NOISE DETECTION ALGORITHM FOR AUTOMATIC EXTERNAL DEFIBRILLATORS

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Nowadays the application of automatic external defibrillators (AEDs) becomes a widespread practice for early treatment of out-of-hospital cardiac arrest patients. A reliable recognition of life-threatening cardiac arrhythmias is required. However, it may be impeded by artifacts, which compromise the quality of the electrocardiogram (ECG). The aim of this study was to develop software procedures for detection of some typical for AED application artifacts, such as: (i) amplifier saturation; (ii) baseline wander; (iii) single steep and high-amplitude artifacts; (iv) tremor. The developed real-time operating procedures were synchronized with the implemented algorithm for ventricular fibrillation detection. Thus, the in-time detection of significant artifacts would prevent from a compromised shock-advisory decision. The presented algorithm was developed in Matlab environment. It was tested with ECG recordings from an out-of-hospital database, which contains various types of noises and different arrhythmias.

Keywords: ECG analysis, shock advisory algorithms, arrhythmias, artifacts

1. INTRODUCTION

Nowadays the application of automatic external defibrillators (AEDs) becomes a widespread practice for early treatment of out-of-hospital cardiac arrest patients. To realize the goal of providing access to AEDs for use by first responders without extensive medical training, the device used must be able to accurately assess the cardiac state of the patient, to detect life-threatening arrhythmias and to make an appropriate therapy decision [1]. An AED has to make its decision on the basis of the electrocardiogram (ECG), obtained by only two adhesive electrodes with variable quality of the electrode contacts and variable positioning on the patient's chest. Since no information about pulse or respiration is fed into the device, the reliable and accurate detection of life-threatening cardiac arrhythmias, only from the surface ECG, is a rather difficult task. It can be further complicated in the presence of noise artifacts overlapping with the analyzed signal. This may lead to inaccurate ECG waveform analysis and wrong shock advisory decision [2]. Artifact is an electrical signal induced in the ECG that is unrelated to the heart signal. Sources of artifact can be characterized as controllable or non-controllable by the responder.

- Controllable artifacts include signals resulting from directly touching the pads, moving the patient, cardiopulmonary resuscitation (CPR), transportation, radio transmissions, etc.
- Non-controllable artifacts may be caused by electrical interference, patient seizures, gasping (agonal respiration), an implantable pacemaker, ect.

A well-designed defibrillator should be capable of correctly discriminating between the actual cardiac signal and significant artifacts, which corrupt the ECG signal to such an extent that rhythm analysis and appropriate defibrillation treatment decisions are compromised. When the artifact detection algorithm does encounter artifact that corrupts the ECG signal sufficiently to interfere with analysis, the AED should alert the user by voice and visual prompts to assist in troubleshooting the problem. For example, the defibrillator should give a voice prompt saying "Analyzing interrupted - Do not touch the patient." or "Analyzing interrupted - Stop all motion." This helps the user to identify the possible source of the artifact so that corrective action can be taken swiftly, saving valuable time for early treatment [3].

Several techniques have been proposed for effective reduction of noise artifacts in ECG signals by adaptive filtering and other complicated procedures [4,5] but they are inapplicable for AEDs because a QRS reference and a multi-lead analysis are applied. Generally the build in AEDs signal preprocessing module includes: (i) high-pass filter with cut-off frequency of 0.67 Hz (up to 1 Hz) to suppress the baseline drift; (ii) a low-pass filter with cut-off frequency of about 30 Hz to reduce muscle noise, and (iii) a comb filter to eliminate the power-line interference. However, this ECG 'monitor-type' filtration [6] is not sufficient to reject the wide variety of high-amplitude artifacts, which are commonly induced during out-of-hospital emergency interventions and have spectral components overlapping with the pure ECG signals.

The aim of this study was to develop software procedures for detection of some typical for AED application artifacts, such as: (i) amplifier saturation; (ii) baseline wander; (iii) single steep and high-amplitude artifacts, which could compromise the correct ECG wave detection in [7]; (iv) tremor with low signal-to-noise ratio. The developed real-time operating procedures were synchronized with the previously implemented algorithm [7] for fully automatic defibrillators. Thus, the in-time detection of significant artifacts would prevent from a compromised shock-advisory decision and would alarm the operator to provide better ECG acquisition conditions.

2. METHOD

2.1 ECG Signals

The ECG signals were selected from a large database of ECG recordings, which were collected by emergency teams during application of automatic external defibrillators (AEDs - FRED, Schiller-Medical SA, France) in real out-of-hospital cardiac arrest incidents. The original signals were converted to 12-bit resolution and sampling frequency of 250 Hz in accordance to the format of public ECG databases. The analysis involved 10s ECG segments, which were classified by biomedical engineer in two general groups – Group 1 with noise free signals and Group 2 with noisy signals. Group 1 contains about 2700 epochs of various non-shockable and shockable arrhythmias, which were previously used for testing of the shock advisory algorithm [7]. The signals in group 2 (about 180 epochs) were divided according to the noise type, as follows: amplifier saturation (Sat), baseline wander (Blw), single steep and high-amplitude artifacts (Noise), electro-myographic (tremor) noise (Emg).

2.2 ECG acquisition

The single-channel ECG signals are acquired through large self-adhesive electrodes placed in standard apex-sternum position for defibrillation (fig.1a). Usually the data are sampled at 250 Hz or 500 Hz, 8-bit to 12-bit amplitude resolution with standard analog filtering of 1-30 Hz 'monitor-type' ECG bandwidth. Since cardiac incidents are usual for patients with implantable pacemakers, the AED input has build-in circuit for detection of pacemaker pulse artifact. This circuit generates synchro-pulse to disable the AC amplifier input during the high-voltage steep-slope PACE pulse and to synchronize the digital PACE pulse preprocessing.

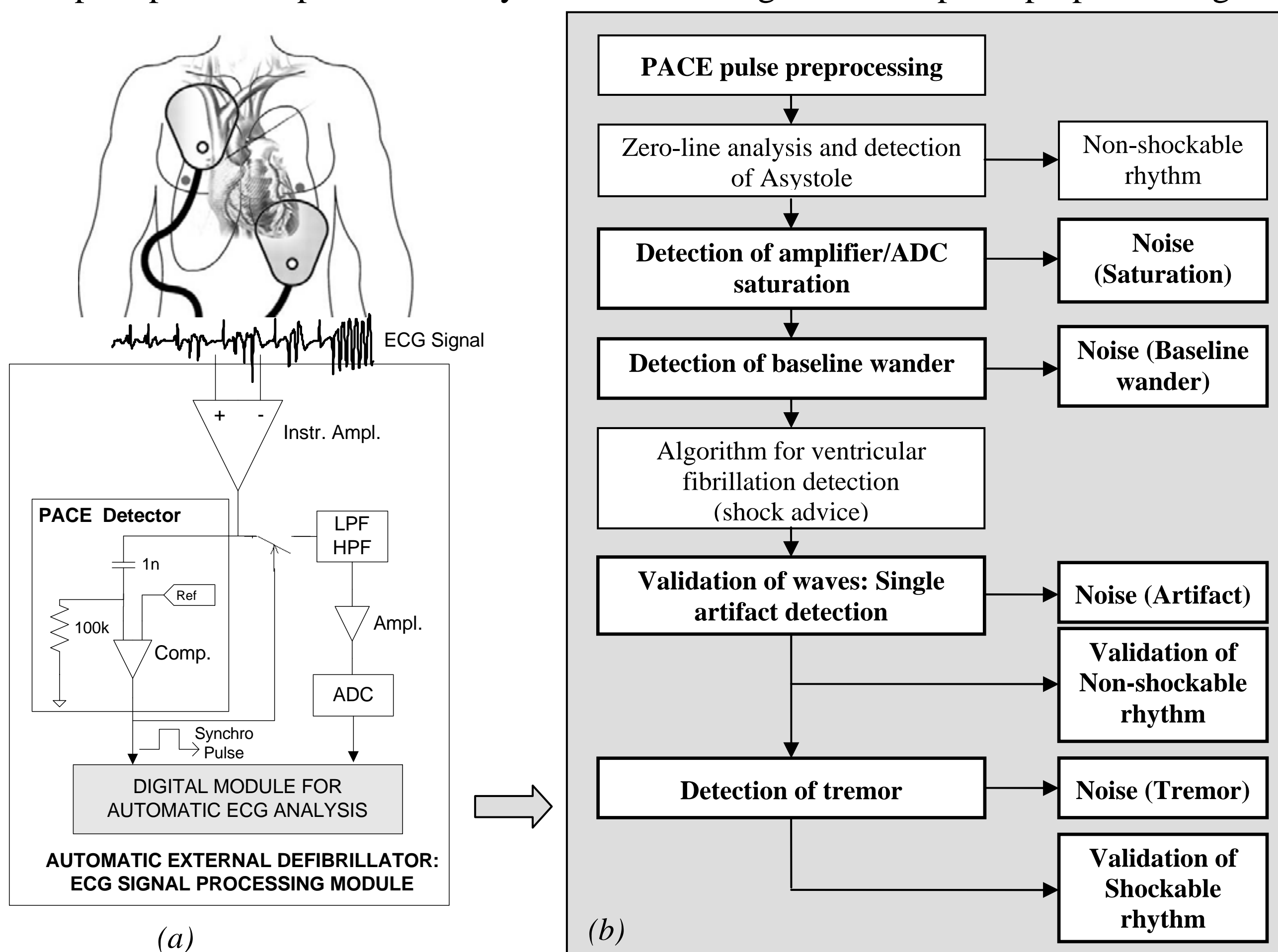

Fig. 1. (a) ECG signal acquisition in AEDs; (b) Algorithm for automatic ECG analysis in AEDs

2.3 Algorithm for noise detection

The digitized ECG signals were analyzed in 10s segments, following the algorithm in fig.1b. We will discuss in details the developed noise detection procedures, which are presented in bolded blocks.

• ***PACE pulse preprocessing***. The pacemaker pulse artifact during 'loss of capture' in VF (heart fibrillates and does not respond to the pacing pulse stimulus), poses a particular problem as its detection may inappropriately be interpreted as a normal rhythm. Therefore, the position of the PACE pulse should be recognized by the PACE Detector synchro-pulse and an identification mark should be stored in the ECG recording. For example, identification 0x7FF for 10 samples (20 ms) is suitable.

During analysis the algorithm replaces these 10 identification samples with interpolation between the signal samples just before and just after the marks. Thus the signal supplied for the next analysis steps is uninterrupted by PACE pulse artifacts.

• ***Detection of amplifier/ADC saturation***. The artifacts induced by touching the pads, bad electrode contact, patient movement, CPR, defibrillation shock, etc. influence the ECG channel. Usually this produces a high-voltage steep-slope signal, which is probably to result in amplifier saturation and loose of information about the true ECG signal. Moreover, the false artifact samples might compromise the correct ECG wave detection. Therefore, it is required to disable the ECG analysis during saturation artifact or to warn the operator to prevent against these controllable artifacts. The algorithm is designed to recognize the amplifier/ADC saturation by detection of three consecutive samples exceeding a predefined saturation level (+/- 2000 samples) – see fig.2.

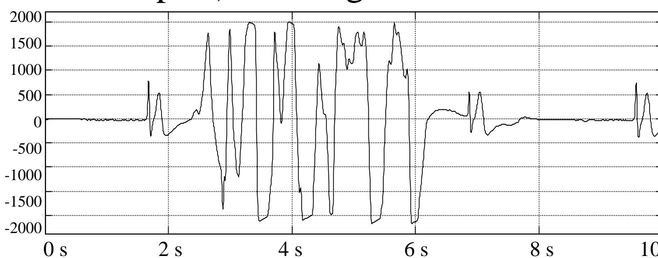

Fig.2 Amplifier/ADC saturation noise

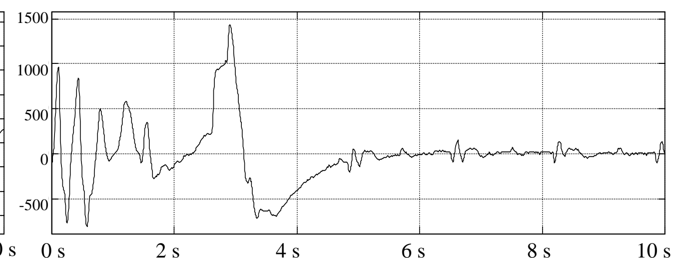

Fig.3 Baseline wander noise

•***Detection of baseline wander*** – Occasionally, the patient movement during transportation or CPR, the deep gasping, the slow amplifier recover after shock, etc. induce baseline wander in the ECG channel. The absence of zero-line crossings blocks the detection of positive and negative waves thus compromising the analysis. In order to provide stable ECG recording, the AED should warn the rescuer to eliminate the controllable sources of 'Blw'. The developed noise detection algorithm recognizes 'Blw' when the ECG signal exceeds $\pm150\ \mu V$ for more than 1.5 s (fig.3).

• ***Validation of waves: Single artifact detection -*** A single steep and high-amplitude artifact (fig.4) may halt the detection of ECG waves in the 10s interval because the amplitude and the slope thresholds are extremely increased. Therefore, the output of the wave detection algorithm (the peaks marked with '•' in Fig.4) must be verified. The verification is based on the following amplitude and slope thresholds:

- *ThrMax_2s, ThrMin_2s* = 2*(mean value of the maximal/minimal ECG signal amplitudes (*MaxAmpl_2s*(*i*), *MinAmpl_2s*(*i*)) within 2 s (*i=1,2..,5*));
- *ThrSlope_2s* = 2*(mean value of the maximal ECG signal slope (*MaxSlope_2s(i)*) within 2 s (*i=1,2..,5*));
- *ThrPosPeaks, ThrNegPeaks* = 2*(mean value of the positive/negative peaks, which are detected by the shock advisory algorithm).

The developed procedure for artifact detection applies the following criteria for comparison between the defined above amplitude and slope thresholds:

Artifact detection (Criterion 1):

$$\mathbf{IF}\left|\begin{array}{l}(ThrPosPeaks > 1.1*ThrMax_2s)\ OR\ (ThrNegPeaks < 1.1*ThrMin_2s)\\ MaxSlope_2s(i) > 1.2*ThrSlope_2s\end{array}\right.$$, where i=1,2,..5

Artifact detection (Criterion 2):

$$\textbf{IF}\left|\begin{array}{l} ThrPosPeaks > 1.1 * ThrMax_2s \\ MaxAmpl_2s(i) > ThrMax_2s \\ MaxSlope_2s(i) > ThrSlope_2s \end{array}\right.$$

Artifact detection (Criterion 3):

$$\textbf{IF}\left|\begin{array}{l} ThrNegPeaks < 1.1 * ThrMin_2s \\ MinAmpl_2s(i) < ThrMin_2s \\ MaxSlope_2s(i) > ThrSlope_2s \end{array}\right.$$

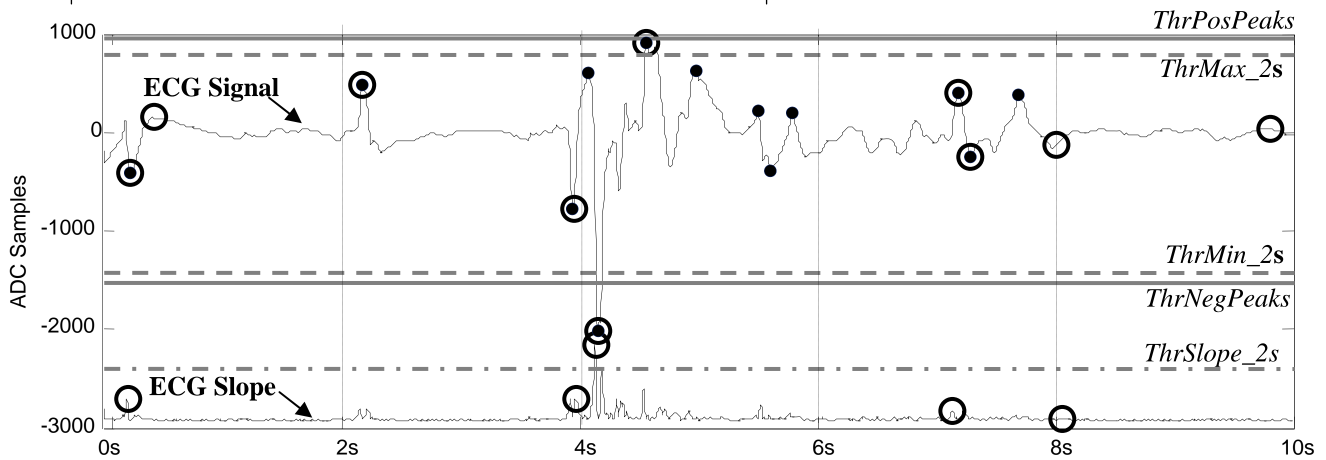

Fig.4. Single artifact detection by amplitude and slope threshold criteria. The thresholds are calculated using the following ECG peaks: '•' – peaks detected by wave detection algorithm; 'o' – Amplitude and Slope extremums within each 2 s interval.

• ***Detection of tremor*** – The 'Emg' artifacts in ECG are quite common in patients with uncontrollable tremor. They are due to muscle action potentials and are visible as irregular superimposed signal fluctuations in the ECG signals. Attempts at low-pass filtering out the tremor were only partially successful due to considerable overlapping of the frequency spectra of ECG and EMG signals. Therefore, the algorithm must alert for significant EMG interference, which predisposes to false detection of multiple waves, i.e. erroneous detection of shockable rhythms. The developed algorithm for detection of tremor recognizes 'Emg' artifact by assessment of the signal-to-noise ratio. It is calculated for the total 10 s ECG segment according to:

$$SNR = (\sum 'Signal'\, samples)/(\sum 'Tremor'\, samples),$$

where *'Signal' sample* and *'Tremor' sample* are ECG signal extremums, which are classified according to a time criterion, i.e. intersample distance less than 50 ms is associated with *'Tremor' sample* otherwise a *'Signal' sample* is counted. When $SNR<3$, we consider that the ECG epoch contains tremor with significant amplitude (fig.5a) that may impede the correct signal analysis. When $SNR>3$, we consider that the noise components will not influence the automatic ECG analysis (fig.5b).

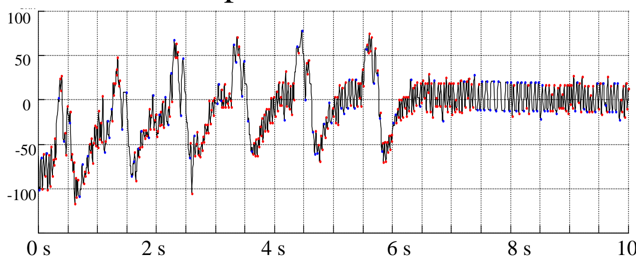

Fig.5a SNR=0.562: the tremor is detected

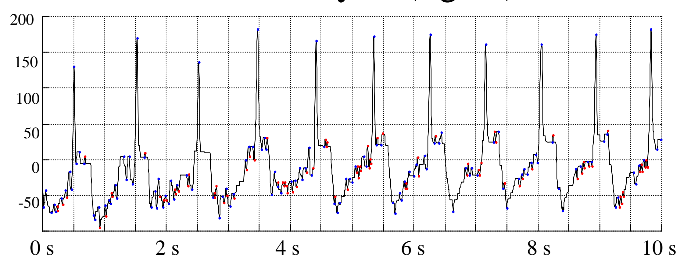

Fig.5b SNR=6.45: the tremor is not detected

3. RESULTS AND DISCUSSION

The automatic ECG analysis, including the algorithm for ventricular fibrillation detection (shock advice) [7] and all noise detection procedures, was developed and tested in Matlab environment. The noise detection algorithm (section 2.3) was tested with all out-of-hospital ECG signals (section 2.1). The results are presented in table1.

	Group 1 - Noise free signals		Group 2 - Noisy signals		
	Correct	Error	Correct	Error 1	Error 2
Number	2686	34	158	12	6
Accuracy	98.8 %	1.2 %	89.8 %	6.8 %	3.4 %

Table 1. Testing of the Noise detection algorithm. 'Correct' – correctly recognized ECG epochs in Group 1 and Group 2; 'Error' - the noise free ECG epochs, which were erroneously classified in Group 2; 'Error 1' – not detected noise in noisy signals which, however, does not impede the correct shock decision;'Error 2' – not detected noise in noisy signals which compromises the correct shock decision.

Despite of the simplicity of the noise detection procedures (designed for real-time operation) they provided a reliable protection against artifacts, which might compromise the automatic ECG analysis. Although the artifacts were not successfully detected in 10 % of the noisy signals, only 3.4 % were crucial for the correct shock advisory decision. Noise detection failures were due to similarity between some artifacts and the typical QRS complexes (or fibrillation waves), considering their amplitudes, slopes and durations. Moreover, the frequent appearance of the artifacts within the 10s ECG segment is an impeding factor, since the artifacts seem to be the peaks for calculation of the thresholds *ThrMax_2s, ThrMin_2s, ThrSlope_2s*.

False noise recognitions were observed in only 1.2 % of all noise free signals (34 of 2720 cases), mostly due to saturations of short duration within the extreme R-peaks of some ectopic beats. Another problem was the interpretation of the rare QRS complexes of the agonal rhythms as single artifacts in case of unstable zero-line and zero-line detection failure. However, most of the problematic rhythms were non-shockable and the false noise alarm would not change the shock advisory decision.

The operation of the noise detection procedures on different levels improves the accuracy for detection of life-threatening arrhythmias in [7].

5. REFERENCES

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