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Clinical paper

Circulation detection using the electrocardiogram and the thoracic impedance acquired by defibrillation pads☆

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ABSTRACT

Aim: To develop and evaluate a method to detect circulation in the presence of organized rhythms (ORs) during resuscitation using signals acquired by defibrillation pads.
Methods: Segments containing electrocardiogram (ECG) and thoracic impedance (TI) signals free of artifacts were used. The ECG corresponded to ORs classified as pulseless electrical activity (PEA) or pulse-generating rhythm (PR). A first dataset containing 1091 segments was split into training and test sets to develop and validate the circulation detector. The method processed ECG and TI to obtain the impedance circulation component (ICC). Morphological features were extracted from ECG and ICC, and combined into a classifier to discriminate between PEA and PR. The performance of the method was evaluated in terms of sensitivity (PR) and specificity (PEA). A second dataset (86 segments from different patients) was used to assess two application of the method: confirmation of arrest by recognizing absence of circulation during ORs and detection of return of spontaneous circulation (ROSC) during resuscitation. In both cases, time to confirmation of arrest/ROSC was determined.
Results: The method showed a sensitivity/specificity of 92.1%/90.3% and 92.2%/91.9% for training and test sets respectively. The method confirmed cardiac arrest with a specificity of 93.3% with a median delay of 0 s after the first OR annotation. ROSC was detected with a sensitivity of 94.4% with a median delay of 57 s from ROSC onset.
Conclusion: The method showed good performance, and can be reliably used to distinguish perfusing from non-perfusing ORs.

Introduction

During resuscitation, recognition of cardiac arrest and detection of return of spontaneous circulation (ROSC) are challenging for both lay rescuers and healthcare personnel.[1,2] The carotid pulse check was the protocol accepted to detect absence or presence of circulation until 1998.[3] It was later proven both time-consuming and inaccurate,[4–8] and is currently only recommended for experienced healthcare providers.[9,10] Current resuscitation guidelines recommend checking for signs of life during cardiopulmonary resuscitation (CPR), such as purposeful movement, breathing or coughing.[11,12] They also recommend using the capnogram, generally available only with intubation, as a decision support tool for ROSC detection. An abrupt increase in CO_2 level to normal values (35–40 mmHg) has been accepted as an indicator of ROSC.[10,13–16] However, there is still a need for a real-time hemodynamic monitor in a resuscitation scenario.[17]

In the context of automated external defibrillators (AEDs), the capnogram is rarely available and the only signals recorded are often the electrocardiogram (ECG) and the thoracic impedance (TI) acquired by defibrillation pads. Both have proven valuable to detect pulse once a possible perfusing rhythm, an organized rhythm (OR), is present.[18–22] The TI signal shows a very small fluctuation (usually less than 100 mΩ) with every effective heartbeat. Studies by Losert et al.[18] and Risdal et al.[19] concluded that a combination of features extracted from ECG and TI allows a proper discrimination between pulse-generating rhythms (PR) and pulseless electrical activity (PEA). Cromie et al. used a single feature computed from the spectrum of the processed TI as a clinical marker of

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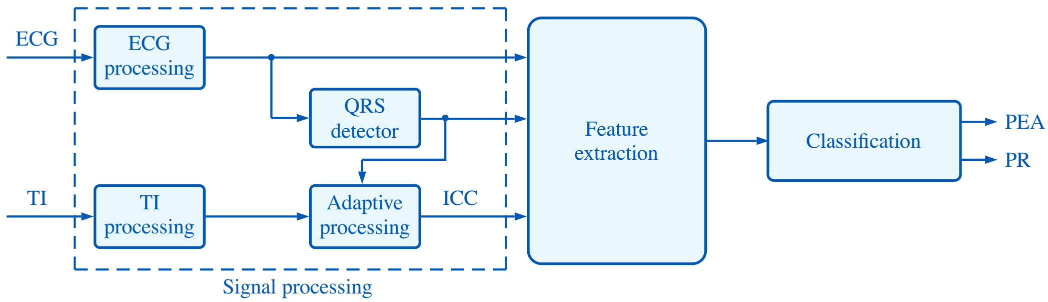

Fig. 1. Overview of the circulation detector consisting of three different stages. First, the signal processing stage where the ECG signal and the TI signal are digitally processed to detect the instants of the QRS complexes, and to extract the ICC signal. Second, the feature extraction stage where features characterizing the waveform of the ECG, ICC, and its first derivative are extracted. Finally, the classifier distinguishes between PEA and PR based on the extracted features.

circulatory collapse in animals[20] and humans.[21] In our previous work, we presented a reliable method to extract the impedance circulation component (ICC) using an adaptive processing scheme, and concluded that morphological features extracted from ICC showed great potential for PEA/PR discrimination.[22]

Here we propose a method to detect circulation based on the ECG and TI. The method is intended to be launched only when a possible perfusing rhythm has been detected, i.e when an OR is detected either by the shock advisory algorithm (SAA) of an AED, or by the healthcare professional using a monitor/defibrillator. For the rest of cardiac arrest rhythms, the procedure established by the resuscitation guidelines would be followed and the method would not be run. The method could be integrated into (1) AEDs to work together with the SAA and (2) monitor/defibrillators as a decision support tool which the healthcare professional could activate (e.g. by pressing a softkey). The circulation detector was designed to discriminate PR from PEA segments using a training set and validated with a test set. Finally, a case study was carried out using different complete episodes to assess two applications of the method: confirmation of cardiac arrest by recognizing absence of circulation during ORs and detection of circulation during resuscitation.

Materials and methods

Data materials

The dataset used in this study was a subset of a large out-of-hospital cardiac arrest (OHCA) registry containing 385 episodes maintained by the Tualatin Valley Fire & Rescue (Tigard, Oregon, USA). The episodes, one per patient, were collected using the Philips HeartStart MRx monitor/defibrillator between January 2010 and December 2014. First, the episodes were visually inspected to identify the segments of interest: the ECG signal to identify ORs with a duration of at least 5 s, and the TI signal to confirm that no artifacts due to chest compressions or ventilations were present. Second, those OR segments were classified as PEA or PR by three expert reviewers (a biomedical engineer, EAl; an emergency medicine physician, MD; and a cardiologist, LGT) using a majority criterion in the basis of available clinical information and the capnography signal. The clinical information derived from the prehospital record consisted of (1) the time of the first detected ROSC in field defined as a palpable pulse in any vessel for any length of time, (2) information about ROSC loss prior to arrival at emergency department, and (3) outcome (death in the field, expired in emergency department, expired post admission or discharged alive). The ROSC onset time was used to define the start of intervals with circulation which was confirmed by a sudden increase in $EtCO_2$ levels to values above 35 mmHg. The information about ROSC loss was used to define the stop of intervals with circulation. If ROSC was not lost, the stop time was defined as the end of the episode. However, if ROSC was lost the stop time was determined by either a sudden decrease in $EtCO_2$ from values above 35 mmHg to values below 20 mmHg, or resume of CPR. The patient outcome was used to confirm the ROSC/noROSC annotations at the end of the episodes.

Each segment contained the ECG (resolution 1.03 μV per least significant bit with bandwidth 0–50 Hz) and the TI (resolution 0.74 mΩ per least significant bit with bandwidth 0–80 Hz) signals. The TI was acquired by applying a sinusoidal excitation current (32 kHz, 3 mA peak to peak) between the defibrillation pads.

A first dataset was composed of 1091 segments extracted from 158 episodes recorded until May 2014. The dataset was randomly split into training (60%) and test (40%) sets to develop and validate the circulation detector. The PR and PEA segments extracted from the same episode were all assigned to either training or test sets.

A second dataset, the case study dataset, was used to test the clinical applicability of the circulation detector. For this purpose 33 complete episodes gathered between June and December 2014 were used. In 15 episodes the patient never recovered ROSC and finally expired. The first three artefact-free OR segments from these episodes were used to assess the capacity of the circulation detector to confirm cardiac arrest by recognizing absence of circulation. In 18 episodes patients recovered ROSC and a clinical annotation of ROSC time was available. After ROSC, the first three segments from these episodes were used to evaluate the ability of the method to detect ROSC during resuscitation.

Circulation detector

Fig. 1 shows the overview of the detector. The ECG signal was processed to remove noise and detect the instants of QRS complexes. The TI signal was processed first, to remove noise and then, using an adaptive scheme based on a recursive least square (RLS) algorithm[23,24] which used the instants of QRS complexes as reference to track and extract the ICC signal. Six waveform features were extracted from processed ECG, ICC and its first derivative that characterize PR and PEA and were then used to build the circulation detector based on a multivariate logistic regression classifier. The training set was used to develop and optimize the circulation detector. Appendix A gives a detailed technical description of the method.

Evaluation and statistical analysis

The inter-rater agreement between the three expert reviewers during the annotation process of the gold standard was evaluated using the Fleiss' Kappa coefficient (κ) and its 95% confidence interval. The performance of the circulation detector was assessed using the test set in terms of sensitivity (capacity to correctly