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A new method to detect ventricular fibrillation from CPR artifact-corrupted ECG based on the ECG alone

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ABSTRACT

During cardiopulmonary resuscitation, chest compressions (CCs) introduce mechanical activity in the ECG and thus preclude a reliable electrocardiographic (ECG) rhythm diagnosis. To achieve a reliable rhythm analysis, chest compression must therefore be interrupted, and therefore, the probability of the restoration of spontaneous circulation (ROSC) is adversely affected. In recent years, a number of algorithms have been developed to distinguish ventricular fibrillation (VF) rhythm from normal sinus rhythm (SR) without chest compression (CC) interruptions. However, the implementation of most of these algorithms relies on the acquisition of reference signals that are strongly correlated with CC artifacts and makes additional hardware alteration inevitable. In the present work, a novel method (the enhanced LMS method) that effectively suppresses CPR artifacts and can easily use the corrupted ECG signal alone is developed for the reliable detection of the VF rhythm during uninterrupted CCs. The enhanced LMS method was tested using mixtures of CC artifacts and real out-of-hospital ECG recordings for different corruption levels, and it was compared with other established algorithms that use the corrupted ECG signal alone, including the morphology consistency evaluation algorithm and the adaptive stop-band filtering algorithm. The validation results indicate that the enhanced LMS method has superior performance in VF/SR rhythm classification under different artifact interference levels. It is shown that the VF rhythm can be reliably detected using only the corrupted ECG alone. The novel method proposed in this study is promising for identification VF from SR with no hardware alterations for clinical cardiopulmonary resuscitation practice.

1. Introduction

It has been observed that ventricular fibrillation (VF) is the initial rhythm in almost half of the out-of-hospital patients who suffer from sudden cardiac arrest [1,2]. Bystander cardiopulmonary resuscitation (CPR) and early defibrillation are the strongly recommended treatments for the restoration of spontaneous circulation (ROSC) in VF cardiac arrest [3,4]. Currently, automated external defibrillators (AEDs) are widely applied for out-of-hospital VF detection and treatment without manual interpretation of the electrocardiograph (ECG) [5,6]. However, because of the rhythm artifacts that are introduced by the mechanical activity in the ECG, the current AEDs can not offer a reliable diagnosis during chest compressions (CCs) [7]. To achieve reliable rhythm analyses, both chest compression and ventilation must therefore be discontinued for 15 s or more [8,9]. As a consequence, the probability of ROSC is adversely affected due to myocardial blood flow drop during these hands-off intervals [10,11]. Recent studies indicate that each 20-s hands-off interval reduces the likelihood of survival by as much as 50% [12]. If a hands-off interval is avoided, then the success rate of a subsequent defibrillation would be improved significantly [13]. Thus, VF detection during the CCs, which would enable the AED to make an accurate and reliable diagnosis without interrupting the CCs, would increase the likelihood of resuscitation success.

Much research has been conducted to distinguish VF from normal sinus rhythm (SR) without CC interruption. In most of the studies, adaptive filters, which utilize additional reference signals that are strongly correlated to the artifacts, were evolved to suppress the CPR artifact [14–17]. Among the many adaptive filters, the modified multichannel adaptive filter (MC-RAMP) described by

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Eilevstjønn et al. has proven to be successful for practical applications to human victims [17]. Alongside the surface ECG, the MC-RAMP uses up to four reference signals, including the thoracic impedance, ECG common mode, compression acceleration and compression depth. Unfortunately, even this more sophisticated method failed to account for each detailed artifact component in the reference channels, which resulted in relatively unsatisfactory performance of the non-shockable rhythm identification. To resolve this problem, a least mean-square (LMS) filter, which records only the CC frequency rather than the entire reference signal, was presented by Irusta et al. [18]. The results show that the simple CPR artifact mode estimated by this LMS filter is resistant to detailed artifact component losses and is valid to filter artifacts in a satisfactory way, especially for shockable rhythms. However, because most of the current AEDs record only the surface ECG signal for the shock/non-shock decision, the additional AED hardware alteration is inevitable for the acquisition of any reference signal, regardless of whether it uses the entire signal in Eilevstjønn's method or only the CCs frequency in Irusta's method. In recent years, new methods that use only the recorded ECG have been proposed. A filter that adapts its characteristics to the ECG spectral content and a four-state Kalman filter that estimates the CPR artifact from the corrupted ECG were described by Gauna et al. and by Aramendi et al., respectively [19,20]. The results of these two methods were not as satisfactory as those using the additional reference signals because the characteristic of the CC artifact is not extracted accurately from the corrupted ECG signal. Recently, a novel algorithm, continuous-wavelet-transformation-based morphology consistency evaluation, was developed by Li et al. for VF detection during CCs [21]. The performance of this morphology consistency evaluation method, which was evaluated using corrupted signals recorded from out-of-hospital cardiac arrest patients, is promising for the reliable detection of the VF during CCs. However, because of the requirement of high-speed calculations, the complicated morphology consistency evaluation method is not clinically useful for real-time rhythm detection. Amman et al. used the coherent line removal algorithm for removal of periodic CC artifact. Unfortunately, the SR/VF rhythms identification performance of this algorithm was not presented while only SNR-improvement was offered [22].

The primary goal of the present study is to develop a new method that uses only the surface ECG signal to reconstruct the original ECG free of artifacts for reliable VF detection during CCs. Compared with other methods, our method aims to search for the CC frequency within the corrupted ECG, which allows us to dynamically estimate the parameters of the CPR artifact model with an LMS filter. The present method was tested using mixtures of CC artifacts and real out-of-hospital ECG recordings for different corruption levels.

2. Methods

The flowchart of the proposed algorithms in the present work is shown in Fig. 1. To acquire accurate VF detection, the CC artifacts should be removed from the corrupted ECG first. Because of the periodic nature of the CCs, the CC frequency that can be extracted from the adaptively filtered ECG is pivotal for the reconstruction of the CC artifact model. Using the CC frequency, the CPR artifact can be effectively modeled with the LMS filtering method. The original VF/SR waveform, which is free of artifacts, can then be reconstructed by subtracting the CC artifact from the corrupted ECG signal. In this way, the VF/SR rhythm during the CCs can be reliably identified using a phase space reconstruction (PSR) algorithm directly from the filtered ECG without other reference signals. The details of the algorithm are introduced in the following sections.

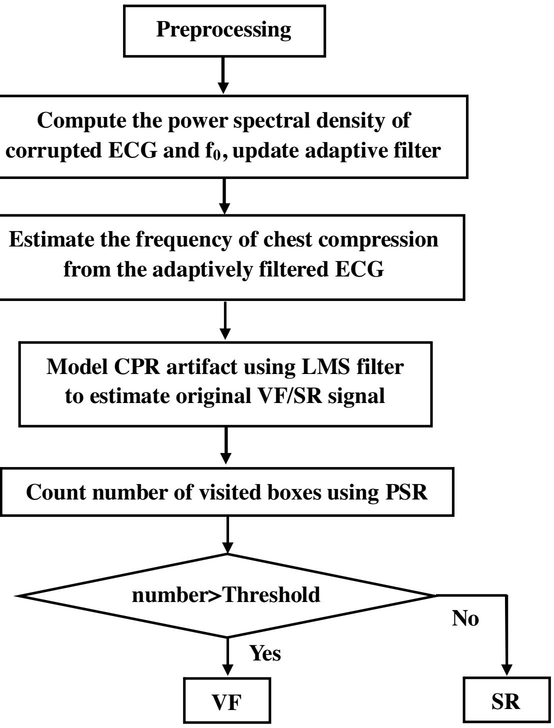

Fig. 1. Flowchart of the algorithm proposed in this study for the VF detection during CCs. f_0: the center frequency of the band-pass filter. LMS: least mean square. PSR: phase space reconstruction method. VF: ventricular fibrillation. SR: sinus rhythm.

2.1. Estimation of the frequency of chest compressions from a corrupted ECG

Some research has indicated that the spectral components of the CC artifact are distributed in the lower frequency band while the original VF/SR signals are spread in the higher frequencies [19]. Based on this arrangement, the main frequency component of the corrupted ECG in the lower frequency band is similar to the fundamental frequency of the CC artifact. In the present work, an adaptive band-pass filter (4-tap, Butterworth approximation, zero-phase, bandwidth 2.2 Hz and the center frequency of the main frequency of the corrupted ECG in the 1–3 Hz frequency range) filtering out the pure ECG signals was designed to extract the CC-related fluctuations from the corrupted ECG signals. The time interval of each CC can be easily estimated as the cycle length between the adjacent maximum depressions on the CC-related fluctuations (see the "+" symbol in the CC-related fluctuation in Fig. 2). The CC frequency was then determined by the inverse of the CC cycle length. To optimize the performance of the adaptive band-pass filter, its center frequency updates in each ECG episode according to the spectral characteristics of the corrupted ECG.

2.2. Estimation of the original VF/SR waveform

The CC artifact model can be constructed using its Kharmonics of the sinusoids with the time-varying amplitude ($C_k(n)$), phase ($\theta_k(n)$) and time-varying frequency of the i-th CC ($f_0(i)$), as described by Eqs. (1) and (2).

$$S_{CC} = \sum_{k=1}^{N} C_k(n)\cos\left(\frac{2\pi k f_0(i) n}{f_s} + \theta_k(n)\right) \quad (1)$$

$$= \sum_{k=1}^{N} a_k(n)\cos\left(\frac{2\pi k f_0(i) n}{f_s}\right) + b_k(n)\sin\left(\frac{2\pi k f_0(i) n}{f_s}\right) \quad (2)$$