Resuscitation (2008) 76, 271—278

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

EXPERIMENTAL PAPER

A method to remove CPR artefacts from human ECG using only the recorded ECG☆

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Received 6 July 2007; received in revised form 1 August 2007; accepted 2 August 2007

KEYWORDS
Automated external defibrillator (AED);
Out-of-hospital CPR;
Cardiac arrest;
Arrhythmia;
CPR artefact suppression

Summary
Aim: To show the possibility of using cardiopulmonary resuscitation (CPR) artefact suppression methods that do not need additional reference signals to model CPR artefacts.
Materials and methods: A CPR suppression method based on a Kalman filter was designed. The artefact was modelled using the fundamental frequency of the compressions, estimated from the spectral analysis of the ECG. Artificial mixtures of human shockable rhythms and CPR artefacts were used to design the algorithm that was then tested on samples obtained from real out-of-hospital cardiac arrest episodes.
Results: The shock/no-shock decision of an automated external defibrillator (AED) was evaluated before and after CPR suppression for 131 shockable and 347 non-shockable samples. The sensitivity improved from 56% (95% CI, 47—64%) to 90% (95% CI, 84—94%). However, the specificity decreased from 91% (95% CI, 87—93%) to 80% (95% CI, 76—84%).
Conclusions: CPR artefacts can be suppressed using methods based on the analysis of the ECG alone. The hardware of current AEDs does not need to be replaced, although better artefact suppression methods exist for modified AEDs with additional reference channels.

Introduction

Ventricular fibrillation (VF) has been observed as the initial rhythm in about 40% of sudden cardiac arrest (SCA) patients.[1,2] Immediate bystander cardiopulmonary resuscitation (CPR) and early electrical defibrillation are the recommended treatment for VF cardiac arrest.[3,4] Each minute delay in defibrillation reduces the probability of survival to hospital discharge by 10—15%.[5,6] In fact, automated

☆ A Spanish translated version of the summary of this article appears as Appendix in the final online version at 10.1016/j.resuscitation.2007.08.002.

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0300-9572/$ — see front matter
doi:10.1016/j.resuscitation.2007.08.002

external defibrillators (AEDs) are currently placed in public locations for use by minimally trained lay persons, thereby shortening the delay to defibrillation.

Current AED algorithms require interruption of CPR for a reliable shock/no-shock decision, as chest compressions may cause rhythmic artefacts in the ECG.[7] However, these ''hands-off'' intervals adversely affect the probability of restoration of spontaneous circulation (ROSC).[8–10] In addition, pauses in chest compressions compromise circulation, and should be avoided in patients with a non-shockable rhythm.

The removal of CPR artefacts from the ECG would enable the analysis of the underlying rhythm without pauses in chest compressions. However, CPR artefacts are very variable, and show an important spectral overlap with human VF.[11,12] They have been removed successfully using adaptive filters, that usually require reference signals from extra equipment to characterize the chest compressions[13–15]. An adaptive method based solely on the surface ECG has also been proposed, but only sensitivity was evaluated using artificially corrupted VF samples.[16]

We describe a new CPR suppression method based on a four-state Kalman filter that only requires the surface ECG. The artefact was modelled using a dynamical estimate of its fundamental frequency, obtained from a spectral analysis of the surface ECG. The filter was developed and optimised using mixtures of ECG recordings and CPR artefacts for various corruption levels. The suppression method was tested using a separate data set of real out-of-hospital ECGs corrupted by CPR.

Materials and methods

Data collection

Training set

Artificially corrupted ECG samples were obtained by adding a clean VF or a clean ventricular tachycardia (VT) and a scaled CPR artefact. The scale coefficient determined the corruption level, i.e., the signal-to-noise ratio (SNR) measured in dB. For further details on the mixture model, see Aase et al.[13]

The training set was an extension of the database used in Aramendi et al.[16] It was completed using additional VF, VT and CPR artefact samples from new sources. The shockable rhythm database consisted of 440 samples (271 VF/169 VT), collected following AHA guidelines to test AED sensitivity.[17] The samples came from three sources: 183 VF/63 VT from the Reanibex 200 AED rhythm library, 47 VF/86 VT digital records from electrophysiology studies conducted at Donostia Hospital (San Sebastián, Spain), and 41 VF/20 VT from out-of-hospital emergency interventions (digitized paper strips). The original sampling rates (250, 360, 500, and 1000 Hz) and resolutions were different ($\leq$5 μV per least significant bit, LSB).

The CPR artefact database contained 41 samples obtained from out-of-hospital resuscitation attempts. CPR was performed on patients in asystole. The samples were collected in Spain (the Basque Country and Madrid) between 1999 and 2006, using the Medtronic LIFEPAK 500 and the Phillips HeartStart AEDs. The original paper recordings were

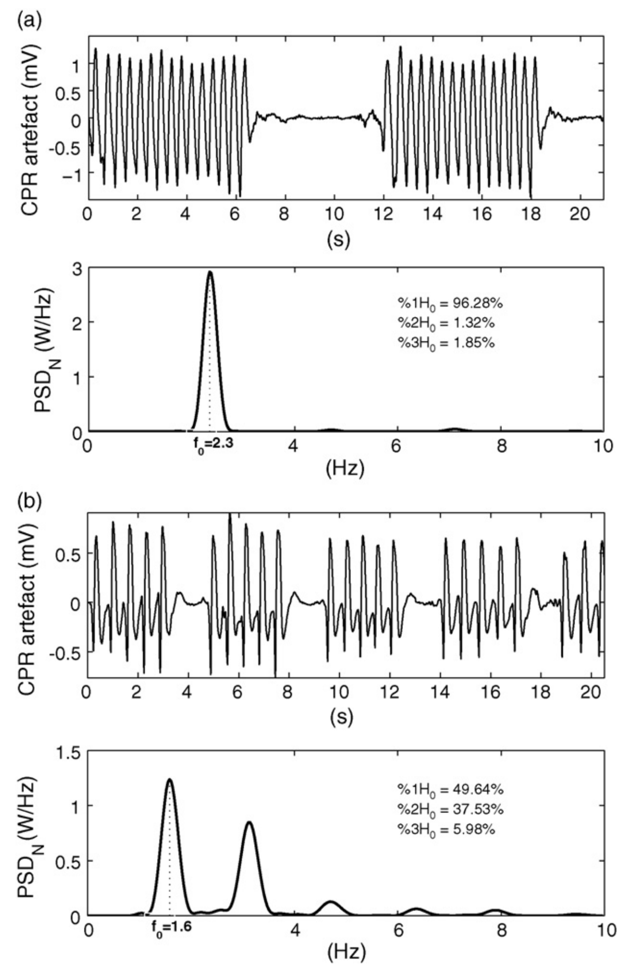

Figure 1 Time and frequency domain representations of two CPR artefact samples, where f_0 is the fundamental frequency. The harmonic content of the first three harmonics is given as percentage of the total power: (a) an example with a high fundamental frequency (2.3 Hz, 138 cpm) and very low harmonic components and (b) an example showing a lower compression rate (1.6 Hz, 96 cpm), but with an important second harmonic that overlaps the frequency components of the shockable rhythms.

digitized using a sampling rate of 500 Hz and a resolution of 5 μV/LSB.

The artefact samples were diverse. The frequency of the compressions varied from 82 to more than 150 compressions per minute (cpm). Furthermore, the waveform during the compression intervals varied between samples, as evidenced by the marked difference in the harmonic components (Figure 1). Table 1 summarises the average values for the entire artefact database.

All the samples of the training set were band pass filtered (0.7—30 Hz) to remove offset and high frequency noise, and were stored using a common sampling rate of 250 Hz.

Test set

The validation data was part of a prospective study aimed at measuring the quality of out-of-hospital CPR.[18] Resuscitation episodes were recorded in three European locations by