

# Performance of Heart Rhythm Analysis during Chest Compressions in Out-of-Hospital Cardiac Arrest

Vessela Krasteva<sup>1</sup>, Irena Jekova<sup>1</sup>, Todor Stoyanov<sup>1</sup>, Sarah Ménétré<sup>2</sup>, Jean-Philippe Didon<sup>2</sup>

<sup>1</sup>Institute of Biophysics and Biomedical Engineering, Sofia, Bulgaria

<sup>2</sup>Schiller Médical SAS, Wissembourg, France

## Abstract

*This study aims to validate a shock advisory system in automated external defibrillators (AEDs) dedicated for ECG analysis during chest compressions (CC), guiding the rescuer to stop CC for rhythms which should be terminated by a defibrillation shock and to continue CC for non-shockable rhythms. The test-validation on a large database of out-of-hospital cardiac arrest interventions shows that the performance can be improved by increasing the duration of analysis. The combination of 3 successive analyses (delaying the decision to 14s after start of analysis) achieves sensitivity of 89.4% (135/151) – ventricular fibrillations, specificity of 98.7% (73/74) – normal sinus rhythms, 81.2% (1357/1671) – asystoles, 89.6% (566/632) – other non-shockable rhythms. Several examples are shown to illustrate the reconstructed ECG during CC that can be visually interpreted with certainty.*

*Improving specificity of ECG analysis during CC is of tremendous importance preventing against frequent false positive interrupting the rescuer and the patient CC-treatment.*

## 1. Introduction

Interrupting chest compressions (CC) by automated external defibrillators (AEDs) for a reliable rhythm analysis on an artifact free ECG can adversely affect hemodynamics during cardiopulmonary resuscitation (CPR) and can decrease resuscitation success rates in out-of-hospital cardiac arrest (OHCA) patients [1].

The amount of CPR interruptions could be decreased by running the AED rhythm analysis during CC in order to advise CPR stop only in case a shock is recommended. Chest compressions induce artifacts in ECG, which considerably affect the accuracy of conventional AED rhythm analysis algorithms, therefore new approaches for rhythm analysis during CPR have been recently developed. Major part of them relies on suppression of CC-artifacts by adaptive filtering (AF) before applying the conventional AED shock advice algorithms. AF uses

one or more reference channels correlated to the artifact interfering with ECG – multichannel recursive adaptive matching pursuit using compression acceleration, compression depth signal, thoracic impedance, ECG [2]; Least Mean-Square filter using the compression depth signal [3,4] and thoracic impedance [5]; motion artifact reduction system using the CPR force signal [6]; independent component analysis using additional ECG channels [7]. AF techniques using as a reference the CC spectral frequency estimated in a single ECG channel have also been proposed [8,9]. The specificity of such solutions is usually between 80-90%, which leads to unwanted CPR interruptions in OHCA.

This study aims to validate a rhythm analysis system based on assessment of time and frequency components of band-pass filtered raw and reconstructed ECG [10] with a large set of OHCA recordings during CC. The accuracy of the system is evaluated in terms of sensitivity and specificity respectively for stopping CC for rhythms which should be treated by a defibrillation shock and continuing CC for non-shockable rhythms.

## 2. ECG Database

The ECG database is collected with Fred Easy AEDs (Schiller Médical, France) used by the fire brigade of Paris in OHCA interventions in 2011. A subset of 2528 ECG strips from 596 patients is identified, including episodes during CC which are followed by noise-free AED analysis periods. Reviewers have annotated CC-episode boundaries (beginning of CC, end of CC) using observations of both ECG and impedance channel (IMP) artifacts. Then the rhythm during AED analysis is identified, including: 74 normal sinus rhythms (NSR), 1671 asystoles (ASYS), 632 other non-shockable rhythms (ONS), 151 ventricular fibrillations (VF). Assuming consistence of the ECG rhythm till 20s before the AED analysis period, these annotations are also considered for the preceding CC episode. All signals are recorded at sampling rate of 500 Hz. The ECGs are band-pass filtered (1 to 30 Hz) as supported by the AED input hardware circuits to remove offset and high-frequency noise.

### 3. Method

This is a test-validation study of an AED shock advisory system, which has been previously introduced for heart rhythm analysis during CC (SAS-CC) [10,11]. Using single channel ECG corrupted by CC-artifacts, the SAS-CC analysis process takes successive decisions by sliding a window of 10s in steps of 2s. The decisions are:

- To continue chest compressions ‘Cont-CC’ for non-shockable rhythms (NSR, ONS, ASYS).
- To stop chest compressions and prepare for shock ‘Stop-CC’ for shockable rhythms (VF).

The criteria and thresholds involved in the SAS-CC decision rule have been set during the training phase [10]. The test phase of this study is not dedicated to adjusting the decision rule but rather to independent assessment of the SAS-CC performance for different arrhythmias in realistic OHCA scenes during CPR by different rescuers.

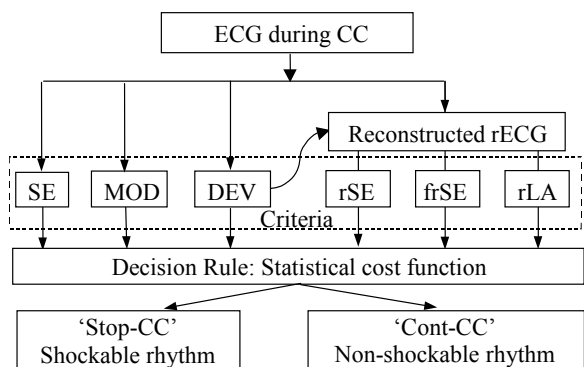


Figure 1. General diagram of SAS-CC.

Six ECG criteria are evaluated in SAS-CC (Figure 1).

Three criteria are derived by analysis of the input ECG:

- Signal Extrema (SE) – deflections from SE in narrow pass-band adjusted for QRS complexes enhancement.
- Level of modulation (MOD) – uniformity of magnitude and temporal features of SE in narrow pass-band adjusted for VF-waves enhancement.
- Deviation (DEV) – mean deviation of compression-to-compression ECG waveforms after band-stop filtering adjusted to suppress the basic CC-artifact patterns.

The DEV computation technique is used to suppress the mean waveform of the CC artifact component and to enhance ECG details, thus partially restoring the ECG rhythm under CC artifacts, named reconstructed ECG (rECG). Three criteria are estimated over rECG:

- Signal Extrema of reconstructed signal (rSE) – deflections from SE calculated over the raw rECG.
- Signal Extrema of filtered reconstructed signal (frSE) – deflections from SE calculated in narrow pass-band adjusted for QRS complexes enhancement in rECG.
- Low-Amplitude of reconstructed signal (rLA) – rating the amplitude of rECG either as extremely low-amplitude, long zero-line or normally ranged.

### 4. Results

The six SAS-CC criteria (SE, MOD, DEV, rSE, frSE, rLA) are statistically evaluated over all ECG strips of the test OHCA database within the 1<sup>st</sup> analysis window of 10s. Analysis of variance (one-way ANOVA) is applied to study the potential of each criterion to distinguish the non-shockable rhythm groups (NSR, ONS, ASYS) from the shockable rhythm (VF) – Figure 2.

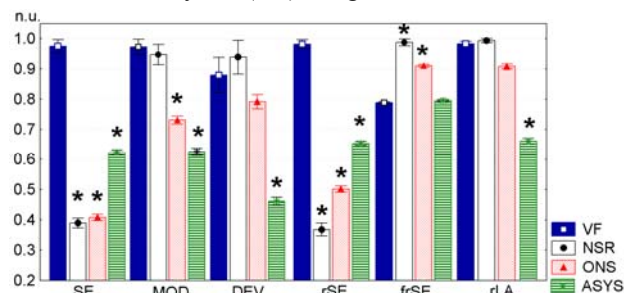


Figure 2. Mean±Standard error of six SAS-CC criteria over the test-validation database. \*p<0.05: Statistically significant differences of NSR, ONS, ASYS vs. VF.

Using all samples in the test OHCA database, three SAS-CC decisions ‘Cont-CC’/‘Stop-CC’ by the 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup> analyses are recorded and compared to the reference ECG annotations to derive specificity (Sp) for NSR, ONS, ASYS and sensitivity (Se) for VF. Table 1 summarizes two SAS-CC performances: 1<sup>st</sup> analysis decision taken at 10s; the combined majority decision among 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup> analyses, delayed to 14s.

The performance of the 1<sup>st</sup> analysis is improved by combining the decisions of 3 successive analyses:

- Sp for correct advice ‘Cont-CC’ is increased for: NSR by 1.4% points (pp) (97.3% to 98.7%); ONS by 4.9 pp (84.7% to 89.6%), ASYS by 4.8 pp (76.4% to 81.2%).
- Se for correct warning ‘Stop-CC’ is increased by 2.6 pp (from 86.8 to 89.4%) for VF.

Table 1. SAS-CC accuracy of the 1<sup>st</sup> and the combined decision evaluated for the test-validation OHCA database.

	VF	NSR	ONS	ASYS
1 <sup>st</sup> Analysis	86.8% (131/151)	97.3% (72/74)	84.7% (535/632)	76.4% (1277/1671)
Combined 1 <sup>st</sup> -3 <sup>rd</sup> Analyses	89.4% (135/151)	98.7% (73/74)	89.6% (566/632)	81.2% (1357/1671)

Figure 3 shows examples of SAS-CC performance on ASYS, ONS, VF rhythms – all analyses on the graphs (a,c,e) are correct; 10s analyses on (b,d,f) are erroneous, but corrected by the decisions of the next two successive analyses. The quality of the reconstruction could be verified by referring to the noise-free ECG signal visible after the annotation mark for End of CC (EoCC).

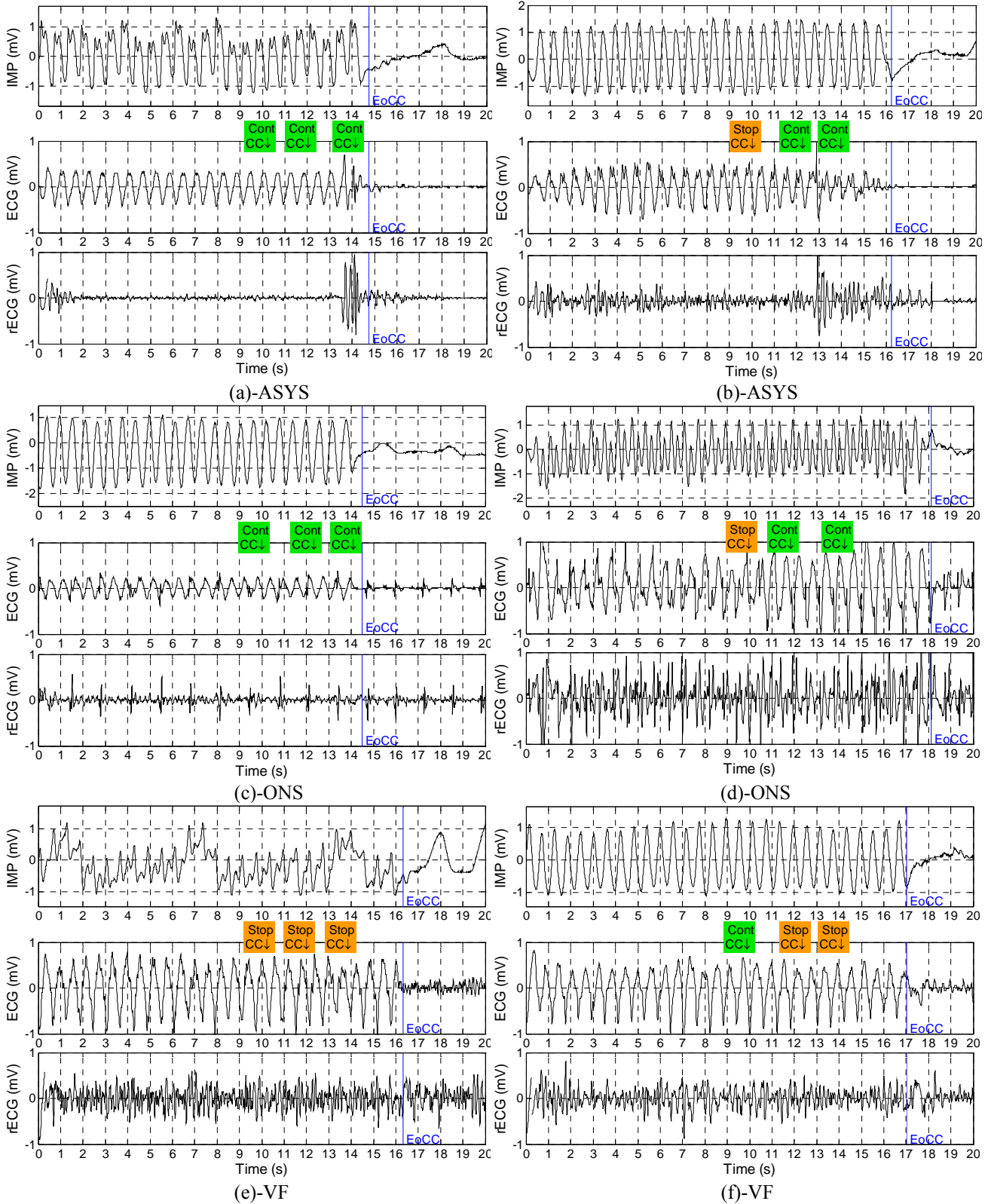


Figure 3. Examples illustrating the SAS-CC performance for ASYS(a,b), ONS(c,d), VF(e,f). The 1<sup>st</sup> trace is IMP channel; 2<sup>nd</sup> trace is ECG channel; 3<sup>rd</sup> trace is reconstructed ECG (rECG), which reproduces to some extent the ECG rhythm under CC artifacts. SAS-CC is run from the beginning of the 20s episode, taking the 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup> analysis decisions ('Cont-CC' or 'Stop-CC') at 10, 12, 14s. The noise-free ECG signal is seen after the annotation mark for End of CC (EoCC).

## 5. Limitations

The sample size of NSR, VF rhythms is below the minimal sample size defined by AHA [12].

## 6. Discussion and conclusions

This study validates an AED shock advisory system designed for analysis of the ECG rhythm during chest compressions using an independent test ECG dataset from OHCA interventions. Six SAS-CC criteria are calculated by using only the input ECG, each one found to significantly discriminate specific non-shockable rhythms vs. VF (Figure 2), i.e. rhythms with QRS complexes (NSR, ONS) are best distinguished by the signal extrema criteria (SE, rSE, frSE), while ASYS have significantly lower values of MOD, DEV, rLA criteria due to the predominantly uniform ECG waveform of compression-to-compression patterns and significantly lower amplitude of the reconstructed signal.

The present study shows that increasing both Sp/Se for decisions ‘Cont-CC’/‘Stop-CC’ is possible by extending the duration of analysis. Taking a combined majority decision of three successive analyses, i.e. delaying the decision by 4s, improves Se/Sp by 1.4-4.9 pp (Table 1). The reported Se is of the same order as other OHCA studies [4,8], while Sp is higher or comparable to [5,8] but not directly comparable to [4], which uses the same data for development and test, thus biasing accuracy at higher levels. Besides, the test sample size in our study is considerably larger than other studies (especially ASYS, ONS), thus validating the performance on thousand more cases of realistic OHCA scenarios. Nevertheless further improvements of the reliability of the rhythm diagnosis during CC are needed in order to fulfill the high AHA performance recommendations for noise-free ECG [12].

Figure 3 (a,b,d,e) show typical cases when CC artifacts are dissimilar in both ECG and IMP channels. This inconsistency does not influence the performance of SAS-CC (analyzing only ECG). Although rECG does not fully restore the underlying rhythm itself, ECG under CC can be visually interpreted with certainty: (i) the reconstructed ASYS contains low amplitude noise components close to the limits for asystole (Figure 3 a); (ii) the reconstructed ONS have visible QRS complexes, even if they differ from the waveforms of the noise-free ECG (Figure 3 c,d); (iii) the reconstructed VF signals are similar to the noise-free VF waves in frequency and amplitude (Figure 3 e,f). CC artifacts deviating from a periodical pattern waveform result in relatively large residuals (Figure 3b).

Improving Sp of rhythm analysis during CC periods is of great importance because it would prevent against frequent false interruptions of the rescuer, thus stopping the patient CPR treatment, known to result in lower rates of patient recovery and defibrillation success [1].

## References

- [1] Eftestøl T, Sunde K, Steen PA. Effects of interrupting precordial compressions on the calculated probability of defibrillation success during out-of-hospital cardiac arrest. *Circulation* 2002;105:2270–73.
- [2] Eilevstjønn J, Eftestøl T, Aase S, Myklebust H, Husøy J, Steen P. Feasibility of shock advice analysis during CPR through removal of CPR artefacts from the human ECG. *Resuscitation* 2004;61:131–41.
- [3] Irusta U, Ruiz J, de Gauna S, Eftestøl T, Kramer-Johansen J. A least mean square filter for the estimation of the cardiopulmonary resuscitation artefact based on the frequency of the compressions. *IEEE Trans Biomed Eng* 2009;56:1052–62.
- [4] Ayala U, Irusta U, Ruiz J, Gonzalez-Otero D, Alonso E, Mazeika R. A new shock advice algorithm designed to classify ECG signals during cardiopulmonary resuscitation. *Computing in Cardiology* 2012;39:25–8.
- [5] Aramendi E, Ayala U, Irusta U, Alonso E, Eftestøl T, Kramer-Johansen J. Suppression of the cardiopulmonary resuscitation artefacts using the instantaneous chest compression rate extracted from the thoracic impedance. *Resuscitation* 2012;83:692–8.
- [6] Berger R, Palazzolo J, Halperin H. Rhythm discrimination during uninterrupted CPR using motion artifact reduction system. *Resuscitation* 2007;75:145–52.
- [7] Granegger M, Werther T, Gilly H. Use of independent component analysis for reducing CPR artefacts in human emergency ECGs. *Resuscitation* 2011;82:79–84.
- [8] De Gauna S, Ruiz J, Irusta U, Aramendi E, Eftestøl T, Kramer-Johansen J. A method to remove CPR artefacts from human ECG using only the recorded ECG. *Resuscitation* 2008;76:271–8.
- [9] Amann A, Klotz A, Niederklapfer T, Kupferthaler A, Wether T, Granegger M et al. Reduction of CPR artifacts in the ventricular fibrillation ECG by coherent line removal. *BioMedical Engineering OnLine* 2010; 9:2.
- [10] Krasteva V, Jekova I, Dotsinsky I, Didon JP. Shock advisory system for heart rhythm analysis during cardiopulmonary resuscitation using a single ECG input of automated external defibrillators. *Ann Biomed Eng* 2010;38:1326–36.
- [11] Didon JP, Dotsinsky I, Jekova I, Krasteva V. Detection of shockable and non-shockable rhythms in presence of CPR artifacts by time-frequency ECG analysis. *Computers in Cardiology* 2009;36:817-20.
- [12] Kerber R, Becker L, Bourland J, Cummins R, Hallstrom A, Michos M, et al. Automatic external defibrillators for public access defibrillation: Recommendations for specifying and reporting arrhythmia analysis algorithm performance, incorporating new waveforms, and enhancing safety. *Circulation* 1997;95:1677–82.

Address for correspondence.

Vessela Krasteva  
Institute of Biophysics and Biomedical Engineering  
Acad. G. Bonchev str., bl.105, 1113, Sofia, Bulgaria  
[vessika@biomed.bas.bg](mailto:vessika@biomed.bas.bg)