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Analyzing cardiac rhythm in the presence of chest compression artifact for automated shock advisory

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Abstract Defibrillation is often required to terminate a ventricular fibrillation or fast ventricular tachycardia rhythm and resume a perfusing rhythm in sudden cardiac arrest patients. Automated external defibrillators rely on automatic ECG analysis algorithms to detect the presence of shockable rhythms before advising the rescuer to deliver a shock. For a reliable rhythm analysis, chest compression must be interrupted to prevent corruption of the ECG waveform due to the artifact induced by the mechanical activity of compressions. However, these hands-off intervals adversely affect the success of treatment. To minimize the hands-off intervals and increase the chance of successful resuscitation, we developed a method which asks for interrupting the compressions only if the underlying ECG rhythm cannot be accurately determined during chest compressions. Using this method only a small percentage of cases need compressions interruption, hence a significant reduction in hands-off time is achieved. Our algorithm comprises a novel filtering technique for the ECG and thoracic impedance waveforms, and an innovative method to combine analysis from both filtered and unfiltered data. Requiring compression interruption for only 14% of cases, our algorithm achieved a sensitivity of 92% and specificity of 99%.

Keywords: ECG; Cardiac rhythm; Resuscitation; Shock advisory; Defibrillation; AED; Chest compression; CPR; Hands-off interval; Artifact removal

Introduction

Cardiopulmonary resuscitation (CPR) is the standard medical treatment for sudden cardiac arrest (SCA), which consists of chest compressions and ventilations that provide circulation in the patient. In about 40% of SCA patients, the initial cardiac rhythm observed is ventricular fibrillation (VF). Defibrillation is interposed between sessions of CPR in order to treat underlying VF. It is known that the probability of successful defibrillation diminishes as the interval between the end of CPR compressions and the delivery of a defibrillating shock increases. Conversely, shortening the interval between the last compression and the shock by even a few seconds can improve shock success [1].

Furthermore, defibrillation does not terminate the underlying causes of VF even if it temporarily corrects the VF. Thus, the underlying causes may induce a recurrence of VF following defibrillation. This phenomenon is known as refibrillation. The present recommendation is to immediately resume chest compressions after the shock delivery for 2 minutes before analyzing the cardiac rhythm again [2]. Some resuscitation thought leaders, however, believe that it may be more beneficial to deliberately interrupt CPR early to deliver a shock aimed at correcting refibrillation.

There are several classes of defibrillators, including manual defibrillators, implantable defibrillators, and automated external defibrillators (AEDs). AEDs differ from manual defibrillators in that AEDs can automatically analyze the ECG rhythm to determine if defibrillation is necessary. In commercially available AEDs, the ECG analysis must be conducted during a non-CPR hands-off period because the electrical artifact induced by CPR-related motion makes the analysis algorithm unreliable. The mechanical activity from the chest compressions introduces artifacts in the ECG that adversely impacts the accuracy of most AEDs' automated shock advisory algorithms to reliably analyze the ECG rhythm [3]. If the AED erroneously makes a false "shock" determination because of the artifact, it may enable the delivery of a shock potentially fatal to the patient. Thus, an adverse seconds-long interval between the end of CPR and

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the delivery of the shock impulse is necessary to provide for a clean analysis. For the same reasons, existing AED shock analysis algorithms are unable to detect and allow treatment for early refibrillation that occur during CPR.

A number of methods have been developed in an attempt to determine an accurate ECG measurement during CPR compressions. A recent publication by Gauna et al. [4] contains a good review of different approaches to rhythm analysis during CPR, both traditional (e.g., filtering CPR artifact) and recent strategies (e.g., rhythm analysis during compression pauses). In general, the traditional methods fall in two categories: either filter out the CPR artifact from ECG, or develop an ECG analysis technique insensitive to CPR artifact. The majority of filtering methods are adaptive techniques which need one or more reference signal other than ECG to characterize the CPR artifact. Many AEDs record thoracic impedance using the same ECG chest pads. However, if the filtering technique needs other reference signals such as chest compression force and acceleration, hardware alterations may be needed.

In this work, first we propose a novel filtering technique which uses the ECG signal itself and the simultaneously-recorded impedance waveform as the only reference signal to filter CPR artifacts. Then we show that such filtering, although significantly improving the performance of automated external defibrillator algorithms, cannot achieve accuracy high enough for practical use. To overcome this limitation, we then propose an innovative way to combine analysis from both filtered and unfiltered data to improve the accuracy of the algorithm.

Materials and methods

Database

In this study we used an off-line modified version of the shock advisory (SA) algorithm available in Philips HeartStart AEDs. This algorithm was trained on a database including only CPR-artifact-free recordings outside of chest compression intervals. Since the SA algorithm was already trained, we only needed to create an independent evaluation database. To do so we used a series of recordings which were collected between March 2002 and September 2004 for a prospective study of CPR quality. That database included ECG, thoracic impedance, and compression depth waveforms from 175 out-of-hospital and in-hospital cardiac arrest patients by several emergency medical centers around Europe and the US, comprising Akershus (Norway), Stockholm, London, Vienna, and the University of Chicago [5].

To study the impact of CPR artifact on the performance of shock advice analysis, we selected continuous 8.5-second segments with CPR followed by 2 seconds transition and then 8.5 seconds without CPR, padded with 2 seconds buffer in the beginning for filter initialization. Each 8.5-second segment consisted of two 4.5-second segments overlapped for 0.5 second. The main reason for 4.5 seconds being the length of each segment was that SA algorithm was designed to analyze ECG segments of such length.

Assuming no rhythm change within a few seconds around the transition time, experts selected 1378 4.5-second ECG segments with and 1378 segments without CPR artifact. Each category included 340 shockable ventricular fibrillation, and 1038 non-shockable segments (342 asystole, 646 pulseless electrical activity, and 50 pulsatile rhythms). Since there is no clinical consensus on which ventricular tachycardia (VT) rhythms should be shocked, we did not include VT in the database.

Filtering CPR artifact

Fig. 1 shows a recording of a VF strip with CPR-induced artifact followed by a strip without artifact. The chest compressions stop at 11.5 seconds. As seen in the first half of the waveforms, CPR artifacts significantly alter the morphology of both ECG and impedance recordings. For most recordings we expect the CPR artifact to show the same general frequency characteristics on both ECG and impedance signals recorded simultaneously through the same chest pads. If we look at short segments of data, say 4.5 seconds, we can assume that the chest compression rate stays constant in such short period. Therefore, we can filter out a significant portion of CPR artifact by using a comb filter tuned to the compression rate. Fig. 2 illustrates this process, which also includes a primary analysis of the impedance channel to prevent unnecessary filtering of the waveforms when there are no compressions. After the ECG data is filtered, we run the same SA designed for artifact-free data on the filtered data.

Fig. 3 shows an example of this filter on 4.5 seconds of the same data shown on Fig. 1. As seen, the filter significantly reduces the amount of CPR artifact on both ECG and impedance waveforms, but it does not completely remove the artifact.

Combining filtered and unfiltered data

Although filtering CPR artifact tremendously helps the analysis, further steps are needed in order to improve the performance of automated external defibrillator during CPR. The main reason is that the components of the compression rate are likely not the only artifact introduced to the ECG signal due to CPR. There are indications that

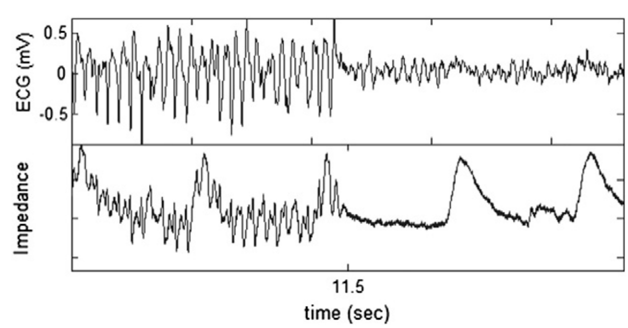

Fig. 1. Example of VF recording with and without CPR artifact. The chest compressions stop at second 11.5. As seen, CPR artifacts significantly alter the morphology of both ECG and impedance recordings. The artifact quickly disappears after stopping the compressions.