

Modeling and Classification of the ST Segment Morphology for Enhanced Detection of Acute Myocardial Infarction

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Abstract

A number of cardiac conditions such as acute pericarditis (PC) and early repolarization (ER) cause ST elevation which mimics ST-segment Elevation Myocardial Infarction (STEMI). Current guidelines recommend analyzing ST segment morphology to distinguish STEMI from these confounders. ST elevation in PC and ER (and possibly in STEMI) is concave (upward) in the JTpeak interval, while a convex or straight ECG ST segment is associated with the diagnosis of STEMI. We developed an algorithm to classify concavity characteristic of the ST segment. A quadratic polynomial regression algorithm was introduced to model the shape of JTpeak interval. Our diagnostic algorithm generated representative beats and measured the fiducial points and standard measurements such as ST level in 12-lead 10-sec segments of ECG recordings. JTpeak interval was modeled by a parabola using a least-squares polynomial regression algorithm, and the features curvature, vertex, and parabola direction, R-squared, and the noise measure were determined. A bootstrap-aggregated tree ensemble classifier determined the ST segment shape. Our algorithm was evaluated on a 12-lead ECG database collected in two medical centers. Morphology analysis of the ST segment by the regression model exhibited significant improvement versus a simple method of concavity detection.

1. Introduction

Cardiac diseases with ST elevation such as pericarditis, early repolarization, LBBB, and LVH confound the diagnosis of ST-segment Elevation Myocardial Infarction (STEMI). Extra features are necessary to distinguish STEMI from ST-elevation confounders. ST segment morphology is a significant feature discriminating STEMI from pericarditis and early repolarization. These confounders always show concave (upward) ST elevation against STEMI with mostly convex or straight-line ST segment. In this study we did not consider LBBB and LVH with typically concave ST-elevation.

Each cardiac condition has a set of specific criteria [1-

4]. The set of criteria for diagnosis of pericarditis includes widespread concave (upward) ST-elevation with PR-segment depression in some leads [5]. Early repolarization is diagnosed by concave upward ST elevation in some leads without reciprocal ST depression, and presence of J-waves or J-point notches/slurs [6]. Ratio of T-wave amplitude to ST level is a major discriminator between early repolarization (high) and pericarditis (low). STEMI is defined by ST elevation with any shape in at least two contiguous leads, ST depression in reciprocal leads, Q-waves, and wide or inverted T-waves [7,8].

Most algorithms determine concavity by simple measures such as the area between the JTpeak interval and the line connecting its ends or the position of the point in the JTpeak interval maximizing the distance from the straight line. However, these simple models behave poorly in the presence of artifact. We modeled the ST segment morphology by a low-dimensional polynomial and defined several features to classify the ST-segment concavity. The criteria to diagnose STEMI or its confounders make use of the concavity feature in addition to the other specific features.

The rest of this paper is organized as follows. Section 2 describes the method and material including the algorithm overview, polynomial regression model, features, database, and classifier. Results are provided in Section 3. Discussion and conclusions are presented in Section 4.

2. Method and Material

2.1. Algorithm Overview

Block diagram of our algorithm is shown in Figure 1. Philips DXL algorithm reads the multi-lead data (12-lead or more) and analyzes them in non-overlapping 10-second segments. Our algorithm generates the representative beat in each segment, identifies the fiducial points, and finds standard measurements such as ST level and JTpeak interval which is the interval between the end of QRS complex (J point) and the peak of T-wave.

The JTpeak interval is modeled by a fitted section of the second-order curve (parabola) using a least-squares polynomial regression. The features such as the

polynomial model error, noise measure, parabola vertex location, and curvature are determined from the fitted curve and the original JTpeak interval. These features determine whether the curve fits the JTpeak properly and if it is concave upward, using a classifier.

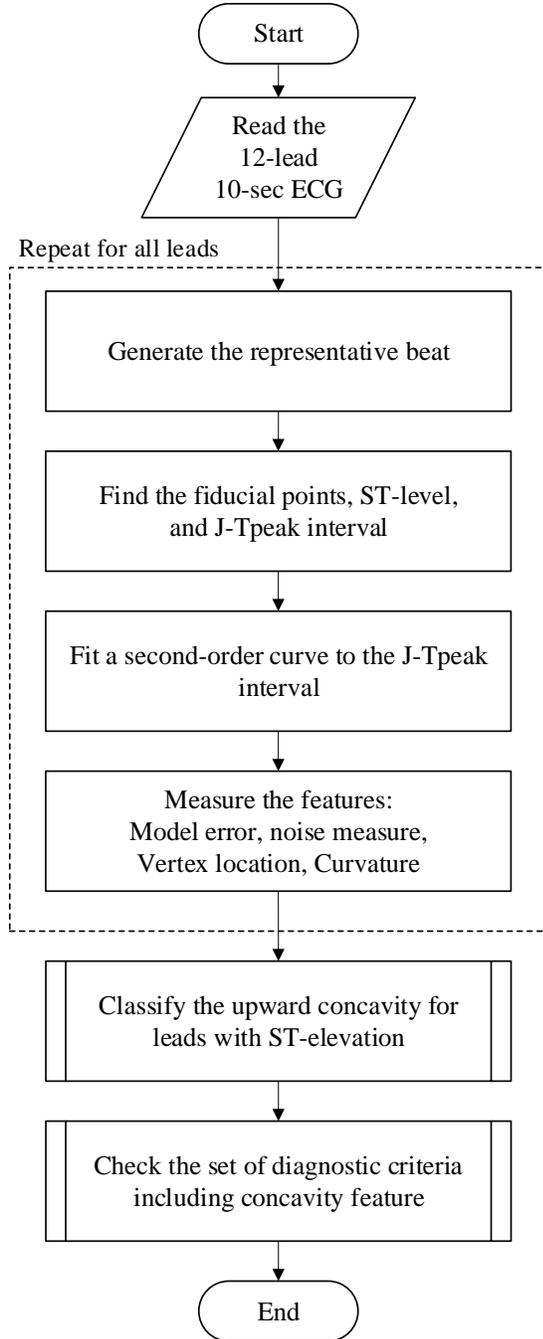


Figure 1. Block diagram of the algorithm. This procedure is repeated for all leads in the data.

Concavity is one of the features used in the set of criteria diagnosing each of the cardiac conditions including STEMI, pericarditis, or early repolarization.

2.2. Polynomial Regression model

Figure 2 displays an example of the quadratic polynomial regression of the JTpeak interval within a representative beat extracted from a 10-second ECG interval. The regression parabola, osculating circle with the curvature radius, and the line connecting both ends of the JTpeak interval are illustrated.

JTpeak interval is modeled by a low-dimensional curve which is a quadratic polynomial (parabola), where the model is identified by only three coefficients, a , b , and c :

$$\hat{y} = ax^2 + bx + c \quad (1)$$

To explicitly derive these coefficients, we used least-squares method to minimize the error between the model and the JTpeak interval comprising N samples: (x_k, y_k) , $k = 1, \dots, N$. The error at each sample k is sum of the squared errors between the model (\hat{y}) and the original signal (y):

$$S = \sum_k (e_k)^2 = \sum_k (y_k - (ax_k^2 + bx_k + c))^2 \quad (2)$$

which is minimized by:

$$\frac{\partial S}{\partial a} = 0, \quad \frac{\partial S}{\partial b} = 0, \quad \frac{\partial S}{\partial c} = 0 \quad (3)$$

The derivatives define a system of three equations which is solved using the Cramer's rule:

$$a = \frac{\Delta_a}{\Delta}, \quad b = \frac{\Delta_b}{\Delta}, \quad c = \frac{\Delta_c}{\Delta} \quad (4)$$

The determinants (Δ 's) are written in closed forms in terms of x_k and y_k , $k = 1, \dots, N$.

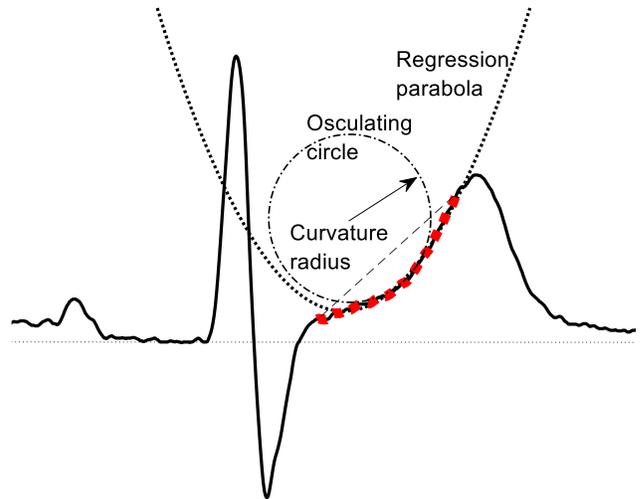


Figure 2. Example of quadratic polynomial regression of the JTpeak interval (big dots). The regression parabola, the osculating circle with the curvature radius, and the line connecting the ends of the JTpeak interval (used in a simple method of concavity detection) are shown.

2.3. Features

Other than the coefficient of the quadratic in the hyperbola equation, a , which shows its opening direction, we take into account other features which determine the goodness of the fit and the location of the parabola section fitting the JTpeak interval.

Model error is the feature describing the difference between the fitted curve and the JTpeak interval and is presented by the coefficient of determination (R-squared):

$$R^2 = 1 - \frac{\sum(\tilde{y}-\hat{y})^2}{\sum(\tilde{y}-\tilde{y}_{ave})^2} \quad (5)$$

where \tilde{y} is the JTpeak interval smoothed by a moving average filter and \tilde{y}_{ave} is its average.

Noise measure is the mean difference between the ECG values and its smoothed version in the JTpeak interval normalized by the range of values in the fitted section of the parabola:

$$NM = \frac{\sum|y-\tilde{y}|}{N \cdot |\tilde{y}_{max}-\tilde{y}_{min}|} \quad (6)$$

Location of vertex of the parabola is a feature which determines the parabola section fitting the JTpick interval:

$$v = -\frac{b}{2a} \quad (7)$$

The feature $\hat{\kappa}_{max}$ is defined as the scaled maximum curvature:

$$\hat{\kappa}_{max} = \max(\kappa) \cdot |\hat{y}_{max} - \hat{y}_{min}| \quad (8)$$

where curvature κ (the measure which determines the degree to which the fitted model is curved) is presented by:

$$\kappa = \frac{|\hat{y}(x)''|}{(1+\hat{y}(x)'^2)^{\frac{3}{2}}} \quad (9)$$

Another feature based on the curvature measure is:

$$\kappa_{ratio} = \frac{\max(\kappa)}{\min(\kappa)} \quad (10)$$

2.4. Database

The algorithm was developed on 12-lead ECG data selected from databases collected in two medical centers. We selected a total of 300 10-sec segments of 12-lead ECG with different diseases annotated from discharge diagnosis or experts' reviews which include STEMI (n=100), PC (n=100), and ER (n=100).

All leads were manually reviewed (RF) and annotated with the binary decision of upward concavity. We selected the leads which showed ST elevation greater than $50\mu V$. As a result, 1,820 concavity-annotated leads were chosen with one of those three diseases. Concavity annotations were used as the reference in our classification.

2.5. Classifier

We developed a bootstrap-aggregated ensemble of decision trees to classify the ST segment concavity. The classifier consists of 100 trees with maximum 100 splits and takes the six described features from 1,820 leads with ST elevation as predictors: coefficient a , R^2 , NM , v , $\hat{\kappa}_{max}$, and κ_{ratio} . The output is binary with the positive event being the concave upward ST segment.

3. Results

Table 1 summarizes the performance of our regression algorithm using a 10-fold cross validation. Also listed for comparison is the performance of a simple method that determines the concavity of ST segment by comparison to a line connecting the JTpeak interval boundaries.

Figure 4 shows the confusion matrix of the outcome. Figure 5 displays the classifier ROC with AUC = 0.97. Figure 6. Illustrates the examples of 12-lead ECG representative beats and fitted parabolas in patients with pericarditis, early repolarization, or STEMI.

True class	0	309	44
	1	40	1427
		0	1
		Predicted class	

Figure 4. Confusion matrix of the classifier outcome.

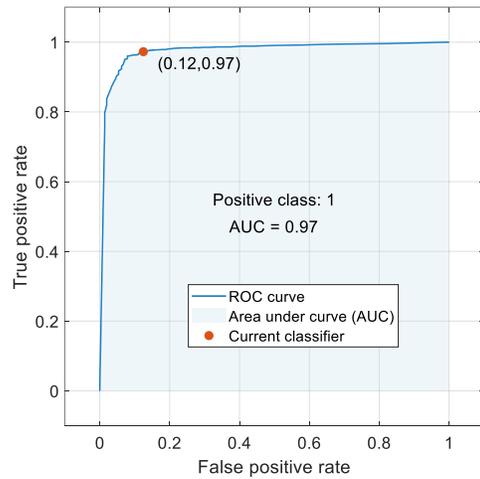
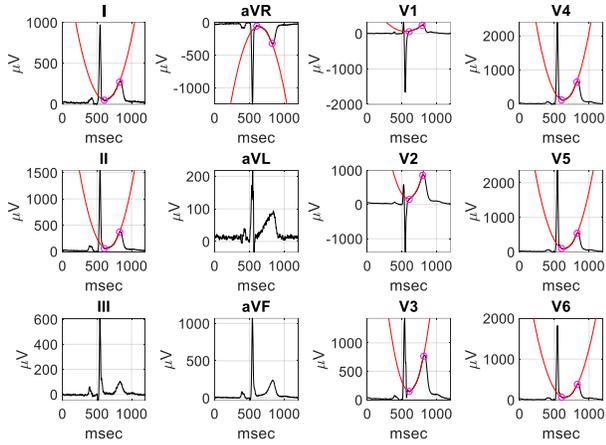
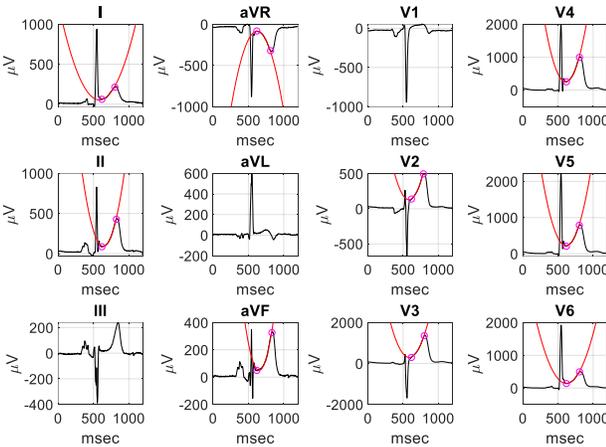


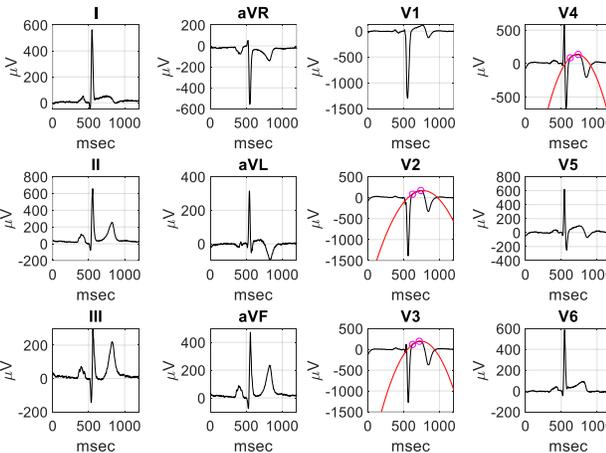
Figure 5. Classifier outcome ROC with AUC = 0.97.



(a) Pericarditis



(b) Early repolarization



(c) STEMI

Figure 6. Examples of 12-lead ECG representative beats in patients with (a) pericarditis, (b) early repolarization, and (c) STEMI. All ST segments with $50\mu\text{V}$ elevation or more are fitted with a parabola. Concavity is inverted in the lead aVR.

Table 1. Regression algorithm performance compared to a simple method

Algorithm	Se(%)	Sp(%)	PPV(%)	NPV(%)
Polynomial	97	88	97	89
Simple	96	58	91	77

4. Discussion and Conclusions

Modeling the ST segment by a polynomial regression model showed significant improvement versus a simple method of concavity detection. The model is low-dimensional, is defined by only three parameters, and is solved using closed form expressions, which makes it computationally efficient and a proper candidate for easy implementation in systems with limited power, memory or processing performance. False cases are mostly due to the borderline concavity, inaccuracies in the JTpeak determination, and high nonlinearity in the curvature equation. Using a large database will enhance the algorithm performance evaluation.

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