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Intelligent use of advanced capabilities of diagnostic ECG algorithms in a monitoring environment

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Abstract A large number of ST-elevation notifications are generated by cardiac monitoring systems, but only a fraction of them is related to the critical condition known as ST-segment elevation myocardial infarction (STEMI) in which the blockage of coronary artery causes ST-segment elevation. Confounders such as acute pericarditis and benign early repolarization create electrocardiographic patterns mimicking STEMI but usually do not benefit from a real-time notification. A STEMI screening algorithm able to recognize those confounders utilizing capabilities of diagnostic ECG algorithms in variation analysis of ST segments helps to avoid triggering a non-actionable ST-elevation notification. However, diagnostic algorithms are generally designed to analyze short ECG snapshots collected in low-noise resting position and hence are susceptible to high levels of noise common in a monitoring environment. We developed a STEMI screening algorithm which performs a real-time signal quality evaluation on the ECG waveform to select the segments with quality high enough for subsequent analysis by a diagnostic ECG algorithm. The STEMI notifications generated by this multi-stage STEMI screening algorithm are significantly fewer than ST-elevation notifications generated by a continuous ST monitoring strategy.

Keywords: ECG; Myocardial infarction; STEMI; ST-elevation; Diagnostic algorithm; Monitoring environment; Artifact; Signal Quality Indicator; SQI; High-frequency noise; Baseline wander; ST-confounders; Alarm fatigue; False positive

Introduction

Acute coronary artery disease including ST-segment elevation myocardial infarction (STEMI) is among the most common causes for hospitalization and death of people in the United States. Early recognition of acute myocardial infarction is critical in order to treat the patient immediately and avoid the dire consequences of myocardial infarction. 12-lead ECG monitoring in the emergency department and assessment of the ST segment deviation is the common approach to detect STEMI early and perform the reperfusion if STEMI is not diagnosed in the initial 12-lead ECG.

The guidelines issued by American College of Cardiology Foundation (ACCF) and the American Heart Association (AHA) have been used initially for diagnosis and treatment of acute myocardial infarction patients, with the latest version of the ACCF/AHA released in 2013 focused on management of STEMI [1]. A literature review including all trials until 2010 and selected publications until 2012 were added to the guidelines, where several additional studies in the following year were highlighted in a review article [2]. A variety of methods for detection of acute myocardial infarction based on the ST-segment deviation have been presented in the literature [3–7].

The Philips DXL diagnostic 12-lead ECG algorithm [8] is able to distinguish ST-segment elevation confounders (such as acute pericarditis, benign early repolarization, RBBB, LBBB and LVH with secondary repolarization changes [9]) from STEMI, which is not common in ST monitoring algorithms. Although the 12-lead ECG is the standard for detecting ischemic coronary events, it provides only a static snapshot. This is why continuous monitoring of dynamic ST-segment changes is preferred. However, ST monitoring algorithms usually do not have the advanced capabilities of diagnostic ECG algorithms specifically in distinguishing STEMI from confounders such as acute pericarditis and benign early repolarization. Consequently, ST monitoring algorithms may generate many real-time notifications which do not need an action by the clinical personnel and only add to alarm fatigue. Therefore, it is desirable to utilize more advanced diagnostic ECG algorithm features in a monitoring environment. However, diagnostic algorithms are generally designed for analyzing low-noise resting ECG recordings

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and are prone to error in high levels of artifact common in a continuous monitoring environment.

In this study, we discuss the design and benefits of a multi-stage STEMI screening algorithm in order to utilize the advanced capabilities of the DXL diagnostic algorithm in a monitoring environment. As an initial step, this screening algorithm selects the 10-s ECG segments with the highest quality for subsequent analysis by the diagnostic algorithm by real-time signal quality indicator (SQI). The combination of SQI, the DXL ST-confounder analysis capability, and an STEMI consistency check results in significantly fewer STEMI notifications compared to ST-elevation notifications generated by a continuous ST monitoring strategy.

Materials and methods

Database

Data used for this research were provided by the Telemetric and Holter ECG Warehouse of the University of Rochester (THEW), NY [10]. This database has been used by researchers in various studies such as ischemia detection [11,12]. We used 1171 standard Mason-Likar 12-lead ECG Holter recordings, each 24-h long, in cohorts of emergency department patients undergoing evaluation for possible acute coronary syndrome. In the E-HOL-12-1172-012 database, Holter recordings were started within 40-min of patient admission to the emergency room. The recordings were sampled at 180 Hz and stored in 16-bit format with an amplitude resolution of 6.25 μV.

Methods

We developed a three stage STEMI screening algorithm to analyze continuous 12-lead ECG recordings. In stage 1, non-overlapping 1-min intervals of a recording are analyzed by our Signal Quality Indicator (SQI) algorithm [13] in order to select the 10-s 12-lead ECG segment with the highest waveform quality within the 1-min interval. Each 1-min data interval is split into 1-s 12-lead ECG sections and the SQI algorithm evaluates the noise level for each lead in each section. The noise measure consists of two components: a high-frequency part (N_{HF}) which accounts for the muscle noise and other fast changing artifacts, and a low-frequency (baseline wander) part (N_{BW}) quantifying the slow variations in the signal. The total noise measure in a 1-s section is defined by the average of weighted sums of high-frequency and baseline wander noise measures on all leads:

$$Noise\ \ Measure = E[\alpha N_{HF} + \beta N_{BW}] \quad (1)$$

where the operator $E[.]$ denotes the average or expected value of the operands, and α and β are the weighting factors determined empirically. In the above equation, high-frequency noise measure (N_{HF}) is the standard deviations of the ECG lead in a short window with the lowest activity within the 1-s section. On the other hand, the low-frequency noise measure (N_{BW}) is identified by the changes to the baseline levels and is defined per lead as the sum of absolute values of the baseline difference between the current 1-s section and each of the last two 1-s sections.

The noise measure in a 10-s segment is the average of all 1-s noise measures defined by Eq. (1) across the segments. We choose the 10-s segment with the best signal quality (lowest noise measure) within all segments in the 1-min interval. In other words, we exclude the lower-quality parts of the ECG recordings.

The next step is to compare the signal quality of the selected 10-s segment against a pre-defined threshold. If the segment lacks acceptable quality, it is discarded and the algorithm proceeds to the next 1-min interval.

In stage 2 of our STEMI screening algorithm, the Philips DXL diagnostic algorithm analyzes the selected 10-s ECG to generate a representative beat, measure the lead-wise STEMI-related features including the ST-segment levels, and identify ST-elevation confounders.

Our study used the STEMI criteria from the 2013 ACCF/AHA guidelines for the management of STEMI. Similarly, the European Society of Cardiology/ACCF/AHA/World Heart Federation task force for the universal definition of myocardial infarction defines STEMI as “new ST elevation at the J point in at least 2 contiguous leads”. The voltage should be greater than 2 mm (0.2 mV) in men or greater than 1.5 mm (0.15 mV) in women in leads V2–V3, and/or greater than 1 mm (0.1 mV) in other leads [1].

In order to avoid generation of false STEMI notifications due to the presence of ST-elevation confounders (such as acute pericarditis and benign early repolarization), the algorithm switches to analysis of the variations in the ST-segment levels (ΔST) which has higher detection precision than absolute ST level analysis.

In stage 3 of the screening algorithm a consistency check is applied to exclude isolated STEMI notifications which are probably false and a result of artifact. This stage increases the robustness of STEMI screening algorithm. This stage is basically a mechanism to check whether STEMI has been consistently detected for a pre-defined interval of several minutes before triggering a STEMI notification.

Fig. 1 shows the block diagram of the STEMI screening algorithm. To evaluate the performance of this algorithm, the ST-elevation episodes were annotated manually by experts reviewing the recordings from patients with a STEMI final diagnosis. Twenty six patients had a final STEMI diagnosis. Potential episodes were detected by an ST monitoring algorithm and ruled in or out manually. Out of 1171 patients, a total of 15 patients with at least one STEMI episode were detected and annotated.

Results

Fig. 2 illustrates the difficulty of STEMI detection in a noisy environment and the results of running our STEMI screening algorithm on a 24-h ECG recording. Significant variation in automated ST level measurements is seen in the segments with a high noise level. In other words, the ST-segment levels measured automatically on noisy waveform may not be accurate (hence large variation) because of the low signal quality.

For illustration purposes, we calculated ST vector magnitude (ST_{VM}). The Horácek matrix was used to