Open-loop Adaptive Filtering for Suppressing Chest Compression Oscillations in the Capnogram During Cardiopulmonary Resuscitation

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Abstract

Capnography is often used for the guidance on ventilation rate during cardiopulmonary resuscitation (CPR). However, capnogram waveform frequently presents oscillations induced by chest compressions (CC), affecting the reliability of ventilation detection. The aim of the work was to evaluate the performance of an open-loop adaptive filter in the cancellation of CC oscillations in the capnogram during CPR. For that purpose, we analyzed 60 episodes from an out-of-hospital (OOH) cardiac arrest registry maintained by TVF&R agency (USA). In 50% of the episodes the capnogram was corrupted by CC oscillations. The goodness of the filtering scheme was assessed by comparing the sensitivity (Se) and the positive predictive value (PPV) of an automated ventilation detector before and after filtering. A fixed-coefficient low-pass filter was also designed for comparison. The results showed that both filters reported a good performance although the adaptive scheme presented a slightly higher PPV (+1.2 points globally). The simpler fixed-coefficient scheme avoids the reference signal, but requires validation with larger datasets to ensure stability.

1. Introduction

Current resuscitation guidelines recommend high quality chest compressions (CC) and ventilations during cardiopulmonary resuscitation, in order to increase survival from out-of-hospital (OOH) cardiac arrest [1]. However, the optimal application of the CPR procedure is not easy for both laypeople and well-trained rescuers [2]. Consequently, different indicators of CPR quality during the intervention are used for this purpose.

Capnography is a non-invasive indicator of the concentration of carbon dioxide in the respiratory gases. Monitoring capnography during CPR is widely used for monitoring ventilation rate in order to prevent unintentional hyperventilation [3]. A clean capnogram is fundamental for a reliable visual analysis of the patient response (Fig. 1A). Unfortunately, different artefacts can frequently be observed in the capnogram during CPR. One of them is induced by CC, and appears superimposed on the capnogram as oscillations at the rate of the compressions and with varying amplitude (Fig. 1B,C). The CC artefact complicates the analysis of the capnogram, compromising the accurate detection of ventilations [4].

This work evaluates the performance of an open-loop adaptive filtering strategy for the cancellation of CC oscillations in the capnogram during CPR. For this purpose, we used a large dataset of OOH cardiac arrest episodes and selected those that were corrupted by CC oscillations. We designed an adaptive stop-band filter to supress the oscillations from the capnogram. We assessed the performance of the filtering scheme by comparing the sensitivity (Se) and the positive predictive value (PPV) of an automated ventilation detector before and after filtering.

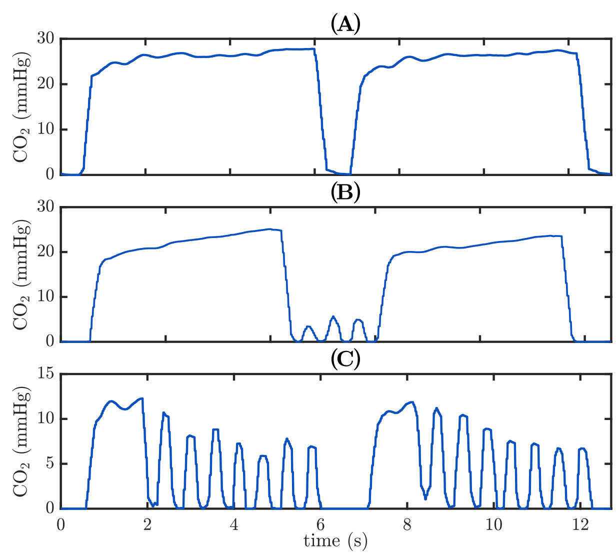

Figure 1. OOH capnograms. A) Clean capnogram B) Corrupted capnogram, with oscillations from CC appearing in the baseline. C) Corrupted capnogram with CC artefact spanning from the plateau to the baseline.

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2. Materials and methods

2.1. Database description and annotation

The dataset consisted of a 60 episodes from a large OHCA registry collected between 2011 and 2016 by Tualatin Valley Fire & Rescue (TVF&R), an advanced life support first response Emergency Medical Services (EMS) agency in Oregon (USA). Episodes were recorded using Heartstart MRx monitor-defibrillators (Philips Medical Systems, Andover, MA, USA) equipped with real-time CPR feedback technology (QCPR, Laerdal Medical, Norway). Capnography was acquired using sidestream technology (Microstream, Oridion Systems Ltd, Israel). The signals used in the study were the capnogram, the compression depth (CD) signal from the QCPR system, and the transthoracic impedance (TI) signal acquired from the defibrillation pads.

We annotated a capnogram as corrupted if evident CC oscillations appeared during more than 1 min of CC time. Half of the 60 episodes were corrupted by the CC oscillations. Clean and corrupted capnograms were randomly allocated into a training set (30 episodes, 15 clean + 15 corrupted) and a test set (30 episodes, 15 clean + 15 corrupted).

Ventilations and CC instances were annotated in all the episodes. Figure 2 shows an example of the annotation process. Ventilations were manually annotated using the TI signal which was low-pass filtered in order to suppress CC oscillations (Fig. 2 middle panel, filtered TI depicted in blue, raw TI in grey). Ventilations were annotated in the position associated to the inspiration onset (vertical lines) corresponding to a rise in the TI. CC instances were annotated in every relative maxima of the CD signal (Fig. 2, top panel, red dots) corresponding to the maximum depth reached at each CC.

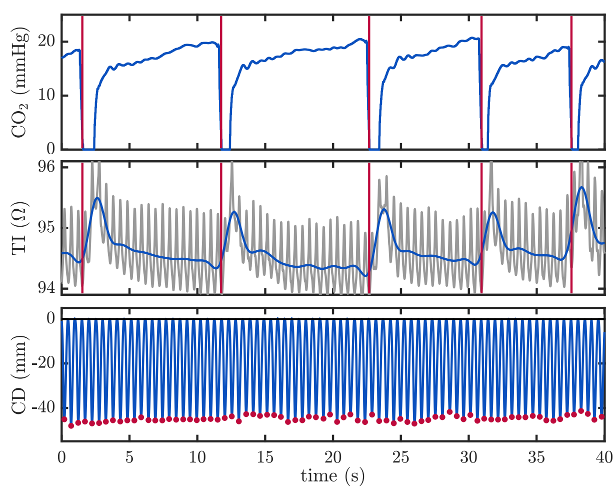

Figure 2. Example of ventilation and CC instance annotation.

2.2. Ventilation detector

The ventilation detection algorithm processes the capnogram and is based on a finite-state-machine model. The capnogram consists of a short inspiration time (low values of CO_2 pressure) and a longer expiration time (high CO_2 values). The aim of the detector to identify the instants corresponding to CO_2 downstrokes and upstrokes.

The algorithm first distinguishes inspiration from expiration identifying potential ventilations. These candidates are characterized by their duration (D_{in}, D_{ex}) and classified as ventilation or non-ventilation, following a decision system based on thresholds (Figure 3). The algorithm is fully described in reference [4].

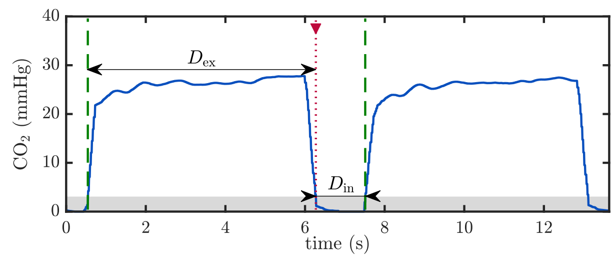

Figure 3. Graphical definition of the detector parameters.

2.2. Filtering strategies

2.2.1 Open-loop adaptive filter

The suppression of the oscillations induced by the CC on the capnogram was based on an open-loop adaptive filter. According to Figure 4, the open-loop adaptive filter is based on the application of the information obtained from a reference input signal to the adjustment of the settings of the filter. In this kind of systems there is no feedback from the output [5].

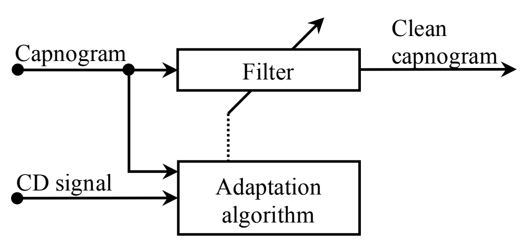

Figure 4. Open-loop adaptive filter diagram.

The open-loop adaptive filtering strategy was designed as a Butterworth band-stop filter, continuously tuned to the average CC rate in 2-s analysis windows. The design parameters were: the order, N_{ol} and the 3dB bandwidth, B_{ol} of the filter, as well as the central frequency of the stop band, f_0. The frequency f_0 was obtained from the annotations of the CC instances on the CD signal (Figure 5). The parameter f_0 was calculated as the average CC rate during 2s-intervals. If the 2s-interval contained less than 3 CC, f_0 was the same as the one used in the previous interval.

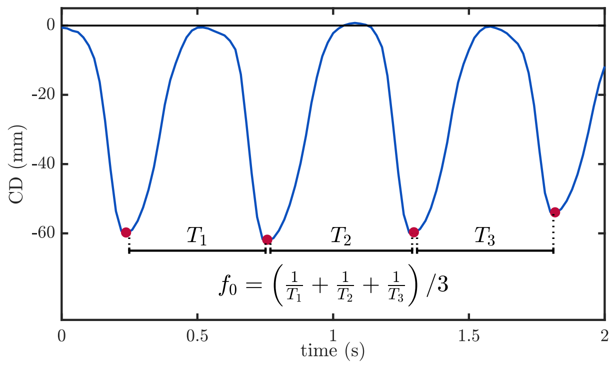

Figure 5. Calculation of parameter f_0.

The order and the bandwidth of the adaptive filter optimized with the training set, selecting finally $N_{\mathrm{ol}} = 2$ and $B_{\mathrm{ol}} = 1Hz$, respectively.

2.2.2 Fixed-coefficient filter

We also used a fixed-coefficient low-pass Butterworth filter for comparison. The design parameters were the order, N_{fc} and the 3dB cut-off frequency of the filter, f_{fc}. After analyzing the spectral characteristics of different capnograms and CD signals, the final values of both parameters were optimized with the training set.

2.3. Performance evaluation

The goodness of the filtering strategy was assessed by comparing the sensitivity (Se) and the positive predictive value (PPV) of the ventilation detector, before and after filtering. Se was defined as the percentage of annotated ventilations that were correctly detected. PPV was defined as the percentage of detected ventilations that were correct. The maximum admissible tolerance for the position of the detection and the annotation was 500ms. We provide separate results for clean and corrupted subsets.

We optimized the adaptive filter parameters (N_{ol}, B_{ol}) and the fixed-coefficient filter parameter (N_{fc}, f_{fc}) with the training set to maximize Se while maintaining PPV above 92%.

3. Results

The order and the bandwidth of the adaptive filter were optimized to $N_{\mathrm{ol}} = 2$ and $B_{\mathrm{ol}} = 1Hz$, respectively. Similarly, the order and the bandwidth of the fixed-coefficient filter were $N_{\mathrm{fc}} = 8$ and $f_{\mathrm{fc}} = 1.5Hz$.

Table 1 summarizes Se and PPV results for the test set, comprising 7195 ventilations. Globally, Se and PPV before filtering were 93.0% and 92.2%, respectively. In case of the fixed-coefficient filter, Se and PPV increased to 97.7% and 94.8%, respectively. The increments were similar in case of the open-loop adaptive filter, with a Se of 97.7% and a PPV of 95.3%.

For the clean set (3905 ventilations), the results stayed stable: Se and PPV were close to 99%, before and after filtering, for both filtering strategies. However, for the corrupted subset (3290) Se and PPV were low: 84.8% and 84.0%, respectively, before filtering. After applying the fixed-coefficient filter, Se increased to 95.4% and PPV to 90.3%. Applying the open-loop filter the increment of the values of Se and PPV are similar to those ones obtained with the fixed coefficient filter (95.6/91.5%, respectively),

Table 1. Se and PPV for the test set, before filtering and after fixed-coefficient (FC) and Open-loop (OL) adaptive filtering.

	Before (Se/PPV)	**FC (Se/PPV)**	**OL (Se/PPV)**
Whole set	93.0/92.2	97.7/94.8	97.7/95.3
Clean	99.8/99.1	99.6/98.7	99.5/98.7
Corrupted	84.8/84.0	95.4/90.3	95.6/91.5

Figure 6 shows the boxplots of Se and PPV values before and after filtering with both strategies. For both filters, the dispersion of Se and PPV was very low before as well as after filtering, in case of the clean episodes. However, the dispersion of both parameters was quite relevant for corrupted episodes before filtering.

The results demonstrate that filtering the capnogram in case of clean episodes maintains good results of Se and PPV, and improve them in presence of artefact.

4. Conclusions

The current resuscitation guidelines for advanced life support recommend the use of the capnogram during CPR. The presence of high-frequency oscillations in the capnogram during CC may difficult the interpretation of the signal.

The work presents two filtering techniques to suppress the oscillations induced during CC: a simple fixed-coefficients filter and an open-loop adaptive filter.

The results demonstrate that the filtering of the capnogram provides a larger reliability in the automated detection of ventilations. The global results obtained for the complete test set, where clean and corrupted episodes were analyzed, are quite similar for both techniques. The improvement is specifically relevant in the presence of the artefact induced by CC. In this case, the open-loop adaptive strategy provides better results, with a better balance between the sensitivity and the positive predictive value. For the clean subset, the results stay stable before and after filtering.

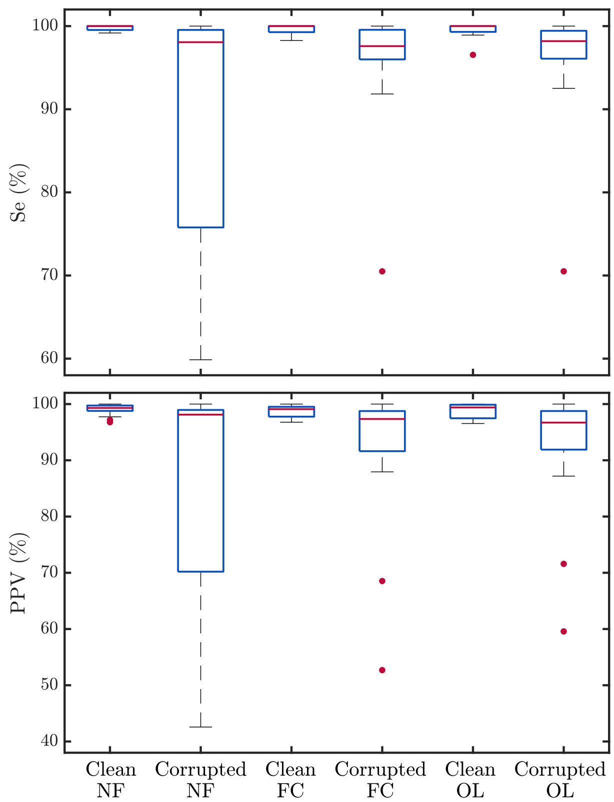

Figure 6. Se and PPV for the test set before filtering (NF, left), after fixed-coefficient filtering (FC, middle) and after closed-loop adaptive filtering (CL, right). Boxes show the median and IQR. Outliers are represented by dots

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References

[1] Soar J, Nolan JP, Böttiger BW, et al. European Resuscitation Council guidelines for resuscitation 2015. Section 3. Adult advanced life support. Resuscitation 2015;95:100-147.

[2] Wik L, Kramer-Johansen J, Myklebust H, et al. Quality of cardiopulmonary resuscitation during out-of-hospital cardiac arrest. JAMA 2005;293:299-304.

[3] Maertens VL, De Smedt LE, Lemoyne S, et al. Patients with cardiac arrest are ventilated two times faster than guidelines recommend: an observational prehospital study using tracheal pressure measurement. Resuscitation 2013; 84(7):921-926.

[4] Leturiondo M, Ruiz J, Ruiz de Gauna S, González-Otero DM, Bastida JM, Daya M. A simple algorithm for ventilation detection in the capnography signal during cardiopulmonary resuscitation. Computing in Cardiology 2017. In press.

[5] Widrow B, Stearns D. Adaptive signal processing. Prentice Hall. 1985.

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