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Clinical paper

Feasibility of the capnogram to monitor ventilation rate during cardiopulmonary resuscitation☆

Elisabete Aramendi[a,*], Andoni Elola[a], Erik Alonso[b], Unai Irusta[a], Mohamud Daya[c], James K. Russell[c], Pia Hubner[d], Fritz Sterz[d]

[a] Communications Engineering Department, University of the Basque Country UPV/EHU, Alameda Urquijo S/N, 48013 Bilbao, Spain
[b] Department of Applied Mathematics, University of the Basque Country UPV/EHU, Rafael Moreno "Pitxitxi", 3, 48013 Bilbao, Spain
[c] Department of Emergency Medicine, Oregon Health & Science University, 97239-3098 Portland, OR, United States
[d] Department of Emergency Medicine, Medical University of Vienna, 1090 Wien, Austria

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ABSTRACT

Aim: The rates of chest compressions (CCs) and ventilations are both important metrics to monitor the quality of cardiopulmonary resuscitation (CPR). Capnography permits monitoring ventilation, but the CCs provided during CPR corrupt the capnogram and compromise the accuracy of automatic ventilation detectors. The aim of this study was to evaluate the feasibility of an automatic algorithm based on the capnogram to detect ventilations and provide feedback on ventilation rate during CPR, specifically addressing intervals where CCs are delivered.
Methods: The dataset used to develop and test the algorithm contained in-hospital and out-of-hospital cardiac arrest episodes. The method relies on adaptive thresholding to detect ventilations in the first derivative of the capnogram. The performance of the detector was reported in terms of sensitivity (SE) and Positive Predictive Value (PPV). The overall performance was reported in terms of the rate error and errors in the hyperventilation alarms. Results were given separately for the intervals with CCs.
Results: A total of 83 episodes were considered, resulting in 4880 min and 46,740 ventilations (8741 during CCs). The method showed an overall SE/PPV above 99% and 97% respectively, even in intervals with CCs. The error for the ventilation rate was below 1.8 min^{-1} in any group, and >99% of the ventilation alarms were correctly detected.
Conclusion: A method to provide accurate feedback on ventilation rate using only the capnogram is proposed. Its accuracy was proven even in intervals where canpography signal was severely corrupted by CCs. This algorithm could be integrated into monitor/defibrillators to provide reliable feedback on ventilation rate during CPR.

1. Introduction

Quality of cardiopulmonary resuscitation (CPR) is a key factor in the outcome of cardiac arrest patients. Advanced life support (ALS) treatment of out-of-hospital cardiac arrest (OHCA) includes good-quality chest compressions (CCs) and a reliable airway management. The 2015 resuscitation guidelines recommend continuous chest compressions after intubation, ventilation rates of 10 min^{-1} and avoidance of hyperventilation.[1] Hyperventilation increases intrathoracic pressure, reshapes the oxygen dissociation curve (increasing oxygen affinity) and behaves as a cerebral vasoconstrictor.[2,3] It has also has been proven to lower coronary perfusion pressure and to contribute to hemodynamic deterioration in animal experiments.[4–8] All these factors decrease the probability of survival.[9,10] Nevertheless rescuers providing pre-hospital CPR often exceed the recommended ventilation rates. Several studies report rates ranging from moderate (14 min^{-1}) to severe (>20 min^{-1}) hyperventilation during long duration OHCA.[5–7,9–12]

CPR feedback systems, either standalone or incorporated into defibrillators, have been shown to improve adherence to guideline recommendations.[13,14] Feedback on CCs based on acceleration, force or thoracic impedance (TI) has been extensively studied;[11,15–17] but little attention has been given to feedback on ventilation rate during CPR. The TI channel, recorded through the defibrillation pads, has been explored to monitor ventilation

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* Corresponding author.
E-mail address: elisabete.aramendi@ehu.es (E. Aramendi).

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rate.[11,18,19] However, an analysis of long resuscitation episodes showed that artefacts limit the reliability of TI for instantaneous feedback on ventilation rate.[17] Currently, no commercial system is available for feedback on ventilation rate using the TI.

The recently released resuscitation guidelines have placed an increased emphasis on the use of the capnogram during CPR to monitor, among other things, ventilation rate and to avoid hyperventilation.[1] During CPR compression artefacts often corrupt the capnogram compromising the accuracy of automatic algorithms for ventilation rate feedback.[20–22] Few such algorithms have been published,[23,24] and their performance during CPR has not been systematically evaluated and/or documented.

This study proposes an automatic algorithm for ventilation detection during CPR based on the typical waveform characteristics of the capnogram and on the use of adaptive thresholds to identify ventilations. The aim of the study is to analyse the feasibility of using the capnogram to provide an accurate automated feedback on ventilation rate and hyperventilation alarms during CPR.

2. Materials and methods

2.1. Data materials

Two datasets of episodes with signals from monitor/defibrillators were used in this study, an out-of-hospital dataset (OHD) and an in-hospital dataset (IHD). The OHD was recorded during cardiac arrest, with manual CPR (CCs and ventilations) provided in all episodes. The signals available to monitor ventilations were the TI and the capnogram. The IHD corresponded to patients who suffered cardiac arrest, some recorded during manual CPR (CCs and ventilations) and some recorded after cardiac arrest during postresuscitation care (mechanical ventilation). They were monitored with the capnogram and the expired air flow.

The OHD was a subset of a large OHCA registry containing 623 episodes maintained by the Tualatin Valley Fire & Rescue (Tigard, Oregon, USA), an ALS first response agency. The episodes were collected using the HeartStart MRx monitor/defibrillator (Philips, Andover, MA) between 2006 and 2009. Ventilations in these episodes were provided manually with an endotracheal tube or laryngeal tube airway. Episodes with at least 20 minutes of concurrent and readable recordings of the compression depth (CD), the TI and the capnogram were included in this study, resulting in a dataset of 62 episodes. The CD signal from the Q-CPR assist pad by Philips was used to identify the intervals with CCs. The capnogram was acquired using Microstream (sidestream acquisition) with a sampling rate of 40/125 Hz and a resolution of 0.004 mmHg per bit. The instants of ventilations were marked in the TI ventilation channel,[11,17] first automatically and then manually reviewed by three experienced biomedical engineers. Reviewers used the capnogram to make a decision in unclear intervals. Fig. 1 shows examples of two episodes of the OHD, where ventilations are visible in both the TI ventilation channel (in black) and the capnogram, for an artefact free interval (panel a), and when CCs were provided (panel b).

The IHD was a subset of the APACHI study conducted by Philips Healthcare at the Medical University of Vienna between November 2012 and January 2014. The APACHI study recorded physiological signals (arterial blood pressure, electrocardiogram, photoplethysmogram, capnogram and airway flow and pressure) from multiple monitors during hemodynamic crisis in the emergency department of the Vienna General Hospital, under the direction of Drs. Sterz and Hubner. From a total of 50 patients enrolled in the trial, the 21 that suffered cardiac arrest and had concurrent recordings of capnogram and ventilatory flow were included. Six of the episodes were recorded during CPR and 15 after resuscitation. The mainstream capnogram was acquired by the NICO 7300 monitor using the

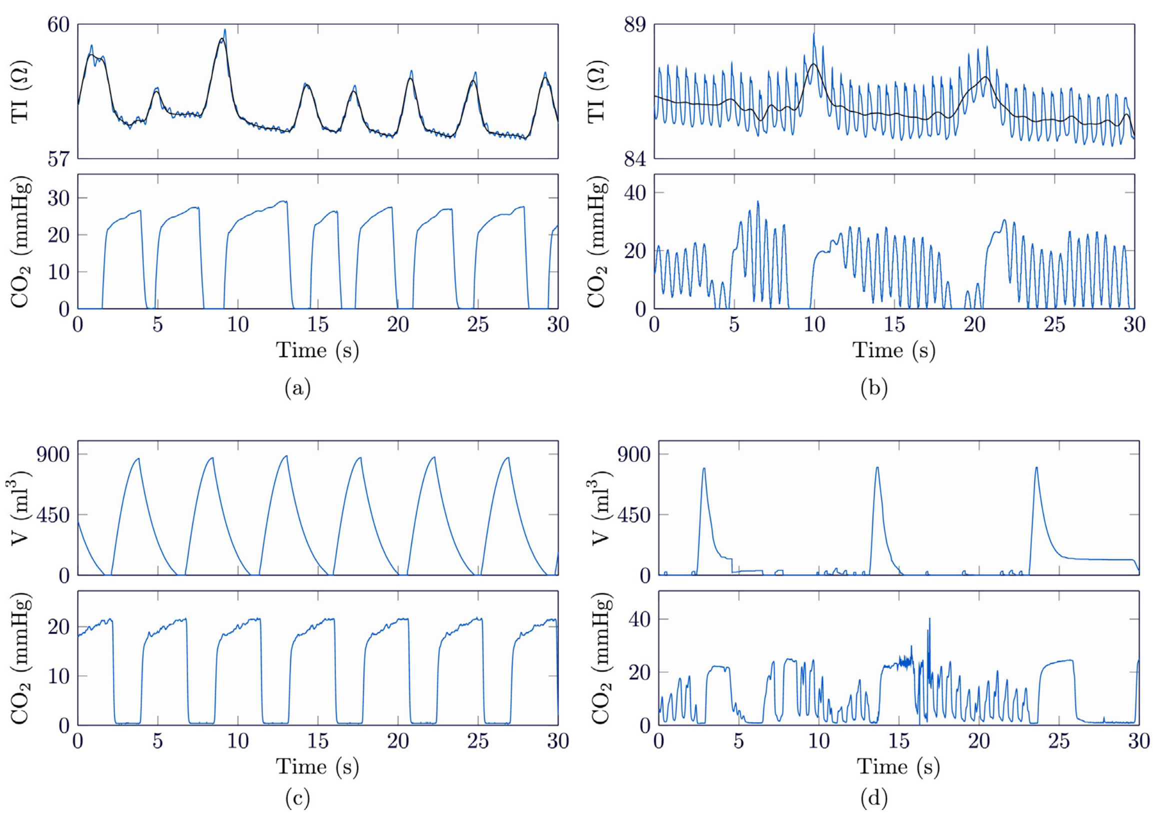

Fig. 1. Intervals from the out-of-hospital and in-hospital datasets, OHD and IHD, showing the capnogram and the Gold Standard (GS) to annotate ventilations. Panels a and b show OHD examples without and with chest compressions, with the impedance ventilation channel (GS) in black on top and the capnogram below. Panels c and d show IHD examples without and with CCs, with the air volume (GS) on top and the capnogram below.