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Rule-based Method for Extent and Localization of Myocardial Infarction by Extracted Features of ECG Signals using Body Surface Potential Map Data

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ABSTRACT

In this study, a method for determining the location and extent of myocardial infarction using Body Surface Potential Map data of PhysioNet challenge 2007 database is presented. This data is related to four patients with myocardial infarction. We used two patients as training set to determine rules and two other patients as testing set of the proposed model. First, T-wave amplitude, T-wave integral, Q-wave amplitude and R-wave amplitude as four features of ECG signals were extracted. Then we defined several rules and proper thresholds for localization and determining the extent of myocardial infarction. To determine the precise location and extent of myocardial infarction, 17-segment standard model of left ventricle was used. Finally, overall accuracy of this method was shown with SO, CED and EPD parameters. We obtained 1.16, 1 and 5.3952 for SO, CED and EPD, respectively, in our test data. Two main advantages of this method are simplicity and high accuracy.

Key words: *Body surface potential map data, electrocardiogram signal processing, electrocardiogram signals, feature extraction, myocardial infarction*

INTRODUCTION

Myocardial infarction (MI) or heart attack occurs when one of the coronary arteries become completely blocked. The part of myocardium for which the blood is supplied by the coronary artery loses its blood supply and will remain deprived of oxygen and other nutrients. There are two ways in which blood is supplied to the myocardium. One of them brings blood to the right side of the heart (right coronary artery) and the other covers the left side of the heart (left main artery).

In general, the infarction can be divided into several anatomical groups: Inferior, lateral, anterior, and posterior infarction. Combinations of these may be observed, such as anterolateral and inferoposterior infarction. Almost all kinds of myocardial infarction involve the left ventricle (LV). It is not surprising because left ventricular muscle has more volume than the other muscles in the heart. The 12-lead electrocardiogram is a standard tool for clinical diagnosis of heart disease and can provide information about the location and extent of MI. For example, abnormal Q waves and ST waves are important indicators of acute and chronic MI, respectively. Here, we provide several examples of previous research about the diagnosis of MI using body surface potential map (BSPM) data.

In 2007, SadAbadi *et al*. presented a method with imposed rules on the extracted features of ECG to determine the location and extent of MI. They extracted two features, which are Q-wave amplitude and ST-segment dispersion, and finally they obtained good results.[1]

In 2010, Arif *et al*. presented an automatic method for MI localization using K-nearest neighbor (KNN). Time domain features like T-wave and Q-wave amplitudes and ST level dispersion were extracted from 12-lead ECG. They used PTB database including 20160 beats of ECG, and after extracting the above features, they used KNN classifier. The sensitivity was 99.97% and the specificity was 99.9% for detecting MI, and the accuracy was equal to 98.3% for localization.[2]

In 2007, Zarychta *et al*., using PhysioNet Challenge 2007 database, offered clinical evaluation method based on the ECG recorded and BSPM with 120 leads that viewed by three cardiologists. They stated that abnormal initial depolarization (in the Q-wave) and initial repolarization (in

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ST-segment) are important factors of chronic and acute MI, respectively. The overall accuracy of that method for the first test patient (Case #3) was obtained in the regions 3, 4, 9, and 10 of the LV have MI and the extent of MI in this patient was 30%, and for Case #4, it was not reported.[3]

In 2008, Vesterinen *et al*. used BSPM data for localization of MI with rest BSPM signals. The labels were determined by angiography and echocardiogram. The features were QRSSTT, QRS and STT integrals, and T-wave amplitude. They reached a differential between anterior and inferoposterior MI with 85% ($P < 0.001$) accuracy.[4]

In 2007, Farina *et al*. used a model-based approach to determine the location and extent of MI. In their method, an optimized physiological model was used to simulate transmembrane voltage (TMV) to compare with data. The EPD were 43 and 14 for Case #3 and Case #4, respectively. The SO parameter was 0.4 and 0.167 for Case #3 and Case #4, respectively, and finally CED was 1 for both patients.[5]

In 2007, Ghasemi *et al*. used a new method based on vectorcardiogram. They assumed that the heart vector is proportional to relevant active depolarization areas. The EPD was 32, SO was 0.933 and CED was 1.[6]

In 2007, Mneimneh and Povinelli used RPS/GMM, and localized and determined the extent of MI. They used PTB database for training and the four patients in PhysioNet challenge database for testing.[7]

In 2010, Nader Jafarnia *et al*. presented a method and extracted features such as Q-wave integrals and QRS complex integrals. They defined the rules on these features to determine the location of MI.[8]

In this study, we used the recorded ECG signal by BSPM and torso plane. Then, we extracted new features of ECG signals, such as T-wave amplitude and R-wave amplitude. After this step, we defined several rules and appropriate threshold levels on these features, and the location and extent of MI with high accuracy were obtained.

MATERIALS

Database

In this study, data from the four patients with MI have been used (PhysioNet Challenge 2007). These data include information of BSPM data with 352 leads on the torso plane (obtained from 120-electrode recording). Also, these data included the standard 12 leads and Frank leads. All these leads, based on their location in the torso plane, have a unique form of ECG signal. Horizontal and vertical lines on torso in this position, based on body surface electrodes and leads, are shown in Figure 1. In this figure, torso plane consists of 17 horizontal and 32 vertical lines and all electrodes are located at the intersection of these lines. This database contains ECG signals of four patients with MI and their MI had been determined with magnetic resonance imaging (MRI) analysis from expert persons. In this study, two patient's data were used for training set to define the rules on ECG waveforms. Then, we used data from two other patients to test our hypothesis and determine the results of the proposed method. It should be noted that the exact location of MI in each patient in this database was presented according to the 17-segment standard model of LV by Cerqueira *et al*. in 2002.[9] Finally, we compared the obtained results with the labeled data and measured the evaluation parameters.

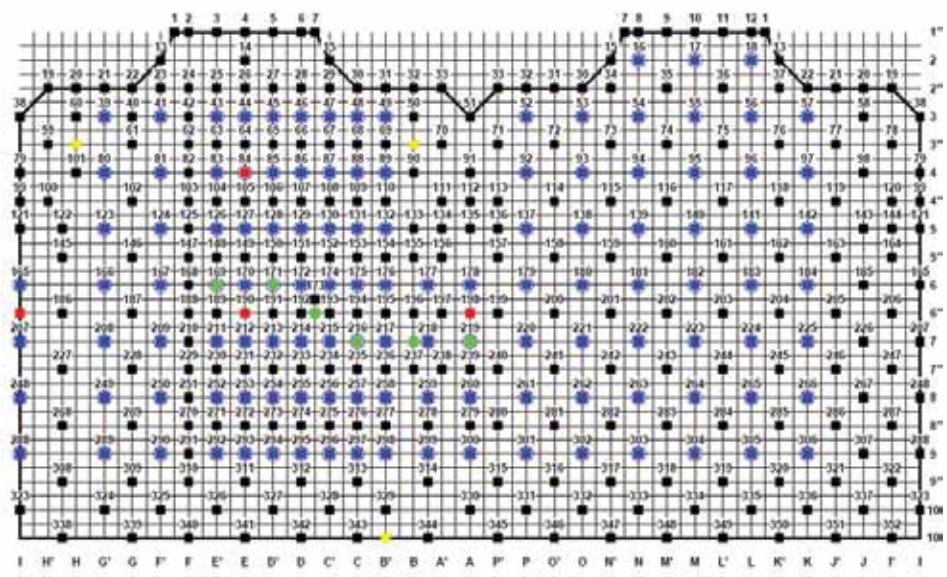

Figure 1: Explanation of horizontal and vertical lines on the torso plane[17]

Body Surface Potential Map

Even though the 12-lead ECG signal is widely used, it has some limitations and, therefore, pushed us to finding other methods. There is lack of appropriate detection of MI in 12-lead ECG. In fact, 50% of MI patients are not diagnosed early by 12-lead ECG because abnormal changes detection does not appear in ECG correctly.[10] The reason is that 12-lead ECG specially records the electrical activity of the LV, while there is no sufficient information on the right ventricle. These constraints can be overcome by BSPM which can be used to obtain the information of ECG, instead of the normal 12-lead ECG.

The BSPM was firstly presented by Waller in 1889.[11] He measured the potential of each location and displayed data for these big quantity locations. The advantage of using BSPM is getting the electrical activity of heart from many points. A BSPM can have 32-213 electrodes in any location on the torso and it can record and display all the information of ECG distributed across the chest.

The main advantage of BSPM is its ability to give detailed information about the location of the electrical field as well as in the time domain, while the standard 12-lead ECG focuses on the time display and has information on a few locations.[12] Also, in 1987, Mirvis compared BSPM with other methods of obtaining ECG and outlined four major advantages of BSPM as follows:[13]

- It is sensitive to the region of cardiac electrical events
- Torso is sampled directly extensively
- Emphasis on spatial characteristics of the heart and
- Evaluates similar models for producing ECG signals.

In 2005, Carly *et al*. compared the detection accuracy of 12-lead ECG with BSPM.[14] In that study, the two standards were used for detection of MI (12-lead ECG and BSPM) and they were compared. This study showed that the BSPM has increased accuracy in determining MI. Unfortunately they also showed that BSPM has less specificity in detecting MI. However, Maynard *et al*. in another study showed that the specificity of the BSPM is acceptable.[15]

Also, McClelland *et al*. compared the interpretation of computer on 80-lead BSPM with the interpretation of the 12-lead ECG, and concluded that the BSPM increases the sensitivity in the detection and diagnosis of acute MI.[16]

Standard Model Segmentation of LV

The heart model in 17 segments is used as an optimal model to predict and determine the location of MI in various diagnostic methods such as imaging methods. This model is now used as a reference model for segmentation of the heart in most studies.[9] In anatomy studies, 102 adults without heart disease were studied. The heart was named by cutting horizontally into three sections: Apical, mid-cavity and basal, and the ratio of the mass of different heart sections per total mass of myocardium is 42% for basal, 36% for the mid-cavity and 21% for the apex of heart. Cerqueira *et al*. model of LV in 17 segments provides the distribution of mass as 35%, 35% and 30% for basal sectors, mid-cavity and the apex of the heart, respectively, and these values are very close to those of anatomical study.[9] The results of this model are shown in Figure 2.

METHODS

First, the data are read by MATLAB software. We have 352 leads for each patient.[17] In fact, we can generate 12-lead ECG signals, and also we have a signal for each lead in the torso plane (i.e. 352 signals), each of them showing different waveforms according to the location and distance from the heart as shown in the following formulae.[17]

```
RA = ((bspmdata. potvals (60,:) + (bspmdata. potvals (101,:))/2;
LA = ((bspmdata. potvals (50,:) + (bspmdata. potvals (90,:))/2;
LL = (3*((bspmdata. potvals (343,:)) + (2*(bspmdata. potvals
     (344,:)))/5;
I = LA – RA,
II = LL – RA,
III = LL – LA,
```

The BSPM data, consisting of ECG data for 352 torso surface sites, are provided for an averaged PQRST complex signal sampled at 1 kHz. The 12 ordinary leads and the Frank leads can be also provided.

First, we loaded the signals in ".mat" format in MATLAB. We had 352 ECG signals (each signal is one cycle of ECG) in 1639 samples for each patient. As the data were

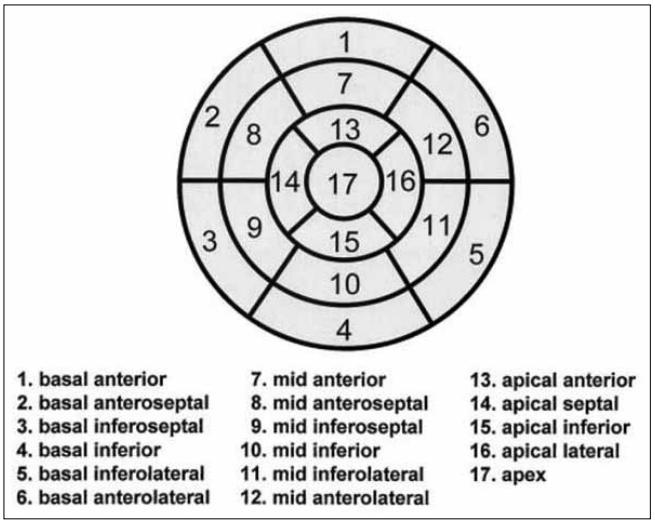

Figure 2: Explanation of 17-segment standard model of left ventricle with the name of each segment

pre-processed, we did not need to do any pre-processing. Then, we extracted the features from these 352 signals and obtained the required rules for localization and determining the extent of MI. Based on the number of rows and columns of the torso plane for each lead, we labelled the features like the T-wave amplitude, T-wave integral, Q-wave amplitude, and the R-wave amplitude, and then plotted the labelled features according to their horizontal and vertical position. The results of this method are shown in Figures 3-6 for the training set.

Determine the location of myocardial infarction

Firstly, we explain the relationship between vertical and horizontal lines in the torso plane with the standard model of the LV. The relationship between vertical lines and the standard model of LV that is expressed in the research of SadAbadi *et al*. is shown in Figure 7.[1]

In this study, we found a relationship between the horizontal lines and the standard 17-segment model of LV. The ratios of different sections in the 17-segment model to the total mass were 35%, 35% and 30% for basal, mid-cavity and apical sections, respectively. As there are 17 horizontal electrode lines on the torso plane (in fact, 33 horizontal lines on which we placed 17 lines of electrodes), 35% of the lines were devoted to the basic (regions 2, 1, 6, 5, 4, and 3 in LV model), 35% to the mid-cavity (regions 8, 7, 12, 11, 10 and 9) and 30% of these lines were devoted to the apical (regions 14, 13, 16, 15 and 17) segment.

As shown in Figure 8, six orange circles (horizontal lines 1-6) with the electrodes in torso plane correspond to basal; the next six lines shown in purple, i.e. horizontal lines 7-12 on the torso plane, correspond to mid-cavity; and five blue horizontal lines 13-17 correspond to apical region. In fact, this figure shows the relationship between horizontal and vertical lines in the torso plane with standard model segmentation of LV.

With these relations between vertical and horizontal lines and the 17-segment model, we can label the location of MI.

Definition rules on the extracted features to determine the location of MI

We can define rules on each extracted feature to identify the location of MI. These rules should separate healthy regions from the MI areas. We can suggest a rule for each feature. In this study, we framed rules from Case #1 and Case #2, and then we applied the rules in the two test patients. Finally, we compared the results with the labels and measured the accuracy of the proposed method.

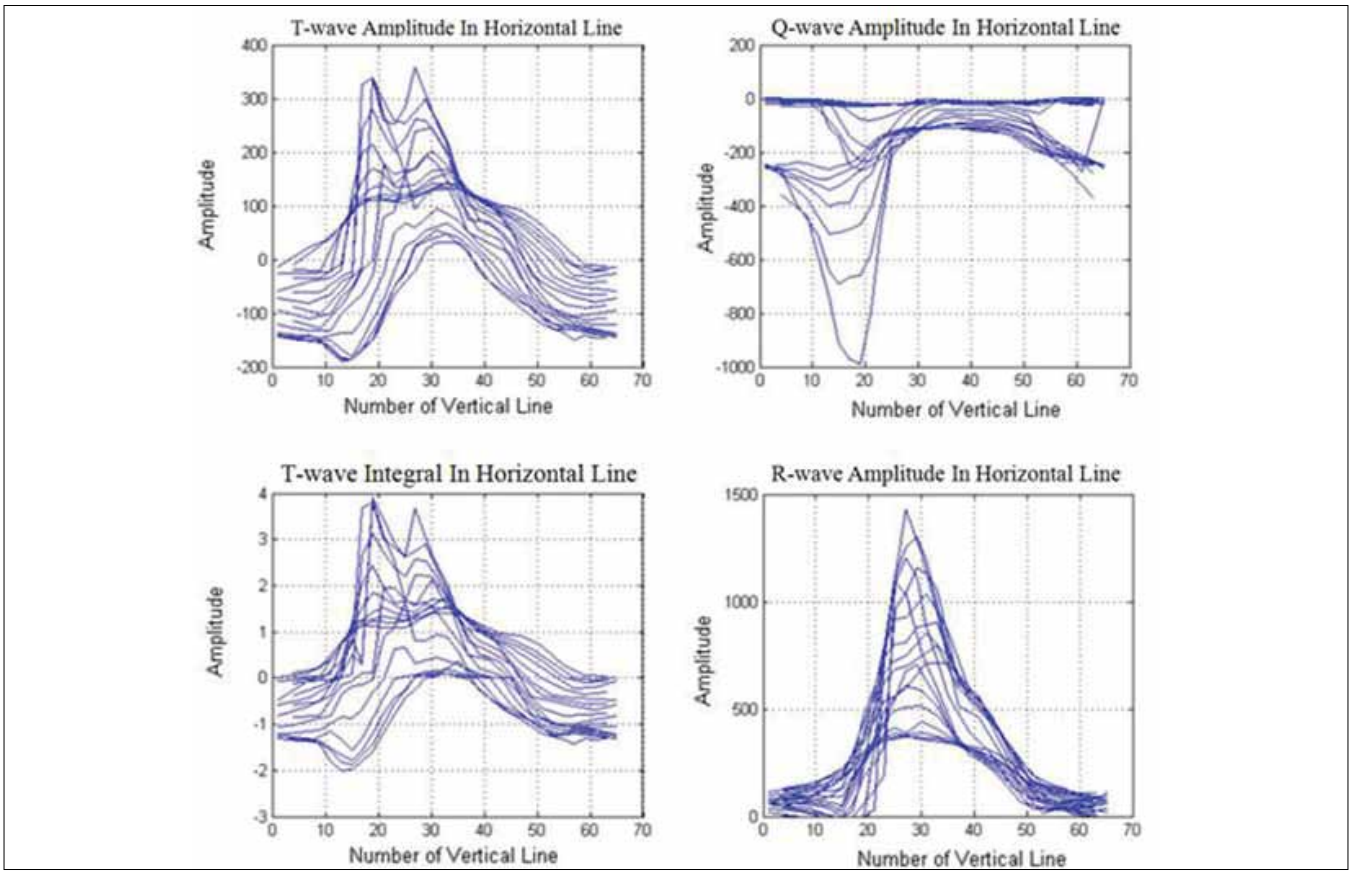

Figure 3: Results of feature extraction base on the number of horizontal lines for Case #1

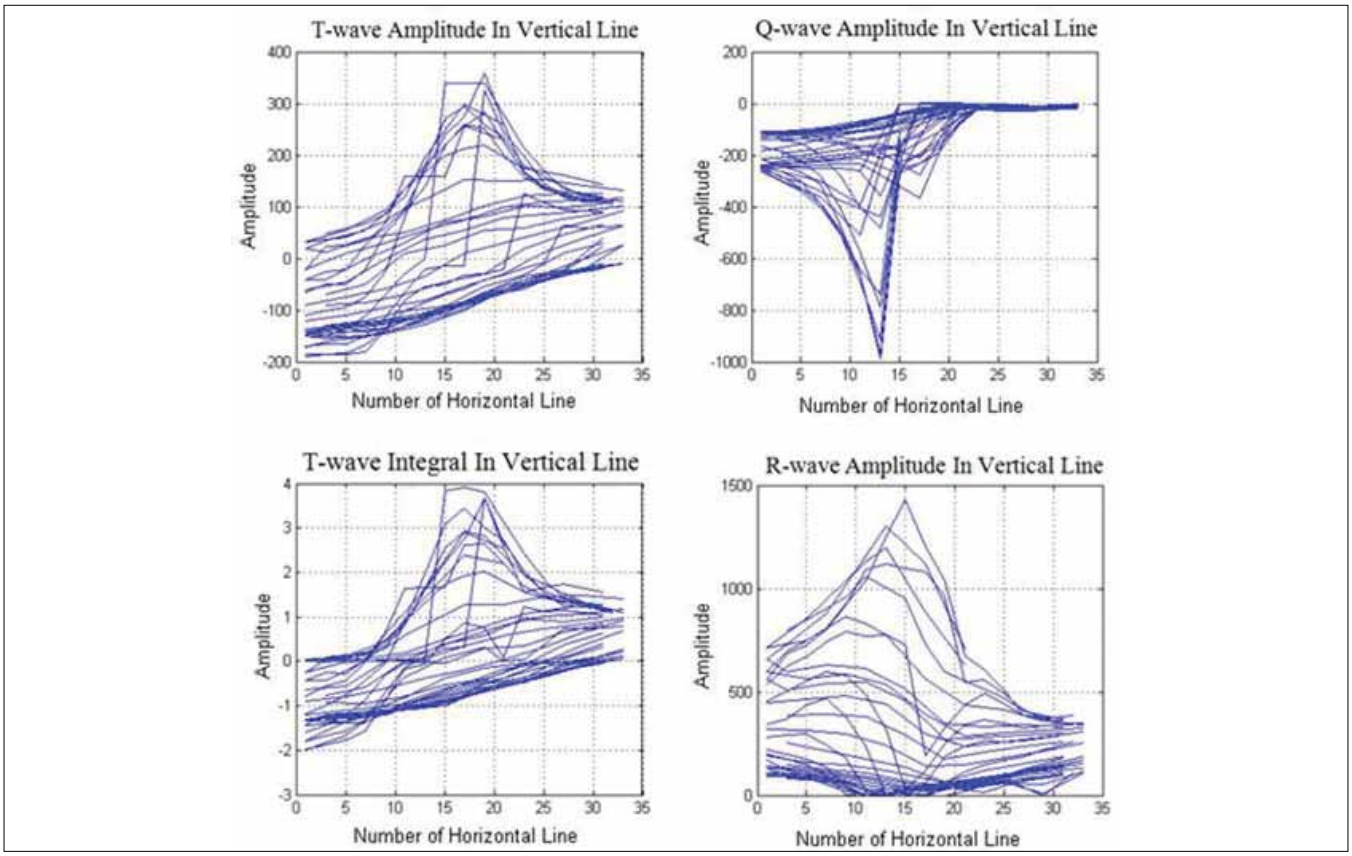

Figure 4: Results of feature extraction base on the number of vertical lines for Case #1

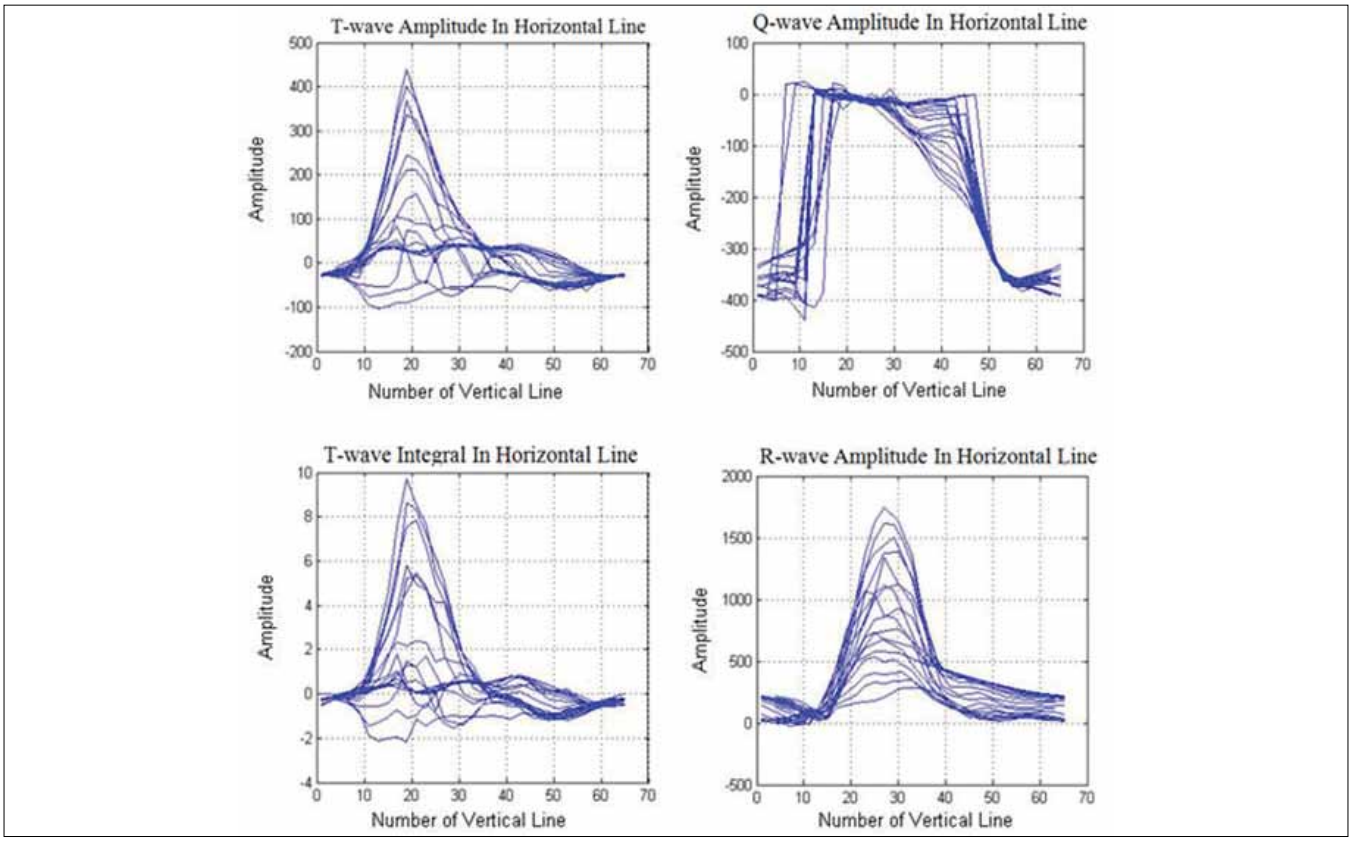

Figure 5: Results of feature extraction base on the number of horizontal lines for Case #2

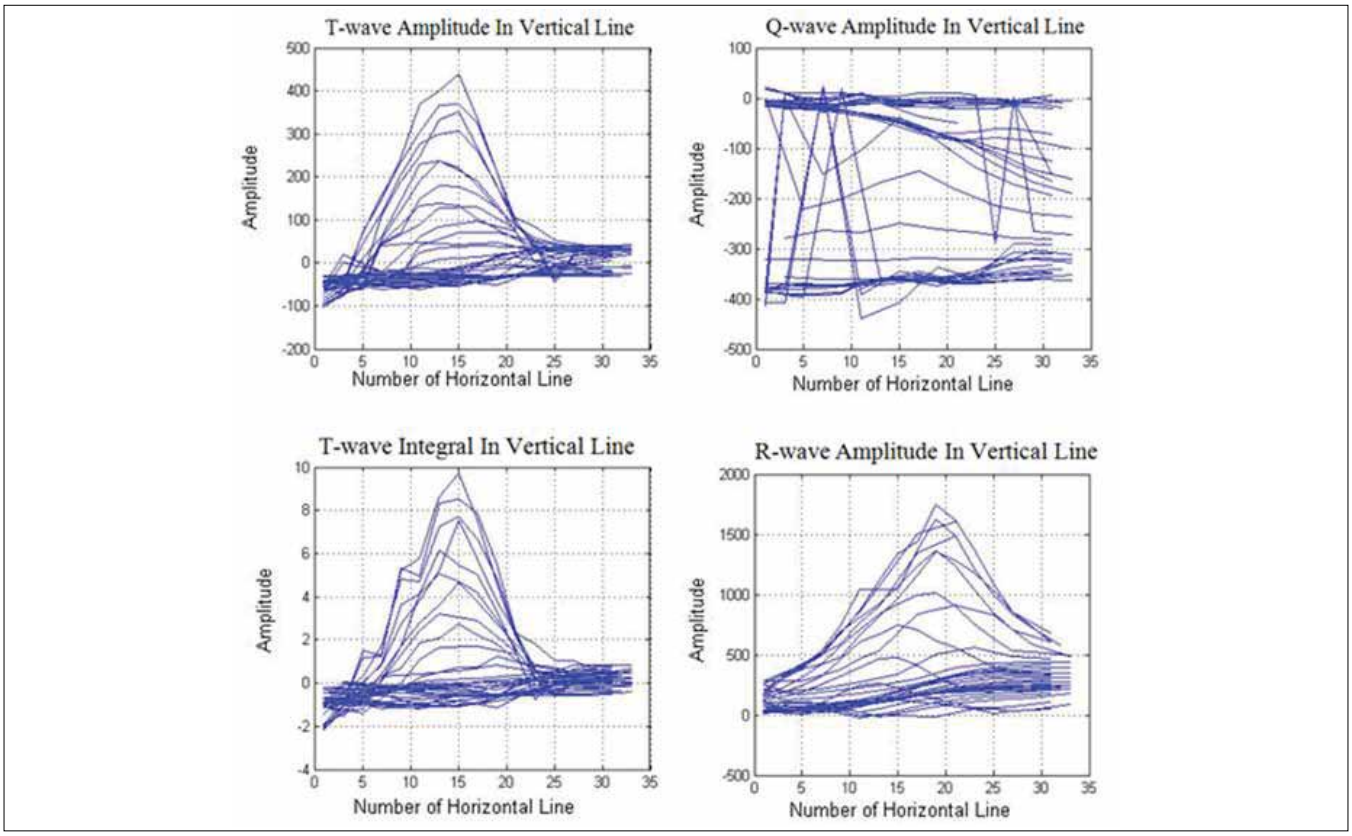

Figure 6: Results of feature extraction base on the number of vertical lines for Case #2

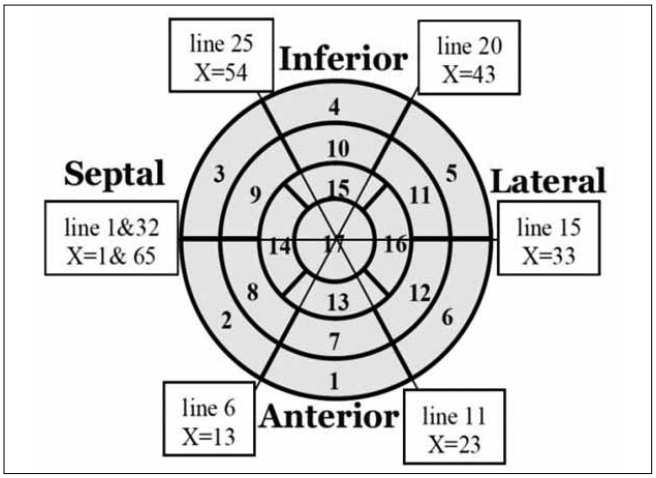

Figure 7: Relationship between vertical lines on the torso plane and the 17-segment standard model of left ventricle

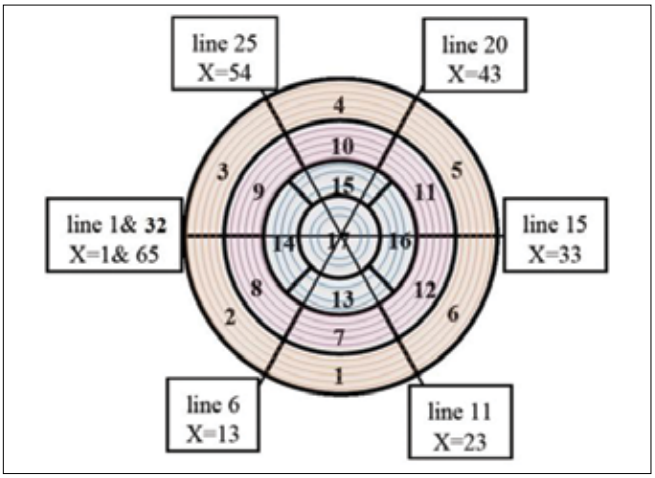

Figure 8: Relationship between vertical and horizontal lines on the torso plane and all parts of the standard model of left ventricle

We defined one threshold in the extracted features in horizontal lines for the R-wave amplitude. We used the condition "R amplitude < 200" to define the MI region. Also, we defined another rule in the horizontal and vertical lines on the T-wave amplitude as the second feature. Here, the condition is "T amplitude ≤ 0."

We defined the third rule on the Q-wave amplitude according to equation 1. Areas that satisfy this equation are healthy; otherwise they are considered as MI region.[1]

$$Th = \frac{1}{5}\{\max(Q\ \text{Amplitude}) - \min(Q\ \text{Amplitude})\} \quad (1)$$

Figure 9 shows how to apply the above rule on the amplitude of Q-wave on the ECG signal for Case #1 as the first patient.

Finally, we applied the fourth rule on the integral characteristics of the T-wave, as shown in Figure 10. According to this rule, signals of leads on the torso plane that T-wave integral is less than 1 are introduced as MI regions.

Determination of MI extent

We used the T-wave integral as one feature to determine the extent of MI. We used equation 2 for determining the MI extent, which is as follows:

$$Mi\ Extent = |Min\ (T\ wave\ Integral)| \times \alpha \quad (2)$$

In this equation, the coefficient α is obtained from the T-wave integral feature from the data of two cases in the training set. Figures 11 and 12 show the results of the T-wave integral as the feature extracted from horizontal lines for Case #1 and Case #2 as the training set, respectively.

We used this formula for the training set and obtained the extent of MI for Case #1 (29.1757%), while in this case, the extent of MI with MRI analysis was 31%. Also, we got the MI extent for Case #2 as 24.2947%, while MRI analysis for this case showed 30%. These results confirm the accuracy of the formula.

Now we are ready to apply the formula in test data. MI extent for Case #3 was obtained to be equal to 47.03%. In this patient, MRI analysis of MI showed 52%. MI extent in Case #4 was obtained to be equal to 13.6%, while MRI analysis showed 14%. The results show high accuracy in the test data.

RESULTS

So parameter is introduced as a standard parameter to determine the performance of different methods used to find the location of MI.[17] This parameter is obtained by dividing the number of common elements between the diagnostic elements by the proposed method with the elements of MI in reality, per sum of the common elements and elements that are not detected by the proposed method and elements that are healthy but have been diagnosed with MI by the proposed method. This parameter is a number between 0 and 1; if the number is closer to 1, it means performance

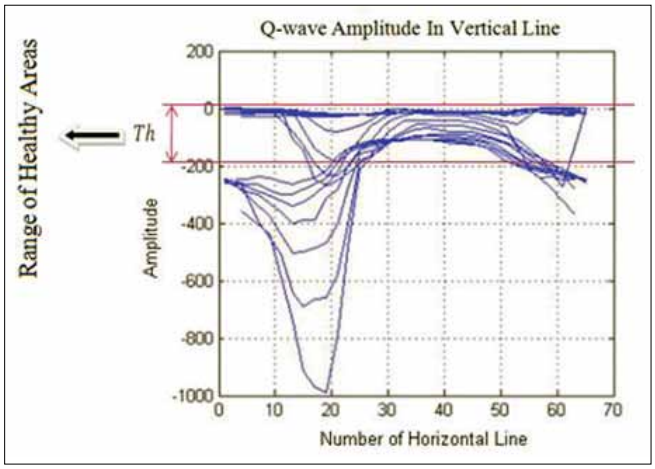

Figure 9: Applying threshold rule on the Q-wave amplitude for Case #1 as the first patient

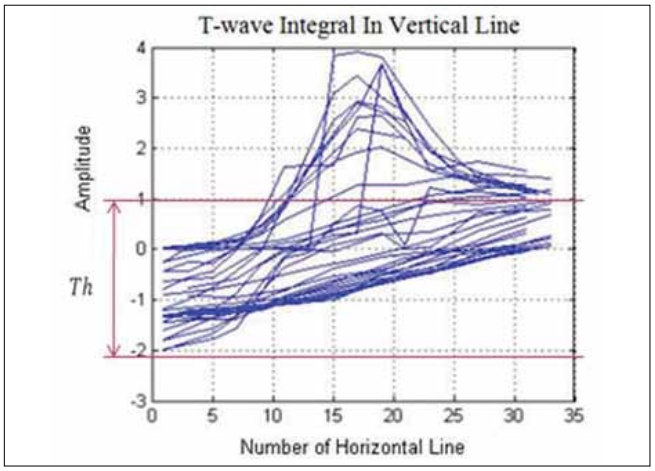

Figure 10: Applying threshold rule on the T-wave integral for Case #1 as the first patient

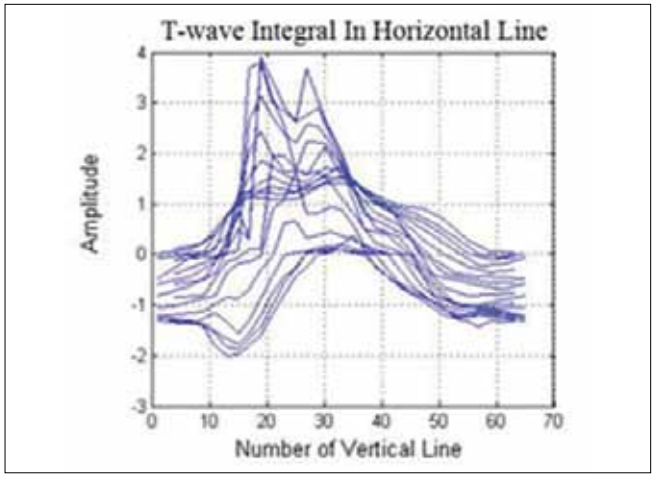

Figure 11: Results of the T-wave integral as the feature on the horizontal lines for Case #1 as the first patient in the training set

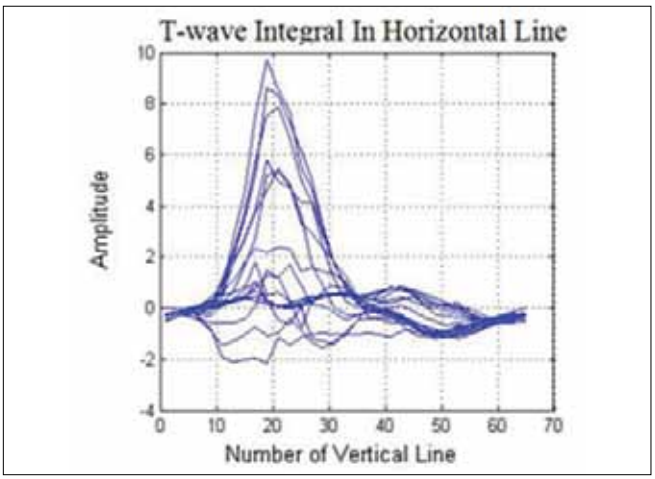

Figure 12: Results of the T-wave integral as the feature on the horizontal lines for Case #2 as the second patient in the training set

of the proposed method is better. Also, CED parameter, defined as the distance between the center region of MI that was diagnosed by our method and compared with standard MRI (which is defined in PhysioNet). In this study, the regions at the geometric center of the heart with MI were diagnosed as the center of MI regions. CED is a numerical value between 0 and 8; lower value shows higher accuracy in the method. EPD parameter is defined by the percentage discrepancy between the MI extent as estimated and as determined from the MRI gold standard, gadolinium MRI. This parameter is a numerical value between 0 and 8, and lower value shows the higher accuracy in the method.

We used all the features and got the MI location in one approach, and in another approach, we used only T-wave integral. But for the extent of MI, we used only T-wave integral.

The results are shown in Tables 1 and 2. In Table 1, it can be seen that the final value of SO parameter for two test patients is 0.89, the final CED parameter value is 6, and the final value of EPD parameter is 5.37. Although these results are good compared with the results of pervious research, there was improvement only when we used T-wave integral as the feature. The results are shown in Table 2. The final value of SO parameter for the two test patients is 1.16, the final CED parameter value is 1, and the final value of EPD parameter is 5.37.

These results show the high accuracy of the proposed method to determine the location and extent of MI by applying the described rules on the extracted features.

DISCUSSION AND CONCLUSION

In this study, a new method to determine the location and extent of MI using BSPM data by defining rules and thresholds on the extracted features is proposed. Results of our method and the results obtained from MRI about the estimated location and extent of MI were compared. The results show the high accuracy of the proposed method. In Table 3, we see the comparison of our results with previous researches.

According to Table 3, the value of SO obtained for Case #3 is equal to 0.66, which is better than four previous researches. The value of SO for Case #4 was obtained as 0.5, which is better than all previous researches. We see the total SO = 0.66 + 0.5 = 1.16 is the best in all researches. With regard to CED parameters, the total for two test cases is obtained as equal to 1 (optimal value may be 0), which is

Table 1: Results of the proposed method using all features for MI location and T-wave integral for MI extent in test data

Patient	Location of MI according to LV segmentation	SO parameter	Centroid location of MI according to LV segmentation	CED parameter	MI extent (%)	EPD parameter
Case #3	2,3,4,5,8,9,10,11,14,15,16,17	0.62	10	0	47.03	4.97
Case #4	1,2,3,4,8,9,10,14	0.27	9	6	13.6	0.4

Table 2: Results of the proposed method using T-wave integral to determine the location and extent of MI in test data

Patient	Location of MI according to LV segmentation	SO parameter	Centroid location of MI according to LV segmentation	CED parameter	MI extent (%)	EPD parameter
Case #3	2,3,4,5,8,9,10,11, 14,15,16	0.66	10	0	47.03	4.97
Case #4	1,2,3,4,9,10, 14,15,17	0.5	14	1	13.6	0.4

Table 3: Final results of the proposed method in comparison with previous researches done on the BSPM data

Researcher	Methods	Results for Case #3			Results for Case #4		
		SO	CED	EPD	SO	CED	EPD
Philip Langley[3]	Clinical evaluation of ECG signals by comments of three cardiologists	0.444	1	22	0.000	4	17
Dmitry Farina[5]	Model-based approach to the localization of infarction	0.400	1	43	0.167	1	14
Masood Ghasemi[6]	Heart vector analysis	0.600	0	11	0.333	1	21
Hamid SadAbadi[1]	Feature extraction and definition rules on features and determining results with semi-manual method	0.500	0	2	0.444	1	6
Mohammed Mneimneh[7]	Feature extraction and training with PTB database in PhysioNet by RPS/GMM approach	0.900	0	25	0.250	1	2
Nader Jafarnia[8]	Neural network	0.7	–	–	0.4	–	–
Proposed method (intersection results of all extracted features for the location of MI, and results of T-wave integral to determine MI extent)	ECG signal processing and automatic method to determine results	0.62	0	4.97	0.27	6	0.4
Proposed method (best results) (by two described rules on T-wave integral to determine the location and extent of MI)	ECG signal processing and automatic method to determine results	0.66	0	4.97	0.5	1	0.4

better than the results of two previous studies and equal to three previous studies. With regard to EPD parameter, the final value for T-wave integral feature was obtained as 5.37 (optimal value is closer to 0). This value, as seen in Table 3, for other previous studies has been reported as 39, 57, 32, 8 and 27. In fact, results indicate excellent performance for EPD parameter in the proposed method.

It should be noted that the main advantages of the proposed method are its simplicity and high accuracy.

SUGGESTIONS FOR FUTURE STUDIES

Future studies can focus on other parameters in ECG signals, such as slope of T-wave, duration of QRS complex, and total signal integral in one cycle from the data of leads in the torso plane to determine the localization and extent of MI to obtain higher accuracy.

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BIOGRAPHIES

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Ali Motie Nasrabadi received a BS degree in Electronic Engineering in 1994 and his MS and PhD degrees in Biomedical Engineering in 1999 and 2004, respectively, from Amirkabir University of Technology, Tehran, Iran. Since 2012, he has been Associate Professor in the Biomedical Engineering Department at Shahed University, in Tehran, Iran. His current research interests are in the fields of Biomedical Signal Processing, Nonlinear Time Series Analysis and Evolutionary Algorithms. Particular applications include: EEG Signal Processing in Mental Task Activities, Hypnosis, BCI and Epileptic Seizure Prediction.

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