Body Surface Potential Mapping of ST Segment Changes in Acute Myocardial Infarction

Implications for ECG Enrollment Criteria for Thrombolytic Therapy

Fred Kornreich, MD; Terrence J. Montague, MD; and Pentti M. Rautaharju, MD, PhD

**Background.** Several large, randomized clinical trials have shown that early thrombolytic therapy substantially reduces early mortality after acute myocardial infarction (MI). In most trials, eligibility criteria include typical chest pain and diagnostic ST segment elevation in two or more contiguous leads of the standard 12-lead ECG. Unfortunately, large areas of the thoracic surface are left unexplored by the standard electrode positions. As a consequence, acute MI patients with ST elevation in regions not interrogated by the conventional electrodes may not receive reperfusion therapy and its attendant benefits.

**Methods and Results.** The present study compares 120-lead body surface potential map (BSPM) data from 131 patients with acute MI and 159 normal control subjects (N). The MI population was stratified according to the location of ventricular wall motion abnormalities evidenced by radionuclide imaging into 76 patients with anterior MI (AMI), 32 patients with inferior MI (IMI), and 23 patients with posterior MI (PMI). BSPM were recorded within 24 hours of admission. Group mean BSPM of the ST segment were obtained for N, AMI, IMI, and PMI by sampling the time-normalized ST-T waveform at 18 equal intervals and averaging the voltages at each electrode site over the first five of these 18 ST-T time instants. Corresponding discriminant maps were also computed for each pairwise comparison (AMI versus N, IMI versus N, and PMI versus N) by subtracting the normal group mean voltages from each MI group mean voltages and by further dividing each resulting difference by the composite standard deviation calculated from the pooled groups. Discriminant analysis for each bigroup classification was also performed using as measurements the ST magnitudes in 120 electrode sites from each individual. Finally, the number of patients in each MI group with ST changes outside the 95% normal range was calculated for each electrode position. The following results were obtained: 1) In each MI group, ST depression departs more significantly from normal values than ST elevation. 2) The most significant ST changes (both ST elevation and ST depression) are observed in IMI, the least significant in AMI. 3) For each pairwise comparison, measurements from two lead sites are entered into the stepwise discriminant procedure: the first measurement is ST depression, the second ST elevation. Classification rates are 82% for AMI, 93% for PMI, and 100% for IMI at a specificity level of 95%. 4) From the six leads selected for optimal classification of the three MI groups, five are outside the area sampled by the conventional precordial electrodes. 5) The use of site-dependent thresholds for ST measurements based on 95% normal range yields the best compromise between sensitivity and specificity. A fixed threshold of 1 mm for ST elevation or ST depression produces increased sensitivity in AMI at the cost of marked loss in specificity and reduces sensitivity in both IMI and PMI with no benefit in specificity.

**Conclusions.** Analysis of BSPM identifies areas on the torso where the most significant ST changes most frequently occur in acute MI. Two leads from areas with the most abnormal ST changes achieve optimal classification in each MI class. Of these six leads, five are outside the standard precordial lead positions. ST depression is the most potent discriminator for each MI group and contains information independent from ST elevation. Quantitative analysis of ST magnitude at each electrode site allows determination of best thresholds for ECG criteria. Appropriate selection of ECG leads may help remove inconsistencies in current ECG selection criteria and improve comparability of treatment results. (Circulation 1993;87:773-782)

**Key Words** • ST segments, elevation • ST segments, depression • ST segments, criteria • ST discriminant maps

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Changes in ST segment in acute myocardial infarction (MI) are attributed to injury currents generated by acutely ischemic cardiac tissue; electrodes directly overlying the injured zone usually record ST segment elevation, whereas those positioned in opposite areas of the torso detect "reciprocal" ST depression.1

In the past 3 years, thrombolytic therapy for acute MI has emerged as the standard of care for appropriately eligible patients.2 In most large, randomized clinical trials, eligibility criteria include acute typical chest pain for at least 30 minutes and diagnostic ST segment elevation in at least two contiguous leads of the standard 12-lead ECG.

Unfortunately, large areas of the thoracic surface are left unexplored by the standard electrode positions, particularly the posterolateral, posterior, and basal portions of the left ventricle as well as most of the right ventricle. As a consequence, patients with ST segment elevation restricted to regions not interrogated by the conventional electrodes will not be included in the protocol and will not benefit from thrombolytic therapy. Also, inadequate sampling of the body surface may fail to correctly define subsets of patients who can benefit most from early thrombolysis. Indeed, most trials have indicated that best results are to be expected in patients with marked ST segment elevation23; when the largest ST changes occur outside the standard lead sites, one may falsely conclude that those patients will benefit only modestly from the treatment. ST segment depression is generally considered an exclusion criterion because it is regarded as a marker of evolving subendocardial ischemia rather than the representation of evolving MI.4 From a biophysical perspective, reciprocal changes are equivalent expressions, albeit in different amounts, of the same events observed on the chest from electrically opposite viewpoints. Therefore, a priori exclusion of patients with ST segment depression may not be justified, since failure to observe corresponding ST segment elevation results, to a large extent, from inadequate lead placement. Finally, ECG criteria for patient enrollment vary widely: whereas many authors accept an ST elevation ≥0.1 mV in any two contiguous leads,5 others require 0.2 or even 0.3 mV.6 Also, several investigators define different thresholds for the limb leads and for the precordial leads and/or accept ST segment depression.6-8

To resolve some of these issues, we compared 120-lead body surface potential map (BSPM) data from 76 patients with anterior MI (AMI), 32 patients with inferior MI (IMI), 23 patients with posterior MI (PMI), and 159 normal control subjects (N). Torso sites where most significant ST changes can be recorded and optimally used for monitoring during and after thrombolysis were identified. Discriminant analysis was performed on map data to assess the independent diagnostic contribution of ST segment depression and elevation. Finally, the range of variability of ST segment magnitude over the thoracic surface was determined in normal subjects and in each MI group, and a rationale for establishing site-dependent thresholds for ECG criteria in acute MI was suggested.

Study Population
We retrospectively studied 406 subjects: 159 normal, 131 with first MI, and 116 with pure left ventricular hypertrophy (LVH) (Table 1). None of the normal subjects had evidence of heart disease by history, physical examination, 12-lead ECG, and, when available, echocardiogram. They were all >30 years old (mean, 43 years). All patients with MI had a typical history of prolonged, ischemic-type cardiac pain and characteristic changes in enzyme levels. In all patients, diagnosis was substantiated by nuclear angiograms during which multigated, 99mTc-labeled blood pool imaging was performed. Radionuclide images were collected within 72 hours of admission. For the purpose of classification, a regional wall motion abnormality score using a nine-segment, four-point scoring system (0, normal; 1, hypokinesia; 2, akinesia; 3, dyskinesia) was derived for each patient by summing the scores of individual segments from each of the following segment groups: anterior group (anterobasal, anterolateral, basal septum, and apical septum segments), inferior group (inferior and inferoapical segments), and posterior (posterolateral and posterobasal segments). A regional wall motion abnormality index was then calculated by dividing the total score in each segment group by the number of segments analyzed. Individual patients were then assigned to the group for which their index was the highest. Patients with isolated apical segment wall motion abnormality were assigned to the anterior group. Eighty-four MI patients (64%) underwent coronary angiography before discharge; 33 patients (39%) had single-vessel disease (≥70% stenosis), 32 (38%) had two-vessel disease, and 19 (23%) had disease in three or more vessels. Subjects in the MI population were 34–81 years old (mean, 56 years); 37 (28%) patients were women, and 94 (72%) were men. All patients had at least one 12-lead ECG recorded in the acute phase of the infarction. Patients were excluded if they had ECG evidence of complete left or right bundle branch block, major nonspecific intraventricular conduction delay (QRS ≥ 126 msec), previous MI, or Wolff-Parkinson-White syndrome. Patients with LVH had either pure left-sided valvular disease or sustained hypertension (150/90 mm Hg or higher). The presence of LVH was assessed from ECG-independent information: echocardiography, cardiac catheterization with coronary angiography and ventriculography, radionuclide angiography, chest radiographs, or cardiac surgery.

Method

Body Surface Mapping
We used previously described methods for recording, processing, and displaying body surface ECG signals.9 Briefly, digitized signals were recorded simultaneously from 117 torso sites and three limb leads, with Wilson's central terminal as reference potential, at 500 samples per

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<th>Table 1. Study Population</th>
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<td><strong>Diagnosis</strong></td>
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second per channel. Tracing quality was monitored visually during the recording; later, the stored data were processed by performing selective averaging and again carefully inspected and edited. All leads judged invalid were deleted and replaced by interpolation of data from surrounding leads. We time-normalized the ST-T waveform and represented it by 180 points. All BSPM were recorded within 24 hours of symptom onset (1–24 hours; mean, 9 hours).

**Map Display**

*Isopotential maps.* Group mean and individual maps are represented during the ST-T waveform as isocontour lines connecting points of equal voltage and sign at selected time instants. Group mean maps were computed separately for the normal group and for each MI group. Sequential maps were obtained by sampling the time-normalized ST-T waveform in 18 equal intervals; the first five instants, starting with the J-point, were selected to represent the ST segment. Further data reduction was achieved by averaging ST segment maps over the first five of 18 ST-T maps, thus producing for each patient and for each group a single map in which each measurement at each electrode site represented the average potential value throughout the ST segment. These maps are equivalent to integral maps with magnitudes expressed in millivolts instead of millivolt-seconds.

*Discriminant maps.* For each time instant, difference maps were computed by subtracting at each electrode site the normal group mean voltage from each MI group mean voltage; sequential discriminant maps for each pairwise comparison were obtained by further dividing each resulting difference by the corresponding composite standard deviation computed from the pooled groups. The values thus achieved, referred to as discriminant indexes (DIs), were strictly proportional to $t$-test statistics and provided, in contrast with difference maps, information on the capability for each measurement at each electrode site and at each instant to separate each class of MI from the normal group. Discriminant maps were also represented as contour lines connecting DIs of equal value and sign at each instant. Mean ST segment discriminant maps were also obtained by averaging discriminant maps over the first five of 18 ST-T instants, thus producing a single map representing, for each group, mean standardized voltage differences throughout the ST segment.

**Feature Extraction and Statistical Analysis**

We used voltage measurements from each individual's averaged ST segment map (i.e., 120 measurements per subject) for classification purposes. Programs of the Biomedical Program Library were used for each bigroup classification (BMDP7M). The statistical procedure involved two steps: First, the best classifiers were selected from the total number of available features by a stepwise selection; second, the selected classifiers were combined into a properly weighted linear discriminant function. To test the robustness of the discriminant function, the jackknife option available in the BMDP7M package was also used. With this procedure, each case is eliminated in turn from the computation and subsequently assigned to one of the groups formed by the remaining cases.

**Results**

*Sites of Most Significant ST Segment Changes*

Figure 1 depicts the sites where the most significant ST segment changes occurred in AMI (panel A), IMI (panel B), and PMI (panel C). In AMI, maximum ST elevation is observed in the midsternal region around $V_2$ to $V_3$, whereas reciprocal ST depression of much lower amplitude is located in the lower left back. The corresponding discriminant map indicates that positive DIs peak above $V_2$ at 1.4 SD and negative DIs reach $-1.7$ SD in the left flank. Both these areas encompass leads in which ST changes depart most from normal values. In IMI, ST maximum is in the lower right anterior chest and ST minimum is in the left precordial region above $V_3$. Positive DIs peak at 2.6 SD in the lower right flank, and negative DIs reach $-4.6$ SD in the left axilar area. ST maximum in PMI lies below $V_6$, whereas ST minimum is above $V_3$. Corresponding DIs achieve peak positive values (2.6 SD) in the lower middorsal area and peak negative values ($-3.6$ SD) in the upper left precordium. Sites of peak negative and positive DIs, indicating in each MI group where ST voltages depart most from normal ST voltages, do not coincide with the sites where maximum and minimum ST voltages are actually measured. Moreover, except for the site of excessive ST elevation in AMI, all other sites are outside the conventional electrode positions. Also, the highest DIs are observed in IMI and in PMI, in which the maps differ from N maps both in pattern and in magnitude; in contrast, AMI maps, which resemble N maps, differ mainly in voltage and produce smaller DIs. Because of the similarity in map patterns between PMI and IMI, a discriminant map, relative to these two groups, was computed by dividing the difference between the respective mean ST maps by the composite SD derived from both populations (Figure 1, panel D). Positive DIs peak at 1.6 SD and negative DIs at $-1.8$ SD, indicating increased ST elevation in the lower right anterior torso and ST depression in the left axilla in the IMI group, respectively. No significant DIs are noticed in the precordial area, suggesting that both groups produce similar patterns (i.e., ST depression) in that particular region of interest.

**Discriminant Analysis for Classification of Acute MI**

Stepwise discriminant analysis was performed for optimal separation of each MI class from 159 normal subjects. Because of the small sample sizes involved in each pairwise comparison, the jackknife option was used, and the procedure was limited to two steps. Features for classification were ST measurements averaged, at each electrode site, over the first five of 18 instants on time-normalized ST-T waveform in each subject. For each pairwise comparison, the first variable, selected by the statistical program and entered in the first step, was an ST measurement originating from a lead with ST depression; in the second step, a lead with ST elevation was selected. Figure 2 represents the lead sites selected for each bigroup separation. Optimal leads for classification of AMI are located in the left flank (ST depression) and above $V_3$ (ST elevation); in IMI, leads originate from the left anterior axillary region (ST depression) and from the lower right anterior chest (ST elevation). The upper left precordium (ST depres-
sion) and the lower left back (ST elevation) are optimal sites for PMI. At a specificity level of 95%, the discriminant functions achieved sensitivities of 82% for AMI, 100% for IMI, and 93% for PMI. The selected lead sites correspond, not unexpectedly, to areas that demonstrated the highest DIS, both negative and positive. Also, since magnitudes of DIS represent the ability of measurements to discriminate between two groups, ST depression, which yielded the largest DIS in all three MI groups, was entered in the first step of the procedure. ST elevation was then selected as the variable best able to improve discrimination in combination with ST depression in each MI group. The essence of multivariate analysis is to reject redundancy when present and to combine variables that contribute independently to the overall classification. To assess nonredundancy in information content of opposite ST measurements, we correlated voltages originating from areas with excessive ST elevation with voltages from areas with excessive ST depression in each MI category. Each such area consisted of three or four leads with similar ST patterns; correlation coefficients were computed, in turn, between each measurement from one cluster (ST depression) and the measurements from the opposite cluster (ST elevation). Depending on the MI group and on the combination of lead pairs in each group, correlation coefficients ranged from \(-0.28\) to \(-0.42\).

A relatively large number of patients (44%) from all MI groups had increased echocardiographic LV mass but were not excluded from the study. However, because ST segment map patterns from LVH subjects

**Figure 1.** Group mean body surface potential maps of patients with anterior myocardial infarction (AMI), inferior myocardial infarction (IMI), posterior myocardial infarction (PMI), and of normal subjects (NR) and corresponding discriminant maps for the separation of normal subjects from patients from each myocardial infarction group (panels A, B, and C) and for the separation of IMI patients from PMI patients (panel D) are depicted from left to right in each panel. Maps represent averaged ST segment voltages computed over the first five of 18 ST-T instants indicated by the blackened surface on reference ECG tracings (see text). Left half of each map represents anterior torso, and right half represents the back. Small circles correspond to V1 through V6 standard electrode positions. Top of the map is at the level of the sternal notch and bottom is at the umbilical level. Contour lines in surface maps are drawn with increments of 20 \(\mu\)V; contour lines in discriminant maps are drawn with increments of 0.5 SD (see text). Solid lines indicate positive values; dotted lines, negative values. The numbers under each discriminant map represent peak positive and peak negative departures from normal values expressed in SD and measured at sites indicated on the discriminant maps by + and −, respectively.

**Figure 2.** Diagram shows unfolded torso with 117 recording sites (three additional electrodes record the limb leads). Black squares correspond to V1 through V6 standard electrode positions. Circles indicate specific leads selected in the discriminant analysis. The signs + and − within each circle indicate whether the corresponding voltage measurements represented ST elevation or ST depression. Leads A+ and A− were selected for optimal classification of patients with anterior myocardial infarction (AMI), leads I+ and I− for patients with inferior MI, and P+ and P− for patients with posterior MI.
FIGURE 3. Group mean body surface potential maps of the normal population at instants indicated by time markers on reference ECG waveform. Maps are selected at instants 1/18 ST-T (J-point), 2/18 ST-T, 3/18 ST-T, 4/18 ST-T, and 5/18 ST-T. Voltages in the maps from the column indicated "ST depression" were obtained by subtracting at each electrode site and at each instant 2 SD from the normal group mean voltages. Voltages in the maps from the column indicated "ST elevation" were obtained by adding at each electrode site and at each instant 2 SD to the normal group mean voltages. Increments in contour lines are ±50 μV. Viewed as a pair at each instant, they represent the upper and lower limits of the 95% normal voltage distribution outside which voltages are considered abnormal.

resemble those observed in AMI,13 particularly as far as ST depression in the left precordium and in the left flank is concerned, the risk exists of wrongly identifying as "MI" patients with LVH but no MI or labeling MI patients as "LVH without MI." Indeed, when directed through the N versus AMI classification model, 53 of 116 patients (46%) with pure LVH were called "AMI" (as opposed to 11% "IMI" calls when tested for N versus IMI or 9% "PMI" calls when the N versus PMI model was considered). Therefore, we performed multivariate analysis by computing discriminant functions at each of the two nodes of a decision-tree structure, considering N versus AMI in the first node and AMI versus LVH in the second node; 49 of 53 LVH subjects (92%) misclassified as AMI were correctly assigned to the LVH group, with five of 62 AMI patients (8%) remaining after the first node misclassified as LVH. The discriminant function in the latter node required an additional ST measurement from a lead located above V₃. In this location, group mean LVH voltages average 10 μV, whereas group mean AMI voltages average 150 μV; the optimal threshold for separating these two groups is 70 μV.

Magnitude of ST Segment Changes: Comparison With Normal Values

Figure 3 depicts isopotential maps at instants 1/18 ST-T (J-point) to 5/18 ST-T. At each instant, voltages deviating from the 95% normal range (mean±2 SD) on either side of the normal distribution are represented as isocontour lines. The maps corresponding to ST minima (mean−2 SD) show that ST depression <−60 μV is outside the lower normal limit anywhere on the thoracic surface and at each instant throughout the ST segment. This is also true for the limb leads, except aVR, with which normal ST depression can reach −80 μV. The maps for maximum ST elevation (mean+2 SD) indicate that the upper limits for ST deviation vary throughout the ST segment and depend on the recording site; ST maxima peak around V₁ to V₃, reaching between 200 and 250 μV at J-point and up to 400 μV at 5/18 ST-T. Values for V₁ and V₃ range from 50 to 100 μV at J-point, increasing to 150 μV at 5/18 ST-T; intermediate voltages are measured in V₄ and V₅.

Figures 4–6 illustrate the quantitative relation between the 95% normal range for ST segment voltages and the corresponding amplitudes observed in the
standard 12-lead ECG and the pair of leads found optimal for each MI class. (As mentioned earlier, each of the leads selected in each MI group originates from clusters of three or four leads with similar characteristics: in each cluster, the program selects the lead with the highest discriminant power [F value]. In fact, since other neighboring leads could have performed almost equally well, some flexibility in lead selection exists.) The results pertain to measurements at the J-point, and the numbers for each lead represent the number of patients (in percent) exceeding the 95% normal range at either side of the normal distribution. Overall, sensitivities are lowest for AMI, highest for IMI, and intermediate for PMI. Abnormal ST elevation in AMI is most often observed in V1 (55%) and V2 (49%); ST depression produces sensitivities of about 40% in the inferior leads. Optimal leads increase sensitivity of ST elevation to 59% (lead 36 above V2) and of ST depression to 74% (lead 86 in the left flank). In IMI, out-of-range ST elevation reaches 88% in lead III and 78% in aVF; ST depression yields sensitivities of 91% in aVL, 81% in V3, and 84% in V6. ST elevation in lead 4 (lower right anterior chest) is seen in 94% of IMI patients, and ST depression in lead 63 (near the left axilla) occurs in 100% of the patients. Results in PMI follow as observed in IMI, albeit with quantitative differences: sensitivities for ST elevation are 61% in lead III and 52% in aVF; for ST depression, they are 70% in aVL and 83% in V2. Lead 111 (lower right back) produces a sensitivity of 78% for ST elevation, and ST depression occurs in 91% of PMI patients in lead 56 (upper left precordium).

**Discussion**

**Optimal Recording Sites for Acute MI**

BSPMs allow identification of torso sites at which the largest ST segment voltages, both positive and negative, can be observed in acute MI. Corresponding discriminant maps show where these changes are statistically most significant. Indeed, measurements from areas with peak DIs represent the number of standard deviations each MI group is away from the normal group and achieve optimal separation between any of the former groups and the latter group. Departure from normal range is highest in the IMI group and smallest in the AMI group. Similar observations were reported by Mirvis14; using a related approach in which only the out-of-range potentials were plotted, he also observed marked deviations from normal range in IMI, contrasting with smaller deviations in AMI. The sites of peak departures from normal values are either in the vicinity of voltage maxima and minima (AMI group) or dislocated with respect to these values (MI and PMI groups). With the exception of one lead located right above V2 and used for recording abnormal ST elevation in AMI, all other leads are outside the areas interrogated by the conventional electrodes.

Sites of peak departures are better suited for designing ECG criteria than sites of maximum or minimum voltages because they represent areas with the smallest overlap between normal and abnormal voltages. When discriminant analysis was performed, measurements from areas with peak DIs were found optimal for classification of patients in each MI category. Because of the small sample sizes involved, only the first two measurements entered in the stepwise procedure and...
corresponding to peak negative and peak positive DIs were selected for each pairwise comparison. Considering the opposite polarity of each pair of measurements chosen for each MI group (Figure 2), bipolar leads derived from these lead pairs were constructed and tested for diagnostic yield. Although the obtained voltages were larger than those of either of the component voltages, their diagnostic capability was no better than that of the separate measurements.

**ST Segment Depression Versus ST Segment Elevation**

Reciprocal ST depression is a biophysical phenomenon that is always to be expected in patients with acute MI with primary ST elevation. Its detection on the body surface depends to a large extent on the electrode system used to record the ECG signals. For example, in IMI and PMI, the inadequate sampling of the anterior chest wall by the standard electrodes explains why precordial ST depression is recorded in some patients and not in others; this, in turn, may account for the disparate results reported in the literature on the prognostic significance of these changes in patients with or without anterior ST depression. The magnitudes of both ST depression and ST elevation depend on the characteristics of the myocardial injury (intensity, location, orientation, age, and size), on those of the volume conductor (heterogeneities, anisotropy), and on the distance between the lesion and the measuring surface electrodes; the quantitative relation between opposite ST changes, therefore, varies considerably from individual to individual. Moreover, the information contained in ST depression is not necessarily redundant with that present in ST elevation. Indeed, correlation coefficients computed between measurements originating in, each MI group, from areas at which reciprocal patterns were observed (i.e., areas including and surrounding each pair of recording sites depicted in Figure 2) averaged −0.42 in AMI, −0.35 in IMI, and −0.34 in PMI. Results from discriminant analysis confirm the independent contribution of ST depression to the separation of each MI category from normal subjects. Moreover, entrance of ST depression in the first step of the stepwise discrimination emphasizes the potent diagnostic capability of these measurements.

ST segment depression is generally not regarded as a reliable marker of evolving Q-wave MI, particularly when present without visible concomitant ST elevation. When observed in the anterior chest, ST depression is viewed as indicating anterior myocardial ischemia or non-Q-wave MI unless accompanied by ST elevation in the inferior leads, in which case inferoposterior MI becomes one of the possibilities. Indeed, only ST elevation is believed to be the definitive marker of transmural ischemia and the early harbinger of subsequent Q-wave development. Several studies support differing views. In a recent report on 576 patients with creatine kinase MB−confirmed acute non−Q-wave MI, Boden et al showed that only 20% of 187 patients with ST elevation developed Q waves, whereas 15% of 252 patients who exhibited early ST depression or T-wave inversion or both evolved subsequent Q waves. Thus, 80% of patients with and 85% without early ST elevation did not develop subsequent Q waves.
The traditional view that equates ST elevation with Q-wave MI and ST depression with non-Q-wave MI was also challenged by Huey et al., who provided further evidence that early ST elevation could be a determinant of both evolving Q-wave and non-Q-wave MI, and by Boden et al., who observed that 23 of 50 patients (46%) with isolated precordial ST depression evolved posterior MI (abnormally tall and wide R waves in V₁ and V₂). Furthermore, comparing patients with ST elevation with patients with ST depression in terms of clinical outcome, Boden et al. noted the absence of a between-group difference in peak creatine kinase, reinfarction, postinfarction angina, or early recurrent ischemia. Willich et al. also reported that patients with non-Q-wave MI whose maximal initial ST deviation was depressed had a worse prognosis than those whose maximal initial ST segment deviation was elevated. These findings in non-Q-wave MI have important clinical implications because most infarcts (within the first several hours) begin without Q waves.

A contribution of ST depression independent of ST elevation has also been investigated by Willems et al. In a recent European Cooperative Study, these authors performed multiple regression analysis and demonstrated a significant and independent correlation of initial ST elevation and reciprocal ST depression with α-hydroxybutyrate dehydrogenase release; indeed, in patients with similar degrees of ST elevation, reciprocal ST depression exceeding median values was associated with greater infarct size in both IMI and AMI compared with patients with lower ST depression.

Quantitative Assessment of ST Segment Changes

Different investigators measure ST shifts at different time instants. One advantage of the J-point over other time instants is that it can be hand measured. However, because it cannot always be clearly identified, other reference points have been proposed. Interestingly, recent data indicate that, although deviations measured at the J-point and later into the ST segment differ significantly, correlation with enzymatic and angiographic estimates of infarct size were not significantly different. In the present study, discriminant functions were computed from ST measurements at different time instants (from ST-T 1/2 to ST-T 5/18) and from the time integral over the first 5/18 of the ST-T waveform; class assignment of patients into each MI group remained practically unchanged. Normal limits for ST segment voltages were calculated from the normal mean voltages ±2 SD at each electrode site at successive instants throughout the ST segment. At the J-point, maximum normal voltages declined from slightly >200 μV around V₁ to V₄, to <50 μV beyond V₅ and V₆. Minimum voltages on the torso are between zero and −30 μV, reaching −50 to −70 μV in the upper right back and the right shoulder only. The percentage of patients outside these limits was calculated in each MI group at each electrode site (Figures 4–6). At high specificity levels, low sensitivities are observed in AMI for both the limb leads and the precordial leads. Recognition rates are higher in PMI and still better in IMI, particularly if ST depression is considered. Optimally selected leads further improve sensitivities, with ST depression achieving the best results.
Most major thrombolytic trials have used a threshold of 1 mm ST elevation for patient inclusion. Although this results in a high sensitivity for AMI when ST elevation occurs in leads V2 to V4, it also produces a marked reduction in specificity in the same leads to <60%. The performance of lead 36 of the BSPM is equally affected. In IMI and in PMI, 1 mm ST elevation in leads II, III, and aVF preserves (and even slightly increases) specificity but is accompanied by either a small (leads III, aVF) or an important (lead 4 in IMI and lead 11 in PMI) loss in sensitivity. Other investigators have used a different threshold for ST elevation in the precordial leads (2 mm) and in the limb leads (1 mm).35 Results from this approach are comparable to those achieved by the 95% normal range rule in AMI when the changes occur in precordial leads V2, V3, or V4. Some authors have accepted ST depression (1 or 2 mm) as an inclusion criterion but in conjunction with ST elevation.6,7 Applying a threshold of 1 mm for ST depression to our data results in a marked and needless drop in sensitivity in each of the MI groups, because no improvement in specificity is noticed. Therefore, to derive selection criteria offering a reasonable compromise between high specificity, with respect to normal values, and optimal diagnostic yield, thresholds for ST changes in acute MI should be tailored to the lead sites from which they originate.

**Limitations of the Study**

The first limitation deals with the sample sizes. Because of the small number of patients in each MI class, we had to limit the number of classification variables to achieve repeatable results22 and use the jackknife option. As a result, no more than two variables were used in the stepwise discriminant analysis for each bigroup comparison. Also, the use of radionuclide imaging as ECG-independent information for stratification of the MI population could lead to ambiguous group assignment, particularly when multiple wall motion abnormalities coexist in various parts of the left ventricle and septum. Therefore, we calculated a wall motion abnormality index based on regional abnormalities and grouped the segments into three broad categories: anterior group, inferior group, and posterior group. It is likely that some amount of overlap still subsists, particularly between the IMI and the PMI groups. We could have used coronary angiography for the purpose of stratification, but because of the retrospective nature of the study, these images were not available in all MI subjects. Moreover, coronary angiography does not always allow identification of the infarct-related artery, nor does it unequivocally establish the relation between the vessel(s) involved and the region of the myocardium affected. In a recent study on ST changes in acute MI patients stratified by occluded coronary vessel, Huey et al23 noted that the proportion of patients with ST depression in the precordial leads and ST elevation in the inferior leads was similar for the left circumflex and the right coronary artery groups and that only ST changes in the lateral leads were helpful in distinguishing the two groups. The latter observation can be related to the IMI–PMI comparison depicted in Figure 1, panel D, in which the best discriminant leads between these two groups are along an axis oriented in a frontal plane from lower right flank to upper left axilla and running parallel to the lead direction of aVL.

Another limitation is the variable delay between onset of symptoms and recording of map data. Indeed, several studies have indicated that ST voltages culminate in the early hours after the acute event and stabilize within 12 hours at roughly 50% of their initial values.24,25 Although this factor does not influence the 95% normal limits used to calculate specificity, sensitivity of ST measurements is unquestionably dependent on the time interval between onset of pain and mapping. It is interesting, however, to note that Walker et al,15 analyzing the prognostic significance of ST segment in patients with acute MI against the time between onset of symptoms and mapping, reported no change in the results with change in map time. A prospective study on a larger number of subjects is required to establish normal limits, stratified by age, race, and sex, and to calculate sensitivities of ST measurements at different lead sites and at various times during evolution of acute MI. The latter aspect may be important, because reduction in mortality has been reported in patients undergoing thrombolytic treatment as late as 13–24 hours after onset of pain, when ST changes are less prominent.36

A final limitation is the classification model itself. Indeed, the discriminant functions used for patient assignment are derived from the pairwise comparison of normal subjects versus each MI class. The model separates >90% of all MI at a high level of specificity with respect to a normal control population. However, several other non-MI entities produce ST changes and have to be ruled out before the classifier is considered specific of acute MI. This is of particular interest in a clinical setting of acute chest pain, in which urgent decisions are required and a diagnostic classifier must recognize acute MI as soon as possible and avoid misdiagnosis in non-MI subjects in view of the possible risks of thrombolytic therapy. In the present study, we identified an additional lead that allowed separation of ST changes ascribed to LVH without MI from ST changes produced by MI with or without LVH. It is very likely that more additional leads will be required for other diagnostic entities. One such entity of particular interest is myocardial ischemia with ST segment shifts and no MI. A related issue is that of ST abnormalities produced by nonischemic diseases. In a recent study,27 we stressed the important contribution of T-wave maps to the recognition of acute MI, with and without Q waves: it is therefore possible that the combination of T-wave with ST segment information may increase specificity of early acute MI patterns.

**Clinical Implications**

The present study identified regions on the torso from which ECG signals could be recorded for optimal recognition of ST segment changes in various anatomical classes of acute MI. Two unipolar leads, originating from areas in which the most significant positive and negative ST segment displacements most often occurred, were selected for each of the three MI groups. These six sites were, with one exception, outside the thoracic region interrogated by the conventional chest leads. This lead set, derived from 120-lead BSPM data, is both practical and tailored to acute MI and is proposed for monitoring the evolution of the acute MI lesion and evaluating the effects of interventional pro-
cures. Because the lead locations correspond to areas where maximum departures from normal values are most constantly observed, they are well suited for deriving reliable ECG criteria for patient inclusion for thrombolytic therapy. The analysis of discriminant maps and the results of statistical analysis emphasize the important, independent contribution of ST depression to diagnosis. In all three MI groups, the combination of ST elevation and ST depression (which is not always possible with the limited chest wall sampling provided by conventional leads) increases sensitivity without loss in specificity. Also, the controversy regarding the presence and significance of ST depression accompanying IMI and PMI can be more reliably addressed by investigating those areas in which these shifts almost always occur (upper left anterior chest and axilla). Improved sampling of the available surface information may also contribute to estimating the true proportion of patients with and without ST changes in the acute phase.

Tuning the amount of ST change to electrode site achieved optimal recognition rates. It is obvious that a 1-mm displacement in distant regions on the torso or in the limbs, where lead strength is small, is not comparable to 1 mm in the midsternal area, where lead strength is maximal. Adjusting and standardizing the thresholds for both ST elevation and ST depression measurements not only improves the performance of selection criteria but also allows better comparability of results from different clinical trials. Since best results from thrombolytic therapy are observed when ST changes are largest, it is important to sample areas in which the most prominent changes occur for identification of patients who would benefit most from intervention. Furthermore, discriminant analysis performed on measurements at the J-point and at other instants throughout the ST segment produced little difference in recognition rates. The choice of a time reference, therefore, should rest on practical considerations only.

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