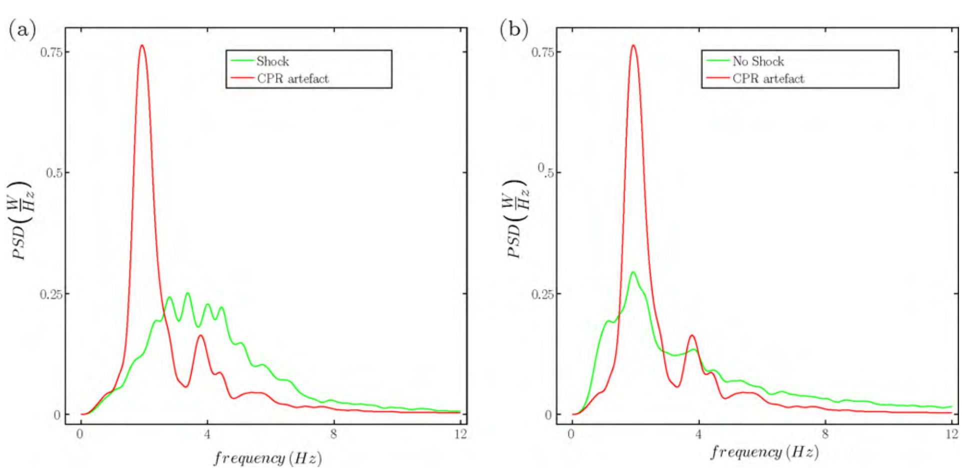

Fig. 1. Average power spectral density (PSD) of the signals under study: the power distributions of the shockable records (a) and the non-shockable records (b) overlap the isolated CPR artefact distribution. .