An Alternative to Derive the Instantaneous Frequency of the Chest Compressions to Suppress the CPR Artifact

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Abstract

The activity due to chest compressions during cardiopulmonary resuscitation (CPR) corrupts the ECG, and adversely affects the diagnosis of Automated External Defibrillators (AED). Filtering methods based on reference signals have been proposed to suppress the CPR artifact, however the acquisition of additional reference signals involves hardware modifications in current AEDs. In this study the transthoracic impedance (TTI) was used as a reference signal. Current AEDs acquire TTI via de defibrillation pads. The improvement in sensitivity and specificity was similar to that obtained using the compression depth estimated via additional accelerometers. The results suggest that TTI can be used as a reference signal to suppress the CPR artifact, which would only involve software modifications in current AEDs.

1. Introduction

Resuscitation outcome following cardiac arrest is strongly dependent on minimizing interruptions in chest compressions during cardiopulmonary resuscitation (CPR). Unfortunately, chest compressions must be interrupted for a reliable rhythm analysis by current automated external defibrillators (AEDs), because the artifacts caused by CPR corrupt the ECG signal. Filtering the CPR artifact would allow a reliable diagnosis during CPR, thus reducing the "hands-off" interval and increasing resuscitation success.

Adaptive filters have been proposed to suppress the CPR artifact, either by analyzing the ECG alone or using additional reference signal(s). The latter provide better results than those based exclusively on the surface ECG. Different signals correlated with the CPR artifact have been proposed [1–3], however incorporating them in the filtering scheme requires important hardware modifications in current AEDs. The instantaneous frequency of the compressions, derived from the chest compression depth (CD) signal, has been proposed to model the CPR artifact [2]. CD is calculated using accelerometers or force-sensor devices located in the compression pads.

The transthoracic impedance (TTI) signal is acquired by AEDs sending an alternating current between the defibrillation pads and measuring the generated voltage through the patient's chest. TTI has been used in cardiac research to measure respiration, cardiac output and ventilation during CPR; recently, it has been shown that chest compressions can be identified using TTI [4] because they cause motion artifacts visible in the impedance signal. In this work TTI acquired through the defibrillation pads was used to derive the instantaneous frequency of the chest compressions required by the adaptive filter described in [2] to suppress the CPR artifact. TTI is currently available in commercial AEDs, and incorporating the suppression system would only require software modifications.

2. Methods

2.1. Description of the database

The dataset used in this study is a subset of a large database acquired in a prospective study of out-of-hospital cardiac arrest patients[5]. The episodes were recorded in three geographical locations between March 2002 and September 2004 in a study coordinated from the Ulleval University Hospital in Oslo. The surface ECG and several additional reference channels were acquired using a modified version of Laerdal's Heartstart 4000 defibrillator. The sampling rate was 500 Hz with a resolution of 1.031 µV per least significant bit. The episodes were annotated by ex-

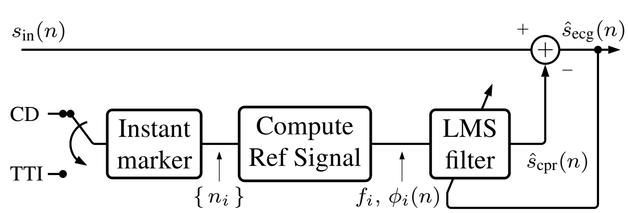

Figure 1. Block diagram of the CPR suppression filter based on the instantaneous frequency of the chest compressions, derived from CD or TTI.

ISSN 0276–6574

Computing in Cardiology 2010;37:545–548.

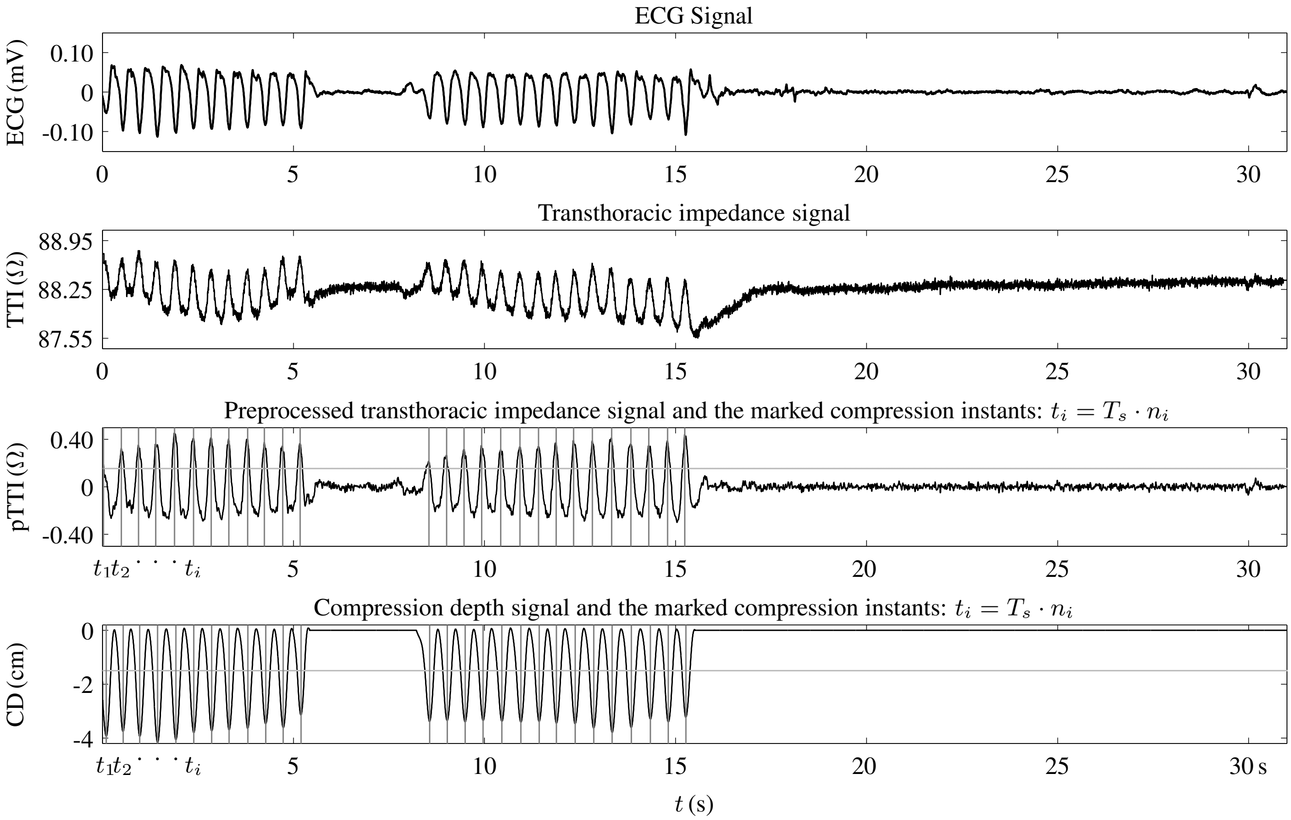

Figure 2. Estimation of the chest compression instants $\{t_i\}$ from the CD and the TTI signal for an asystole (no underlying heart rhythm) corrupted by CPR. In the initial 15.5 s interval CPR was performed and the activity due to the chest compressions is visible in the ECG, the CD and the TTI signals; in the final 15.5 s CPR was stopped. The chest compressions can be automatically detected identifying the positive peaks of the preprocessed TTI signal (pTTI) and the negative peaks of the CD signal.

pert reviewers into five rhythm types: ventricular fibrillation (VF) and ventricular tachycardia in the shockable category and asystole, pulseless electrical activity and pulse generating rhythms in the non-shockable category.

The extracted dataset contains 380 records from 299 patients, 88 are shockable and 292 non-shockable. Each record includes the ECG, the CD signal (computed from the acceleration signals as described in [6]) and the TTI signal. All the signals were downsampled to 250 Hz and the ECG was bandpass filtered (0.7–30 Hz). The records have a duration of 31 s divided in two consecutive 15.5 s intervals: an initial interval corrupted by CPR followed by a free of artifact interval (see Fig. 2). The goodness of the CPR suppression filter can be evaluated by comparing the diagnosis of an AED before and after artifact filtering in both intervals.

2.2. CPR artifact suppression filter

Fig. 1 shows the block diagram of the filtering scheme which is described in detail in [2]. For an additive CPR artifact the clean ECG, $\hat{s}_{\text{ecg}}(n)$, can be computed by subtracting the estimate of the artifact, $\hat{s}_{\text{cpr}}(n)$, from the corrupted ECG, $s_{\text{in}}(n)$:

$$\hat{s}_{\text{ecg}}(n) = s_{\text{in}}(n) - \hat{s}_{\text{cpr}}(n). \quad (1)$$

The artifact is modeled as an almost periodic interference using harmonics of slowly changing amplitude and phase. The amplitude and phase of each harmonic in $\hat{s}_{\text{cpr}}(n)$ was estimated by an adaptive filter based on the LMS algorithm, which tracks the evolution of the spectral composition of the artifact as described in [2]. In the absence of chest compressions the estimated artifact was made zero, following a transition period.

The fundamental frequency of the model of the artifact is the frequency of the chest compressions, which is assumed to be constant during each compression cycle but variable from cycle to cycle. This frequency can be estimated using either the CD or the TTI signal to mark the instants when the chest compressions were given:

$$\{t_i\} = T_s \cdot \{n_i\}, \quad (2)$$

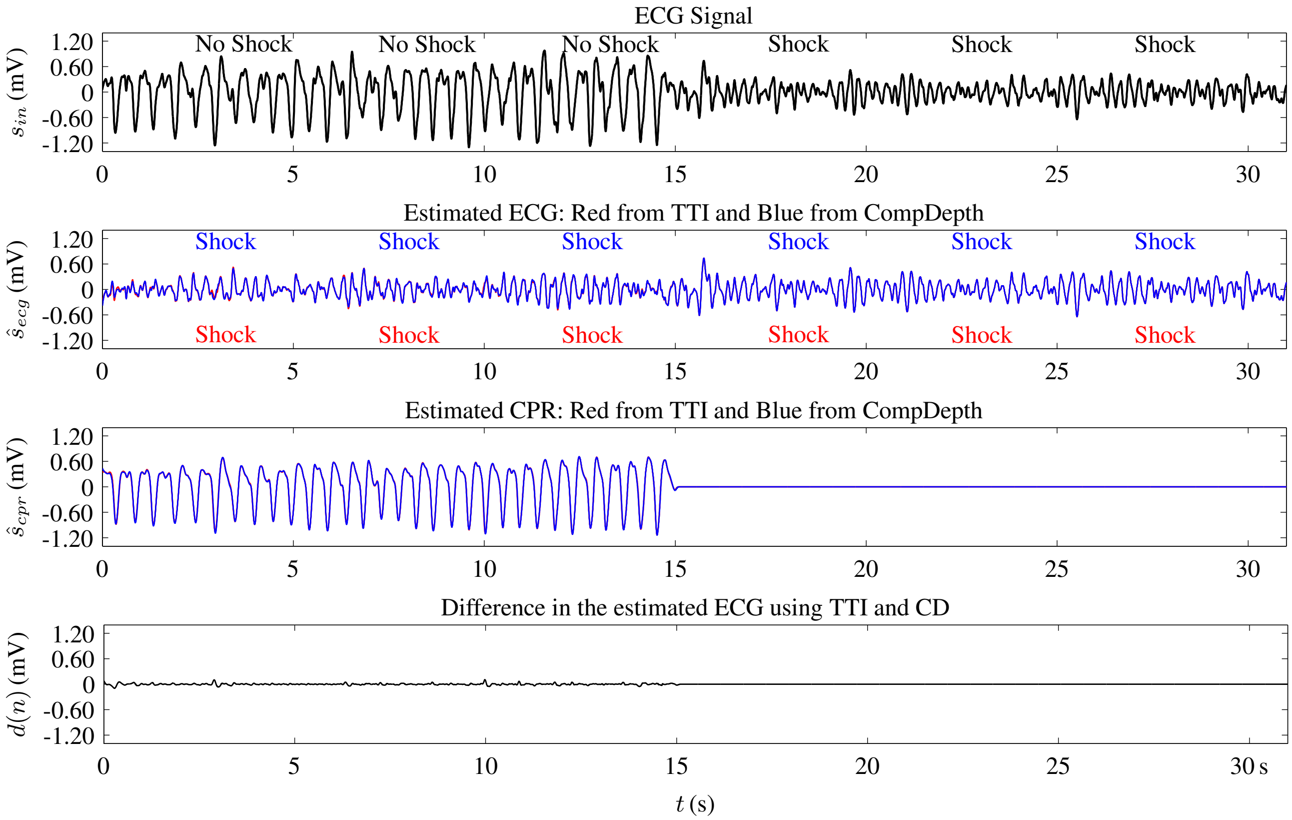

Figure 3. Filtering example for a VF corrupted by a CPR artifact using the $\{t_i\}$ obtained from the CD and the TTI signals. Before filtering, the CPR artifact produces an incorrect no shock diagnosis. After filtering the AED correctly diagnoses the underlying VF as shockable. The estimated ECG is similar using the $\{t_i\}$ estimated either using the CD or the TTI signal. The last panel shows the difference between the estimated ECGs using the TTI and the CD signals: $d(n) = [\hat{s}_{\text{ecg}}(n)]_{\text{TTI}} - [\hat{s}_{\text{ecg}}(n)]_{\text{CD}}$.

where T_s is the sampling period. These instants are then used to compute the instantaneous frequency and phase of the fundamental component of the reference signal needed to compute $\hat{s}_{\text{cpr}}(n)$:

$$f_i = \frac{1}{T_s(n_{i+1} - n_i)} \qquad n_i \leq n < n_{i+1}, \tag{3}$$

$$\phi_i(n) = 2\pi \frac{n - n_i}{n_{i+1} - n_i} \qquad n_i \leq n < n_{i+1}. \tag{4}$$

2.3. Automatic detection of the instants of chest compressions

Fig. 2 shows a CPR artifact for an underlying asystole (no rhythm), the variations in the ECG are consequently due to the chest compressions. The corresponding CD and TTI signals reflect the changes caused by the chest compressions. This section describes the procedure to automatically mark the $\{t_i\}$ compression instants in the CD and TTI signals.

The negative peaks of the CD signal occur when the chest is fully compressed, these events can therefore be used to mark the instants when the chest compressions are given. A negative peak detector for peaks under a threshold of -1.5 cm was used to detect the $\{t_i\}$ instants in the CD signal, Fig. 2 shows an example.

During CPR there are variations in the TTI signal due to ventilations (low frequency) and chest compressions. The TTI signal was first preprocessed (1–30 Hz) to eliminate fluctuations caused by ventilations and enhance the compression complexes. Then the $\{t_i\}$ instants were determined using a positive peak detector for peaks above a threshold adapted to each record, Fig. 2 shows an example.

The sequences of instants $\{t_i\}$ extracted from both the TTI and the CD signals were used to compute the instantaneous frequency, f_i, and phase, $\phi_i(n)$, needed to estimate $\hat{s}_{\text{cpr}}(n)$ in the filtering scheme shown in Fig. 1. The performance of the CPR suppression filter for the two sets of $\{t_i\}$ was then compared.

2.4. Evaluation

The results obtained using the TTI and the CD signals were evaluated, before and after filtering, in terms of the sensitivity and specificity of an AED algorithm. The offline version of the shock advice algorithm found in the Reanibex 200, by Osatu S.Coop. (Ermua, Spain), was used. This algorithm analyses three 4.8 s non-overlapping windows and recommends shock when two or more windows are classified as shockable.

3. Results

Fig. 3 shows an example of a corrupted ECG filtered both using the $\{t_i\}$ instants derived from the TTI signal and the CD signal. In the final 15.5 s interval there is no artifact and the VF rhythm was correctly identified as shockable by the AED algorithm. In the initial 15.5 s interval the CPR artifact produces a wrong non-shockable AED diagnosis before filtering. However, the rhythm was correctly classified as shockable after filtering when the $\{t_i\}$ were detected using either the TTI or the CD signal.

The sensitivities and specificities before and after filtering for the two 15.5 s intervals were computed for the 380 records of the dataset. For the interval corrupted by CPR, the initial 15.5 s, the sensitivity and the specificity before filtering were 55.68% and 92.12% respectively. After filtering, the sensitivity and the specificity were 92.05% and 89.38% when the $\{t_i\}$ were obtained from the CD signal; and 95.45% and 86.30% from the TTI signal.

For the interval without CPR, the final 15.5 s interval, the sensitivity and the specificity before filtering were 93.18% and 98.29% respectively. After filtering, the sensitivity and the specificity were 94.32% and 98.63% when the $\{t_i\}$ were obtained from the CD signal; and 93.18% and 98.63% from the TTI signal.

4. Discussion and conclusions

CD has been previously used as a reference signal to estimate the chest compression instants in filtering schemes that suppress the CPR artifact. However, the acquisition of the CD signal requires incorporating additional hardware in current AEDs, such as accelerators or force sensors. This study compares the performance of a CPR suppression filter when the chest compression instants are estimated using the TTI and the CD signals. There is a similar improvement in sensitivity and specificity using either signal, the TTI signal can therefore be used instead of the CD signal to suppress the CPR artifact. A filtering method based on the TTI signal could easily be integrated with small software changes into current AEDs because many commercial AED acquire the TTI signal through the defibrillation pads.

Acknowledgements

This work received financial support from the Spanish Ministry of Science and Innovation through the project TEC2009-10460.

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