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Clinical Paper

Reliability and accuracy of the thoracic impedance signal for measuring cardiopulmonary resuscitation quality metrics☆

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ABSTRACT

Aim: To determine the accuracy and reliability of the thoracic impedance (TI) signal to assess cardiopulmonary resuscitation (CPR) quality metrics.
Methods: A dataset of 63 out-of-hospital cardiac arrest episodes containing the compression depth (CD), capnography and TI signals was used. We developed a chest compression (CC) and ventilation detector based on the TI signal. TI shows fluctuations due to CCs and ventilations. A decision algorithm classified the local maxima as CCs or ventilations. Seven CPR quality metrics were computed: mean CC-rate, fraction of minutes with inadequate CC-rate, chest compression fraction, mean ventilation rate, fraction of minutes with hyperventilation, instantaneous CC-rate and instantaneous ventilation rate. The CD and capnography signals were accepted as the gold standard for CC and ventilation detection respectively. The accuracy of the detector was evaluated in terms of sensitivity and positive predictive value (PPV). Distributions for each metric computed from the TI and from the gold standard were calculated and tested for normality using one sample Kolmogorov–Smirnov test. For normal and not normal distributions, two sample *t*-test and Mann–Whitney *U* test respectively were applied to test for equal means and medians respectively. Bland–Altman plots were represented for each metric to analyze the level of agreement between values obtained from the TI and gold standard.
Results: The CC/ventilation detector had a median sensitivity/PPV of 97.2%/97.7% for CCs and 92.2%/81.0% for ventilations respectively. Distributions for all the metrics showed equal means or medians, and agreements >95% between metrics and gold standard was achieved for most of the episodes in the test set, except for the instantaneous ventilation rate.
Conclusion: With our data, the TI can be reliably used to measure all the CPR quality metrics proposed in this study, except for the instantaneous ventilation rate.

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1. Introduction

Delivery of high quality cardiopulmonary resuscitation (CPR) is a key component of current resuscitation guidelines.[1,2] Minimally interrupted chest compressions (CCs), with a rate of at least 100 min^{-1} and at least 5 cm depth, are recommended along with allowance for full chest recoil on completion of each compression. Guidelines also recommend oxygenation to be provided with a ventilation rate of 8–10 min^{-1} in intubated patients. Several studies have revealed that low quality CCs, and pauses in CCs are associated with poorer outcomes in animals[3–5] and humans.[6–12] Hyperventilation has also been linked to poor outcomes in animals,[13,14] although the negative effect of hyperventilation has recently been questioned in animals.[15] Nevertheless, suboptimal quality of CPR is common in both in-hospital and out-of-hospital cardiac arrest (OHCA).[6,10–12,14,16–19]

Procedures such as episode debriefing or the incorporation of feedback systems into defibrillators have been developed to improve CPR quality. A standardized review of resuscitation episodes permits reporting of rescuer performance in terms of CPR quality metrics related to CCs and ventilations. Efforts have been made to streamline these reports by defining the CPR quality metrics that should be reported.[20] Systems for real time feedback on CPR have proven effective to improve quality metrics,[21]

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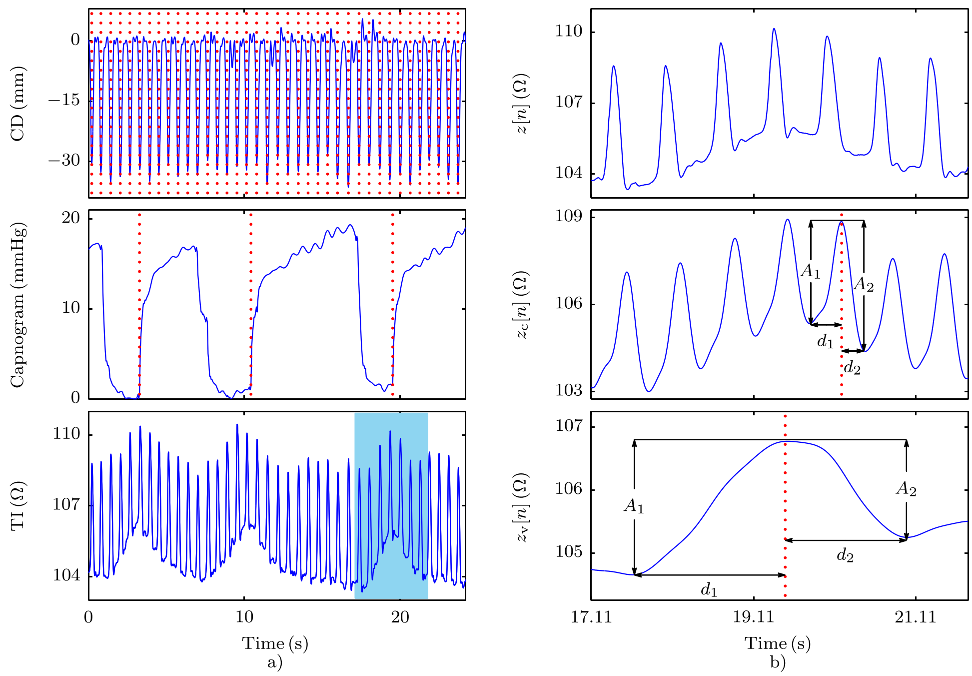

Fig. 1. Examples of the signals comprised in each episode: CD, capnogram and TI signals from top to bottom in panel a. Reviewers' annotations of CCs and ventilations are depicted as red dotted lines in CD and capnogram signals respectively. Panel b shows (from top to bottom) in more detail the segment colored in blue in the TI signal of panel a, $z[n]$, the same segment processed to enhance CCs, $z_c[n]$, and the same segment processed to enhance ventilations, $z_v[n]$. The extracted features are also represented in both $z_c[n]$ and $z_v[n]$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

although no evidence has been provided on the positive effect on survival. The feedback on too slow CCs or hyperventilation can help guide rescuers towards metrics recommended by guidelines.[17,22–25]

In the context of advanced life support (ALS), the monitor/defibrillators may be equipped with acceleration/force sensors as well as capnography and pulse oximetry modules. These may be used to assist the rescuer on the CPR quality. In the context of basic life support (BLS), some automated external defibrillators (AEDs) also offer acceleration/force sensors for feedback, but these are relatively expensive accessories for widespread use. There are also several standalone CPR feedback devices: some highly functional such as CPRmeter (Laerdal, Stavanger, Norway) or TrueCPR (Physio Control, Redmond, WA, USA) which are also expensive and not widely used in BLS, and some others more affordable for training purposes. Therefore, often the only patient interface is defibrillation pads, and only the electrocardiogram (ECG) and TI signals are available.

CCs and ventilations cause fluctuations of different characteristics in the TI signal. The TI signal can be used to identify CCs[17,26–28] and ventilations.[17,29–32] Although the compression depth is associated with outcome, it has been reported that it cannot be measured using the TI signal.[33,34] Therefore, the identification of CCs and ventilations in the TI only allows to evaluate quality metrics related to presence and rate. Algorithms for CC detection using the TI signal are integrated into commercial software for episode reviewing, and algorithms for ventilation detection have been recently proposed using the TI.[29,30] Their global performance is provided in terms of sensitivity and positive predictive value (PPV).[26] Nevertheless, detailed analysis of the utility of the TI signal for CC/ventilation metrics is needed.

The purpose of this study was to analyze retrospectively OHCA episodes to determine the reliability and accuracy of using the TI to evaluate seven quality metrics related to the presence and rate of the CCs and the ventilations. An efficient detector for CCs and ventilations was developed, and the reliability and accuracy of each of the seven CPR metrics was evaluated globally and for each patient.

2. Materials and methods

2.1. Data materials

The dataset used in this study was a subset of a large out-of-hospital cardiac arrest (OHCA) registry containing 623 episodes maintained by the Tualatin Valley Fire & Rescue agency (Tigard, Oregon, USA). The episodes, one per patient, were collected using the Philips HeartStart MRx monitor/defibrillator between 2006 and 2009. From the original database only 199 episodes had the compression depth signal (CD), the TI signal and the capnogram. Those episodes where the three signals were concurrent for at least 20 min were selected. A total of 63 episodes with mean (SD) duration 41 (11) min comprised the dataset. The CD signal (sampling rate 250 Hz) was computed from the force and the acceleration recorded through a CPR assist pad. The TI signal was recorded through the defibrillation pads by applying a sinusoidal excitation current (32 kHz, 3 mA peak-to-peak) with a resolution of 0.74 mΩ per least significant bit, a bandwidth of 0–80 Hz and a sampling rate of 200 Hz. The capnogram was acquired using Microstream (sidestream acquisition) with a frequency rate of 40 Hz and a resolution of 0.004 mmHg per bit.

For the CC-detection the CD was used as gold standard. The instants of CCs were automatically marked applying a fixed threshold of −15 mm and manually reviewed (panel a in Fig. 1). For ventilation detection, the capnogram was used as gold standard and ventilations were annotated independently by three experienced biomedical engineers relying on visual inspection (panel a in Fig. 1). Intervals where capnography was disconnected (0.90% of the time) or uninterpretable because the ventilation pattern was not clearly recognizable (11.65% of the time), were excluded from the analysis. However, no intervals of the TI were discarded due to poor quality or artifacts. A total of 2575 min were analyzed,

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