A Four-Lead Real Time Arrhythmia Analysis Algorithm

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Abstract

Multi-lead ECG analysis is an effective method to improve detection accuracy and reduce false positive alarms. A four-lead arrhythmia analysis algorithm that processes up to four ECG leads is described. QRS complexes detected in each lead are compared to determine their acceptability. Once the QRS complexes are found acceptable, the information from all the acceptable leads is synthesized to detect and classify them. The arrhythmia analysis section then calculates heart rate and detect the arrhythmia. The AHA and MIT-BIH databases (DB1) as well as four-lead Mindray databases (DB2~DB5) were used to evaluate the performance of the algorithm. The results for DB1 show QRS detection and classification performance against the standard databases. Testing with data from DB2 and DB3, shows that QRS detection and classification accuracies when using four-lead analysis is superior to the results obtained using fewer leads. For DB2~DB5 the false and missed lethal alarms were reduced more than 75% and 90% respectively using the four lead algorithm compared to two lead analysis.

1. Introduction

Patient monitoring systems used in clinical care analyze signals acquired from patients and are expected to be accurate and easy to use. However, accuracy depends on the signals analyzed as well as their quality. Considering the analysis of the electrocardiogram (ECG), the choice of leads analyzed and the presence of noise and artifact could result in false alarms as well as missed arrhythmia alarms. The former has become a major concern because it is associated with alarm fatigue which has been one of ECRI's Top 10 Health Technology Hazards [1]. As far back as 1989, the American Heart Association suggested that monitors should be able to analyze three or more leads [2]. The use of multi-lead analysis has several advantages. Since artifacts often contaminate certain leads, unless the single or two-lead algorithm is configured to use the proper leads, there is a risk of missing lethal arrhythmia (ARR) alarms. ECG electrodes could become partly or fully detached or have contact failures which may result in loss of monitoring when using single or two-lead analysis while multi-lead algorithms could remain uninterrupted. Others have already proposed multi-lead analysis. JY Wang proposed a method to evaluating signal quality so the best leads can be selected for analysis [3]. Some researchers have implemented multi-lead detection by summing the normalized results of each lead [4], but its performance is highly dependent on the detection threshold used.

In this article, a real time arrhythmia analysis algorithm that processes up to four ECG leads to improve the detection and classification of the QRS complexes is discussed. Synthesizing the results from four leads, false and missed alarms are reduced significantly.

2. Methods

The proposed four-lead real time arrhythmia analysis algorithm includes four essential steps (Figure 1). QRS complexes form each of four leads of the ECG signals are detected and classified first. QRS complexes from each lead are matched using a time window. Then the data from the four-leads are synthesized to determine whether the matched QRS complex is a valid beat or not. If yes, the four-lead synthesized signal is used to classify the beat. This step is followed by the arrhythmia analysis.

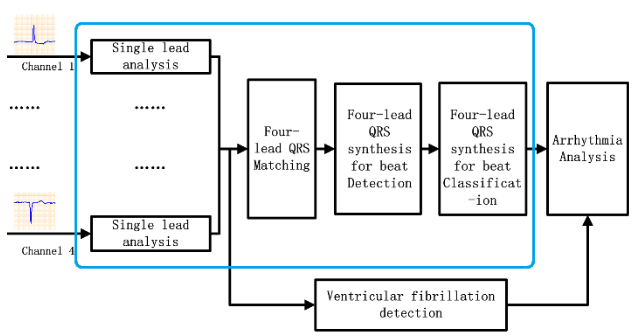

Figure 1. Schematic diagram of the four-lead real time arrhythmia analysis algorithm.

2.1. Single lead analysis

After preprocessing each lead of the signal such as resampling and notch filtering, QRS complexes from each

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lead are detected and classified. The single lead QRS detection technique has been used over the years. Two well-known methods are those by Pan-Tompkins [5] and by Li et al [6] which employs the wavelet transform. The Pan-Tompkins algorithm uses bandpass filtering and nonlinear transformation to enhance the QRS complex, making it easier to detect them. The other method uses the wavelet transform (WT) to locate sharp characteristic points of the QRS complex. Given the increased computational complexity involved with using WT, the former method is preferable for real time ECG analysis.

2.2. Four-lead QRS matching

The location of the QRS complex corresponding to a specific beat should be the same in each lead. Since thresholds and beat detection parameters used could be different for each lead, the locations of the QRS complexes as detected in individual leads could be slightly different. The four-lead QRS matching scheme matches QRS complexes detected by the four single lead detectors for the same beat, and marks them as a group of matched QRS complexes. There are two steps in this process:

(1) Locating candidate QRS complexes for matching

Beat detection in the four individual leads does not occur at the same instant as mentioned above. In order to guarantee real-time analysis and accuracy of the algorithm, a moving matching window with the appropriate width is used to locate the QRS candidates. Each heart beat results in a QRS complex in each lead considered. Consequently, there is at most one QRS complex in each lead that can be allowed to participate in QRS matching analysis and there are at most four QRS candidates in the matching window (Figure 2).

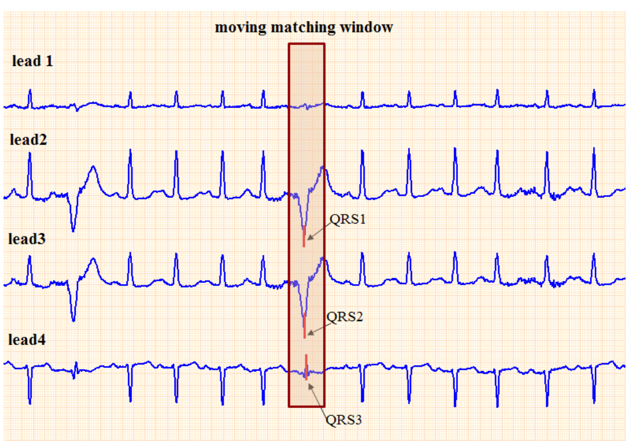

Figure 2. An example of four-lead QRS matching. QRS1, 2, 3 detected by single lead analysis are confirmed as a matched set.

(2) Matching the QRS complexes in the window

Because of possible differences in amplitudes and noise levels for each lead, one could have false QRSs among the candidates. The distance between the peak-position of the QRS complexes is limited to preset values. The R-R interval and relative peak-position of each QRS are used for matching. The matched QRS complexes are grouped together.

2.3. Four-lead synthesis for beat detection

When a group of matched QRS complexes is found, the four-lead QRS synthesizer will decide whether this group of QRS complexes is generated by a true beat or not. In this step, the QRS metrics calculated by each single lead detector are analyzed individually instead of using a composite four lead signal.

(1) Every lead has a matched QRS

QRS complexes detected in each lead could either be valid ones or spurious ones generated by artifact. Even if all the leads have a matched QRS, it is important to analyze the QRS morphology and noise level.

(2) Some of the leads have matched QRS

Depending on the amplitude and noise level, QRS complexes may not be detected in some leads. The four-lead algorithm will use the lead without a matched QRS as a secondary lead (Figure 3), while the others are considered matched leads. This is accomplished as follows:

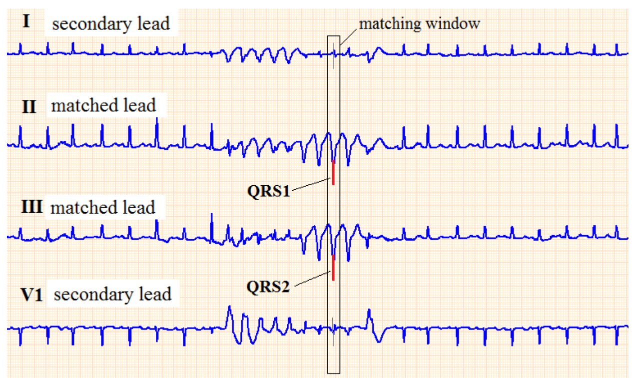

Figure 3. An example of four-lead synthesis for QRS detection. QRS complexes (QRS1, QRS2) could be detected only in leads II, and III while no detection was possible in the other leads.

a) Evaluation of signal quality in each lead

Signal quality will affect the performance of the four-lead detector. It is evaluated by analyzing the noise level and signal amplitude. Detections from leads with higher signal quality are considered to be more reliable.

b) Determination of the validity of the QRS

Signal quality and prior QRS metrics for the secondary and matched leads are used to decide whether a group of matched QRSs corresponds to a real beat. Leads that have irregular RR intervals or inferior signal quality will typically be considered untrustworthy.

2.4. Four-lead synthesis for beat classification

Once a group of matched QRS complexes is confirmed as corresponding to a true beat, information regarding beat morphology and classification (normal, ventricular, etc.) as determined for each lead by the single lead detectors is synthesized to arrive at a final classification.

(1) Selection of a set of matched QRS types

At this point, each of the matched QRS complex has been classified by its corresponding single lead analyzer. The information used by the four-lead classifier is based on the number and types of the matched QRSs. For example, in Figure 4, the individual leads within the "matching window" are classified as (N, N, N, V).

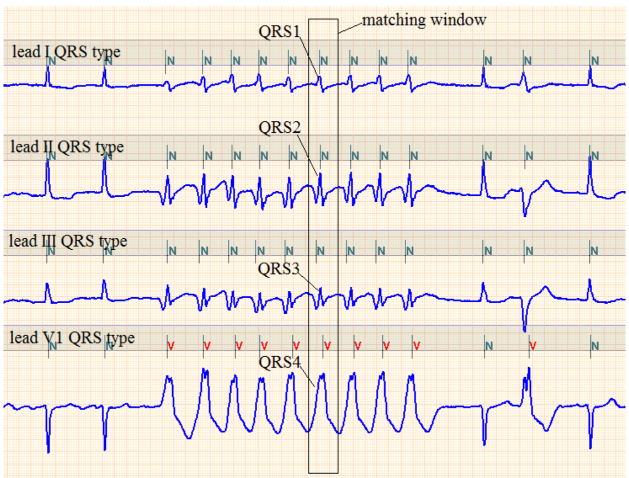

Figure 4. An example of the four-lead QRS combined classification. The ventricular tachycardia event is clearly seen only on lead V1.

(2) Classification of the QRS complex

The strategy used for the final classification depends on the combination of the matched QRS types. A count of the number for each QRS type is first obtained. The synthesizer will concentrate on analyzing the QRS types with the lowest count. Parameters such as average R-R interval of the dominant beat, QRS power, width etc. are used to evaluate the reliability of the minority decision. If the counts for both beat types (N and V) are the same, the synthesizer will check whether all the QRSs with type V have the characteristics of a ventricular beat. If not, the final decision will class this beat as normal. For example, if the combination is (N, N, N, V), the final classification result will tend to be normal. However, if the changes in morphology of the QRS in the lead with beats classed as ventricular is significant compared to the dominant QRS template, certain rules are used to decide if this is sufficient to indicate that the decision from the other leads is incorrect and to classify the entire matched set as ventricular.

2.5. Arrhythmia analysis

Based on the QRS detection and classification results of the four-lead system, HR values and ARR alarms are generated (arrhythmia analysis block in Figure-1). The ARR alarms are divided into two groups - Lethal ARR alarms (Asystole, Ventricular fibrillation, Ventricular tachycardia, Ventricular Brady, Extreme Tachy, Extreme Brady), and nonlethal ARR alarms.

2.6. Ventricular fibrillation detection

Ventricular fibrillation (VF) detection is independent of the four-lead algorithm. A complexity-based method is used for synthetically detecting VF. The method uses complexity calculations while incorporating a plurality of feature values and thus is able to differentiate more effectively between various types of ECG signals [7].

3. Results

3.1. Database Description

Details regarding the databases used in the study are to be found in Table 1. DB1 was made up of the standard AHA Database with 78 records and MIT-BIH Arrhythmia Database with 44 records. DB2 and DB3 are collections of ECG signals from CCUs and ICUs. DB4 contains data from a CCU telemetry unit. DB5 was collected using Mindray patient monitors from ICUs, CCUs, and NICUs of 3 hospitals.

Table 1. Summary of training and test database.

Dataset	DB1	DB2	DB3	DB4	DB5
use	Training		Test		
cases	122	100	100	400	300
hours	67	32	32	400	300
channel	2	4	4	4	4
patients	A	A	A	A/ Paced	A/P/N/ Paced
quality	mixed	noisy	noisy	noisy	mixed

Acronyms: A: Adult, P: Pediatric, N: Neonate

3.2. Evaluation Methods

Except for DB1 which only had two leads available, the four-lead algorithm was configured to function either in the single lead mode (1L) using lead II, two-lead mode (2L) using leads II, and V, three-lead mode (3L) using leads I, II and V, and four-lead mode (4L) using leads I, II, III, and V. Beat detection and classification performance for these lead combinations was evaluated using the methods described in ANSI/AAMI EC57: 2012.

The ability of the algorithm to reduce false alarms (FA) and missed alarms (MA) in the four lead mode compared to the two lead mode was evaluated. Results from the two modes were compared and visually confirmed to ensure accuracy.

3.3. QRS detection and classification performance

In order to compare the performance of the algorithm to results published in the literature, the beat detection and classification statistics for DB1 are presented in Table 2.

Table 2. Beat detection and classification performance results for the datasets in DB1

Database	AHA	MIT-BIH
Q Se (%)	99.89	99.90
Q +P (%)	99.95	99.85
V Se (%)	96.03	96.59
V +P (%)	98.84	96.98
V FPR (%)	0.114	0.228

3.4. Algorithm performance in four modes of analysis

The best performance (beat detection and classification) for the two datasets used (DB2 and DB3) was obtained when four leads were used for analysis.

Table 3. Beat detection and classification performance for different numbers of analysis leads

Dataset		Q Se (%)	Q +P (%)	V Se (%)	V +P (%)	V FPR (%)
DB2	1L	91.72	98.18	75.24	93.18	0.943
	2L	98.99	99.13	88.88	97.21	0.408
	3L	99.41	99.13	89.29	97.23	0.404
	4L	99.46	99.13	93.40	97.27	0.417
DB3	1L	96.61	96.56	69.76	60.02	3.525
	2L	99.48	99.32	86.28	84.84	1.169
	3L	99.58	99.67	88.24	90.89	0.673
	4L	99.61	99.65	92.82	91.88	0.623

3.5. Reduction of false and missed lethal arrhythmia detections

Table 4. Lethal ARR Alarms Performance

Database	DB2&DB3		DB4		DB5	
Lead mode	2L	4L	2L	4L	2L	4L
True ARR	415	570	755	693	111	122
False ARR	93	20	239	48	194	33
Missed ARR	216	6	1	0	34	2
FA SR (%)	78.49		79.92		82.99	
MA SR (%)	97.22		100		94.12	

Table 4 shows that, when used in the four lead mode, the FA suppression ratio (SR) was more than 75% in every database while the MA suppression ratio was more than 90% in each database.

4. Discussion and conclusions

The results for DB1 show that the proposed algorithm works well using only two leads. It performed even better in the four-lead mode (results for DB2-DB5). Even in the case of DB4 which contained noisier signals as they were recorded in a telemetry unit with ambulatory patients, the algorithm performed much better in the four lead mode compared to the two lead mode. A significant reduction in the rate of FA and MA calls resulted when used in the four-lead mode compared to the two-lead mode for all the databases as seen in Table 4.

Theoretically, utilizing more leads equates to analyzing more information and algorithm performance could be expected to improve. In practice, increasing the number of leads analyzed will lead to a more complicated design of the system and require more processing power. Balancing design complexity and performance improvement, four-lead analysis was seen to offer good clinical performance.

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