

Validation of Arrhythmia Detection Library on Bedside Monitor Data for Triggering Alarms in Intensive Care

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Abstract

False Intensive Care Unit (ICU) alarms induce stress in both patients and clinical staff and decrease the quality of care, thus significantly increasing both the hospital recovery time and re-hospitalization rates. Therefore, PhysioNet/CinC Challenge 2015 encourages the development of algorithms for the analysis of bedside monitor data for robust detection of life-threatening arrhythmias. We participated in the Challenge with: (i) a closed source implementation of Arrhythmia Detection Library (ADLib, Schiller AG), including modules for lead quality monitoring, heartbeat detection, heartbeat classification and ventricular fibrillation detection; (ii) an open source Pulse Wave Analysis Module for verification of the hemodynamic status based on arterial blood pressure and photoplethysmogram signals; (iii) an open source Alarm Decision Module for final alarm rejection/validation.

Our best scored entry in the real-time event is: score 79.41%, with 93%/83% true positive/negative rates. The average/max running time is 12.5/29.5% of quota.

1. Introduction

There are studies reporting that only 2% to 9% of alarms in the Intensive Care Unit (ICU) are important for patient management [1], 6% to 40% are true but clinically insignificant, while ICU false alarms are prevalent with rates as high as 86% [2]. False alarms mainly induce stress in both patients and clinical staff [3,4] and decrease the quality of care [5] that is reported to significantly increase both the hospital recovery time [3] and re-hospitalization rates [6].

The bedside monitoring systems rely on real-time automated ECG analysis for triggering ICU alarms at the time of occurrence of critical arrhythmias. Our team had defined real-time processing techniques for basic ECG analysis modules: QRS detection [7], heartbeat

classification [8], ventricular fibrillation/tachycardia detection [9], lead quality monitoring for the recognition of diagnostically useful ECG [10, 11]. Our experience for real-time pulse wave (PW) detection using arterial blood pressure (ABP) [12] would support online monitoring systems with improved ICU false alarms rate that is reported in cases of supplementary ABP analysis [13, 14].

This study aims to validate the Arrhythmia Detection Library (ADLib, Schiller AG) for robust detection of life-threatening cardiac arrhythmias, participating in the 2015 PhysioNet/CinC Challenge [15] with a closed source entry in Event1 (real-time).

2. Challenge database

Two bedside monitor datasets are used [15]: training set (750 recordings with alarm annotations shown in Table1); a blinded test set (500 recordings, publicly unavailable for the purpose of scoring), including 2 ECG leads and up to 2 pulsatile waveforms (photoplethysmogram (PLETH), ABP), sampled at 12-bit, 250Hz, passed through FIR band pass filter [0.05-40Hz] and mains notch filter. The alarm is annotated at 5:00 of each record, triggered by an event appearing up to 10s before that might be present in any signal channel. All signals can be contaminated by artifacts, noise and disconnection failure.

Table 1. Definition of five ICU alarms: asystole (ASYS), extreme bradycardia (BRADY), extreme tachycardia (TACH), ventricular tachycardia (VTACH), ventricular flutter/fibrillation (VFIB), and the distribution of true and false alarm annotations in the training database.

Alarm type	Alarm definition	True alarms	False alarms
ASYS	0 beats in 4s	22	100
BRADY	≥5 beats, HR<40bpm	46	43
TACH	≥17 beats, HR>140bpm	131	9
VTACH	≥5 ventr. beats, HR>100bpm	89	252
VFIB	Fibrillation waves in 4s	6	52

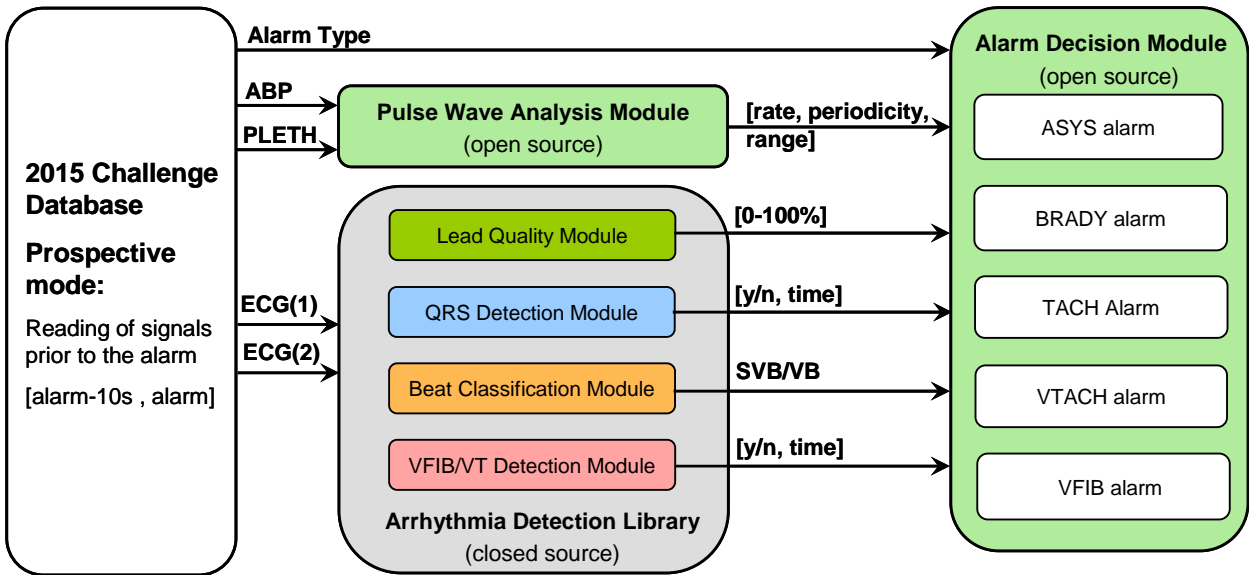


Figure 1. Flow chart of the Challenge test environment for participating in Event 1 (real-time): reading of signals and interactions between developed signal processing modules.

3. Method

The Challenge test environment (Figure 1) involves: a closed source implementation of ADLib (Schiller AG) for ECG analysis; an open-source Pulse Wave Analysis Module (PWAM) for verification of the hemodynamic status based on ABP and PLETH signals (if available); an open source Alarm Decision Module (ADM) for final alarm rejection/validation. PWAM and ADM are adapted to the Challenge setting with noisy signals.

3.1. Arrhythmia Detection Library

The Schiller's ADLib is a real-time ECG monitoring system which embeds four basic ECG processing modules (Figure 1), providing online feedback for an alarm condition with no need for a retrospective scan.

Lead Quality (LQ) Module: LQ(0-100%) is scanned within sliding 4s intervals for calculation of the signal-to-noise ratio when three noise levels are measured in the high, medium and low frequency bands for detection of spike noises, powerline interference and baseline wander, respectively [10]. The minimal LQ is indicative for diagnostically useful ECG, involved in our previous study for online detection of the optimal moment to start the record of a 10s resting ECG [11].

QRS Detection Module: Pre-filters based on min/max filtering approach that completely reset deviations ($\leq 13\text{ms}$ or $\geq 150\text{ms}$) to the neighboring previous value are embedded to prevent the QRS detector from erroneously triggering on pacemaker spikes or step-like changes of the baseline level, as well as reducing the chance for false triggering on the T waves. The QRS detection method is based on the ECG gradient calculation (18ms distance)

that is compared to a weighted average of upper and lower thresholds, which are adaptively updated: the upper threshold converges to the long-term ECG gradient during peak segments while the lower threshold is just a long-term average of the whole ECG gradient. Extra detections are prevented within a dead time of 150ms.

Beat Classification Module: Implements a low resource-cost beat classifier of supraventricular (SVB) and ventricular (VB) beats, without a need for local expert intervention, following special considerations for real-time application: (1) simple correlation threshold criterion for finding close match with a predominant normal (reference) beat template; (2) easy measurement of morphology and RR-variability features; (3) fast classification process by means of a classification tree model. The beat classification module has been previously validated on large-sized ECG databases [8].

VFIB Detection Module: The presence of VFIB arrhythmia is scanned within sliding 4s intervals using 3 variables: (1) Heart rate (HR) from the QRS detector; (2) Ventricular rate (VR) estimated from the location of periodic peaks in the normalized autocorrelation function, corresponding to the dominant frequency within the scanned window; (3) Phase Space Number (PSN) calculated from the number of hits in 2D histogram of phase space map, indicating higher signal irregularity in VFIB than normal ECG [16].

Two conditions are taken into account:

- C1: ($\text{VR} \geq 180\text{bpm}$) or ($\text{VR} \geq 130\text{bpm}$ and $\text{VR} > 1.2\text{HR}$)
- C2: ($\text{PSN} \geq 200$).

A new VFIB episode is detected if C1 and C2 are both fulfilled. The episode is continued as long as at least one C1 or C2 is fulfilled. The episode is ended if none of the conditions is fulfilled anymore.

3.2. Pulse Wave Analysis Module (PWAM)

Both ABP and PLETH signals are passed through 1Hz low-pass filter. Three PW features are measured:

(1) *PWrate* is proportional to the fundamental PW period [17], derived with the assumption that the pulse signal has a quasi-sinusoidal waveform.

(2) *PWleakage* is measured by the formula of Kuo and Dillman [17]. Small values are verifying the PW signal periodicity that is not interrupted by artefacts and noises.

(3) *PWrange* is measured as the peak-to-peak amplitude deviation, used for verification of significant level of pulsations or presence of extreme artefacts.

3.2. Alarm Decision Module

ADM applies linear decision rules, considering the following tunable parameters (Table 2):

ADLib (Arrhythmia analysis)

- *ECG leads* for analysis: ECG(1) and/or ECG(2).
- *Scan interval* for alarm detection: the length of a sliding window that iteratively scans the signal parameters within 10s before the alarm.

ADLib (LQ analysis)

- *LQ threshold* for rejection of alarms, triggered by low quality leads. The alarm specific thresholds are defined according to the statistics in Figure 2.

PWAM (ABP/PLETH analysis)

- *PW features* to verify the pulse hemodynamics (*PWrate*, *PWrange* above a threshold) only if ABP or PLETH are available without significant artifacts, i.e. they maintain stable regularity (*PWleakage* below a threshold). The alarm specific thresholds in Table 2 are derived within the range of minimal overlap between statistical distributions of true and false alarms (Figure 3).

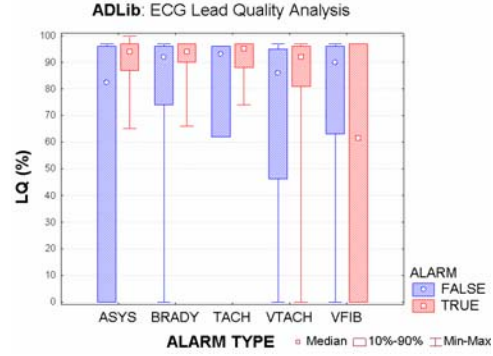


Figure 2. LQ statistics over training dataset.

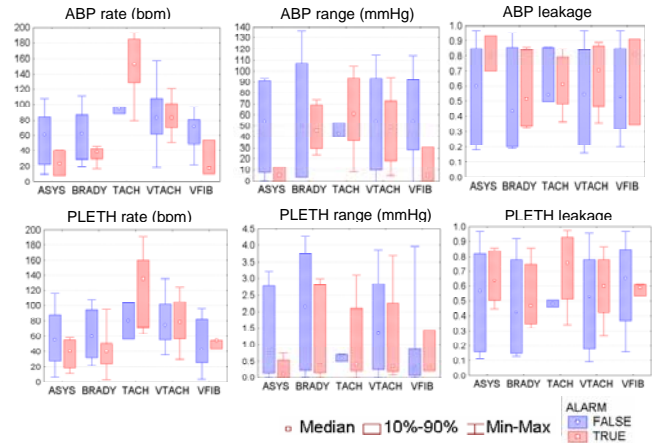


Figure 3. PW features statistics over training dataset.

Results and Discussion

The test environment is adapted to prospective mode, scanning all available signals within 10s prior to alarm.

The Challenge evaluates entries by the three indices:

- True Positive Rate: $TPR = TP / (TP + FN)$ (%)
- True Negative Rate: $TNR = TN / (TN + FP)$ (%)
- Score = $(TP + TN) / (TP + TN + FP + 5 * FN)$,

Table 2. ADM decision rules: alarm-specific settings of our top-scored entry (red/blue: fixed/tunable parameters)

Alarm type	Scan interval	Alarm detection by ADLib (Arrhythmia analysis)	Alarm rejection by ADLib (LQ)	Alarm verification by PWAM (PW features)	Comments:
ASYS	3.5s	QRS detector: 0 beats ECG Lead: ECG(1), ECG(2)	LQ: <65%	PWrate: >25 bpm ABPrange: [15-150] mmHg PLETHrange: [0.2-5] n.u.	Pulse presence
BRADY	7.5s	QRS detector: ≤ 5 beats ECG Lead: [ECG(1), ECG(2)] → min	LQ: <65%	PWleakage: <0.55 PWrate: >45 bpm ABPrange: [30-150] mmHg PLETHrange: [0.2-5] n.u.	Periodicity (no noise) Pulse rate above the low limit Normal hemodynamics
TACH	7.5s	QRS detector: ≥ 16 beats ECG Lead: ECG(1), ECG(2)	LQ: Not used	PWleakage: <0.55 PWrate: [30-125] bpm	Periodicity (no noise) Pulse rate in normal range
VTACH	3s	QRS detector: ≥ 5 beats Beat Classifier: ≥ 3 ventricular beats ECG Lead: [ECG(1), ECG(2)] → max	LQ: <80%	PW features: Not used	Due to their indefinite behavior for ventricular beats
VFIB	4s	VFIB detector: true VF/VT ECG Lead: ECG(1), ECG(2)	LQ: Not used	PWleakage: <0.55 PWrate: [40-150] bpm ABPrange: [30-150] mmHg PLETHrange: [0.3-5] n.u.	Periodicity (no noise) Pulse rate in normal range Normal hemodynamics

where TP and FN are true positives and false negatives for annotated true alarms; TN and FP are true negatives and false positives for annotated false alarms. The score weighs FNs more heavily than FPs, therefore, ADM rules are adjusted towards slightly higher TPR=93% than TNR=83%, obtained for our Challenge best score (Table3): 79.41 (real-time event). The Detailed statistics of different entries, showing the combined performance of ADLib (arrhythmia analysis) and the supplementary modules - ADLib (LQ analysis) and PWAM (PW features) is shown in Table 4.

Table 3. Top scored entry in the Challenge Official phase. The average/max running time is 12.5/29.5% of quota.

Alarm	Training set			Blinded test set		
	TPR	TNR	Score	TPR	TNR	Score
ASYS	100%	97%	97.50	83%	96%	88.02
BRADY	98%	86%	88.31	100%	90%	93.81
TACH	99%	89%	95.91	98%	80%	90.76
VTACH	82%	71%	62.46	85%	77%	69.92
VFIB	100%	87%	87.90	78%	80%	69.70
Real-time	-	-	-	93%	83%	79.41
Retrospect	-	-	-	93%	84%	79.56
Average	97%	86%	85.63	93%	84%	79.49

Table 4. Influence of ADM rules on the overall alarm detection performance, presented as TPR/TNR (Score). The performance on the training/test set is shown in the 1st/2nd rows of each alarm. The best score on the test set is highlighted as a part of the top scored entry.

Alarm	ADLib (ECG)	+ADLib(LQ)	+PW features
ASYS	96/77%(77.81)	91/93%(87.11)	100/97%(97.5)
	67/92%(77.09)	50/98%(74.87)	82/96%(88.02)
BRADY	93/53%(65.23)	93/70%(72.18)	98/86%(88.31)
	79/55%(48.84)	79/62%(51.94)	100/90%(93.81)
TACH	96/55%(81.75)	not tested	99/89%(95.91)
	94/60%(76.30)		98/80%(90.76)
VTACH	73/68%(54.3)	82/71%(62.46)	not tested
	79/67%(59.74)	85/77%(69.92)	
VFIB	100/87%(87.9)	not tested	100/92%(93.16)
	78/80%(69.7)		56/90%(66.92)

Strengths of the study: (i) ADLib performs single and multichannel, real-time arrhythmia analysis (ii) ADLib improves performance, rejecting ECG alarms triggered by low quality leads; (iii) PWAM provides real-time hemodynamic information that slightly improves ECG alarm verification, enabled only when ABP/PLETH signals are not disturbed by artifacts.

Limitations of the study: (i) Limited score for VTACH and VFIB could be further overcome by adequate ECG arrhythmia, LQ and PW analysis adapted to noisy ICU environments;(ii) Retrospective mode is not implemented - the information from signals after the alarm is not analysed that might further gain in performance.

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