Temporal Analysis of the Depolarization Wave of Healed Myocardial Infarction in Body Surface Potential Mapping

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Background: We studied the ability of different time segments of the depolarization wave recorded with body surface potential mapping (BSPM) to detect and localize myocardial infarction (MI).

Methods: BSPM was recorded in 24 patients with remote MI and in 24 healthy controls. Cine and contrast-enhanced magnetic resonance imaging (MRI) was used as a reference method. Patients were grouped according to anatomical location of their MI. The QRS complex was divided into six temporally equal segments, for which time integrals were calculated.

Results: The time segments of the QRS complex showed different MI detection capability depending on MI location. For anterior infarction the second segment of the QRS complex was the best in MI detection and the optimal area was on the right inferior quadrant of the thorax (time integral average -1.5 ± 1.8 mVms patients, 1.0 ± 1.6 mVms controls, $P = 0.002$). For lateral infarction the first segment of the QRS complex performed best and the optimal area for MI detection was the left fourth intercostal area (time integral average 1.8 ± 1.0 mVms patients, 0.7 ± 0.5 mVms controls, $P = 0.024$). For inferior and posterior MI the mid-phases of the QRS complex were the best and the optimal area was the mid-inferior area of the thorax (time integral average -6.2 ± 8.3 mVms patients, 3.3 ± 4.3 mVms controls, $P = 0.002$; -9.1 ± 6.1 mVms patients, 0.6 ± 7.1 mVms controls, $P = 0.001$, respectively).

Conclusions: Time segment analysis of the depolarization wave offers potential for improving the detection and localization of healed MI.

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body surface potential mapping; myocardial infarction; magnetic resonance imaging; depolarization; time integral

The left ventricular (LV) depolarization in a normal heart begins in the septum and spreads to the apex and anterior LV wall, from endo- to epicardial direction. At 40 ms from the QRS onset most of the surface of the anterior wall has undergone activation. Finally, the depolarization wave spreads to the basal regions of the heart.¹

Body surface potential mapping (BSPM) provides greater diagnostic information than 12-lead electrocardiogram (ECG) for old myocardial infarction (MI)²⁻⁵ and acute MI,⁶⁻¹¹ also when additional right ventricular or posterior leads are added.¹²

Contrast-enhanced magnetic resonance imaging (MRI) has been shown to detect subendocardial MIs missed by single-photon emission computed tomography (SPECT),¹³ and has recently been used to determine myocardial viability and infarction damage.¹⁴

Our hypothesis was that the electrocardiographic abnormalities of healed MIs manifest at different time segments of the QRS complex, depending on the location of the infarction.

We studied the temporal segment of the QRS that would show the best discriminative accuracy from

normal condition, and used contrast-enhanced MRI as an accurate reference method.

METHODS

Patients and Controls

The study population consisted of 48 subjects: 24 patients with coronary artery disease and 24 healthy controls (Table 1). All of the patients had a history of one or more remote (range 1.5 months to 17 years) MIs and angiographically verified coronary artery disease. Of the 24 patients, 20 had triple-vessel disease, 3 had two-vessel disease, and 1 had single-vessel disease. The exclusion criteria were bundle branch or fascicular block in 12-lead ECG. The healthy controls had no history of heart disease, and had normal results in exercise ECG and in rest echocardiography. All of the study subjects gave their informed consent. The research protocol was approved by the local ethics committee and complied with the Declaration of Helsinki.

Body Surface Potential Mapping

Resting BSPM with 120 unipolar leads covering the whole thorax was recorded for 5 minutes, as reported previously.¹⁵ In addition, 3 limb leads were recorded according to the correct Mason-Likar placement with electrodes on the right and left shoulder and on the left hip.^{16,17} Wilson's central terminal was used as a reference potential for all of the leads. The electrodes were mounted on 18 strips, placed on the subject's thorax vertically with horizontal spacing determined by the dimensions of the upper body. The highest electrode density was on the left anterior chest (Fig. 1). After band-pass filtering from 0.16 Hz to 300 Hz, the signals were digitized with a sampling rate of 1000 Hz.

Figure 1. The body surface potential map (BSPM) electrode layout. The electrodes are mounted on 18 vertical strips. The dimensions of the upper body determine the horizontal spacing of the electrodes. Squares represent the 12-lead ECG chest leads. Vertical line runs at the level of the fourth parasternal intercostal space. Leads are labeled by numbers 1–124.

Magnetic Resonance Imaging and Image Analysis

The localization and extent of the infarcted myocardium were determined by the combined method of cine and contrast-enhanced MRI, which was used as a reference method. Patients were positioned supine on the table of a 1.5-T imager (Magnetom Vision; Siemens, Erlangen, Germany) and imaging was performed with a body array coil as a receiver. Transverse, oblique sagittal, and double-oblique LV long-axis scout images were obtained to determine the final short-axis imaging plane. A LV

Table 1. Characteristics of Study Groups

	Patients	Controls	P Value
Number of subjects	24	24	
Male/Female	21/3	18/6	
Age (years)	62 ± 9 (range 46–82)	52 ± 10 (range 29–67)	0.001
Duration of QRS (ms)	97 ± 10 (range 81–116)	92 ± 7 (range 76–101)	0.058
LVEF (%)	49 ± 14	66 ± 7	<0.001

Mean ± standard deviation. LVEF = left ventricular ejection fraction. P value for the difference between the patient and the control group is shown in the right column.

short-axis orientation was selected for MRI to minimize partial volume effects. Five short-axis sections of 10 mm thickness 15 mm apart were imaged with a electrocardiographically gated cine-MRI method, which produces a series of LV wall images within the cardiac cycle every 40 ms. The perfusion of the LV wall of the same sections was imaged during contrast agent injection (0.05 mmol/kg gadopentate dimeglumine, Magnevist; Schering, Helsinki, Finland) and the late enhancement of the myocardium was observed for 20 minutes with an inversion recovery turboflash sequence.¹⁸ The larger extracellular volume in the infarcted myocardium appears as increased signal intensity during the late enhancement period.

The myocardial segment was classified to be infarcted when the diastolic wall thickness was less than 5.5 mm, there was less than 2 mm systolic thickening, or there was significant late enhancement of more than 2 standard deviations (SD) of normal myocardium.¹⁸⁻²⁰

Other Imaging Methods

All patients underwent coronary angiography with standard techniques. Luminal diameter stenosis of >50% in at least one of the main coronary arteries was considered significant. Of the 24 patients, 15 also underwent a cineangiography to localize LV wall motion abnormalities and to determine LV ejection fraction (LVEF). Nine patients and all controls underwent echocardiography to localize LV wall motion abnormalities and to determine LVEF (Table 1).

For 22 patients thallium [²⁰¹Tl] SPECT stress imaging with redistribution imaging at 4 hours was performed. A patient was considered having MI if the signal intensity was <75% of maximum signal intensity, both under stress and in rest. Nine patients underwent positron emission tomography (PET) imaging of the heart with [¹⁸F] fluorodeoxyglucose ([¹⁸F]FDG).²¹ Fixed defect was diagnosed as MI.

Segmentation and Patient Classification

The myocardium was divided into 16 segments, according to the American Heart Association's (AHA) recommendation of LV segmentation.²²⁻²³ These segments were combined to form eight anatomical regions: anterobasal, anterior, anteroseptal, lateral, inferoseptal, apical,

inferior, and posterior.²¹ MRI findings were compared with echocardiography, cineangiography, PET, and SPECT. In 21 patients at least one of the other imaging methods was consistent with MRI in detecting MI.

Patients were classified according to the MI location (Table 2). A patient was considered having anterior MI, if the infarcted myocardium was located within the anterobasal, anteroseptal, or anterior segment. A patient was considered having apical MI, if the infarcted myocardium was located within the apical segment. MI in inferoseptal, or posterior segment, or both, was considered posterior MI. Inferior segment involvement alone, or in combination with inferoseptal segment, was considered inferior MI. Lateral segment involvement alone, or in combination with posterior segment, was considered lateral MI. Thus, a patient could be assigned into more than one group. Based on 12-lead ECG, the patients were diagnosed with Q-wave MI (QMI), according to the Minnesota code, or non-Q-wave MI (NQMI).²⁴

Analysis of BSPM Signals

The BSPM data were visually inspected for validity of the recording, and signal-averaged according to criteria of 0.9 or greater correlation of the QRS complex to a selected template beat and maximum noise of 50 μ V. It also was required that the T wave fits an envelope of 110-200 μ V around the template beat.²⁵ The baseline was defined from a 20 ms section of the PQ segment. Invalid leads were deleted and replaced by interpolation of data from the surrounding leads.²⁶ Automatic identification of the QRS onset and offset was performed after bidirectional high-pass filtering of the

Table 2. Patient Classification According to the Myocardial Infarction Location

Infarction Groups	Number of Patients	QMI/NQMI	Age (years)
Anterior	10	6/4	63 $\pm$ 11
Lateral	5	2/3	60 $\pm$ 9
Inferior	11	6/5	65 $\pm$ 8
Posterior	11	7/4	66 $\pm$ 9
Apical	12	8/4	63 $\pm$ 10

Mean $\pm$ standard deviation. A patient can be assigned to more than one group. NQMI = non Q-wave myocardial infarction; QMI = Q-wave myocardial infarction.

depolarization wave.²⁷ For each patient, the median QRS onset and offset were calculated. QRS was divided into six temporally equal segments, referred to as sextiles. The QRS time integrals were determined for each individual within each sextile.

Discriminant Index

Discriminant indexes (DI) were calculated as described by Kornreich et al.⁷ DI was used to identify the optimal recording locations to separate the MI group from the control group. First, the mean value of the control group was subtracted from the corresponding mean of the MI subgroup. The difference was then divided by the pooled standard deviation of the MI group in question and the control group.

The DI value is directly proportional to the *t*-value in the Student's *t*-test. The greater the absolute DI value ($|DI|$), the better the ability of the lead to differentiate between the two groups. Negative DI values indicate higher and positive DI values lower parameter values for the patient group as compared to the control group.

Isocontour Maps

Isocontour maps were drawn for average QRS time integrals of each MI group, of the control group, and for the corresponding DI values. For visual inspection, the isocontour maps were divided into four quadrants on the anterior torso, which were bounded laterally by the right and the left midaxillary lines and in caudo-cranial direction by the midsternal line and the fourth intercostal space. These quadrants translated into right superior, right inferior, left superior, and left inferior quadrant. If the best values were found at the border of these quadrants, the location was referred to as mid inferior (border of right and left inferior) or the left fourth intercostal (border of left superior and inferior) area.

The sextile with the greatest number of leads exceeding a $|DI|$ of 1 was chosen to be the optimal time segment for MI detection. The best lead was chosen to be the lead with the greatest $|DI|$ within this time segment.

Statistical Analysis

Continuous values are presented as mean $\pm$ SD. The significance of difference between the groups was determined with the Mann-Whitney U test. Correlations between the parameters were

examined with Pearson's correlation coefficient (*r*). Receiver operating characteristic (ROC) curves were created to assess the performance of the parameters in the optimal leads, as judged by DI value. A 2-tailed P-value ≤ 0.05 was considered statistically significant. The Statistical Package for the Social Sciences (SPSS, Inc., Chicago, IL) for Windows (version 10.0) biostatistics software was used.

RESULTS

Infarcted myocardium was found in the anterior region in 10 of the patients, in the lateral region in 5, in the inferior region in 11, in the posterior region in 11, and in the apical region in 12 of the patients (Table 2). QMI, in the 12-lead ECG, was found in 11 patients. QMIs were found in all MI groups.

Temporal Analysis

In the anterior MI group the optimal QRS time segment for MI detection was the second sextile with 30% of the leads (37 leads) differentiating between the patients and the controls ($P \leq 0.05$) and with 23 leads having $|DI| > 1$ (Tables 3 and 4). The number of leads with $|DI| > 1$ diminished during subsequent sextiles. In the first sextile there were only two leads with $|DI| > 1$.

In the *lateral MI group* the optimal QRS time segment was the first sextile with 23% of the leads (28 leads) differentiating between the patients and the controls ($P \leq 0.05$) and with 33 leads having $|DI| > 1$ (Tables 3 and 4). The number of leads with $|DI| > 1$ diminished during the subsequent leads.

In the *inferior MI group* the optimal QRS time segment was the third sextile with 47% of the leads (58 leads) differentiating between the patients and the controls ($P \leq 0.05$) and with 35 leads having $|DI| > 1$ (Tables 3 and 4). The number of leads with $|DI| > 1$ diminished during subsequent leads.

In the *posterior MI group* the optimal QRS time segment was the fourth sextile, with 20% of the leads (25 leads) differentiating between the patients and the controls ($P \leq 0.05$), and with 13 of them having $|DI| > 1$ (Tables 3 and 4).

In the *apical MI group* the optimal QRS time segment was the fifth sextile with 39% (48 leads) of the leads differentiating between the patients and the controls ($P \leq 0.05$), and with 19 of the leads with $|DI|$ exceeding 1 (Tables 3 and 4). During the third to fourth sextiles in 16 leads $|DI|$ exceeded 1.

Table 3. The Optimal Time Segments of the QRS Complex and the Corresponding Optimal Recording Areas in Myocardial Infarction Patient Groups and the DI and Time-Integral Values in the Optimal Leads

Infarction Groups	The Optimal Sextile	The Optimal Chest Area	DI	Time-Integral Patients (mVms)	Time-Integral Controls (mVms)	P Value
Anterior	2nd	Right inferior	-1.24	-1.5 ± 1.8	1.0 ± 1.6	0.002
Lateral	1st	Left 4th intercostal	1.43	1.8 ± 1.0	0.7 ± 0.5	0.024
Inferior	3rd	Mid inferior	-1.31	-6.2 ± 8.3	3.3 ± 4.3	0.002
Posterior	4th	Left inferior	-1.20	-9.1 ± 6.1	0.6 ± 7.1	0.001
Apical	5th	Right superior	-1.37	-7.7 ± 3.5	-2.5 ± 2.7	<0.001

Mean ± standard deviation. DI = discriminant index.

Distribution of Body Surface Potentials in the Optimal Sextiles

For the *anterior MI group* the time integral values were lower than for the control group over most of the anterior thorax, especially on the right side (Tables 3 and 4, Fig. 2). The optimal location was the right inferior quadrant, the best lead being number 13 (average QRS integral -1.5 ± 1.8 mVms MI group, 1.0 ± 1.6 mVms control group; P = 0.002; area under ROC curve 83%).

For the *lateral MI group* the time-integral values were higher than for the controls over most of the anterior thorax (Tables 3 and 4, Fig. 2). The optimal location was the left fourth intercostal area, the best lead being number 60 (average QRS integral 1.8 ± 1.0 mVms MI group, 0.7 ± 0.5 mVms control group; P = 0.024; area under ROC curve 83%).

The *inferior MI group* had lower time-integral values than the control group over the mid-inferior part of the anterior thorax, the optimal lead being number 34 (average QRS integral value -6.2 ± 8.3 mVms MI group, 3.3 ± 4.3 mVms control group; P = 0.002; area under ROC curve 83%) (Tables 3 and 4, Fig. 2).

For the *posterior MI group* the time-integral values were lower than for the control group over the inferior part of the anterior chest. The optimal location was the left inferior quadrant, the best lead being number 48 (average QRS integral -9.1 ± 6.1 mVms MI group, 0.6 ± 7.1 mVms control group; P = 0.001; area under ROC curve 84%) (Tables 3 and 4, Fig. 2).

For the *apical MI group* the optimal area was the right superior quadrant, with lower time-integral values for the MI than the control group, the best

Table 4. The Optimal Leads for Infarction Detection in Each Sextile of the QRS in Each Myocardial Infarction Patient Group

Infarction		1 st	2 nd	3 rd	4 th	5 th	6 th
Anterior	Number of leads with [DI] > 1	2	23	18	15	11	5
	The optimal lead label	18	13	21	20	24	121
	AUC in the optimal lead	80%	83%	86%	86%	85%	77%
Lateral	Number of leads with [DI] > 1	33	26	29	17	5	0
	The optimal lead label	60	61	20	20	30	10
	AUC in the optimal lead	83%	78%	89%	98%	83%	69%
Inferior	Number of leads with [DI] > 1	2	6	35	25	15	0
	The optimal lead label	68	21	34	17	17	91
	AUC in the optimal lead	79%	82%	83%	76%	85%	69%
Posterior	Number of leads with [DI] > 1	0	0	9	13	0	3
	The optimal lead label	68	27	34	48	24	30
	AUC in the optimal lead	72%	70%	81%	84%	72%	83%
Apical	Number of leads with [DI] > 1	0	0	16	16	19	0
	The optimal lead label	54	21	53	39	24	44
	AUC in the optimal lead	69%	73%	83%	84%	90%	82%

Mean ± standard deviation. AUC = area under receiver operating characteristic curve; DI = discriminant index.

Figure 2. Isocontour maps of the QRS segment time integrals and of the corresponding discriminant indexes (DI). Left column: the time integrals of each patient group during the optimal sextile. Middle column: the time integrals of the control group during the same sextile. Right column: the corresponding DIs. Visually, the average time-integral maps of the infarction group and the control group, within the optimal sextile, are not distinct, whereas the DI maps are divergent for each infarction patient group. The maps are displayed with anterior thorax to the left and back of the torso to the right. The vertical and horizontal lines mark the borders of the quadrants on the anterior torso. The thick solid line = zero line; the thin solid line = positive values; dashed line = negative values. The isocontour step is 1.0 mVms for the anterior, lateral, and inferior infarction patient groups and for the corresponding sextiles in the control group, and 2.5 mVms for the posterior and apical infarction groups and the corresponding sextiles in the control group. The isocontour step is 0.2 for the DI maps.

electrode being number 24 (average QRS integral -7.7 ± 3.5 mVms MI group, -2.5 ± 2.7 mVms control group, $P < 0.001$; area under ROC curve 90%) (Tables 3 and 4, Fig. 2).

DISCUSSION

Main Findings

This study showed that the use of QRS segmentation in body surface potential mapping may improve the localization of healed myocardial infarction. We found that the ability to detect MI was different for various time segments of the depolarization wave, depending on the location of the infarct scar. Furthermore, the optimal body surface areas were distinct for each MI location.

Analysis of Time Segments of the QRS Complex

Anterior MI was best detected during the early part of the QRS complex, as expected. However, the very first sextile was inferior to all the other sextiles in performance. For the lateral MI the first half of the QRS complex was the most informative. The first sextile was optimal with positive DIs over the anterior thorax, which reflected reciprocal negative DIs from the back. Huey et al. have represented a concordant finding with abnormal R waves in leads V_1 or V_2 in patients with left circumflex coronary artery-related MI.²⁸ Notable in our study also was the superior performance of the early QRS as compared to the late QRS in lateral MI. The inferior and posterior MIs were best detected during the mid QRS, with MI detection for inferior MI peaking slightly earlier than for posterior MI. The apical MI was best detected during late QRS.

The timing of best performance within the QRS complex is in agreement with the known sequence of distribution of the depolarization wave in the heart¹ except for the early detection of lateral and late detection of apical MI. The apical MI was well detected also during the mid phases of the QRS.

Spatial Distribution of QRS Changes

In our patients anterior MI manifested as negative DI values over most of the anterior chest during all time segments. Thus, the MI group had decreased time-integral values anteriorly due to the loss of myocardium in the anterior LV wall. Inferior and posterior MI manifested as negative

DI values over the anterior lower thorax during the mid QRS. These observations are in agreement with the findings of Montague et al.²⁹ In their study anterior MI appeared as negative values over the anterior thorax and inferior MI as negative values over the inferior torso during depolarization.

Medvegy et al. studied the concordance between the depolarization wave features of BSPM and exercise SPECT, angio-, and ventriculography.⁵ The concordance between the BSPM features and the reference methods suggested that BSPM could localize NQMI. Our study, using as a reference method contrast-enhanced MRI, which is more specific for detecting subendocardial infarct scars,³⁰ also supports the concept that BSPM can localize NQMI.

The optimal leads for the MI detection in all patient groups lay exclusively outside the standard 12-lead ECG. The optimal leads were not located in the same areas as the greatest deviations of the integral values from zero. These findings call for further studies to optimize the set of leads to detect healed MI, especially in the state of acute ischemia.

Related Signal Analysis Techniques

Reinhardt et al.³¹ also examined the influence of the infarct scar location on intra-QRS analysis using signal-averaged ECG. Anterior MIs were distinguished from inferior MIs by more prominent changes in spectral analysis of QRS complex, recorded with modified Frank leads. Shibata et al.³² found, by body surface mapping, a different body surface location of maxima of high frequency components in the final 20 ms portion of QRS complex for anterior MI, inferior MI, and the controls.

Earlier studies have investigated the effect of a myocardial scar, detected at autopsy³³ or by thallium-201 perfusion images,³⁴ on the QRS loop of the vectorcardiogram. In vectorcardiogram electrical potentials are presented as a single dipole whereas BSPM gathers abundant spatial information and is thus theoretically superior to the vectorcardiogram, especially when temporal segmentation analysis is applied.

Limitations of the Study

There is an inherent source of bias in QRS time-integral segmentation. The depolarization wave is delayed within and adjacent to the infarcted myocardium due to the peri-infarction block.³⁵

Accordingly, in our study the QRS duration was, on average, slightly longer in MI patients. The peri-infarction block could explain the slight discrepancy between timing of the optimal MI detection and known depolarization sequence, especially in patient groups with combined MIs. The results should be considered preliminary since the number of study subjects was small, especially the number of patients in the lateral MI group. However, we tried to overcome this by using contrast-enhanced MRI as an accurate reference method for localizing the myocardial infarction scar. The contrast-enhanced MRI allows for the detection of even small subendocardial scars, enabling MI detection and localization in patients with NQMI and well-preserved LVEF also. Patients were slightly older than the controls, but it is unlikely that such an age difference would meaningfully change the studied parameter values.

CONCLUSIONS

The MI detection ability of the different QRS time segments depends on the location of healed MI. It is noteworthy that the optimal leads for MI detection in common infarction sites lie outside the standard 12-lead ECG. The localization of MI can be improved by time-integral analysis of different segments of QRS complex and by choosing optimal leads for each suspected MI location. Accurate detection of the existing myocardial damage by improved electrocardiographic techniques could help in decision making in interventional cardiology.

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