Body Surface Electrocardiographic Mapping to Assess Left Ventricular Diastolic Overload in Valvular Heart Disease

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Summary

In order to assess diastolic overload by electrocardiogram (ECG), we performed body surface ECG mapping (MAP), and then compared the results with echocardiographic, roentgenographic and cardiac catheterization findings. Eighty-seven unipolar electrocardiograms were simultaneously recorded for the following groups: 1) 40 normal subjects, 2) 46 patients with diastolic overload [32 patients with aortic regurgitation (AR) and 14 patients with mitral regurgitation (MR)]. QRS isopotential maps were constructed at 10, 20, 30, 40, 50 and 60 msec from the QRS onset. On the potential departure map, the area where the QRS voltage was greater than the normal limits (mean+2SD of normal control) was designated as “+2SD area”. In patients with diastolic overload, +2SD area was found on the left anterior chest and back at 40, 50 and 60 msec from QRS onset. Subjects were classified into the following 3 groups according to the location of their +2SD area: 1) group A (n=23) in which the +2SD area was found on the left anterior chest and back, 2) group B (n=17) in which the +2SD area was found only on the back, and 3) group N (n=6) in which no +2SD area was found. Group A had a markedly greater left ventricular end-diastolic internal dimension than the other groups (A 63.6±6.8 mm, B 53.9±5.5 mm, N 50.7±6.0 mm, A vs. B, N p<0.01), and a greater cardiothoracic ratio than the other groups (A 58.5±5.6%, B 52.5±7.0%, N 52.3±4.7%, A vs. B, N p<0.01). There was no significant difference in wall thickness among the 3 groups. The regurgitation severity assessed by cardiac catheterization was greater in group A than in the other groups. Among AR patients, the +2SD area was located on the upper back and the upper anterior chest, whereas among MR patients, it tended to be located on the lower portions. The potential departure map is a useful noninvasive analytic method for determining the extent and grade of diastolic overload. Furthermore, the location of the +2SD area may be used to discriminate between AR and MR.
The conventional electrocardiogram (12-lead ECG) and vectorcardiogram (VCG) are widely used for diagnosis of left ventricular hypertrophy. Ever since Cabrera showed that the differences in the electrocardiographic findings of left ventricular overload were due to hemodynamic factors such as pressure or volume overload, many investigators have studied characteristic changes using 12-lead ECG or VCG in various left ventricular overload diseases. These methods, however, give little information about the back or the upper and the lower chest, and also seem to be insufficient for detailed analysis of the electrocardiographic changes seen in left ventricular overload disease. It is also difficult to determine the diseased valve and the severity of regurgitation in volume overload caused by valvular heart diseases by 12-lead ECG or VCG.

Body surface mapping, employing electrocardiographic lead points spread over the entire thorax, offers information about potential distribution over the back, and upper and lower anterior chest. Moreover, using the departure map technique, we can detect abnormal potential distributions out of the normal range.

In this study, we performed body surface mapping in patients with left ventricular volume overload disease (aortic regurgitation and mitral regurgitation), and compared it to echocardiographic and cardiac catheterization findings. The purpose of this study is to determine the characteristic ECG mapping changes diagnostic of a specific diseased valve and its severity.

Materials and Methods

Subjects:
1) Diastolic overload disease
From the 190 patients evaluated for symptomatic aortic or mitral valve regurgitation with cardiac catheterization at Yamagata University Hospital from April 1980 through March 1987, 46 patients satisfying all of the following criteria were selected for this study [32 with aortic regurgitation (AR), and 14 with mitral regurgitation (MR)].

(1) Valvular dysfunction limited to either the aortic valve (AR) or the mitral valve (MR).

(2) In AR cases, no significant peak systolic pressure gradient present between the left ventricle and the systemic artery. In MR cases, no peak
pressure gradient present between the left atrium and the left ventricle.

(3) No conduction disturbance such as right bundle branch block or left bundle branch block. QRS duration did not exceed 100 msec.

(4) No other heart disease such as myocardial disease, ischemic heart disease, congenital heart disease or severe congestive heart failure (New York Heart Association class IV).

(5) No severe pulmonary hypertension (PA systolic pressure <40 mmHg).

(6) No premature ventricular contraction or severe arrhythmia while recording body surface ECG mapping and echocardiogram.

(7) Good echocardiographic recordings.

(8) No right ventricular dilatation on two-dimensional echocardiogram.

The patient group consisted of 29 men and 17 women, from 17 to 79 years of age (mean 49.2 years).

2) Normal control group

A control group of 40 normal volunteers was also used. They were all men, aged from 22 to 52 years. All had normal physical and electrocardiographic findings. None had a history of heart disease or hypertension. All subjects gave their consent before the study commenced.

All patients with diastolic overload disease underwent cardiac catheterization, body surface mapping, chest X ray and echocardiography within 2 weeks.

**Methods:**

1) Body surface mapping

Map recording: Body surface mapping was performed using a body surface potential mapping system, the HPM 5100 unit (Chunichi Den-shi).\(^5\)\(^-\)\(^7\) Eighty-seven unipolar electrodes were distributed over the entire thoracic surface with Wilson’s central terminal as reference (Fig. 1). Standard 12-lead ECGs and the Frank X, Y, Z ECGs were sampled simultaneously. Then, the stored signals of each ECG were displayed on a graphic terminal (Tektronix, 4006-1). If a noise was detected in any of the signals, the data sampling was repeated. The flat portion of the PQ segment was chosen for the baseline. After the baseline adjustment, the data were recorded on a magnetic cassette tape in a digital format. This system had a resolution of 10 \( \mu \)V, in a dynamic range of +5 mV, with a data sampling rate of 1000 samples/sec/channel. The data sampling was done at the resting expiratory stage in the supine position.

The onset of QRS was determined from superimposed Frank X, Y, Z leads and spatial magnitude. The mean and standard deviation (SD) of the
normal control group were obtained from 40 normal volunteers. At 10, 20, 30, 40, 50 and 60 msec from the onset of the QRS, the departure index (DI) was calculated by the following formula for each lead. The distributions of the DI were displayed as the potential departure map.

\[ \text{DI} = \frac{x - \text{mean of normal}}{\text{SD of normal}} \]

On the departure map, the body surface region in which the potentials were greater than the normal limit (mean + 2SD) was designated as the "+2SD area". The area of each +2SD area region was calculated using a distance of 5 cm between each lead point.

For each lead, ventricular activation time (VAT) was determined as the duration of time from QRS onset to the most rapid decrease in QRS voltage (dV/dt min).\(^7\)

2) 12-lead ECG

To analyze the QRS complex on the 12-lead ECG, the precordial voltage combination of Sokolow and Lyon was measured in each patient (SV\(_1\)+ larger R wave in V\(_5\) or V\(_6\) on 12-lead ECG).\(^8\)

3) Cardiac catheterization

Retrograde left ventriculography and aortography were performed via
the femoral artery by a standard technique. Each case was graded using Sellers' classification. The grade of regurgitation was analyzed by 2 or more examiners without knowledge of other clinical data.

4) M-mode echocardiogram

M-mode echocardiograms were recorded using standard techniques with a 3.4 MHz transducer interfaced to a TOSHIBA SSH-40A. M-mode echocardiogram was recorded by standard techniques and the findings were analyzed independently by 2 different physicians who had no previous knowledge of any clinical data of the patients. The interventricular septal thickness (ST), the posterior wall thickness (PWT), the left ventricular end-diastolic internal diameter (LVIDd) and the left atrial diameter at end-systole (LAD) were all measured according to the recommendations of the American Society of Echocardiography. Wall thickness (WT) was calculated by the following equation. \( WT = ST + PWT \) (mm)

5) Determination of cardiac size on the roentgenogram

The roentgen examination of cardiac size was determined in posteroanterior projection. We measured the cardiothoracic ratio (CTR; the ratio between the transverse cardiac diameter and the greatest internal diameter of the thorax).

Statistical analysis:

Statistical analysis was performed by analysis of variance. P<0.05 was considered significant.

Results

1. Potential departure map

Out of the 46 patients with volume overload, +2SD area was found in 40 patients (87%). A certain tendency for the +2SD area to appear on the back at the late phase of the QRS, such as 40, 50 and 60 msec from onset of QRS was observed. Particular attention was paid to these +2SD areas at late QRS phase in AR and MR patients. We classified subjects into the following 3 groups according to the appearance and localization of the +2SD area at 50 msec from the QRS onset:

Group A: +2SD area was located on the back and the left anterior chest, and contained both H3 and H4 lead regions which constituted the midpoint between the midaxillary line and the mideclavicular line \( (n=23, \ AR=16, \ MR=7) \).

Group B: +2SD area was located only on the back, or on the back and left lateral chest not containing the H3 and H4 lead points \( (n=17, \ AR=12, \ MR=5) \).
Fig. 2-a. Departure maps from a patient in group A. The dotted area of the departure map indicates +2SD area (where the departure index was more than 2). The interval between contour lines represents a difference of 1 in the value departure index. Positive area means relative increase of the voltage. A "+" implies maximum and a "-" implies minimum. From times of 40 msec to 60 msec, the +2SD area spread to the back and to the left anterolateral chest. The maximal departure index at 50 msec was located on the left anterior chest. The +2SD area formed a tongue-like protrusion. The LVIDd of this case was 76 mm. The regurgitation severity of AR was 3.

Group A

H.S. 70 y.o. M

msec

LVId = 76 mm

Front Back

Fig. 2-b. All wave forms from the same patient as in Fig. 2-a.

Group N: No appearance of a +2SD area (n=6, AR=4, MR=2).

MR=5).

Figs. 2, 3 and 4 show representative cases of groups A, B and N. Figs. 2-a, b and c show potential departure maps, all wave forms and vectorcardiograms, obtained from a patient in group A. The patient had grade 3 aortic
regurgitation by cardiac catheterization. The left ventricular end-diastolic internal diameter (LVIDd) was 76 mm. The CTR was 61.5%. The +2SD area was located on the left anterolateral chest and back, and contained the H3, H4 lead region at the late phase of the QRS complex. The shape of the +2SD area at 50 msec from the QRS onset was similar to that of a tongue, so this distribution pattern was called “the tongue-like protrusion”. All cases of group A had this characteristic “tongue-like protrusion” pattern.

Fig. 3 is from a patient in group B. The patient had grade 2 AR. The LVIDd was 55 mm. The CTR was 50.0%. At 40, 50 and 60 msec, the +2SD area occurred only on the back, not making a tongue-like protrusion.

Fig. 4 is from a patient in group N. The patient had grade 1 AR. The LVIDd was 43 mm. The CTR was 50.5%. No +2SD area was present on the departure maps.

**Comparison with ventricular activation time:**

The ventricular activation times (VAT) at each lead point were compared among groups A, B and N. The VAT at the left anterior chest lead point was delayed significantly in group A (at H4 lead, A 50±7.1 msec, B 39.6±6.2 msec, N 36.2±4.9 msec, A vs. B, N p<0.01).

**Comparison with echocardiographic findings:**

The echocardiographic findings of groups A, B and N were compared with each other (Fig. 5). The LVIDd of group A was significantly greater than those of both groups B and N (A 63.6±6.8 mm, B 53.9±5.5 mm, N 50.7±6.0 mm, A vs. B, N p<0.01). The size of the +2SD area at 50 msec was moderately correlated to the LVIDd in AR (r=0.60). However, as for wall thickness and LAD, there were no significant differences among the 3
Fig. 3. Departure maps from a patient in group B. The +2SD area during later phases occurred only on the back. The maximal departure index at 50 msec was located on the back. The LVIDd of this case was 55 mm. The regurgitation severity as determined by cardiac catheterization was 2.

Fig. 4. Departure maps from a patient in group N. This case had no +2SD area. The LVIDd was 43 mm. The regurgitation severity as determined by cardiac catheterization was 1.

Fig. 5. Left ventricular internal dimension in the diastolic phase (LVIDd) and the wall thickness in groups A, B and N. The LVIDd in group A patients was significantly greater than that in those of the other groups (* p< 0.01). Bars indicate mean±SD. LVIDd=left ventricular internal dimension; wall thickness=intraventricular septum thickness and left ventricular posterior wall thickness.
groups. LAD in MR patients was significantly greater than in AR patients (MR 46.1±7.3 mm, AR 28.0±4.3 mm, AR vs. MR p<0.01).

**Comparison with cardiac catheterization findings:**

Table I summarizes aortographic gradings of AR. In group A, 12 cases out of 16 (75%) had a regurgitation degree of 3 or greater. In group B, however, only 3 cases out of 12 (25%) had a regurgitation degree of 3 or greater. Table II summarizes left ventriculographic grading of MR. In group A, 6 cases out of 7 (86%) had a regurgitation grade of 3 or greater.

**Comparison with CTR on the roentgenogram:**

The CTR of groups A, B and N were compared with each other. The CTR of group A was significantly greater than those of both groups B and N (A 58.4±5.5%, B 52.5±7.0%, N 52.5±4.7%; p<0.01 A vs. B, p<0.01 A vs. N).

**AR vs. MR:**

In addition to these findings, differences between AR and MR by the +2SD area on the potential departure map were observed. In both AR and MR, the +2SD area was located on the back and the left anterolateral chest in group A, and only on the back in group B. In patients with AR, the +2SD area spread to the upper anterolateral chest and upper back. Con-

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Table I. Cardiac Catheterization Severity and Departure Map
Groups in Patients with AR

Table II. Cardiac Catheterization Severity and Departure Map
Groups in Patients with MR
versely, in patients with MR, the +2SD area spread to the lower anterolateral chest and the lower back. Therefore, close attention was paid to the following 2 lead points which were thought to represent the AR and the MR characteristic forms (Fig. 6); lead J6, located on the left upper lateral back, and J2, located on the lower lateral back. For each point, the departure index (DI) was then examined to determine whether or not it was equal or greater than 2 (DI≥2 means the voltage was equal or greater than the normal mean +2SD) (Fig. 7).

**Fig. 6.** The representative departure map pattern of AR and MR, at a time of 50 msec. Upper panel: Departure map from a patient with AR. The +2SD area is located on the upper side of the back and the anterior chest. The departure index at the J2 lead point is more than 2, but the voltage at 50 msec is still within normal limits. Lower panel: Departure map from a patient with MR. The +2SD area is located on the lower side of the back and left anterolateral chest containing the J2 lead point region.

**Fig. 7.** Chart depicting whether or not the departure index was greater than 2 at either the J6 or the J2 lead points. DI≥2: The voltage was greater than normal mean +2SD.
1) J6 lead point
As for AR, 23 out of 28 cases (82%) had DI index equal or greater than 2. On the other hand, among MR patients, only 2 out of 12 cases (16.7%) had DI equal or greater than 2. This trend was especially apparent in group A, in which all the patients with AR (100%) had DI equal or greater than 2, while all the patients with MR were within normal limits (0%).

Assuming that patients whose DI≥2 at J6 had AR, the sensitivity for AR (AR pattern positive/total AR patients) was 82%, the specificity (AR pattern negative/total MR patients) was 84%, and the overall predictive accuracy [(AR patients with AR pattern positive+MR patients with AR pattern negative) / (total AR patients+total MR patients)] was 82.5%.

2) J2 lead point
The number of cases which had a departure index greater than 2 for MR was 8 out of 12 (66%), while for AR it was only 8 out of 28 (28%). Assuming that patients whose DI≥2 at J2 had MR, the sensitivity for MR was 66% and the specificity was 72%. The predictive accuracy was 70%.

2. 12-lead ECG and VCG findings
We examined the precordial voltage combination of Sokolow and Lyon (SV1+larger RV5 or V6) on 12-lead ECG. Hypertrophy was diagnosed when the value of SV1+RV5 or V6 was greater than 3.5 mV. In AR, 29 of 32 cases had a SV1+RV5 or V6 value greater than 3.5 mV. In MR, all cases had voltages greater than 3.5 mV. Therefore, using the Sokolow and Lyon criteria, almost every case with valvular heart disease was shown to be hypertrophic. The correlation coefficient between Sokolow and Lyon voltage and LVIDd was 0.35.

The maximal QRS vector of groups A and B was directed significantly more posterior than that of group N (group A -39.2±39.8°, group B -37.2±39.8°, group N 0.8±20.2°; p<0.01 A vs. N, p<0.01 B vs. N). However, it was not significantly different between groups A and B. The QRS loop in the horizontal plane showed a “figure of eight” pattern in 10 cases, 9 cases from group A and 1 case from group B.

DISCUSSION

1) The significance of the “+2SD area”: comparison with echocardiographic findings and CTR on roentgenogram
Diastolic overload disease (AR and MR) has been discussed as a type of left ventricular hypertrophy (LVH).11)-13) Cabrera et al11,12) pointed out that the amplitude of the R wave on the right sided leads, including V1, is increased in patients with AR. In left ventricular diastolic overload disease, an in-
crease in the R wave in the leads on the left anterior chest is well known. In this study, the +2SD area appeared at the late phase of the QRS (from the late R wave to the S wave). This +2SD area was located on the back and sometimes spread to the lateral and anterior chest. The departure map findings from diastolic overload diseases displayed these characteristic patterns of the +2SD area with respect to appearance time and location. Furthermore, patients who had greater LVIDd and greater CTR had the +2SD area spread to the left anterior chest, forming “a tongue-like protrusion”. This tongue-like protrusion of the +2SD area on the anterior chest was considered to be useful when diagnosing LV dilatation and when determining the grade of regurgitation.

Moreover, many authors have previously discussed the correlation between the degree of left ventricular dilatation and the QRS interval. In this study, the relationship between the ventricular activation time (VAT) and departure map group was also studied. It was found that the VAT at the left anterior chest lead point was delayed in group A. VAT prolongation might, in part, contribute to the abnormal potential increase of the late QRS phase appearing as the +2SD area.

Patients with a +2SD area (groups A and B) showed left posterior deviation of the maximal QRS vector on the horizontal plane of the VCG, however, no correlation was found between +2SD area size and direction of the maximal vector. Since characteristic changes in departure maps were found in the late QRS phase, it was understandable that the maximal QRS vector could not separate groups A and B.

The presence of a +2SD area on the departure map at the late QRS phase on the 12-lead ECG indicates either more positive or less negative potential. In this study, the appearance of a +2SD area at the late phase of the QRS, corresponding to the decrease of the S wave amplitude in that area, was thought to reflect the conduction delay in the anterior chest area. The increased QRS voltage was thought to be attributed to the following factors: 1) increased left ventricular surface, 2) increased intracavitary blood volume, 3) closer proximity of the ventricle to the chest, and 4) increased VAT caused by either damaged or stretched left conduction pathway and elongated myocardium.

2) AR vs. MR

In this study, both AR and MR could easily be identified by the location of the +2SD area at 50 msec. In the J6 lead point examination, the overall AR diagnosis predictive accuracy was 82.5%, the sensitivity was 82.1% and the specificity was 83.3%. The predictive accuracy of confirmed group A cases was especially high (100%). Additionally, for the cases which were
not diagnosed by the J6 lead point examination, it was likely for the +2SD area to be located on the upper side in cases of AR, and the lower side in cases of MR. These results demonstrated that the departure map technique was useful in identifying AR and MR. Identification by VCG has been discussed by many authors.\textsuperscript{13,14,16} They said their results were useful in cases with severe LV dilatation (>65 mm). In this study, AR and MR could be identified from the mapping pattern. The differences in mapping patterns between AR and MR cases remain unclear from the results of this study. The following two hypotheses, however, have been considered. First, we suppose that in AR, the overload occurs mainly on the outflow tract, and in MR mainly on the inflow tract of the left ventricle. The difference in the location of the overload region of the left ventricle may have caused the difference in the location of the +2SD area. Secondly, we suppose the situation of the left ventricle may have also caused the difference in the +2SD area location. In MR, a dilated left atrium may drive the left ventricle lower.\textsuperscript{11,23} In this study, patients with MR had significantly greater end-systolic left atrial diameters than those with AR.

3) Diastolic overload vs. essential hypertension

We previously reported the changes in the QRS departure map of 36 patients with essential hypertension.\textsuperscript{24} We showed a relationship between the location of increased wall thickness and the appearance time of the +2SD area. The patients with a +2SD area at the early phase of the QRS had increased septal thickness and those with a +2SD area at the late phase had increased left ventricular posterior wall thickness.\textsuperscript{24} In patients with hypertension, however, the location of the +2SD area at the late phase of the QRS varied. It was either on the back, on the lateral chest, or on the anterior chest, and its location was not as constant as in AR or MR. Whereas in this study, among cases of diastolic overload, we showed a relationship between the LVIDd and the distribution pattern of the +2SD area at “late” phase of the QRS complex.

4) Clinical implications and limitations

We considered the departure map findings reflected the regurgitation severity as stated above. If we set the criterion that group A has 3 or greater AR severity, then the sensitivity would be 80%, and the specificity would be 75%.

The determination of regurgitation grade by use of noninvasive methods has been discussed. The UCG Doppler is an established method of determining the regurgitation grade, however, in some cases (Murray JA et al reported 22%)\textsuperscript{25} it does not yield clear echo recordings (for example, in such cases as obesity, pulmonary emphysema, etc). Also difficulties have
been encountered when trying to determine a good sampling point for the Doppler UCG, as well as other technical problems which remain topics of discussion. For such cases, we think the departure map technique may prove to be useful. It is thought that the departure map technique used in conjunction with the Doppler method will enhance the ability of noninvasive determination of the regurgitation grade in AR and MR. In this study, normal control data were obtained from men only. However, it would be better if the normal range was calculated from control subjects matched by age, sex, body height and body weight. It may be possible that the departure map technique is useful in the diagnosis of combined valvular disease. For these points, further studies will be conducted in the near future. Previously it has been reported that potential departure mapping, which reveals abnormal ECG measurements exceeding normal ranges, was useful in assessing myocardial infarction and hypertrophic heart disease.6,7,24) In this study, the departure map technique was found to be useful for determining the severity of diastolic overload and classifying AR and MR.

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