Assessment of Myocardial Infarct Size with Body Surface Potential Mapping: Validation against Contrast-Enhanced Cardiac Magnetic Resonance Imaging

Minna M. Kylmälä, M.D.,^{*,†} Teijo Konttila, M.Sc.,^{‡,1} Paula Vesterinen, M.D., Ph.D.,^{*,†,1} Sari M. Kivistö, M.D., Ph.D.,[§] Kirsi Lauerma, M.D., Ph.D.,[§] Mats Lindholm, M.Sc.,[‡] Heikki Väänänen, M.Sc.,[‡] Matti Stenroos, M.Sc., Ph.D.,[‡] Markku S. Nieminen, M.D., Ph.D.,^{*} Helena Hänninen, M.D., Ph.D.,^{*} and Lauri Toivonen, M.D., Ph.D.^{*}

From the ^{*}Division of Cardiology, Heart and Lung Center, Helsinki University Central Hospital, Helsinki, Finland; [†]BioMag Laboratory, Hospital District of Helsinki and Uusimaa HUSLAB, Helsinki University Central Hospital, Helsinki, Finland; [‡]Department of Biomedical Engineering and Computational Science, Aalto University, Espoo, Finland; and [§]Department of Radiology, HUS Medical Imaging Center, Helsinki University Central Hospital, Helsinki, Finland

Background: Assessment of myocardial infarct (MI) size is important for therapeutic and prognostic reasons. We used body surface potential mapping (BSPM) to evaluate whether single-lead electrocardiographic variables can assess MI size.

Methods: We performed BSPM with 120 leads covering the front and back chest (plus limb leads) on 57 patients at different phases of MI: acutely, during healing, and in the chronic phase. Final MI size was determined by contrast-enhanced cardiac magnetic resonance imaging (DE-CMR) and correlated with various computed depolarization- and repolarization-phase BSPM variables. We also calculated correlations between BSPM variables and enzymatic MI size (peak CK-MBm).

Results: BSPM variables reflecting the Q- and R wave showed strong correlations with MI size at all stages of MI. R width performed the best, showing its strongest correlation with MI size on the upper right back, there representing the width of the “reciprocal Q wave” ($r = 0.64$ – 0.71 for DE-CMR, $r = 0.57$ – 0.64 for CK-MBm, $P < 0.0001$). Repolarization-phase variables showed only weak correlations with MI size in the acute phase, but these correlations improved during MI healing. T-wave variables and the QRSST integral showed their best correlations with DE-CMR defined MI size on the precordial area, at best $r = -0.57$, $P < 0.0001$ in the chronic phase. The best performing BSPM variables could differentiate between large and small infarcts at all stages of MI.

Conclusions: Computed, single-lead electrocardiographic variables can estimate the final infarct size at all stages of MI, and differentiate large infarcts from small.

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Address for correspondence: Minna M. Kylmälä, Division of Cardiology, Heart and Lung Center, Helsinki University Central Hospital, P.O.B. 340, 00029 HUS, Finland. Fax: + 358 9 5042412; E-mail: minna.kylmala@hus.fi

¹These authors contributed equally to this study.

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After acute myocardial infarction (MI), an important prognostic factor for both patient outcome and left ventricular (LV) function is the size of the MI. Accurate and precise noninvasive methods are nowadays available for determination of MI size and location. Yet these methods, such as cardiac magnetic resonance imaging (CMR), myocardial perfusion, and metabolic imaging techniques, are not readily available. Electrocardiography (ECG), in contrast, is easy and quick to perform even at the bedside; 12-lead ECG is routinely performed on patients with cardiac symptoms, and is the most important clinical tool in MI diagnosis.

Body surface potential mapping (BSPM), an electrocardiographic measurement that uses multiple leads covering the front and back chest, records electrical activation of the heart from a much larger thoracic surface area than does the conventional 12-lead ECG.¹ BSPM has been shown to be more sensitive in the detection of acute as well as chronic MI.^{2,3} A variety of ECG variables, such as amplitudes and time-voltage integrals from depolarization as well as repolarization phases, can be computed and automatically analyzed from BSPM data. Our group found earlier that computed ECG variables improve sensitivity in detection of chronic and subacute MI as compared to Q-wave analysis from 12-lead ECG.⁴ We have also shown that in acute MI patients, computed ECG variables can predict recovery of myocardial function.⁵ Although ECG is routine in MI diagnostics, assessment of MI size by ECG is not current clinical practice. Our aim was to learn whether single-lead ECG variables computed from BSPM recordings could serve in MI quantification. In different stages of MI, from the acute phase to complete healing, we sought the best ECG variables and the best thoracic recording locations for assessment of MI size.

METHODS

Patients

Patients with acute coronary syndrome were recruited during office hours at the Coronary Care Unit of Helsinki University Central Hospital. The inclusion criterion was chest pain lasting a minimum of 20 minutes within 48 hours of recruitment, associated with findings suggestive of acute ischemia in the initial 12-lead ECG (ST-segment elevation, -depression, or T-wave inversions in ≥ 2

Table 1. Patient Baseline Characteristics

Patients (n)	57 (male 45)
Age (years)	60.1 $\pm$ 10.0
BMI (kg/m ²)	27.0 $\pm$ 4.2
Previous MI in clinical history (n)	8
Hypertension (n)	23
Maximal CK-MBm (μ g/L)	137 $\pm$ 163
Culprit artery (n)	
LAD	33
RCA	16
LCX	8

Data presented as number (n) or mean $\pm$ SD.

BMI = body mass index; MI = myocardial infarction; LAD = left anterior descending coronary artery; LCX = left circumflex coronary artery; RCA = right coronary artery.

contiguous leads). Exclusion criteria were bundle branch block, atrial fibrillation, or pacemaker. Of the 79 patients initially recruited, only the data of those 57 participating in the final control were included in analyses.

For study subject characteristics, see Table 1. The clinicians' initial 12-lead ECG interpretation was ST-elevation MI (STEMI) in 41 patients, and acute coronary syndrome without ST elevations in 16. Most of the patients, 50, had a release of cardiac biomarkers indicating acute MI (CK-MBm $> 5 \mu$ g/L or TnT $> 0.03 \mu$ g/L). All patients underwent coronary angiography in the acute phase, and those 55 with significant stenosis ($> 50\%$ of luminal diameter) were revascularized by percutaneous coronary intervention (PCI) or coronary artery bypass grafting. In patients with STEMI, time to thrombolysis or primary PCI from onset of symptoms was 4.9 ± 6.4 hours.

All study subjects gave their written informed consent. The research protocol was approved by the local ethics committee and complied with the Declaration of Helsinki.

Body Surface Potential Mapping

Recording and Analysis of BSPM

BSPM was recorded at inclusion, within 48 hours (10.7 ± 14.4) after the onset of chest pain. The acute BSPM measurement was done in 38 patients following urgent reperfusion therapy (thrombolysis or PCI), while 19 patients had stabilized spontaneously before the recording. Recording of BSPM was repeated during recovery at 16 ± 14 days, and then again in the chronic phase

after complete healing of the MI, at 331 ± 111 days after the index event.

Resting-BSPM for 5 minutes was recorded with 120 unipolar leads covering the whole thorax (plus limb leads) using one Mark 6 and one ActiveTwo biopotential amplifier from Biosemi (Amsterdam, The Netherlands). Wilson's central terminal, defined from the limb leads, served as the reference potential for the chest leads. The electrodes were mounted on 18 strips, 5 cm apart, placed on the subject's thorax vertically with horizontal spacing determined by upper body dimensions (Fig. 1).

BSPM data were visually inspected for validity of the recording and signal-averaged according to criteria of a 0.9 or greater correlation of the QRS complex with a selected template and noise $<30 \mu\text{V}$. The T wave was required to fit in an envelope of 110–150 μV around the template.⁶ The baseline was estimated using a third-order spline function fitted to consecutive PQ segments. Invalid leads were replaced by interpolation of data from surrounding leads according to a method modified from that of Oostendorp et al.⁷ The QRS start and end were determined automatically from the vector magnitude of a representative precordial set of high-pass filtered leads, following the guidelines of Simson.⁸ The J point was determined for each lead separately as the time instant of the maximum curvature of the signal returning to the ST level around the QRS end.⁹ Time points of the apex and the end of the T wave were determined automatically as described elsewhere.¹⁰

ECG Variables Calculated from BSPM

From BSPM data, ECG variables were calculated automatically using special software developed at the Department of Biomedical Engineering and Computational Science, Aalto University. The computed variables comprise amplitudes, slopes, time intervals, time-voltage integrals, and time-voltage areas from both de- and repolarization phases of the QRSSTT complex. The ECG variables are listed and defined in Table 2. The best performing ECG variables are illustrated in Figure 2.

Cardiac Magnetic Resonance Imaging

Cardiac magnetic resonance imaging with delayed contrast enhancement (DE-CMR) was performed in all 57 patients after complete healing, 6–12 months after the index event. DE-CMR was

performed on a 1.5 T clinical scanner (Sonata, Siemens Medical Solutions, Helsinki University Hospital, Finland). MI location was determined by gadolinium delayed enhancement.^{11,12} A bolus of 0.2 mmol/kg of contrast agent (gadodiamide, OminscanTM, GE Healthcare, Horten, Norway) was administered. About 5–10 minutes later short axis images (typically 6–10) were scanned by a breath-hold T₁-weighted segmented inversion-recovery turbo-FLASH sequence (TR 750, TE 4.3, TI 300, matrix 256 × 256, slice thickness 6 mm). Identical sequence parameters were used on each system wherever possible. The myocardium was divided into 16 segments according to the recommendation of the American Heart Association.¹³ The presence, in each segment, of gadolinium delayed enhancement was considered indicative of myocardial scar. In each segment, determination of the area of the myocardial scar was by manual tracing. Total LV infarct size was determined as percentage of the LV, calculated as the sum of segmental myocardial scar areas divided by the total area of all segments.

CK-MBm Measurements

CK-MBm was measured according to routine clinical praxis: at arrival at the hospital, the following evening or morning, or both. The maximum value of these measurements served as a measure of final MI size. In most patients, measurement of this maximum value occurred 12–24 hours after onset of chest pain.

Statistical Analysis

Continuous variables are expressed as mean $\pm$ SD. Correlations between ECG variables and MI size were examined with the linear Pearson's correlation coefficient (*r*). A correlation coefficient ≥ 0.5 was considered strong. Patients were grouped according to the presence and size of MI, using the median value of infarction percentage to separate large and small infarcts. ECG variables in these groups were compared by one-way ANOVA. A *P*-value <0.05 was considered statistically significant.

RESULTS

Final MI Size by DE-CMR and CK-MBm

Final MI size was estimated as the percentage of LV infarct scar by DE-CMR after complete healing

Figure 1. Body surface potential mapping layout of the 120 thoracic leads, mounted on 18 adhesive strips and placed according to anatomical landmarks as indicated. Horizontal line marks 4th intercostal space. Standard ECG chest leads V₁ to V₆ marked with a square for reference. The best recording sites yielding the highest correlations with computed ECG variables and left ventricular infarct percentage are highlighted with red and blue circles.

of the MI, and by acute-phase peak CK-MBm. In those 44 patients with infarct scar evident on DE-CMR, the LV infarct percentage was $14 \pm 11\%$ (range: 0.7–51), and EF $49 \pm 11\%$ (range: 24–70). In the 13 patients with no infarct scar, the EF was $59 \pm 8\%$ (range: 47–72). CK-MBm and LV infarct percentage had a significant correlation, $r = 0.64$, $P < 0.000.1$. CK-MBm was $88 \pm 80 \mu\text{g/L}$ in patients with infarct percentage below the median, $<11\%$, and $235 \pm 194 \mu\text{g/L}$ in those with infarct percentage $\geq 11\%$; EF in these patients was $55 \pm 7\%$ and $45 \pm 11\%$, respectively.

Assessment of LV Infarct Percentage by ECG Variables at Different Stages of MI

At all stages of MI from acute to chronic, the best recording sites—showing the highest correlations between the computed ECG variables and with final MI size as defined by DE-CMR—were on the precordial area of the thorax, close to standard leads V₃ to V₆, and reciprocally on the right upper back. The correlations at these two recording sites were of different sign. These best recording sites are demonstrated in Figure 1.

Table 2. BSPM-Derived Computed ECG Variables

Q width	Time interval from QRS start to the first positive peak, to the moment when signal amplitude increases 30 μ V above minimum value after QRS start.
R width	Time interval from QRS start to the first negative peak, to the moment when signal amplitude decreases 30 μ V below maximum value after QRS start.
Ramp	Peak (negative or positive) amplitude during first 15–44.75% of the QRS.
Samp	Amplitude of the first opposite-sign peak after the Ramp.
1st QRSint	Integral of the first quartile of QRS.
2nd QRSint	Integral of the second quartile of QRS.
3rd QRSint	Integral of the third quartile of QRS.
4th QRSint	Integral of the fourth quartile of QRS.
QRSint	Integral of entire QRS complex.
QRSSTint	Integral from onset of QRS to end of T wave.
QRSTTarea	Integral of the absolute values from onset of QRS to end of T wave.
Jamp	Amplitude at J point.
ST60amp	Average amplitude at 58–62 ms from QRS end.
ST80amp	Average amplitude at 78–82 ms from QRS end.
ST60slope	Slope from QRS end to 60 ms from QRS end.
ST80slope	Slope from QRS end to 80 ms from QRS end.
ST60int	Integral between QRS end and 60 ms from the QRS end.
ST80int	Integral between QRS end and 80 ms from the QRS end.
STint	Integral of the first half of interval from QRS end to median T-wave end.
STTint	Integral from QRS end to T-wave end.
Tamp	T-apex amplitude.
T80int	Integral from 80 ms before to 80 ms after the T-wave apex.
TPEint	Integral from T-wave apex to T-wave end.

Correlation of ECG Variables in the Chronic Phase with LV Infarct Percentage

Depolarization Variables

In the chronic phase, all QRS variables describing the Q- and the R wave showed good correlations with MI size, both on the precordial area and the upper back (Table 3). On the upper back, the polarity of QRS is of opposite sign of polarity on the precordial area. Thus, Q waves on the precordial area are seen as positive deflections on the upper back, while R waves on the precordial area are represented by negative deflections on the upper back. Interestingly, the variables describing the initial part of the QRS, hereafter called the “Q-wave variables,” clearly performed best on the upper back; variables describing the second quartile of the QRS, hereafter called the “R-wave variables,” performed slightly better on the precordial area. The R width on the upper back, what we herein call the width of the “reciprocal Q wave,” showed the strongest correlation with MI size of all ECG variables studied ($r = 0.71$, $P < 0.0001$), wider reciprocal Q waves meaning larger MI size (Fig. 3A). On the upper back, the 1st QRSint describes the reciprocal Q wave as

well, and showed a strong, positive correlation with LV infarct percentage ($r = 0.57$, $P < 0.0001$) (Fig. 3B). The Q width on the precordial area had a strong correlation with MI size ($r = 0.52$, $P < 0.0001$), being clearly weaker, however, than that of the R width on the upper back. The 1st QRSint showed a moderate, negative correlation with MI size on the precordial area ($r = -0.38$, $P = 0.004$). The Ramp and the 2nd QRSint, describing the R wave, showed strong, negative correlations on the precordial area ($r = -0.57$ and $r = -0.56$ respectively, $P < 0.0001$) (Fig. 3C). The QRSint also showed a strong, negative correlation with MI size on the precordial area ($r = -0.58$, $P < 0.0001$). On the right upper back, the R-wave variables had nearly as strong correlations as on the precordial area ($r = 0.55$ for Ramp and $r = 0.53$ for 2nd QRSint, $P < 0.0001$); the QRSint showed only a weak correlation on the upper back ($r = 0.34$, $P = 0.01$).

The second part of the QRS was less informative with regards to MI size than was the first part (Table 3). The S wave seemed to shrink with increasing MI size. On the back, the S wave is a positive deflection, a mirror image of that on the precordial area. The Samp performed slightly better on the back than on the precordial area,

Figure 2. (A–C) QRSSTT complexes in the chronic phase in patients with no infarct or with large infarct. In the left column, above, are piled complexes of all patients, and below, single representative examples within each group (no infarct vs large infarct). The optimal leads differentiating the groups are displayed. The single QRSSTT examples highlight the best performing BSPM variables, the highlighted regions are further enlarged in the column to the right: (A) Lead 112, 1st QRSint (blue) is negative in a patient without infarct, and positive in a patient with a large infarct; R width (width of the “reciprocal Q wave”) between arrows is wider in the patient with a large infarct. (B) Lead 54, 2nd QRSint (hatched) and QRSint (yellow) are positive and greater, and Ramp is higher in a patient without infarct compared to a patient with a large infarct. (C) Lead 72, T80int (green) and STTint (hatched) are positive and greater, and Tamp positive in a patient without infarct compared to a patient with a large infarct. Lead numbers refer to the BSPM layout in Figure 1. ECG variables are defined in Table 2.

having a moderate, negative correlation with LV infarct percentage ($r = -0.42$, $P = 0.001$) on the back. The 3rd QRSint and 4th QRSint, also describing, at least in part, the S wave, had weaker correlations.

Repolarization Variables

In the chronic phase, most of the repolarization variables had good, negative correlations with MI size on the precordial area (Table 3). The inverse correlations on the upper back were also significant, but clearly weaker. On the precordial area, the T-wave variables performed the best; the smaller or the more negative the T wave, the larger the MI size ($r = -0.55$ to $r = -0.57$,

$P < 0.0001$) (Fig. 3D). The STTint, QRSSTTint, and QRSSTTarea showed good negative correlations with MI size on the precordial area as well ($r = -0.50$ to $r = -0.54$, $P < 0.0001$). The correlations of the ST-segment variables were weak, at best $r = -0.35$ for ST80amp, and $r = -0.36$ for ST80slope on the left upper back, $P < 0.01$.

Correlation of ECG Variables in the Acute Phase with LV Infarct Percentage

The depolarization variables that performed well in the chronic phase showed good correlations with DE-CMR already in the acute phase, in corresponding locations (Table 3). Also in the acute

Table 3. ECG Variables and Their Best Correlations with DE-CMR-Determined LV Infarct Percentage at Different Stages of MI

ECG Variable	Acute Phase			Recovery Phase			Chronic Phase		
	r max	P-Value	Lead	r max	P-Value	Lead	r max	P-Value	Lead
1st QRSint	0.56	<0.0001	112	0.56	<0.0001	112	0.57	<0.0001	112
2nd QRSint	-0.59	<0.0001	61	-0.59	<0.0001	55	-0.56	<0.0001	54
3rd QRSint	-0.43	0.0009	61	-0.42	0.002	55	-0.39	0.003	54
4th QRSint	0.32	0.02	90	n.s.			0.34	0.01	82
QRSint	-0.62	<0.0001	54	-0.58	<0.0001	55	-0.58	<0.0001	54
Ramp	-0.60	<0.0001	67	-0.59	<0.0001	62	-0.57	<0.0001	61
Samp	-0.51	<0.0001	104	-0.53	<0.0001	113	-0.42	0.001	105
R width	0.64	<0.0001	112	0.65	<0.0001	112	0.71	<0.0001	112
Q width	0.59	<0.0001	71	0.47	0.0003	61	0.51	<0.0001	60
Jamp	-0.30	0.02	5	0.28	0.04	54	0.28	0.03	112
ST60amp	-0.30	0.02	5	0.36	0.008	63	-0.30	0.02	88
ST80amp	-0.33	0.01	5	0.29	0.04	63	-0.35	0.008	80
ST60int	-0.29	0.03	5	0.33	0.02	63	n.s.		
ST80int	-0.30	0.02	5	0.33	0.01	63	n.s.		
STint	-0.30	0.03	5	0.28	0.04	63	-0.31	0.02	81
ST60slope	0.32	0.01	55	-0.30	0.03	115	0.27	0.04	70
ST80slope	0.28	0.04	47	-0.32	0.02	115	-0.36	0.006	88
Tamp	-0.40	0.002	75	-0.54	<0.0001	72	-0.55	<0.0001	72
T80int	-0.36	0.006	75	-0.52	<0.0001	72	-0.57	<0.0001	72
TPEint	-0.36	0.006	71	-0.54	<0.0001	72	-0.56	<0.0001	72
STTint		n.s.		-0.38	0.004	72	-0.52	<0.0001	72
QRSSTTint	-0.42	0.001	71	-0.50	0.0001	69	-0.54	<0.0001	69
QRSSTTarea	-0.35	0.007	119	-0.51	<0.0001	111	-0.50	<0.0001	111

Correlations ≥ 0.5 are highlighted.

DE-CMR = contrast-enhanced cardiac magnetic resonance imaging; LV = left ventricle.

For explanation of ECG variables, see Table 2.

phase, the Q- and R-wave variables showed strong correlations with final MI size, and performed better than the S-wave variables. Again, the width of the reciprocal Q wave (R width) had the highest correlation with MI size of all variables ($r = 0.64$, $P < 0.0001$ on the right upper back). This correlation was somewhat lower than in the chronic phase. The other Q- and R-wave variables showed similar or slightly stronger correlations in the acute than in the chronic phase, in the same or neighboring leads.

The repolarization variables showed their best correlations with MI size on the precordial area, as they did in the chronic phase, but these correlations were much weaker (Table 3). Clearly, the repolarization variables did not perform as well as the depolarization variables acutely. The T-wave variables and QRSSTTint showed moderate, negative correlations with MI size on the precordial area ($r = -0.36$ to -0.42 , $P < 0.01$); the correlations of the ST-segment variables and the QRSSTTarea with MI size were weaker, and the correlation of the STTint was insignificant.

Correlation of ECG Variables in the Recovery Phase with LV Infarct Percentage

The depolarization and repolarization variables performed best in the same locations during recovery as in the acute and chronic phases, and the correlations fell between these two (Table 3). As in the acute and chronic phases, the Q- and R-wave variables showed the strongest correlations with MI size, the best variable being the width of the reciprocal Q wave (R width) ($r = 0.65$, $P < 0.0001$). The repolarization variables showed better correlations during recovery than in the acute phase, but still did not perform quite as well as in the chronic phase.

Comparison of ECG Variables in Patients with Large, Small, and No Infarcts

Patients with large infarcts, as defined by an LV infarct percentage above the median ($>11\%$), had significantly different values for their best

Figure 3. Correlations of the best performing ECG variables in the chronic phase with left ventricular infarction percentage determined by contrast-enhanced magnetic resonance imaging.

performing ECG variables than did patients with small or no infarcts. BSPM could distinguish patients with a large infarct from those with a small or no infarct at all time points, from the acute phase to complete healing of MI (Table S1).

In the chronic phase, the width of the reciprocal Q wave (R width) was wider, and the 1st QRSint was positive, or at least less negative on the right upper back in patients with a large MI than in patients with a small or no MI ($P < 0.001$) (Figs. 4A and B). On the precordial area, the Ramp, 2nd QRSint, QRSint, Tamp, T80int, STTint, and QRSSTTint were smaller in patients with a large MI than in ones with a small or no MI ($P \leq 0.01$) (Figs. 4C and D). Some of these best performing ECG variables could

differentiate between large and small infarcts (R width, 1st QRSint, T80int, and QRSSTTint; $P \leq 0.03$), but no statistically significant difference appeared between the groups of patients with small versus no infarcts. Figure 2 shows QRSSTT complexes in patients with large versus no infarct at the best recording sites.

The depolarization variables could distinguish large from small infarcts already in the acute and recovery phases, in a similar fashion as in the chronic phase. Repolarization variables, too, could distinguish large from small infarcts in the recovery phase. However, in the acute phase, the QRSSTTint was the only repolarization variable showing a significant differentiating capacity.

Figure 4. Values of the best performing ECG variables in the chronic phase in patients with large, small, or no infarct. Large and small infarcts separated by median infarct size determined by contrast-enhanced cardiac magnetic resonance imaging: large infarcts $\geq 11\%$, small infarcts $< 11\%$ of the left ventricle. P values are for large infarct versus small or no infarct. Boxes indicate medians, first and third quartiles; whiskers indicate minimum and maximum values, falling within $1.5\times$ the interquartile range from the upper or lower edge of the box; outliers are indicated by points, falling outside $1.5\times$ the interquartile range.

Correlation of ECG Variables with CK-MBm

The highest correlations between ECG variables and peak CM-MBm values were close to the same recording sites yielding the best correlations between ECG variables and DE-CMR. The best performing ECG variables showed strong correlations with CK-MBm at all stages of MI: Width of the reciprocal Q wave (R width), Ramp, and 2nd QRSint all showed strong, positive correlations on the right upper back ($r \geq 0.54$, $P < 0.0001$); the QRSint showed a strong, negative correlation on the precordial area ($r \leq -0.53$, $P < 0.0001$). In the acute phase, the Ramp and 2nd QRSint performed the best; during recovery and in the chronic phase, the width of the reciprocal Q wave (R width) showed the best correlation with CK-MBm (Table S2).

The repolarization variables performed weaker than the depolarization variables at all stages of MI. Only in the acute phase did the ST60amp and ST80amp show strong, positive correlations with CK-MBm on the precordial area ($r = 0.52$ and $r = 0.51$, respectively, $P < 0.0001$), performing better than the Jamp ($r = 0.42$, $P = 0.001$). During recovery, no repolarization variables performed well; the ST60amp and QRSSTTint showed moderate correlations with CK-MBm on the precordial area. In the chronic phase, the QRSSTTint had a good correlation with CK-MBm on the central upper back ($r = 0.53$, $P < 0.0001$), the other repolarization variables showing moderate correlations (Table S2).

DISCUSSION

Our results show that computed, single-lead ECG variables can estimate final MI size acutely, during

MI healing, and in its chronic phase. We found the best performing ECG variables and their best recording locations by using BSPM with 120 chest leads. The patients had acute coronary syndrome and were analyzed as one group irrespective of culprit artery.

Assessment of LV Infarct Percentage by BSPM

LV infarct percentage was defined by DE-CMR after complete healing of the MI. Overall, the infarcts were small to moderate, reflecting the timely reperfusion therapy. The median value of LV infarct percentage was 11%. Of multiple depolarization as well as repolarization variables, the Q- and R-wave variables, as well as the integral of the entire QRS, performed the best, having strong correlations with MI size at all stages of MI.

Depolarization Variables

At all stages of MI, the best variable was the width of the reciprocal Q wave, that is, R-width on the upper back. Together with the 1st QRSint, the R width showed a strong, positive correlation with MI size on the right upper back. In healthy individuals, the initial deflection of the QRS is negative on the back, representing a mirror image of the R wave in precordial ECG leads; analogically, Q waves on the precordial area are reflected as R waves reciprocally on the back.⁵

What is well established is that Q waves indicate permanent myocardial damage after an infarction. Irrespective of MI age and location, classical Q waves (30–40 ms in width) are associated with larger MI size.^{14–17} Even if small infarcts do not necessarily yield classical Q waves, we could show that even small computed Q waves correlated with MI size. Earlier, we found that in left anterior descending coronary artery (LAD)- and right coronary artery (RCA)-related MIs, the 1st QRSint was the best depolarization variable to predict, after acute MI, recovery of myocardial function.⁵ In this study, the 1st QRSint was positive, or close to zero, at the best recording location on the right upper back in most patients with the largest infarcts. At this site, in all patients (but one) with a small or no infarct, the 1st QRSint was negative, similar to healthy individuals.

Ramp, 2nd QRSint, and QRSint showed strong, negative correlations with MI size on the precordial area, close to standard leads V₃ to V₅. In the acute phase, these variables showed correlations almost as strong as the R width; in the chronic phase, however, the R width clearly showed the strongest correlation of all variables. Studies using precordial or body surface mapping have correlated R- and Q waves with MI size. Significant correlations appeared between the sum of R-wave amplitudes and the extent of LV dyssynergy ($r = -0.42$), EF ($r = 0.51$), and enzymatic MI size ($r = -0.57$) after anterior MI; no correlation appeared, however, between the sum of R-wave amplitudes and EF in inferior MI. The number of Q waves showed a significant negative correlation with EF in anterior ($r = -0.50$) as well as inferior ($r = -0.63$) MI, and the sum of Q-wave amplitudes had a significant positive correlation with enzymatic MI size ($r = 0.61$). Q waves did not, however, correlate with extent of LV dyssynergy.^{18–20} The number of Q waves was recently shown to correlate with MI size by DE-CMR; however, anterior MIs caused fewer Q waves confined to the precordium, whereas inferior MIs were associated with a larger body surface area of Q waves involving the inferior front and back chest.¹⁵

R and S waves, together with Q waves, are considered in the Selvester QRS score, the best validated ECG method for quantification of myocardial infarct.²¹ This score has been validated in computer models, in postmortem studies, and in clinical studies using enzyme assessment, thallium perfusion imaging, and CMR. In the subacute and chronic phases of infarction, it correlates well with MI size in all the main coronary artery perfusion regions.^{22–24}

Repolarization Variables

Repolarization variables were clearly inferior to depolarization variables in the acute phase, but in the chronic phase showed comparable, strong correlations. The T-wave variables (Tamp, T80int, TPEint) performed the best, already showing strong correlations during recovery. The STT and QRSSTT integrals showed strong correlations in the chronic phase, but slightly lower than did the T-wave variables. At all time points, these repolarization variables, all including a T wave had their best recording site on the precordial area, close to

standard leads V₅ and V₆, where they showed a negative correlation with MI size. The ST-segment variables showed only weak correlations with MI size, and the best recording locations varied at all stages.

After reperfusion for STEMI, the significance of T-wave polarity is dependent on time relative to the acute event. In the acute phase, negative T waves in infarction-related leads are associated with smaller enzymatically determined MI size, better LV function, and long-term outcome if these initially negative T waves later turn positive; in patients with persistent negative T waves the clinical outcome is worse.^{25,26} Positive T waves in the acute phase without early inversion predict, however, larger MI size and more early complications.^{27,28} That dynamic T-wave changes are accentuated in the acute phase can explain why our correlation between T-wave variables and MI size improved with time, as the T wave-changes stabilized. One study has found a moderate, negative correlation between DE-CMR-defined MI size and T-wave amplitudes in chronic MI, but only for inferior MI. In anterior MI and in the overall population, such a correlation was not significant.²⁹ That study measured the T-wave amplitudes in leads showing the greatest ST elevation, and what cannot be ruled out is whether T-wave amplitudes in another location would have performed better.

Previously, residual ST-segment elevation after reperfusion therapy has been shown to correlate with MI size by CMR and perfusion imaging in STEMI patients.^{30,31} In MI patients presenting without ST elevations, ST depression in the acute phase is associated with adverse long-term prognosis.³² With time, the ST segment returns to normal, irrespective of reperfusion therapy,³³ making it less than surprising that correlations between ST segment and MI size in the chronic phase should be weak. The reason that our ST-segment variables acutely showed poor correlation with CMR-defined MI size may be attributed to the pooled cohort of infarcts in different regions of the LV.

BSPM Variables versus CK-MBM

LV infarct percentage by DE-CMR correlated well with CK-MBM, indicating that peak CK-MBM measured in the acute phase reflects final MI size. Studies show peak CK-MBM to correlate with

MI size determined by imaging and histology in patients with and without reperfusion.^{34,35}

The same depolarization variables showing the best correlations with LV infarct percentage, except for the 1st QRSint, also showed strong correlations with CK-MBM, and at the same lead locations. However, the best recording site for the R-wave variables was also on the upper back, as was true for the width of the reciprocal Q wave. Here, these best performing variables showed strong, positive correlations with CK-MBM at all time points.

Repolarization variables were inferior to depolarization variables at all time points. In the acute phase, the ST60 and ST80 amplitudes showed strong, positive correlations with CK-MBM on the precordial area, although their correlations with DE-CMR were weak. This could be due to the fact that peak CK-MBM not only reflects final MI size, but is also affected by washout after reperfusion therapy in STEMI.³⁶ In the chronic phase, only the QRSSTTint showed a strong, positive correlation with CK-MBM on the upper back; during recovery no repolarization variables showed such strong correlations.

Limitations

We pooled STEMIs and non-STEMIs caused by different culprit-artery lesions. Despite our patient-population heterogeneity, we found strong correlations with various ECG variables and MI size, and at all stages of infarction. The explanation could be that in a majority of the patients, infarct scar distribution was multifocal, being present in one or both perfusion beds other than the culprit-artery related bed. The reliability of our results is strengthened by the fact that the best performing variables showed their best recording locations at the same sites all throughout the infarction process.

Our acute-phase results cannot be applied early during the acute phase, because at the time of the acute measurement, patients had been successfully reperfused or had stabilized spontaneously.

Because we could not time the CK-MBM measurement exactly, timing of measurement of the peak CK-MBM value varied among patients, being between 12 and 24 hours from onset of chest pain in most. Despite this, the peak CK-MBM value correlated strongly with LV infarct percentage by DE-CMR, indicating that peak CK-MBM value reflected final MI size.

CONCLUSION

Automatic, BSPM-derived single-lead ECG variables succeeded in assessing the size of permanent myocardial injury at all stages of infarction, from the acute phase to complete healing, irrespective of the acute ischemic event's location. Of all variables, the R width on the upper back—there representing the reciprocal Q wave—showed the strongest correlation with MI size. R-wave variables and the QRS integral performed well on the precordial area. T-wave variables showed strong correlations during recovery and in the chronic phase, but no repolarization variables performed well acutely.

In summary, computed single-lead ECG variables correlate with MI size, and differentiate large infarcts from small. Automatic quantification of MI size by the use of only a few ECG leads may have the potential to be applied in clinical practice.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Table S1. Average Values of Chronic-Phase ECG Variables Grouped According to LV Infarct Percentage by DE-CMR.

Table S2. ECG Variables and their Best Correlations with CK-MBm at Different Stages of MI.