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Hands-off Intervals during Cardiopulmonary Resuscitation: Duration and Effect on the ECG Analysis

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Summary: Recent works are aimed at development of shock advisory systems (SAS) for automated external defibrillators (AEDs), which continuously analyze the electrocardiogram (ECG) during non-interrupted chest compressions (CC). Being also part of the cardiopulmonary resuscitation (CPR), small 'hands-off' intervals (CC pauses) for insufflations are interrupting the CC, and thus the SAS analysis process. This study is applied on 530 CC-contaminated ECG strips taken from 168 patients who undergo out-of-hospital resuscitation interventions with AEDs. A statistical study of the short duration CC pauses is performed, showing non-normal distribution with median value of 4 seconds, quartile range between 3 and 5 seconds, min-max range between 1 and 10 seconds. Another focus is the effect of skipping the CC pauses on the SAS accuracy by supplying continuous non-linear CC-corrupted ECG signal for analysis. The SAS is tested with different coupling intervals [t1, t2], where t1 is the time before the CC pause, t2 is the time after the CC pause, t1+t2=10 seconds. The SAS accuracy on CC-corrupted linear signals [10s+0s] compared to non-linear signals [9s+1s], [8s+2s], [7s+3s], [6s+4s], [5s+5s] shows insignificant difference ($p>0.05$) for the different arrhythmia: ventricular fibrillation between 86% and 90.3%, normal rhythms between 88.4% and 93.5%, asystole between 80.4% and 87.3%. Several examples illustrate the performance of the SAS analysis process on various CC artefacts and ECG arrhythmias.

Keywords: CPR artefacts, Cardiac compression pauses, Shock advisory system, AED.

1. INTRODUCTION

Cardiopulmonary resuscitation (CPR) has been advised as the best treatment for out-of-hospital cardiac arrests (OHCA) before the arrival of an automated external defibrillator (AED) [3]. Minimum 'hands-off' intervals during CPR are advised to improve the success rate of defibrillation since chest compressions (CC) are supplying non-interrupted blood flow to the brain, the heart and other vital organs. CC thus prevent from ischemia and increase the rate of return to spontaneous circulation [2, 5, 6, 7]. According to the ERC

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2005 protocol for basic life support [3], the CPR is performed for 2 minutes or 5 cycles (30:2) - each cycle includes 30 non-interrupted chest compressions followed by 2 rescue breaths (insufflations). The short interruption of the cardiac compressions is an important factor that has to be considered during the electrocardiogram (ECG) analysis process of the AED in presence of CC artefacts.

This work aims to study the duration of the hands-off intervals and to assess the possibility for continuous scan of the ECG rhythm under cardiac compressions, skipping the short hands-off periods of insufflations interrupting the CC.

2. MATERIALS AND METHODS

ECG data

This study is applied on a large ECG database with artefacts from CPR manipulations administered on 168 persons in cardiac arrest. All victims underwent OHCA intervention with AEDs (FredEasy, Schiller Medical SAS, France) used as a first aid by the fire-fighters in the region of Nancy (July 2006 – January 2007). The advantage of such database is the large excerpt of CC artefacts captured via the defibrillation pads and induced by different rescuers on various ECG arrhythmias.

We have extracted a subset of 530 CC-contaminated ECG strips, composed by:

- 1st CC-contaminated ECG episode ≥ 10 seconds;
- CC pause (hands-off interval) - between 1 and 10 seconds;
- 2nd CC-contaminated ECG episode ≥ 1 second.

The examples in Fig.1, 2 illustrate two ECG strips in full length. Two independent reviewers have annotated manually the subset of CC-contaminated ECG strips, as follows:

1) *Annotation of the End of CC (EoCC) and Begin of the next CC (BoCC)* by parallel observations over the ECG channel and the impedance channel. The mechanical movements during CC are typically visible in both channels as large waves with the period of the cardiac compressions (85-115 cpm) (see Fig. 1, 2). Since high-amplitude ECG signals might impede the recognition of the CC episode onset/end (Fig.1), the abrupt transitions (in amplitude and periodicity) within the impedance channel are the typical indicators for EoCC and BoCC annotation.

2) *Annotation of the ECG rhythm* observed during the CC pause (noise-free segment). Fig.1, 2 illustrate two typical examples with unrecognizable rhythm during the CC-contaminated episodes and clearly seen ECG rhythm during the CC-pause. Therefore, the rhythm annotation during the CC-pause is adopted for the full length ECG strip in concord to the assumption of consistent ECG rhythm. The annotation is following the AHA classification scheme for non-shockable and shockable rhythms [4]:
   - Non-shockable rhythms (NS):
     - Normal Rhythms (NR) – normal sinus rhythm, supraventricular tachycardia, sinus bradycardia, atrial fibrillation and flutter, heart block, rhythms with premature ventricular contractions and idioventricular rhythms;
     - Asystoles (ASYS) – ECG signals with peak to peak amplitude <150 μV for at least 4 seconds.
   - Shockable rhythms (S):
     - Ventricular Fibrillation (VF) - coarse ventricular fibrillation with amplitude >200μV.

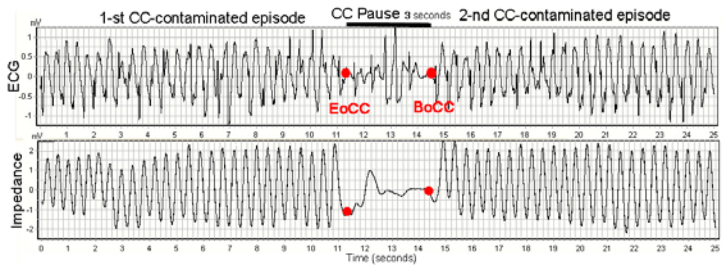


Fig. 1 NR rhythm: Example of brief short duration CC pause for insufflations. 1st trace – ECG channel; 2nd trace – impedance channel

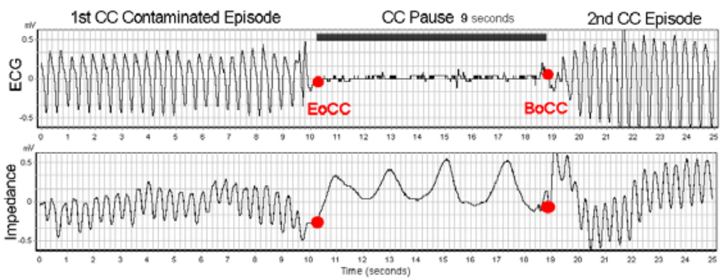


Fig. 2 ASYS: Example of prolonged short duration CC pause for insufflations

Short duration CC pauses

Our study involves CC-contaminated ECG strips with short duration CC pauses (≤ 10 seconds). Such pauses are the most frequently seen during the OHCA interventions, typically for the period of insufflations. We aim to derive the probability distribution of the short duration CC pauses width as a major factor interrupting the process of the ECG rhythm analysis during continuous CPR. For this purpose we measure the time between EoCC and BoCC annotation in all ECG strips included in the study. Fig.1, 2 illustrate the ECG and impedance signals for two cases of short duration CC pause with a length of 3 and 9 seconds. We should note that the study does not take into consideration the long duration CC pauses during intubation, AED rhythm assessment and eventual consequent defibrillation as they might be associated with rhythm transitions.

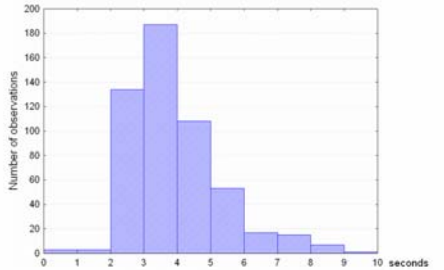
Effect of skipping the short duration CC pauses on the shock advisory system accuracy

In a previous study, we introduced a shock advisory system (SAS) based on a time-frequency ECG analysis for automatic recognition of shockable/non-shockable rhythms in presence of non-interrupted CC artefacts [1]. The SAS analysis process takes 10-second episode of CC-contaminated ECG at the input and produces CC-artefact free ECG at the output, named reconstructed ECG. In this work we test the accuracy of the same SAS applied in presence of CC artefacts interrupted by short duration CC pauses. The continuous operation of SAS is provided by feeding CC-corrupted ECGs to the input and removing the CC pause (between EoCC and BoCC annotations). Namely, t1 seconds of ECG before EoCC are added to t2 seconds after BoCC. Our tests are applied on CC signals (t1+t2=10 s) with different coupling intervals [t1+t2]:

- [10s+0s] – the CC signal is linear, taken fully before the EoCC annotation;
- [9s+1s], [8s+2s], [7s+3s], [6s+4s], [5s+5s] – the signal is non-linear, taken partially before EoCC and partially after the BoCC annotations.

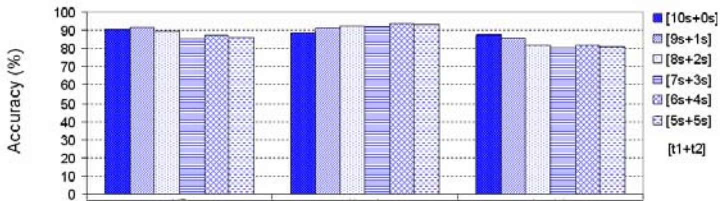
3. RESULTS AND DISCUSSION

Statistics for the observed duration of the short duration CC pauses is presented in Fig.3. The distribution is not normal (K-S test, D=0.228, $p<0.01$). The minimal time required for rescue breathing is above 2 seconds, thus changing the shape of the distribution towards higher values of duration. There are few (<5) cases with CC pauses shorter than 2 seconds, which correspond to accidental CC interruptions not for delivering of rescue breathing. The median duration of the observed CC pauses is 4 seconds, with quartile range between 3 and 5 seconds.



	Valid N	Median (seconds)	Quartile Range (seconds)	Min (seconds)	Max (seconds)
CC pauses	530	4	(3 ÷ 5)	1	10

Fig. 3 Histogram of the hands-off intervals duration



	VF	NR	ASYS
[10s+0s]	90.3 % (196/217)	88.4 % (486/550)	87.3 % (751/860)
[9s+1s]	91.3 % (84/92)	91.0 % (132/145)	85.7 % (234/273)
[8s+2s]	89.4 % (76/85)	92.7 % (114/123)	81.6 % (204/250)
[7s+3s]	85.2 % (69/81)	92.0 % (92/100)	80.4 % * (172/214)
[6s+4s]	87.0 % (67/77)	93.5 % (72/77)	81.7 % (143/175)
[5s+5s]	86.0 % (49/57)	92.9 % (52/56)	81.1 % (116/143)

Fig. 4 Accuracy of the SAS for rhythms VF, NR, ASYS

The results are presented for different coupling CC intervals [t1+t2].

Note: The number of the analyzed cases decreases as the time t2 increases because t2 is limited up to the end of the extracted CC strip.

* $p < 0.05$ compared to the case [10s+0s]

The accuracy of SAS is summarized in Fig. 4. For CC-corrupted linear signals [10s+0s], the sensitivity (Se) for VF is 90.3 %, the specificity (Sp) for NR is 88.4 % and Sp for ASYS is 87.3 %. Comparative analysis of the SAS accuracy on CC-corrupted non-linear segments shows non significant difference (p>0.05). This is an indication that SAS performance is not worsening in case of splitting the CC artefacts before and after the short pause in one continuous signal applied for analysis. Depending on the rhythm type, different relations are observed when the influence of the 2nd CC episode (time *t2*) increases and the influence of the 1st CC episode (time *t1*) decreases, respectively. For VF signals, a trend for Se decrease is observed (up to the most crucial case t1=t2=5s). The same trend is observed also for ASYS up to (7s+3s). For NR signals, the trend is opposite, showing Sp increase up to (6s+4s).

Several examples (Fig. 5-9) illustrate the performance of the SAS, designed to take a shock decision ('NS' stands for no shock or 'S' stands for shock) at each consecutive 1-second interval. Trace 3 of each example represents the reconstructed signal, used by SAS to get the decision 'NS' or 'S'. It shows the ability of the SAS to reproduce the ECG rhythm under CC applying internal algorithms for patterns matching.

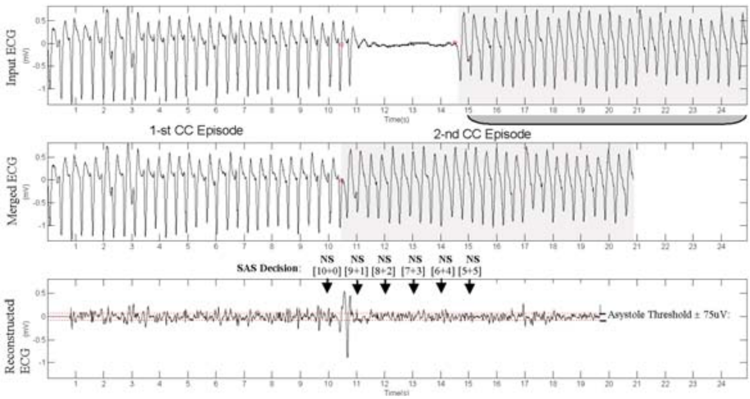


Fig. 5 ASYS corrupted by CC.
Trace 1 is the full-length CC-contaminated ECG strip.
Trace 2 is the non-linear signal obtained after sticking the 1st CC episode and the 2nd CC episode (the grey zone), one after another.
Trace 3 is the non-linear signal reconstructed by SAS

In the first example (Fig. 5), ASYS is corrupted by a CC artefact with waveform variation before and after the CC pause. This waveform difference does not deteriorate the correct 'NS' decision of SAS, starting from step [10s+0s] up to step [5s+5s]. Observations at the SAS output prove adequate reconstruction with signal amplitude mostly within the asystole threshold, considering both segments before and after the skipped CC-pause. There is only small transient peak visible at offset t1 (trace 3).

The example in Fig. 6 shows NR with narrow QRS complexes corrupted by CC artefact. The analysis of the non-linear ECG shows stable recognition of 'NS', starting from the step [10s+0s] up to the step [5s+5s]. The QRS complexes appear also in the reconstructed signal of the non-linear segment, even they are of slightly different shape (see trace 3).

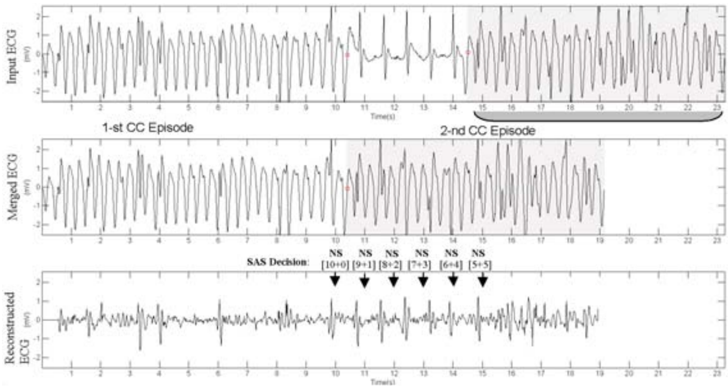


Fig. 6 NR with sharp QRS complexes corrupted by CC

The example in Fig. 7 represents a rhythm disorder with wide complexes. The CC artefacts before and after the pause have considerably different shapes and the transition is apparent in the composed non-linear ECG segment (trace 2), as well as in the reconstructed signal (trace 3). Although during the 1^{st} CC episode SAS is not able to reconstruct high-amplitude complexes, the recognition of 'NS' rhythm for steps [10s+0s], [9s+1s] is correct. Worsened results are obtained during the transition process at the beginning of the 2^{nd} CC episode when the SAS reconstructed signal resembles VF and SAS erroneously detects 'S' rhythm for steps

[8s+2s] and [7s+3s]. At step [6s+4s] when the influence of the 2nd CC episode becomes significant, the SAS recognition is again correct 'NS'.

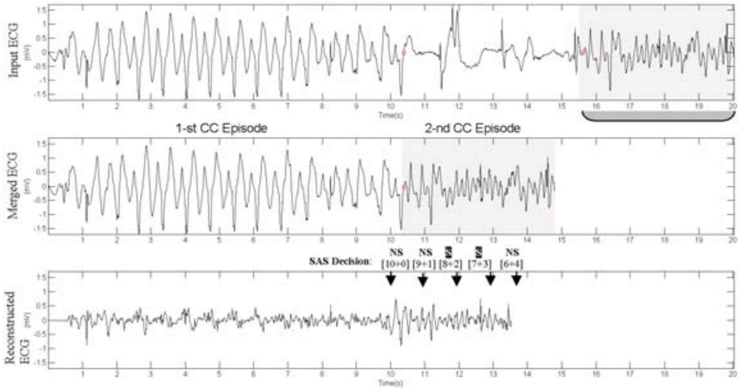


Fig. 7 NR with wide QRS corrupted by CC

Fig. 8 represents an example of VF rhythm corrupted by CC artefacts. The SAS operation is adequate with VF-like reconstructed signal and stable 'S' decision for all consecutive analysis steps, starting from [10s+0s] up to [5s+5s].

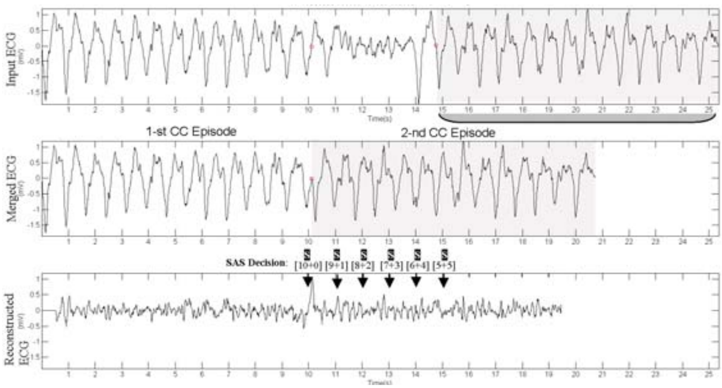


Fig. 8 VF corrupted by CC

Fig. 9 represents another VF signal corrupted by CC artefacts. The specific sharp waveform of the artefact, especially during the 2nd CC attempt leaves sharp residuals in the reconstructed signal. They compromise the SAS decision at [7s+3s] and [6s+4s]. However, all other analysis steps on both the linear and the non-linear segments are associated with correct SAS decision.

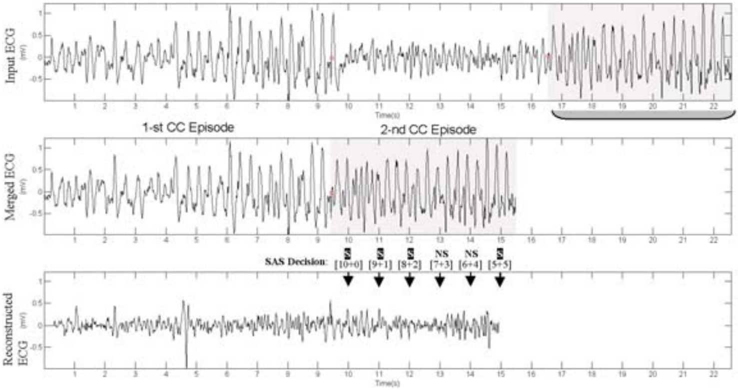


Fig. 9 VF corrupted by CC

4. CONCLUSIONS

Short duration 'hands-off' intervals with median duration of 4 seconds (quartile range between 3 and 5 seconds), interrupting each sequence of 30 CC cycles (15-20 seconds), are an important factor which have to be considered in the design of the ECG analysis process during CPR. Special SAS is designed to analyze the ECG rhythm in presence of CC artefacts by algorithms for frequency analysis and pattern matching, however, the problem of loss of these artefacts for several seconds may deteriorate the shock advisory decision. This study shows an application of the SAS for the analysis of non-linear, merged CC artifacts, taken before and after the CC pause. Different coupling intervals are tested [9s+1s], [8s+2s], [7s+3s], [6s+4s], [5s+5s], proving for all of them non significant difference ($p>0.05$) of the SAS accuracy compared to the linear segment [10s+0s]: ventricular fibrillation between 86% and 90.3%, normal rhythms between 88.4% and 93.5%, asystole between 80.4% and 87.3%. Several examples illustrate the performance of the SAS analysis process on various CC artefacts and ECG arrhythmias. A problem in a real application, however, remains the detection of CC pause onset/offset to form the non-linear signal.

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