Assessment of Right Ventricular Overload in Patients with Chronic Pulmonary Disease by 12-lead Electrocardiography, Vectorcardiography, and Body Surface Electrocardiographic Mapping

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Twenty-eight patients with chronic pulmonary diseases were examined with standard 12-lead electrocardiogram (ECG), vectorcardiogram (VCG), and body surface ECG mapping (MAP). The electrocardiographic findings were compared with results of 99mTc radionuclide right ventriculography or TI-201 myocardial scintigraphy. In a stepwise multiple regression analysis between the electrocardiographic parameters and right ventricular ejection fraction, only the amplitude of the negative P wave in V2 (r = 0.69), the posterior force of P loop in VCG (r = 0.71), and the size of −2SD area at 50 msec QRS potential departure map (r = 0.55) were selected as the parameters in standard ECG, VCG, and MAP, respectively. On the radionuclide ventriculography and myocardial scintigraphy, 14 patients were judged to have right ventricular overload. The criteria by VCG, and MAP had better sensitivity and specificity for right ventricle overload than those by 12-lead ECG. VCG criteria of Chou et al had sensitivity of 93% and specificity of 71%. MAP criteria, departure index of F3 or F4 ≤ −2, had sensitivity of 86% and specificity of 79%. The electrocardiographic findings by standard 12-lead ECG, VCG and body surface ECG mapping are useful parameters for the non-invasive detection of right ventricular overload in patients with chronic pulmonary diseases.

It is well known that right ventricular overload and right ventricular hypertrophy result from chronic pulmonary diseases and deeply influence the prognosis of the disease itself. Many investigators have studied electrocardiographic changes in chronic pulmonary diseases. In 1963, Expert Committee of World Health Organization defined “chronic cor pulmonale” as “hypertrophy of the right ventricle resulting from diseases affecting the function and/or the structure of the lung, except when these pulmonary alterations are the result of diseases that primarily affect the left side of the heart or of congenital heart disease.” In the committee report, the following changes were raised as criteria of right ventricular hypertrophy in pulmonary disease, “cor pulmonale” in the standard 12-lead electrocardiogram (ECG); 1) the presence of a qR pattern with delayed R wave in V1 (onset of intrinsicoic deflection more than 0.03 second), or in V3R or V4R, 2) in the absence of qR pattern, a combination of at least two of the following changes; alteration in the ratio R/S in the left chest leads with R/S less than 1 in V5, predominant S wave in standard lead I, presence of an incomplete right bundle branch block with QRS less than 0.12 second. Many 12-lead ECG criteria have been proposed for right ventricular hypertrophy (RVH) and especially for RVH in patients with chronic pulmonary diseases.

Key words:
ECG
VCG
Body surface mapping
Cor pulmonale
Right ventricular ejection fraction

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VCG criteria of RVH

1. Chou et al.  
QRS loop  
H | H | F  
| | |  
-20% | -20%  
(1 or more)  

2. Fujita et al.  
QRS loop  
H | R | P  
L | S  
P/A ≥ 2.8  
R/L ≥ 0.6  
P/L ≥ 1.8  
Ap/Pp ≥ 1.8  
A | P  
(1,2: RVH suspected) (3,4: RVH)  

3. Pp ≥ 0.07 mV

Fig. 1. Vectorcardiographic criteria of Chou et al, Fujita et al, and us for right ventricular overload.

We have reported pulmonary disease. However, most of these criteria were based on autopsy findings, and seemed too strict for the early detection of right ventricular overload in patients with chronic pulmonary disease.

On the other hand, vectorcardiogram (VCG) were developed as a method to analyze the changes of electrical force in all direction equivalently. Some investigators demonstrated the usefulness of vectorcardiogram in the early detection of right ventricular overloading in patients with chronic pulmonary diseases. Body surface ECG mapping (MAP) is increasingly used for the clinical situations also in lung diseases. Using many lead points all over the thorax, we can detect electrical changes on the upper or lower anterior chest and on the back which were not obtained by the standard 12-lead ECG.

In this study, we thoroughly studied the electrocardiographic changes by standard 12-lead ECG, VCG, and body surface ECG maps. We then investigated the relationships of these ECG findings and the right ventricular overload assessed noninvasively by the radionuclide right ventriculography and myocardial scintigraphy.

**METHODS**

**Subjects**

In the Yamagata University Hospital, 90 patients with chronic pulmonary diseases were examined standard 12-lead ECG, VCG, and body surface ECG mapping. From these 90 patients, 28 patients who performed 99mTc radionuclide right ventriculography or T1-201 myocardial scintigraphy were selected for the study population. The 28 patients were 23 men and 5 women, 13 patients with chronic pulmonary emphysema, 4 with bronchial asthma, 4 with chronic bronchitis, 6 with fibrotic lung disease, 1 with old pulmonary tuberculosis.

**Standard 12-lead ECG and VCG**

Standard 12-lead ECG and VCG by Frank lead system were recorded and analyzed by use of a microcomputer-assisted ECG analysis system JOEL 980B (Nippon Denshi, Japan).

In the standard 12-lead ECG, we measured amplitude of R in V1, S in V1, R/S in V1, R in V5, R in V6, S in V5, S in V6, R/S in V5, R/S in V6, the sum of R in V1 and S in V5, (R/S in V1)/(R/S in V5), R in aVR, ventricular activation time in V1, mean axis of QRS, amplitude of P in II, P in III, P in aVF, positive wave of P in V1 (PpV1), negative wave of P in V1 (PnV1), positive wave of P in V2 (PpV2), and negative wave of P in V2 (PnV2).

We also examined the criteria of Sokolow and Lyon, WHO, Roman et al, Sasamoto, and pulmonary P5. The criteria of Sokolow and Lyon were: R in V1 ≥ 0.7 mV, S in V1 < 0.2 mV, S in V5 or V6 ≥ 0.7 mV, R in V1 + S in V5 or V6 > 1.05 mV (in individuals over 5 years), R in V5 or V6 < 0.5 mV, R/S in V5 or V6 < 1.0, R in aVR ≥ 0.5 mV, (R/S in V5)/(R/S in V1) ≤ 0.4, R/S in V1 > 1.0 (> 5.0 in individuals under the age of 5), delayed onset of the intrinsicsoid deflection 0.04 to 0.07 second in V1 and/or V2, depression of the ST segment and inversion of the T waves in V1, less often V2 and V3 when R ≥ 0.5 mV, or in aVL or aVF when R ≥ 0.5 mV, or right axis deviation of mean QRS axis > +110 degree. The criteria of WHO were; 1) the presence of a qR pattern with delayed R wave in V1 (onset of intrinsicsoid deflection more than 0.03 second), or in V3R or V4R, 2) the absence of qR pattern, a combination of at least two of the following changes; alteration in the ratio R/S in the left chest leads with R/S less than 1 in V5, predominant S wave in standard
body surface ECG mapping

Fig. 2. Electrode site on the body surface. Eighty-seven lead points were arranged lattice like (13 × 7 matrix), except for four lead points in both midaxillary regions, and covered the entire thoracic surface. Columns A, E, and I were positioned in the right midaxillary, midsternal, and left midaxillary lines, respectively. Columns B-D and F-H were evenly spaced between columns A-E and E-I, respectively. Column J was located so as to make the distance between columns I and J equal to that between H and I. Column M was located similarly. Columns K and L were evenly spaced between columns J and M. Lead points E6 and E4 were located on the second and fifth intercostal space, respectively. Row 5 was located equidistant between rows 6 and 4. Rows 7 and 3–1 were located so as to make the distances between adjacent rows equal. The location of leads V1 to V6 were also indicated by dots.

lead I, presence of an incomplete right bundle branch block with QRS less than 0.12 second. The criteria of Roman et al were; right axis deviation > +110 degree, R/S in V1 > 1.0, or R/S in V6 ≤ 1.0. The criteria of Sasamoto et al. were right axis deviation > +100 degree, or R/S in V5 or V6 ≤ 1 when S in V5 or V6 ≥ 0.7 mV. Pulmonary P was judged to be present when P in II, III or aVF ≥ 0.25 mV.

In the vectorcardiogram, we measured the posterior force (P), anterior force (A), rightward force (R), leftward force (L) of the QRS loop, P/A, R/L, P/L, the ratio of the sum of the area of the right posterior, right anterior, and left anterior quadrants to the area of the total QRS loop in the horizontal plane, the ratio of the right posterior quadrant to the total QRS loop in the horizontal plane, posterior force (Pp), anterior force (Ap), and inferior force (Ip) of

Body surface ECG mapping

Map recording

Body surface ECG mapping was performed with a body surface potential mapping system, HPM-5100 unit (Chunichi Denshi Co., Nagoya, Japan).8,26 Eighty-seven ECG leads were placed over the torso, 59 leads on the anterior chest and 28 leads on the back (Fig. 2). ECG data was sampled simultaneously with the Wilson's central terminal as reference, at a rate of 1000 samples/sec. Standard 12-lead ECGs and the Frank X, Y, and Z lead ECGs were also sampled simultaneously. The flat portion of the PQ segment was chosen for the baseline. Data was recorded on a magnetic cassette tape in a digital format. This system had a resolution of 0.01 mV, in a dynamic range of ±5 mV. The data sampling was done at the resting expiratory level in the supine position.

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Data analysis

The ECG signals were processed off-line on a minicomputer VAX 11/750 (DEC) using the program for departure map analysis developed in our institution. The onset and the offset of the QRS were determined from superimposed Frank X, Y, Z leads and the spatial magnitude. For each subject, the potential at 10, 20, 30, 40, 50, and 60 msec after the onset of QRS and the timeintegral value from the Q onset to S offset (AQRS) were calculated at each lead (Fig. 3). For each value, mean and standard deviation (SD) of the normal control were determined from the 40 normal volunteers. Departure index (DI) was calculated for each potential or timeintegral value (x) of each lead by the equation:

\[ \text{departure index (DI)} = \frac{x - \text{mean}}{\text{SD}} \]

- x: measured potential or timeintegral of a patient
- mean: mean of the 40 normal controls
- SD: standard deviation of the 40 normal controls

Body surface distributions of DI were displayed as the potential departure map at 10, 20, 30, 40, 50, and 60 msec, and AQRS departure map. On the departure maps, the area of abnormal increase or decrease (DI > 2 or DI < -2) was designated the +2SD area or -2SD area. The size of these area was measured assuming the distance of leads points on the body surface as being 5 cm apart.

On each map, the rectangular area represents the torso surface, with the left half reflecting the anterior chest and the right half the back. Thus, both the right and left edges represent the right midaxillary line. Each contour line connects points of equal potential, timeintegral value, or DI, and the sites of the maximum and the minimum are indicated by + and -. On the iso-potential maps and QRS isointegral maps, the dotted area indicated the positive potential or timeintegral value. On the departure maps, the dotted area indicated the +2SD area, and the hatched area indicated the -2SD area.

We also measured the size of +2SD area, -2SD area, maximal departure index, and minimal departure index in 10, 20, 30, 40, 50 and 60 msec from the onset of QRS, and AQRS.

Radionuclide right ventriculography

The radionuclide right ventriculogram was obtained at rest in the supine position. A 20 mCi bolus of 99 m-technetium human serum albumin with saline solution was flushed into the right antecubital vein. Data was collected using an Ohio Nuclear Sigma 410S scintillator camera.
Y.S. 

CPE

I

V1

II

V2

III

V3

aVR

V4

aVL

V5

aVF

V6

Fig. 5. Standard 12-lead ECG and QRS potential and AQRS departure maps from a patient with chronic pulmonary emphysema.

interfaced to DEC Gamma 11 processing system, PDP 11/34. We performed first pass studies in a 30-degree right anterior oblique view using a low energy and high-resolution 30 degree slant-hole collimator. The region of interest (ROI) of the right ventricle was set manually viewing the sequential images. The background ROI was set on the left lung field outside of the right ventricular apex. Right ventricular ejection fraction (RVEF) was calculated by the background-corrected time activity curve from the right ventricular ROI. RVEF ≤ 40% were considered abnormal.31

Myocardial scintigraphy

Thallium-201 myocardial scintigraphy was performed at rest. A bolus of 2 mCi TI-201 was injected from the antecubital vein. Ten minutes after the administration of TI-201, scintigraphic imaging was done in the 30 degree right anterior oblique, anterior, 45 degree left anterior oblique, and left lateral projections. All images were recorded until a preset count of 1000 counts/cm² data density could be achieved. An Ohio Nuclear Sigma 410S gamma imager equipped with a slant-hole collimator and a 20% window centered on the 80 keV X-ray peak was used for data recording.19 All images were recorded on X-ray film for visual interpretation by two or more experienced observers without knowledge of clinical history or the results of other tests. The visualization of the right ventricular free wall with right ventricular enlargement was considered as a sign for overloading.

Statistical analysis

In 17 patients who underwent radionuclide right ventriculography, stepwise multiple regression analysis between the RVEF and parameters in the standard 12-lead ECG, RVEF and those in VCG, and RVEF and those in MAP were performed by use of the statistical analysis program SPSSX (Statistical Package for the Social Science-X).32

Next, in the total 28 patients, we examined the sensitivity, specificity, and overall predictive accuracy of each standard 12-lead ECG, VCG and MAP criteria for right ventricular overload.

sensitivity = true positive/(true positive + false negative)
specificity = true negative/(true negative + false positive)  
overall predictive accuracy = (true positive + true negative)/total population
Right ventricular overload was judged to be present when RVEF ≤ 40% or RV free wall was visualized on myocardial scintigraphy.

RESULTS
Findings in 12-lead ECG, VCG and MAP in patients with RV overload

On the radionuclide ventriculography and myocardial scintigraphy, 14 patients out of the 28 patients were judged to have right ventricular overload.

Figure 4 represents standard 12-lead ECG, VCG, QRS potential and AQRS departure maps from a patient with chronic bronchitis. He had RVEF of 30.4%, and was judged to have right ventricular overload. On 12-lead ECG, right axis deviation of mean QRS axis (+104 degree), increase of R in V1, deep S in V4 and V5, increase of positive wave and negative wave in V1 and V2 were observed. On VCG, rightward shift of QRS loop in the mid to late phase was noted. On the body surface QRS departure maps, abnormal increase of the potential, indicated by +2SD area (dotted area) were observed on the right anterior chest and on the lower right back at 40, 50 and 60 msec. Abnormal decrease of potential, indicated by -2SD area (hatched area) was seen on the left precordium at 40, 50 and 60 msec. These changes were also found in the AQRS departure map, abnormal increase on the right anterior chest and lower back, abnormal decrease on the left precordium.

Figure 5 represents another case of right ventricular overload with chronic pulmonary emphysema. RVEF was 34.3%. On the 12-lead ECG, decrease of R in V1 to V4, deep S in V4 and V5, and negative P wave in V1 and V2 were observed. On the departure maps, abnormal decrease of potential on the middle to lower anterior chest, at 40, 50 and 60 msec, especially on left precordial lead F3 at 40 msec were noted. Abnormal positive area was found on the upper back on 50 and 60 msec. AQRS departure area looked like a summary of these changes.

In patients with RV overload, increase of R in V1, decrease of R and increase of S in V5 and V6, and increase of negative P wave in V1 and V2 were frequently noted on the standard 12-lead ECG. On VCG, increase of the rightward anterior or posterior force and decrease of the leftward force in the QRS loop, and increase of the posterior force of P-loop were frequent in patients with RV overload.

On the departure maps, characteristic changes in patients with right ventricular overload were; abnormal positive area on the right anterior chest or on the back at the late phase of QRS and AQRS, abnormal negative area around the left

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TABLE 1 SENSITIVITY, SPECIFICITY AND OVERALL PREDICTIVE ACCURACY OF THE ELECTROCARDIOGRAPHIC CRITERIA FOR RIGHT VENTRICULAR OVERLOAD IN PATIENTS WITH CHRONIC PULMONARY DISEASES

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
<th>Overall predictive accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ECG</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sokolow-Lyon (V1 QRS)</td>
<td>79</td>
<td>57</td>
<td>68</td>
</tr>
<tr>
<td>(V5, V6 QRS)</td>
<td>29</td>
<td>79</td>
<td>53</td>
</tr>
<tr>
<td>Roman</td>
<td>57</td>
<td>86</td>
<td>71</td>
</tr>
<tr>
<td>WHO</td>
<td>29</td>
<td>79</td>
<td>53</td>
</tr>
<tr>
<td>Pulmonary P*</td>
<td>31</td>
<td>100</td>
<td>66</td>
</tr>
<tr>
<td>PnV2 ≥ 0.05 mV*</td>
<td>62</td>
<td>93</td>
<td>64</td>
</tr>
<tr>
<td><strong>VCG</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chou</td>
<td>93</td>
<td>71</td>
<td>82</td>
</tr>
<tr>
<td>Fujita</td>
<td>86</td>
<td>64</td>
<td>75</td>
</tr>
<tr>
<td>Pp &gt; 0.07 mV*</td>
<td>62</td>
<td>79</td>
<td>70</td>
</tr>
<tr>
<td><strong>MAP</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+2SD area of AQRS</td>
<td>50</td>
<td>64</td>
<td>57</td>
</tr>
<tr>
<td>+2SD area of 50 or 60 msec</td>
<td>71</td>
<td>64</td>
<td>68</td>
</tr>
<tr>
<td>DI of F3, F4 &lt; -2 at 40 msec</td>
<td>86</td>
<td>79</td>
<td>82</td>
</tr>
<tr>
<td>-2SD area ≥ 200 cm² at 50 msec</td>
<td>43</td>
<td>93</td>
<td>68</td>
</tr>
</tbody>
</table>

*: excluding one patient with atrial fibrillation.

precordium at mid to late phase of QRS. Departure index of lead F3 or F4 at 40 msec were frequently negative than −2. From the results, we constructed criteria in departure map as following:

1. the size of +2SD area of AQRS ≥ 50 cm², on the right anterior chest or on the back,
2. the size of +2SD area of potential at 50 or 60 msec from the onset of QRS ≥ 50 cm², on the right anterior chest or on the back,
3. departure index of lead F3 or F4 of the potential at 40 msec from the onset of QRS ≤ −2.

Relationship between the 12-lead ECG, VCG and MAP parameters and RVEF

Figure 6 represented the results of the multiple regression analysis between the electrocardiographic parameters and RVEF. Among the parameters on the standard 12-lead ECG, only PnV2 (the amplitude of the negative P wave in V2) correlated significantly with RVEF (r = 0.69). No other parameters added to increase the correlation coefficients with RVEF. Among the parameters on VCG, only Pp (the posterior force of P loop) correlated significantly (r = 0.71). Among the parameters on departure maps, only the size of −2SD area of the QRS potential at 50 msec from the onset of QRS correlated significantly with RVEF (r = 0.55).

From these results, we set the following criteria for RV overload and added to the examination of the sensitivity, specificity and overall predictive accuracy:

1. PnV2 ≥ 0.05 mV,
2. Pp ≥ 0.07 mV,
3. the size of −2SD area of the potential at 50 msec from the onset of QRS ≥ 200 cm².

Diagnostic performance of 12-lead ECG, VCG and MAP criteria for RV overload

Table I summarized the sensitivity, specificity, and overall predictive accuracy of each criteria in standard 12-lead ECG, VCG, and QRS departure map. Among the standard 12-lead ECG, the criteria of Sokolow and Lyon had highest sensitivity but low specificity. Among the parameters in the Sokolow and Lyon criteria, those about the change of the QRS amplitude in V5 or V6 had better sensitivity than those about the QRS
amplitude change in V1. Pulmonary P had high specificity but low sensitivity. PnV2 criteria had high specificity and relatively higher sensitivity.

VCG criteria of Chou et al and Fujita et al had better sensitivity and specificity than those in 12-lead ECG. Also, the Pp criteria showed better diagnostic performance. Among the Map criteria, departure index of F3, F4 had best diagnostic performance. In general, VCG and Map had better sensitivity and specificity than 12-lead ECG.

DISCUSSION

There have been many studies with electrocardiographic changes in chronic lung diseases by standard 12-lead ECG1–12 VCG17–21 and body surface mapping28–30. The findings of 12-lead ECG in patients with RV hypertrophy or RV overload were summarized as followings: (1) increase of R wave and decrease of S wave, sometimes associated with ventricular activation time prolongation and ST-T changes, in the right precordial leads, as V1, V3R, etc, (2) decrease of R wave and increase of S wave in the left precardial leads such as V5 and V6, (3) rightward shift of the mean QRS axis. The changes in vectorcardiogram also summarized into the rightward shift of the QRS loop in the mid to late phase, increase of the rightward anterior or posterior force and decrease of the leftward force. These changes in VCG are concordant to the findings in 12-lead ECG, and considered to reflect the electrical changes caused by RV overload.

Our study revealed that (1) PnV2 (posterior wave of P in V2) and Pp (posterior force of the P loop on VCG) correlated well with RVEF, (2) the size of −2SD area at 50 msec QRS potential departure map also correlated with RVEF, (3) Among the criteria about QRS for RV overload, criteria on VCG and MAP had better sensitivity and specificity than those on 12-lead ECG, (4) QRS changes in the left precardial leads were more sensitive for RV overload than QRS changes in the right precardial leads. We considered that for the early detection of RV overload in patients with chronic pulmonary disease, re-evaluation of the cut-off point of these criteria is needed in a larger study population.

The increase of the posterior force of P was also observed in chronic lung disease12,33. Smit et al12 reported that negative P amplitude in V1 were significantly lower in patients survived <5 years than in patients survived ≥5 years. These P wave changes were not directly correlated with P pulmonale, the increase of inferior force33. The mechanisms of the increase of posterior force of P were not revealed in this study, but it may related to the dilatation of the right atrium.

Smit et al12 studied the ECG changes for long term prognosis in 128 patients with chronic obstructive pulmonary disease. In their study, P amplitude in II and S amplitude in V6 were the predictor of five-year survival. Follow-up study like that must be done in the future.

For the early detection of right ventricular overload in patients with chronic pulmonary disease, ECG changes during the acute worsening or in the stress test as exercise may be useful. Kilcoyne et al8 studied the dynamic ECG changes during the acute worsening phase of the chronic obstructive pulmonary disease. They demonstrated that when arterial O2 saturation fell below 85% one or more of the following fluctuations were seen; (1) a rightward shift of the mean QRS axis of 30 degree or more, (2) T-wave abnormalities in right precardial leads, (3) ST depressions in leads II, III, and aVF, and (4) transitory right bundle branch block. Also, Wilson et al20 demonstrated that rightward shift of the QRS loop in VCG were closely correlated with mean pulmonary arterial pressure in exercise test.

The electrocardiographic findings by standard 12-lead ECG, VCG and body surface ECG mapping are useful parameters for the non-invasive detection of right ventricular overload in patients with chronic pulmonary diseases.

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