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Clinical paper

Enhancement of capnogram waveform in the presence of chest compression artefact during cardiopulmonary resuscitation

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ABSTRACT

Background: Current resuscitation guidelines emphasize the use of waveform capnography to help guide rescuers during cardiopulmonary resuscitation (CPR). However, chest compressions often cause oscillations in the capnogram, impeding its reliable interpretation, either visual or automated. The aim of the study was to design an algorithm to enhance waveform capnography by suppressing the chest compression artefact.

Methods: Monitor-defibrillator recordings from 202 patients in out-of-hospital cardiac arrest were analysed. Capnograms were classified according to the morphology of the artefact. Ventilations were annotated using the transthoracic impedance signal acquired through defibrillation pads. The suppression algorithm is designed to operate in real-time, locating distorted intervals and restoring the envelope of the capnogram. We evaluated the improvement in automated ventilation detection, estimation of ventilation rate, and detection of excessive ventilation rates (over-ventilation) using the capnograms before and after artefact suppression.

Results: A total of 44 267 ventilations were annotated. After artefact suppression, sensitivity (Se) and positive predictive value (PPV) of the ventilation detector increased from 91.9/89.5% to 98.0/97.3% in the distorted episodes (83/202). Improvement was most noticeable for high-amplitude artefact, for which Se/PPV raised from 77.6/73.5% to 97.1/96.1%. Estimation of ventilation rate and detection of over-ventilation also upgraded. The suppression algorithm had minimal impact in non-distorted data.

Conclusion: Ventilation detection based on waveform capnography improved after chest compression artefact suppression. Moreover, the algorithm enhances the capnogram tracing, potentially improving its clinical interpretation during CPR. Prospective research in clinical settings is needed to understand the feasibility and utility of the method.

Introduction

Treatment of out-of-hospital cardiac arrest (OHCA) by advanced life support (ALS) usually includes advanced airway placement, administration of medications along with high quality cardiopulmonary resuscitation (CPR) [1–3].

Most monitor-defibrillators are equipped with electronic carbon dioxide (CO_2) detectors which allow end-tidal CO2 (ETCO2) measurement. ETCO2 is the partial pressure of carbon dioxide at the end of an exhaled breath, and reflects ventilation and perfusion of the patient [4]. Electronic CO_2 detectors can be of two types: those that report the results in a numeric display (non-waveform detectors), and those that provide waveform graphical display where the respiratory cycle can be directly observed [2,5]. The latter have become more important, since the last release of international resuscitation guidelines emphasized the use of waveform capnography for ALS guidance and patient monitoring [2,3]. Currently, waveform capnography can be used for assessing the correct placement of the tracheal tube and monitoring ventilation rate. Other potential uses of waveform capnography include monitoring of CPR quality [5–7], early detection of restoration of spontaneous circulation [5,8] and determining patient prognosis during CPR [9,10].

To be clinically interpretable, the different phases of the respiratory cycle must be identifiable in the capnogram during CPR, including the end of expiration where ETCO2 is measured. However, several studies have reported the appearance of fast oscillations synchronized with chest compressions superimposed on the capnogram [11–13], often completely obscuring the normal tracing. This distortion could negatively affect waveform capnography in three aspects: causing errors in

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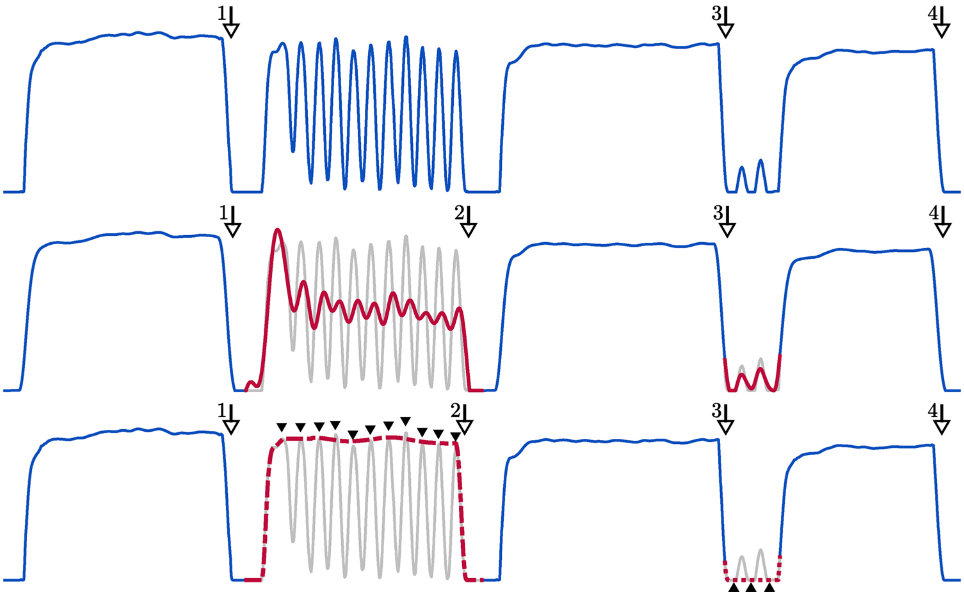

Fig. 1. Alternatives for chest compression artefact suppression. A distorted capnogram is depicted at the top. Each vertical arrow indicates a ventilation. Oscillations of type III impede the correct detection of the second ventilation. The middle panel represents in red the resulting waveform after applying one of the filters proposed in reference [15]. The bottom panel illustrates the extraction of the envelope waveform capnography through the detection of, respectively, the local maxima of the original capnogram in the plateau and the local minima in the baseline.

the automated detection of ventilations and consequently in the estimation of ventilation rate, impeding reliable measurement of ETCO2 values, and limiting CPR providers since distorted capnograms are difficult to interpret.

In a recent study, we retrospectively analysed monitor-defibrillator recordings from OHCA episodes and reported that 42% of capnograms were distorted by chest compression oscillations [14]. That study also quantified significant errors in the capnogram-based estimation of ventilation rate, attributable to the oscillations interference. In a follow-up study, we proposed a solution to remove chest compression oscillations from the capnogram by filtering, which improved the automated detection of ventilation rate. Unfortunately, filtered capnograms were far from being reliable for clinical interpretation [15].

In this study, we explored an alternative method to suppress chest compression oscillations from the capnography waveforms. The method was designed to improve ventilation detection and more importantly, to provide a capnogram that was reliable for clinical interpretation. For quantitatively assessing the goodness of the method, the accuracy of a capnogram-based algorithm for ventilation detection was tested before and after applying the suppression method. In addition to ventilation detection, we also quantified the improvement in the computation of ventilation rate and in the detection of excessive ventilation rates.

Materials and methods

Data collection and annotation

Data were extracted from a database of OHCA episodes collected between 2011 and 2016 as a part of the Resuscitation Outcomes Consortium (ROC) Epidemiological Cardiac Arrest Registry. The data collection for the ROC Epistry was approved by the Oregon Health & Science University (OHSU) Institutional Review Board (IRB00001736). Patient private data was not available for the study. Episodes were recorded using Heartstart MRx monitor-defibrillators (Philips, USA), equipped with real-time CPR feedback technology (Q-CPR) and waveform capnography using sidestream technology (Microstream, Oridion Systems Ltd, Israel). Ventilation was provided through an endotracheal tube, supraglottic airway (King Laryngeal Tube) or with a bag-valve mask device.

This study analysed the monitor-defibrillator recordings of 202 patients, containing at least 20 min of concurrent capnogram, compression depth (CD) signal, and transthoracic impedance (TI) signal acquired through the defibrillation pads. We used the annotations from a previous study [14], in which biomedical experts classified the episodes as distorted if chest compression artefact appeared during more than one minute of the chest compression time. Furthermore, experts classified the artefact into three types according to its location: type I (chest compression oscillations appearing in the expiratory plateau of the capnogram), type II (in the baseline), and type III (oscillations spanning from the plateau to the baseline) [14]. Finally, experts annotated each ventilation using the low frequency component of the TI signal, as the impedance of the chest measured through defibrillation pads fluctuates during each ventilation [16–18]. Resulting ventilation annotations were used in the present study as the gold standard to quantify the effectiveness of the suppression method.

Chest compression artefact suppression method

Filtering techniques have been widely proposed in the literature to remove chest compression artefact from the electrocardiogram during CPR [19–23]. Likewise, those techniques can be applied to a distorted capnogram. An example of filtering is shown in Fig. 1. A segment of a distorted capnogram is depicted in the top panel. Each vertical arrow indicates a ventilation. Oscillations of type III impede the correct detection of the second ventilation. The middle panel represents (in red) the resulting capnogram after applying one of the filters proposed by Gutierrez et al. [15]. The filtered capnogram appears highly distorted and, although all ventilations are correctly detected, the waveform is not easily interpretable.

The principle of the method proposed in the present study relies on the hypothesis that the envelope of the capnogram could be a reliable tracing for clinical interpretation. An example of the method's performance is given in the bottom panel of Fig. 1. As the artefact morphology and location is variable [14] the algorithm distinguishes between low and high CO_2 concentration intervals to determine how to extract the envelope of the capnogram. The algorithm, which can operate in real-time, detects the local maxima in the plateau phase and applies a smoothing filter to restore the upper envelope of the capnogram (see the dashed red line depicted in the bottom panel of Fig. 1). Similarly, local minima are detected in the capnogram baseline to extract the lower envelope (see the dotted red line). A detailed explanation of the algorithm is provided in the supplementary materials published online with the electronic version of this article.

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