COMPARISON OF SPECTRAL COMPONENTS OF CPR COMPRESSIONS AND VARIOUS SHOCKABLE AND NON-SHOCKABLE RHYTHMS IN ECG

Ivan Asenov Dotsinsky*, Irena Ilieva Jekova*,
Jean-Philippe Didon#, Vessela Tzvetanova Krasteva*

* Centre of Biomedical Engineering "Prof. Ivan Daskalov" - Bulgarian Academy of Sciences
Acad.G.Bonchev str. Bl.105, 1113, Sofia, Bulgaria, e-mail: vessika@clbme.bas.bg
Schiller Medical SAS, 4 rue L. Pasteur, F-67160 Wissembourg, France

This report is related to a preliminary study in support to the novel AED feature required, that is to analyse the ECG and propose shock advisory decision even during CPR. We investigated the frequency spectra of a large set of pure CPR compressions on asystole and real noise-free shockable and non-shockable ECG signals taken from out-of-hospital resuscitation interventions over 10 s episodes, as well as, over each single CPR cycle and heartbeat. The deviation of the spectral components of successive CPR cycles and various spectral parameters are estimated. Statistical analysis of the spectral characteristics allows to specify the most probable behavior of CPR and to design filters that minimally suppress the significant ECG frequency components and keep useful information for discrimination of shockable and non-shockable rhythms.

Keywords: ECG signal processing in AEDs, Cardio-Pulmonary massage, FFT

1. INTRODUCTION

Continuous cardiopulmonary resuscitation (CPR) is the best treatment of out-of-hospital cardiac arrests since it contributes to the sustained cerebro-vascular function until the arrival of an automatic external defibrillator (AED). The actual guidelines for resuscitation and use of AEDs require interruption of the CPR massage during automated analysis of the electrocardiogram (ECG) [1]. The chest compression artifacts originating mainly from the electrode-to-skin interface with possible components arising from the mechanical stimulation of the heart and thoracic muscles [2] could lead to false AED shock advisory decision. However, long interruptions of CPR result in lack of cerebral and myocardial blood flow and can significantly reduce the recovery rate of spontaneous circulation and the 24-hour survival rate [3,4]. It is expected that the future concepts in basic life support will enhance the CPR effect by allowing continuous CPR even during the ECG analysis process in AEDs. For this purpose the CPR artifacts should be effectively removed.

Recently many approaches on CPR artifacts suppression have been developed, based on high-pass filters with fixed coefficients [5], adaptive filters using the thoracic compressions as a reference signal [6], sophisticated adaptive approaches requiring up to four reference signals strongly correlated to the interference [7], etc. However, the problem is opened for building a CPR filter with minimal supression of the significant ECG frequency components. The optimal filter design could be defined after discovery of evidences for discrimination between the spectra of CPR and the different ECG arrhythmias.

2. METHODS

2.1. ECG Dataset

ECG episodes of 10 s were studied containing pure CPR artifacts, as well as various types of arrhythmia (Table 1). They all were extracted from a large database collected by trained paramedics during out-of-hospital resuscitation interventions with AEDs. The ECG signal is taken between the large self-adhesive electrodes on chest apex-sternum position for defibrillation which is equivalent to lead II. The pure CPR artifacts were considered only for CPR interventions on asystole. The noise free arrhythmia episodes, representative for 4 non-shockable and 2 shockable rhythms, were extracted during AED analysis when no artifacts from external interventions were present. A total number of 40 different cases per CPR and per rhythm category were investigated. All ECG signals are sampled at 500 Hz.

LABEL	TYPE	RHYTHM TYPE	DESCRIPTION	NUM
CPR	-	CPR on Asystole	Visible CPR artifacts followed at the end by isoelectric line of no electrical activity	40
NSR	Non-shockable	Normal sinus rhythm	P, QRS, T waves are visible	40
NR	Non-shockable	Normal rhythm	Ectopic beats, atrial fibrillation, bundle branch blocks and bradycardias	40
SVT	Non-shockable	Supraventricular tachycardia	Tachycardia with supraventricular origin and rate above 120 bpm	40
VTlo	Non-shockable	Slow ventricular Tachycardia	Tachycardia with ventricular origin and rate below 150 bpm	40
VThi	Shockable	Rapid ventricular tachycardia	Tachycardia with ventricular origin and rate above 150 bpm	40
VF	Shockable	Ventricular fibrillation	Coarse VF with amplitude above 0.25 mV	40

Table 1. Description of the ECG rhythms involved into analysis.

2.2. Signal processing

CPR signals

- *Step1*: Detection of CPR cycles – in-house developed algorithm based on continuous integration of all samples over 10 s episode and detection of zero-line crossings was used;
- *Step2*: Fast Fourier Transform (FFT) was applied to estimate two types of CPR spectra - (1) the spectra of each CPR cycle; (2) CPR spectra over 10 s episode.

Non-shockable rhythms (NSR, NR, SVT, VTlo)

- *Step1*: QRS detection - the algorithm described in [8] was applied.
- *Step2*: Extraction of heartbeats within a window around the R-peak (R): [R-0.3*RRmin; R+0.7*RRmin], where RRmin is estimated to be the minimal RR interval within the 10 s segment.
- *Step3*: Estimation of FFT of each individual heartbeat.

Shockable rhythms (VThi, VF)

- *Step1*: Detection of significant peaks by the designed algorithm in [9].
- *Step2*: Extraction of waves around the peaks by taking the half interval between two successive peaks.
- *Step3*: Estimation of FFT of each individual wave.

Additionally, all 10 s ECG strips were subjected to Short-Time Fourier Transform (STFT) to study the time-frequency domain behavior of CPR and arrhythmia. The spectrogram was obtained by applying a sliding Gaussian window with length of 400 ms. The frequency range was limited to the significant components up to 25 Hz.

3. RESULTS

Signal processing, time-frequency domain analysis and statistics were implemented in the software package MATLAB 7.0.

3.1. Spectra of CPR cycles

First, the spectrogram over 10 s ECG strips was derived to observe the time-frequency behavior of continuous CPR massage. Such spectrograms are depicted in Fig. 1 (b), showing the well visible, almost periodical nature of sustained CPR compressions in respect to frequency and intensity.

Secondly, we derived valuable quantitative measures of the individual CPR cycles, including rate of compressions and different FFT parameters (defined in Table 2). On one hand, we evaluated the mean value of the parameters, averaged over all CPR cycles. On the other hand, we evaluated the standard deviation of some parameters, informative about variations over successive CPR cycles within 10 s episode. The later is important to predict the periodicity of CPR.

Two typical examples of CPR spectra are shown in Fig. 1 - the mean spectra of all CPR cycles is bolded in (c), FFT for the full 10 s episode is shown in (d).

PARAMETER	DESCRIPTION	UNIT	MEAN	MIN	MAX	STD.DEV.
CPRFreq(Mean)	Averaged freq. of successive CPR cycles	Hz	2.35	1.70	3.33	0.35
CPRRate(Mean)	Averaged rate of successive CPR cycles	bpm	140.9	101.7	200.0	20.8
CPRRate(Std)	Standard deviation of the rate of successive CPR cycles in 10 s episode	bpm	5.11	1.40	30.0	5.28
CPRRate(Std-Norm)	CPRRate(Std) normalized to the averaged CPR rate in 10 s episode	%	7.38	2.54	33.05	6.14
FFTPeakFreq(Mean)	Averaged freq. corresponding to the maximal peak in FFT of one CPR cycle	Hz	2.14	1.54	3.06	0.35
FFTPeakFreq(Std)	Standard deviation of FFTPeakFreq(Mean) estimated for all CPR cycles in 10 s episode	Hz	0.10	0.06	1.47	0.23
FFTPeakAmpl(Std)	Standard deviation of the peak amplitude in FFT for all CPR cycles in 10 s episode	Norm.	0.14	0.03	0.29	0.06
FFTFreqLo25%(Mean)	The lowest freq. for which the mean FFT spectra of all CPR cycles in 10 s is higher than 25 % of the peak amplitude	Hz	0.44	0.32	0.69	0.07
FFTFreqHi25%(Mean)	The highest freq. for which the mean FFT spectra of all CPR cycles in 10 s is higher than 25 % of the peak amplitude	Hz	6.27	3.51	12.54	1.95
FFTFreqLo75%(Mean)	The lowest freq. for which the mean FFT spectra of all CPR cycles in 10 s is higher than 75 % of the peak amplitude	Hz	1.24	0.94	1.97	0.20
FFTFreqHi75%(Mean)	The highest freq. for which the mean FFT spectra of all CPR cycles in 10 s is higher than 75 % of the peak amplitude	Hz	3.35	2.36	5.58	0.64

Table 2. Parameters estimated for the CPR cycles

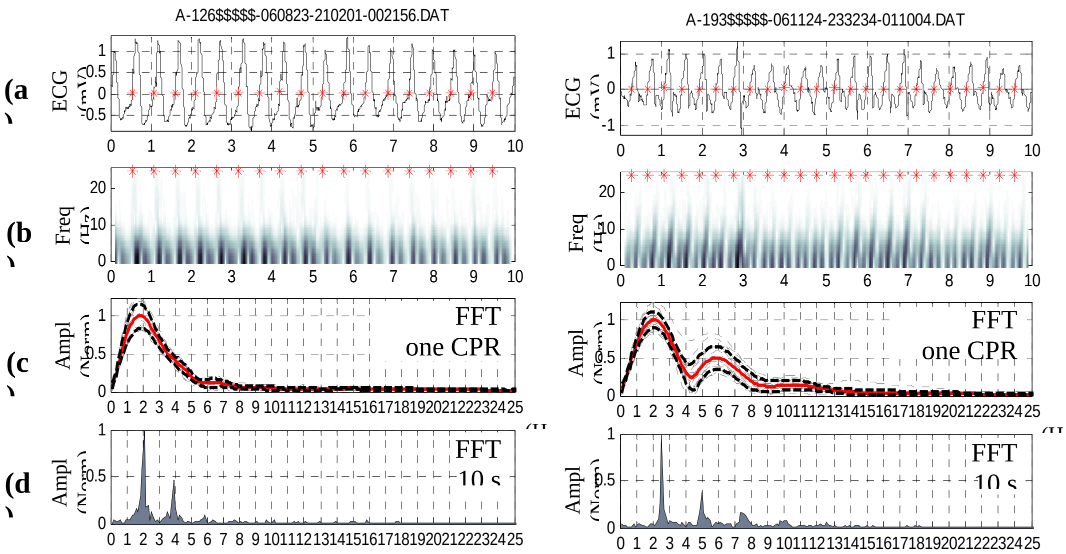

Figure 1. Two examples of 10 s CPR signals: (a) CPR in ECG;''-detected CPR cycles; (b) The spectrogram estimated by STFT; (c) FFT of all CPR cycles; the mean FFT is represented by bolded line, the mean FFT ± Std is represented by bolded-dashed line; (d) FFT estimated over the full 10 s episode.*

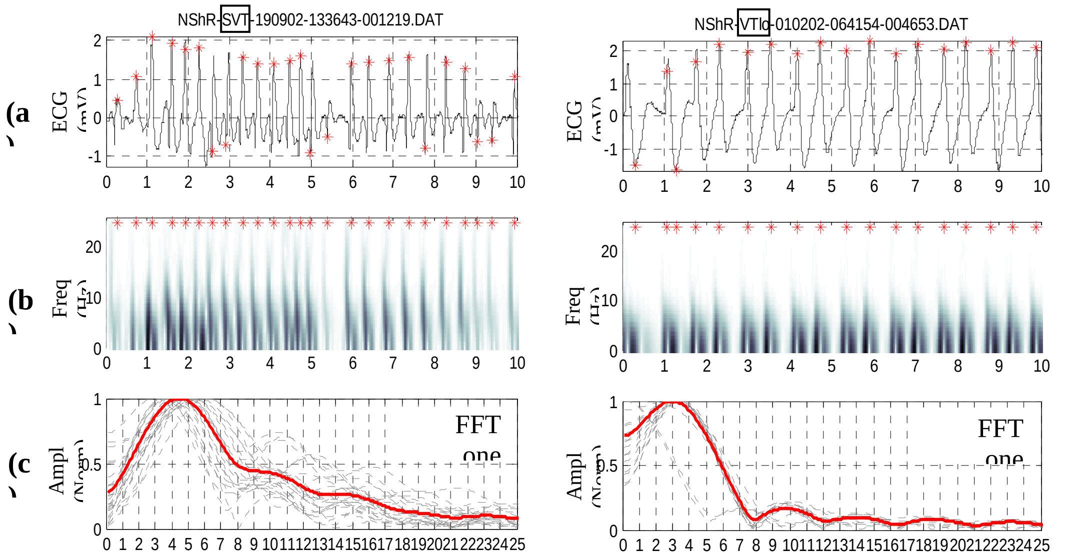

Figure 2. Examples of 10 s episodes of Non-shockable rhythms. (a) ECG;'' - detected QRS; (b) The spectrogram estimated by STFT; (c) FFT of all hearbeats is depicted by dashed lines; the mean FFT is represented by bolded line.*

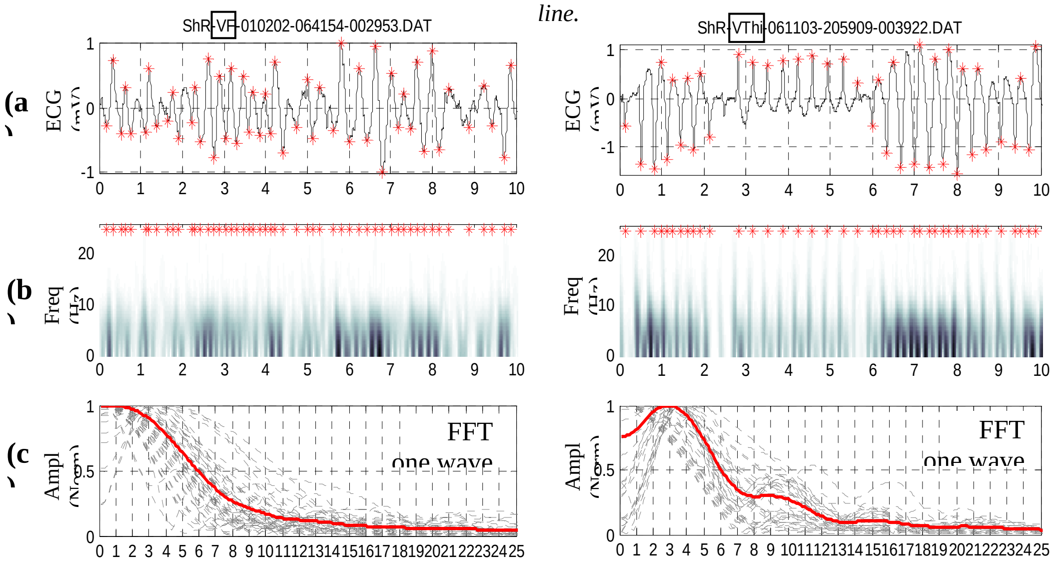

Figure 3. Examples of 10 s episodes of Shockable rhythms. (a) ECG;'' - detected waves; (b) The spectrogram estimated by STFT; (c) FFT of all waves is depicted by dashed lines; the mean FFT is represented by bolded*

3.2. Mean spectra of non-shockable/shockable arrhythmia versus CPR

Fig. 2, 3 represent two examples of non-shockable and shockable arrhythmia with calculated spectrogram and FFT of each individual heartbeat/wave. Mean FFT was derived for each 10 s episode as shown by the bolded line in Fig. 2,3 (c).

Statistical analysis was applied to calculate the mean spectra for the different rhythm categories and CPR, involving 40 cases for each group - see Fig. 4.

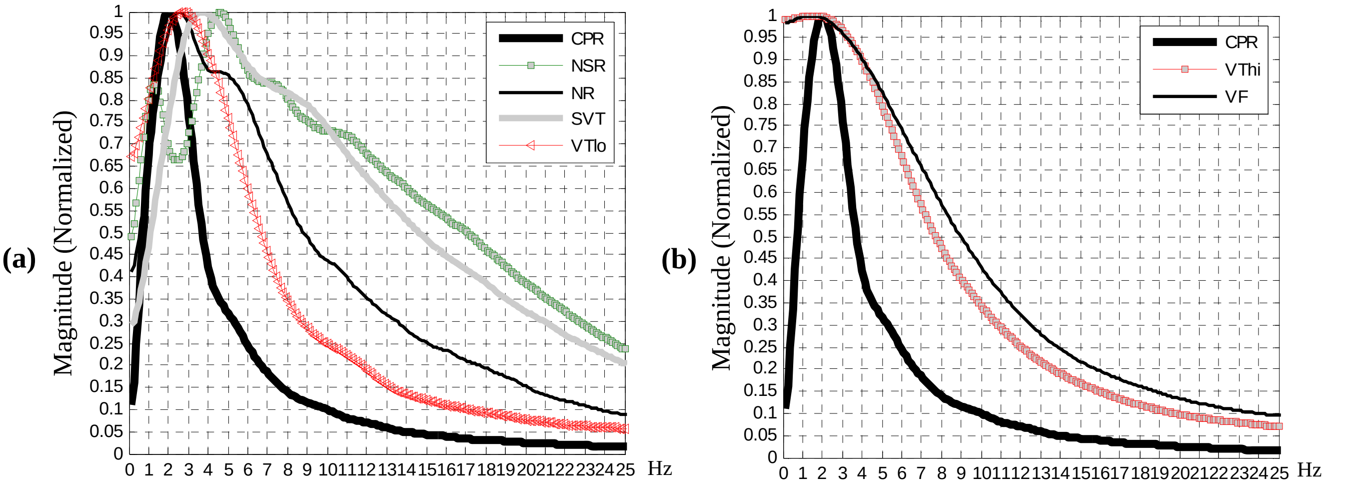

Figure 4. Mean FFT spectra of: (a)CPR and Non-shockable rhythms; (b) CPR and Shockable rhythms.

PARAMETER	CPR	NSR	NR	SVT	VTlo	VThi	VF
FFTPeakFreq (Hz)	2.1	4.1	3.4	5.0	2.5	1.2	1.6
FFTFreqHi50% (Hz)	4.1	13.2	8.4	13.5	6.6	7.9	9.2
FFTFreqHi20% (Hz)	6.8	23.9	15.1	22.1	10.8	13.2	15.1

Table 3. Parameters estimated from the mean spectra of the different rhythm categories and CPR.

We estimated the difference between the mean spectra of each rhythm category and CPR (Fig. 5), to find evidences for their discrimination in the frequency domain.

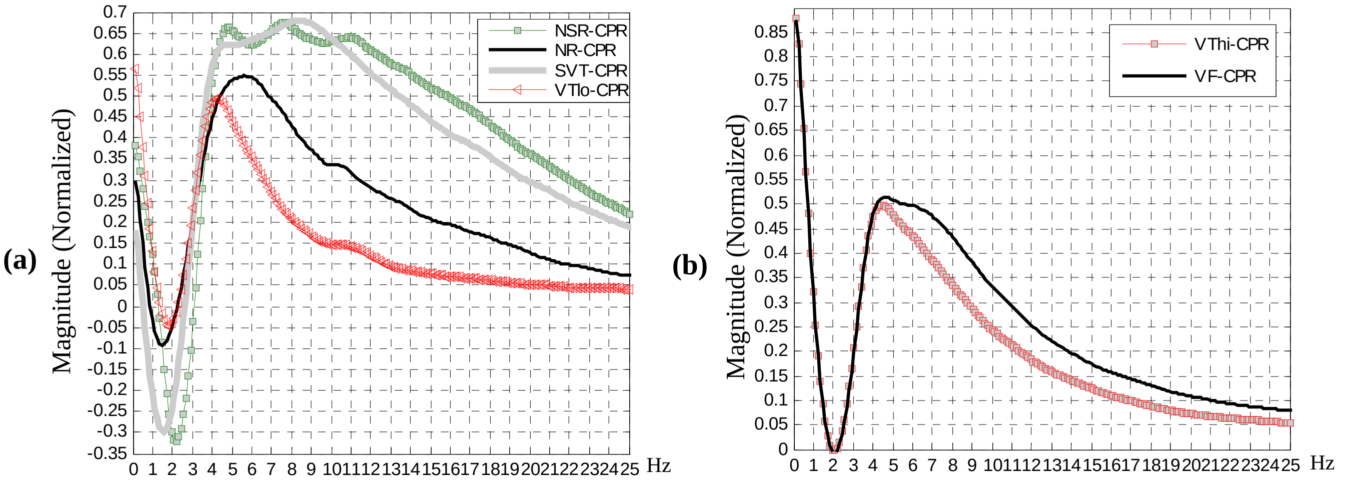

Figure 5. Mean FFT spectra difference of: (a) Non-shockable rhythms and CPR; (b) Shockable rhythms and CPR

PARAMETER	NSR	NR	SVT	VTlo	VThi	VF
FFTPeakFreq (Hz)	7.7	5.6	8.4	4.3	4.4	4.5
FFTFreqLo50% (Hz)	3.9	4.3	3.7	3.9	3.9	3.9
FFTFreqHi50% (Hz)	16.5	7.2	13.8	4.8	5.5	6.8
FFTFreqLo20% (Hz)	3.4	3.1	3.1	3.1	3.1	3.1
FFTFreqHi20% (Hz)	25.5	15.4	24.3	8.2	11.4	13.8

Table 4. Parameters estimated from the difference spectra of the rhythm category and CPR.

4. Discussion and Conclusions

Spectral periodicity of CPR cycles – The spectrogram (Fig.1b) shows the trained operator's ability to maintain periodic compressions in rate, frequency and amplitude. The deviation of the CPR rate is 7.4 % (5.1/140 bpm), the deviation of FFTPeakAmpl is 14 %, and FFTPeakFreq is less sensitive with jitter of about 0.1 Hz/2.14 Hz.

CPR spectrum *(10 s vs. CPR cycles)* – CPR spectrum derived for 10 s is showing maxima only at CPR rate and its harmonics (Fig.1d). Typically, the 10 s FFT does not match the FFT of one CPR cycle (Fig.1c), which is wider and corresponds to the deviation of the CPR waveform from the sinusoidal wave. Therefore, a notch filter adjusted to the CPR rate, is not adequate to fully suppress the CPR artifact.

CPR spectral components – As estimated from FFT of the individual CPR cycles, we found the following characteristics: FFTPeakFreq = 2.1 Hz; the bandwidth (1.2 ÷ 3.4) Hz, which is recommended to extract major components of the CPR waveform; the bandwidth (0.4 ÷ 6.3) Hz, containing influential CPR components.

Spectral components of arrhythmia vs. CPR – the main task is to find frequency bands, for which the overlapping between CPR and ECG spectra is minimal. At the following central frequency and bands we found the most distinguished spectra of each rhythm category: NSR (7.7 Hz, 3.9 ÷ 16.5 Hz), NR (5.6 Hz, 4.3 ÷ 7.2 Hz), SVT (8.4 Hz, 3.7 ÷ 13.8 Hz), VTlo (4.3 Hz, 3.9 ÷ 4.8 Hz), VThi (4.4 Hz, 3.9 ÷ 5.5 Hz), VF (4.5 Hz, 3.9 ÷ 6.8 Hz). If we assume ECG superimposed with CPR, a high-pass filter at 6.3 Hz (above the influential CPR components), is suitable to enhance the QRS complexes of non-shockable rhythms with the highest frequency content, i.e. NSR, SVT and NR. Since VTlo and VThi complexes, and VF-waves fall within the CPR frequency band, one could assess the outputs of 3 band-pass filters adjusted at the specific frequency band of each arrhythmia to find evidences for the existence of typical components distinctive for the respective arrhythmia.

Acknowledgements: This study has been supported by Schiller AG.

5. References

[1] Handley A.J., R. Koster, K. Monsieurs, G.D. Perkins, S. Davies, L. Bossaert, *European Resuscitation Council Guidelines for Resuscitation 2005 – Section 2. Adult basic life support and use of automated external defibrillators*, Resuscitation, Vol 76, pp S7-23, 2005.

[2] Fitzgibbon E., R. Berger, J. Tsitlik, H.Halperin, *Determination of the noise source in the electrocardiogram during cardiopulmonary resuscitation*, Crit Care Med, Vol. 30(Suppl.4), pp S148-153, 2002.

[3] Eftestol T., K. Sunde, P.A. Steen, *Effects of interrupting precordial compressions on the calculated probability of defibrillation success during out-off-hospitals cardiac arrest*, Circulation, Vol. 105, pp 2270-2273, 2002.

[4] Yu T., M.H. Weil, W. Tang, S. Sun, K. Klouche, H. Povoas, J. Bisera, *Adverse outcomes of interrupted precordial compression during automated defibrillation*, Circulation, Vol. 106, pp 368-372,2002.

[5] Strohmenger H., K. Lindner, A. Keller, I. Lindner, E. Pfenninger, *Spectral analysis of ventricular fibrillation and closed-chest cardiopulmonary resuscitation*, Resuscitation, Vol. 33, pp 155-161, 1996.

[6] de Gauna S.R., J. Ruiz, U. Irusta, E. Aramendi, A. Lazkono, J.J. Guttierez, *CPR artefact removal from VF signals by means of an adaptive Kalman filter using the chest compression frequency as reference signal*, Computers in Cardiology, Vol. 32, pp 175-178, 2005.

[7] Aase S.O., T. Eftestol, J.H. Husoy, K. Sunde, P.A. Steen, *CPR artefact removal from human ECG using optimal multichannel filtering*, IEEE Trans. Biomed. Eng., Vol. 47(11), pp1440-1449, 2000.

[8] Iliev I., V. Krasteva, S. Tabakov, *Real-time detection of pathological cardiac events in the electrocardiogram,* Physiol. Meas., Vol. 28, pp. 259-276, 2007.

[9] Krasteva V., I. Jekova, *Assessment of ECG frequency and morphology parameters for automatic classification of life-threatening cardiac arrhythmias,* Physiol. Meas.**,** Vol. 26, pp 707-723, 2005.