

Quantitative Analysis of Exercise Electrocardiograms and Left Ventricular Angiocardigrams in Patients with Abnormal QRS Complexes at Rest

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SUMMARY The ECG changes during exercise are described in 71 patients with a previous anteroseptal or anterolateral infarction (ANT-MI) and in 73 patients with an old posterior or inferior wall infarction (INF-MI). Left ventricular angiograms in 95 patients yielded a good correlation between areas of dyssynergy and the QRS pattern at rest. The ST changes in patients with coronary artery disease and a normal ECG at rest, and in normal subjects, were oriented toward the right, posteriorly and superiorly. In patients with INF-MI

ABNORMAL QRS PATTERNS in the electrocardiogram (ECG) at rest are a strong indication of anatomical or functional abnormalities of the heart,^{1, 2} and it is generally accepted that even slight ST-T depressions in the resting ECG may be associated with coronary artery disease (CAD).³ Recent studies indicate that the exercise ECG can give additional information on the presence of coronary artery obstruction⁴⁻⁶ and on the prognosis of patients with abnormal ECGs at rest.⁷ However, the interpretation of the exercise ECG in these patients is difficult since it is not known how the abnormal QRS complex and ST segment at rest influence the ST changes during exercise.

In this paper a systematic analysis of the ECG changes during exercise in patients who had electrocardiographic evidence of an old myocardial infarction is reported. Different types of ST changes could be anticipated. ST depressions in left precordial leads have been observed in patients with severe CAD demonstrated by selective coronary arteriography.⁴⁻⁶ ST elevations during exercise have been reported in the first two months after an anterior wall infarction⁸ and in patients with a ventricular aneurysm.⁹⁻¹¹ Since the QRS pattern at rest is related to abnormalities in the left ventricular contraction pattern² the spatial orientation of the exercise-induced ST changes was subjected to correlation analysis with the presence of dyskinetic areas in the wall of the left ventricle documented by cine ventriculography. Criteria based on the observations in this study are proposed for interpretation of the ECG changes during exercise in patients with an abnormal ECG at rest.

Patient Selection and Methods

Orthogonal electrocardiograms (Frank lead system) were analyzed during exercise from 162 male patients with an abnormal ECG at rest. Seventy-one patients had a QRS pattern compatible with an old anteroseptal or antero-

and inferior wall dyssynergy, the ST changes were more inferiorly oriented. Anteriorly-oriented ST changes were associated with anterior wall or apical dyssynergy and with ANT-MI. Thus the spatial direction of the ST changes during exercise is related to three independent factors: those factors which cause the ST changes in normal subjects, the degree of myocardial ischemia in that particular case, and the extent of dyssynergic areas in the wall of the left ventricle.

lateral infarction, 73 had Q waves which indicated an old inferior or posterior wall infarction, and 18 patients had an abnormal ST-T segment only. The ECGs were compared with a reference group of 86 normal subjects selected from a population survey in Rotterdam and with records from 41 patients with a normal ECG at rest and CAD documented by selective coronary arteriography.¹²

In 54 out of the 162 patients with an abnormal ECG at rest and in the 41 patients with a normal ECG, a left ventricular angiogram was obtained during cardiac catheterization. These 95 patients all had obstructions of 70% or more in the selective coronary arteriogram. Left ventricular wall motion was analyzed in the right anterior oblique position (RAO). Areas with an abnormal contraction pattern were described qualitatively as hypokinetic when systolic movement was less than normal, akinetic when no inward movement was observed during systole or dyskinetic when a paradoxical systolic movement was seen.¹³ The expression, dyssynergy, was used as a general term for any of these abnormal patterns of systolic wall movement.

Patients were grouped according to location of dyssynergy: anterior wall, apical region, or the inferior wall.

All subjects underwent a graded exercise test on a bicycle ergometer with workload increments of 10 W/min or 30 W/3 min until near exhaustion, unless symptoms like angina pectoris or dyspnea occurred before this load.¹² The ECG was analyzed by digital computer every second or third minute during the test. The computer system, the selective averaging procedure, and the automatic waveform analysis have been described in detail.¹⁴ Eight time-normalized amplitudes were computed in the PQ segment, in the QRS complex, and in the ST interval.^{1, 12} Here the third PQ amplitude (P3) corresponds to the maximum spatial magnitude of the P wave, while the last ST amplitude (ST8) corresponds to the maximum spatial magnitude of the T wave.¹²

Results

ECG Pattern At Rest and During Exercise

The ECG measurements during exercise in normal sub-

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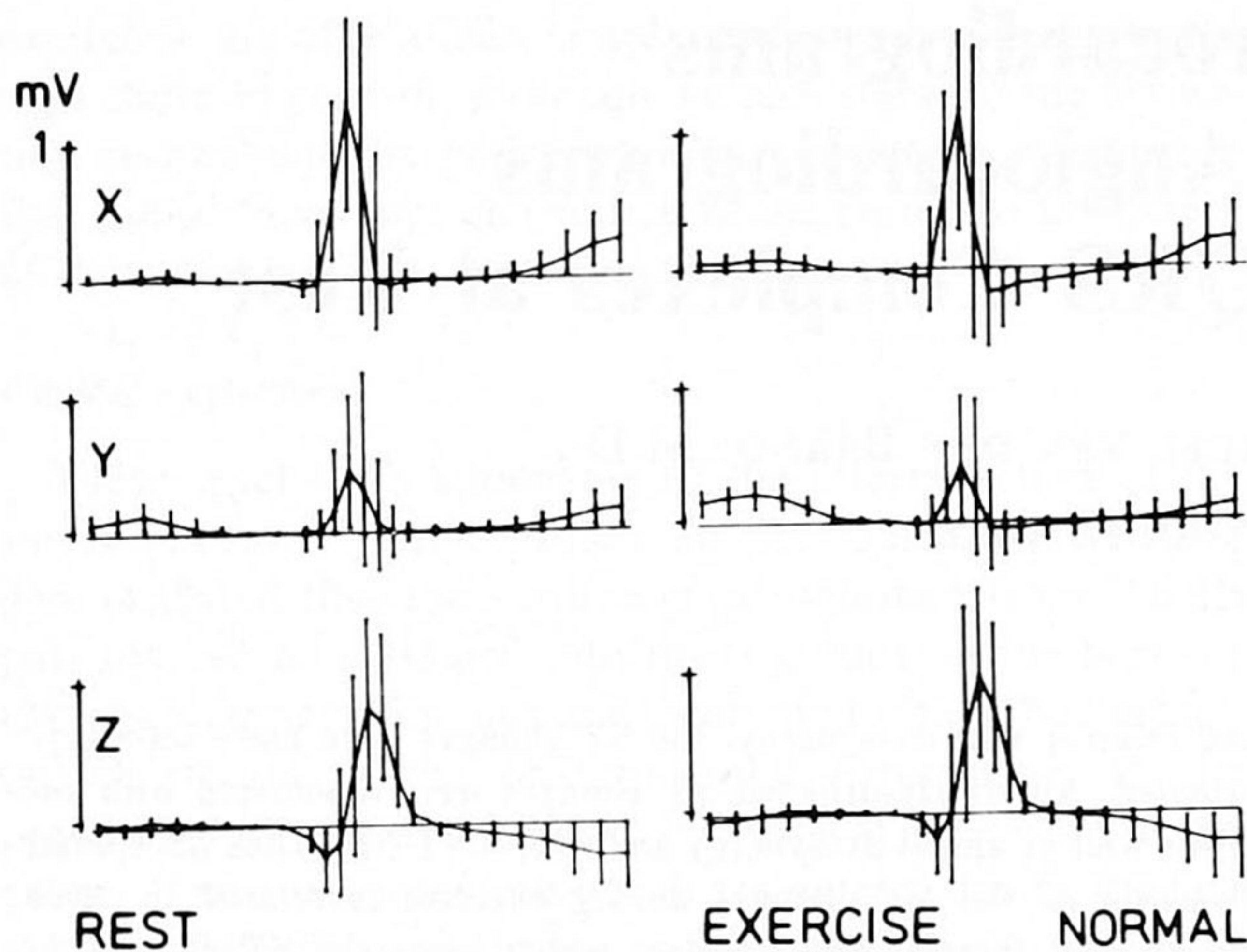


FIGURE 1. Means and 5 to 95% ranges of the time-normalized ECG amplitudes in 86 normal subjects. The bars indicate the 5-95% ranges of the measurements. The mean points at each measurement have been connected and simulate a combined waveform. The amplitude calibration is 1.0 mV. The left panel represents the records at rest, in a sitting position; on the right, the measurements at the highest workload are presented. Note the augmentation of the P waves during exercise, as well as a deepening of the S waves in leads X and Y followed by a ST junctional depression.

jects were similar to observations made earlier in a smaller series.¹² The P wave increased during exercise, the S wave deepened, and a depression of the J point with an ascending ST segment was observed in leads X and Y. The T waves in leads X and Y during exercise were lower than those at rest (fig. 1).

In the patients with a normal ECG at rest (CAD), similar changes were observed in the P wave and QRS complex. In addition, a horizontal ST segment depression occurred in leads X and Y. Also some posterior displacement was found in the ST segment in lead Z (fig. 2).

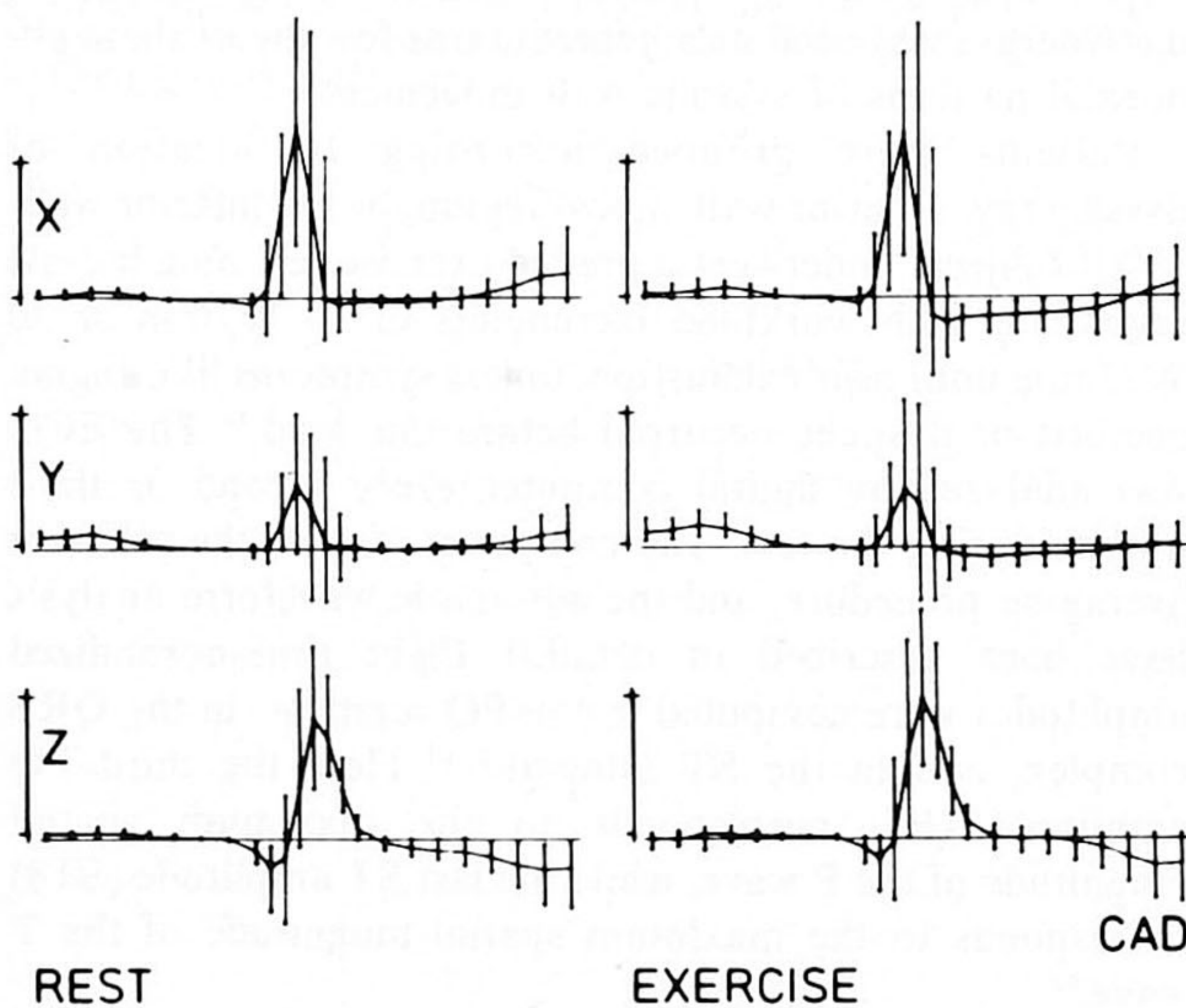


FIGURE 2. Means and 5 to 95% ranges of the time-normalized ECG amplitudes in 41 patients with coronary artery disease. Note that P wave and QRS changes are similar to those in normal subjects (fig. 1). There is a horizontal ST depression in lead X, and to a lesser degree, in lead Y.

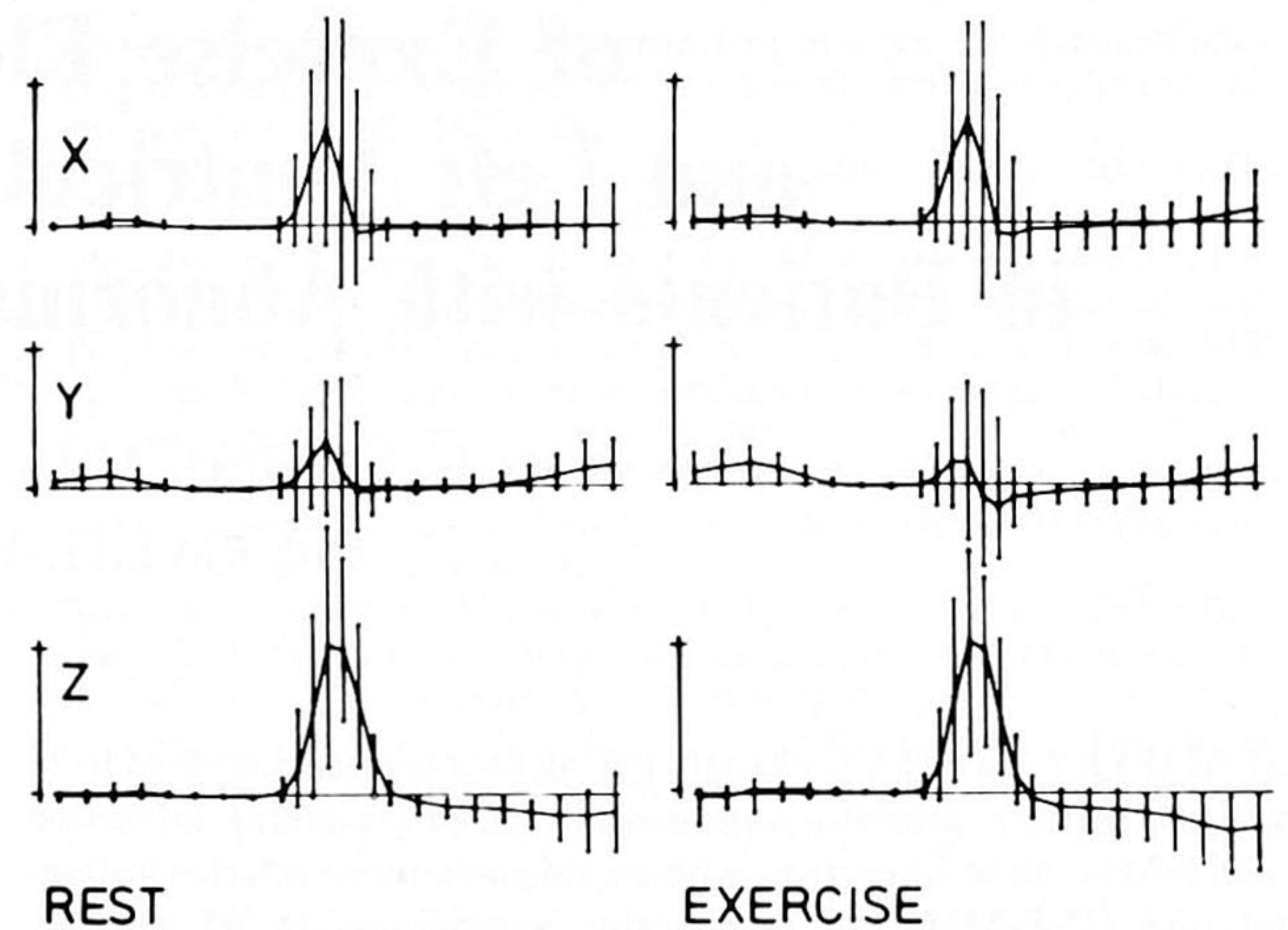


FIGURE 3. Time-normalized ECGs at rest and at the highest workload from 71 patients with an old anteroseptal or anterolateral infarction. Note the absence of anterior forces, no Q wave in lead Z, at rest. During exercise the P waves increased in all three leads, the S waves deepened in leads X and Y. ST depression was found in some cases in all leads, ST elevation appeared in some patients in leads X and Z.

Seventy-one patients had electrocardiographic evidence at rest of an old anteroseptal or anterolateral infarction (ANT-MI). The means and 90% ranges of the time-normalized P, QRS, and T waves of these cases have been presented in figure 3. The absence of a Q wave in lead Z is caused by the previous infarction. The ST segments at rest were close to normal, but in many patients the T wave in lead X was inverted at rest. During exercise, the T waves deepened in leads X and Y. The ST segment shifted predominantly toward the right, superiorly, anteriorly, which caused ST depression in all three leads. In some patients, however, a ST elevation appeared in lead X and to a lesser degree in Z.

In figure 4, the ECGs at rest and during maximum exercise have been plotted from 73 patients with an old inferior

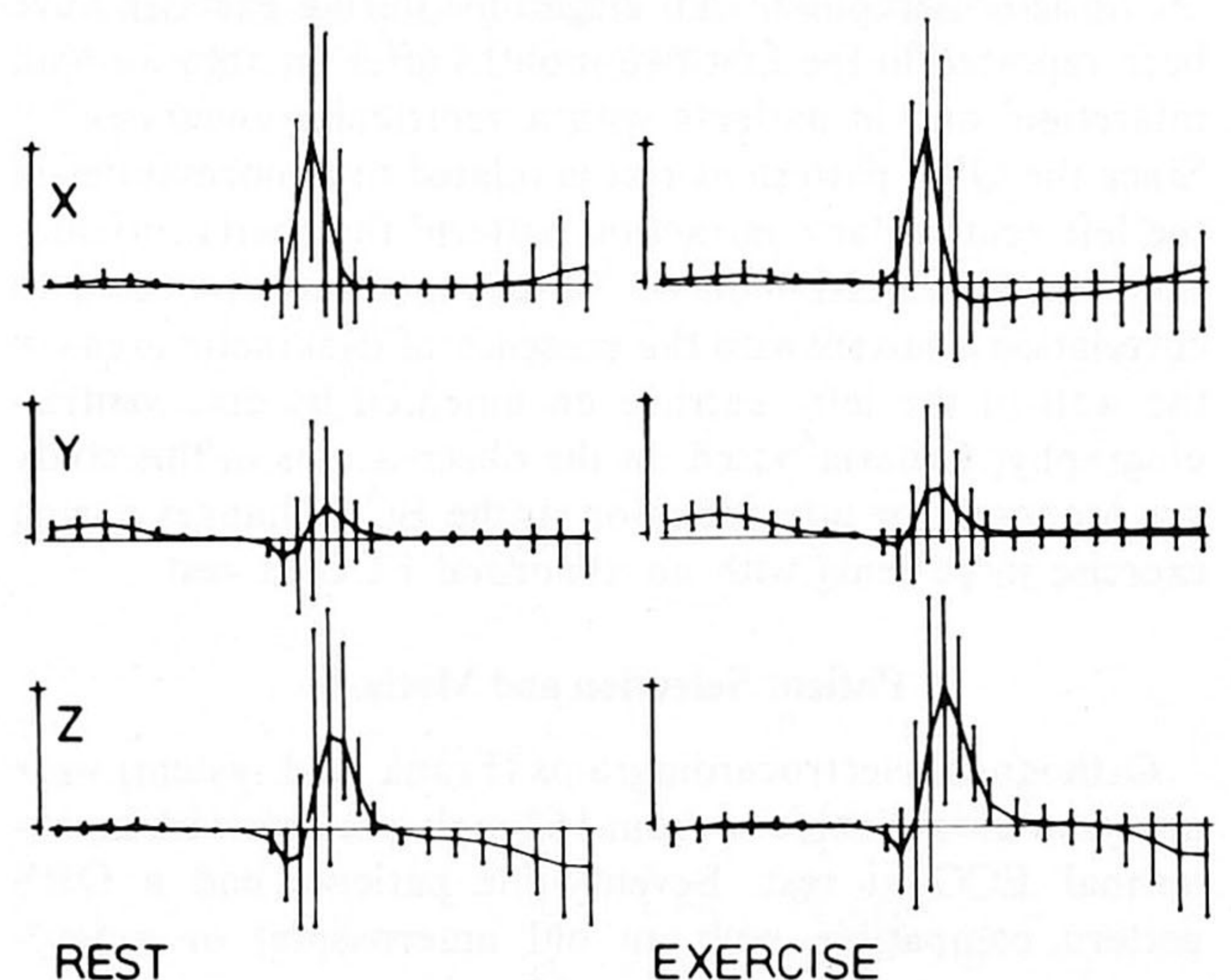


FIGURE 4. Time normalized ECG from 73 patients with an old inferior wall infarction. See legend to figure 3. Note the deep Q waves in leads Y and Z at rest. During exercise a marked ST depression appeared in lead X and a ST elevation in lead Z. Lead Y showed ST depression in some patients and ST elevation in others.

TABLE 1. ST Changes During Exercise in Relation to the QRS Complex

Lead	X	Y	Z
CAD	↓	↓	↑
ANT-MI	↓↑	↓	↓
INF-MI	↓	↑↓	↑

↓ = ST depression; ↑ = ST elevation; ↑ ↓ ST elevation in some and ST depression in other patients.
 Abbreviations: CAD = coronary artery disease; Ant-MI = anterolateral or anteroseptal myocardial infarction; INF-MI = inferior or posterior wall infarction.

or posterior wall infarction (INF-MI). Here the Q waves in leads Y and Z are deeper than normal. At rest slight ST depressions and negative T waves were observed in many patients in leads X and Y, while the ST pattern in lead Z was normal. During exercise the ST segment shifted toward the right and posteriorly, which caused further ST depression in lead X and ST elevation in lead Z, while in lead Y ST depression occurred in some patients, ST elevation in others. These results are summarized in table 1.

ECG Changes Related to the QRS Pattern

Comparison of the effects of exercise on the ECG in ANT-MI (fig. 3) and INF-MI (fig. 4) with the effect in normal subjects (fig. 1) and patients with a normal ECG at rest (fig. 2) is difficult because the initial resting ECGs are different. Therefore the difference between the measurement at rest and that during exercise were computed for each subject or patient. In order to separate the changes in magnitude of the ECG from the changes in spatial orientation, polarcoordinates were introduced (fig. 5).

No significant differences were observed in the orientation or magnitudes of either the mean P changes or the QRS changes in these four groups.

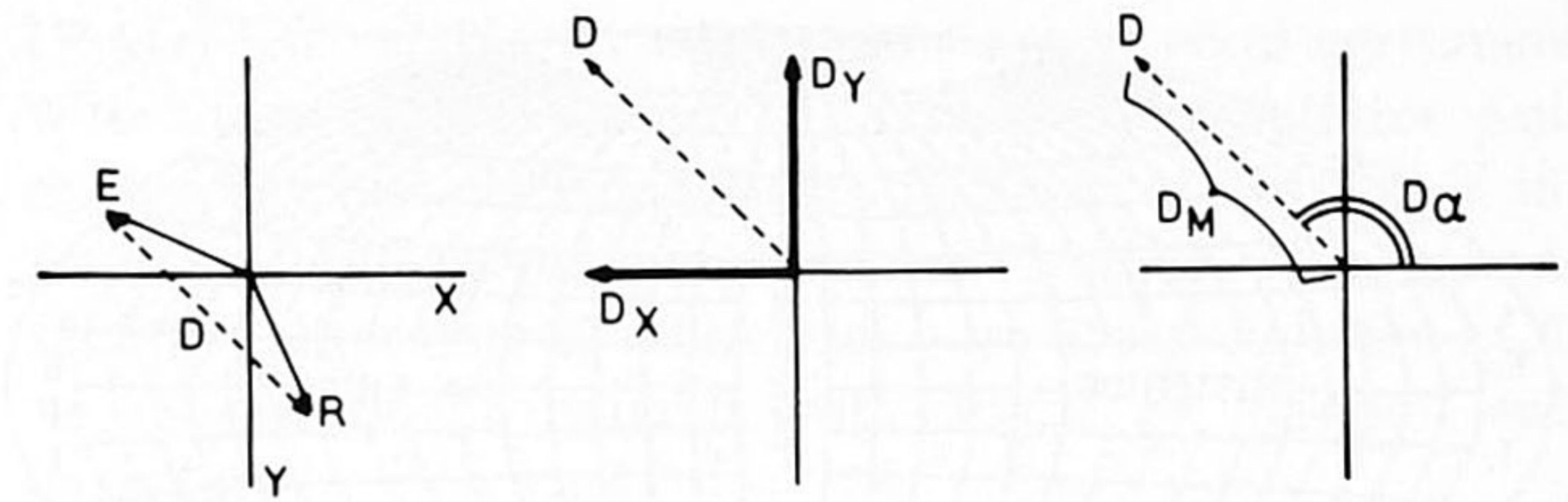


FIGURE 5. ECG changes during exercise. In the panel on the left side, R represents the projection in the frontal plane of a given ST vector at rest. This vector is oriented toward the left, inferiorly. During exercise the same vector is oriented toward the right, superiorly (E). The difference between R and E can be expressed as the vector D, which represents the change of the ST vector during exercise. In the middle the vector D is shown in the center of the coordinate system. D can be represented by its components along the coordinate axes D_x and D_y . Another representation is given in the panel on the right by the vector magnitude M and the angle α between D and the positive X axis. These polar coordinates (M, α) have the advantage that the magnitude and the orientation of the ECG changes can be analyzed separately.

In figure 6 the spatial orientation of the changes of the $\frac{3}{8}$ ST amplitudes (ST3) during exercise is plotted on the face of a globe. The different regions of the globe are defined in figure 7. These plots demonstrate clearly that these changes in the normal reference population and in patients with a normal ECG at rest form a cluster in the right, superior region of the globe. In patients with ANT-MI, the points are scattered more widely, but most are found in the left, anterior, superior region. Patients with INF-MI form a cluster which is more inferiorly and posteriorly located than in normal subjects.

The magnitudes of the ST3 changes during exercise are plotted against the changes in heart rate in figure 8. The normal range of these gradual changes is indicated by two

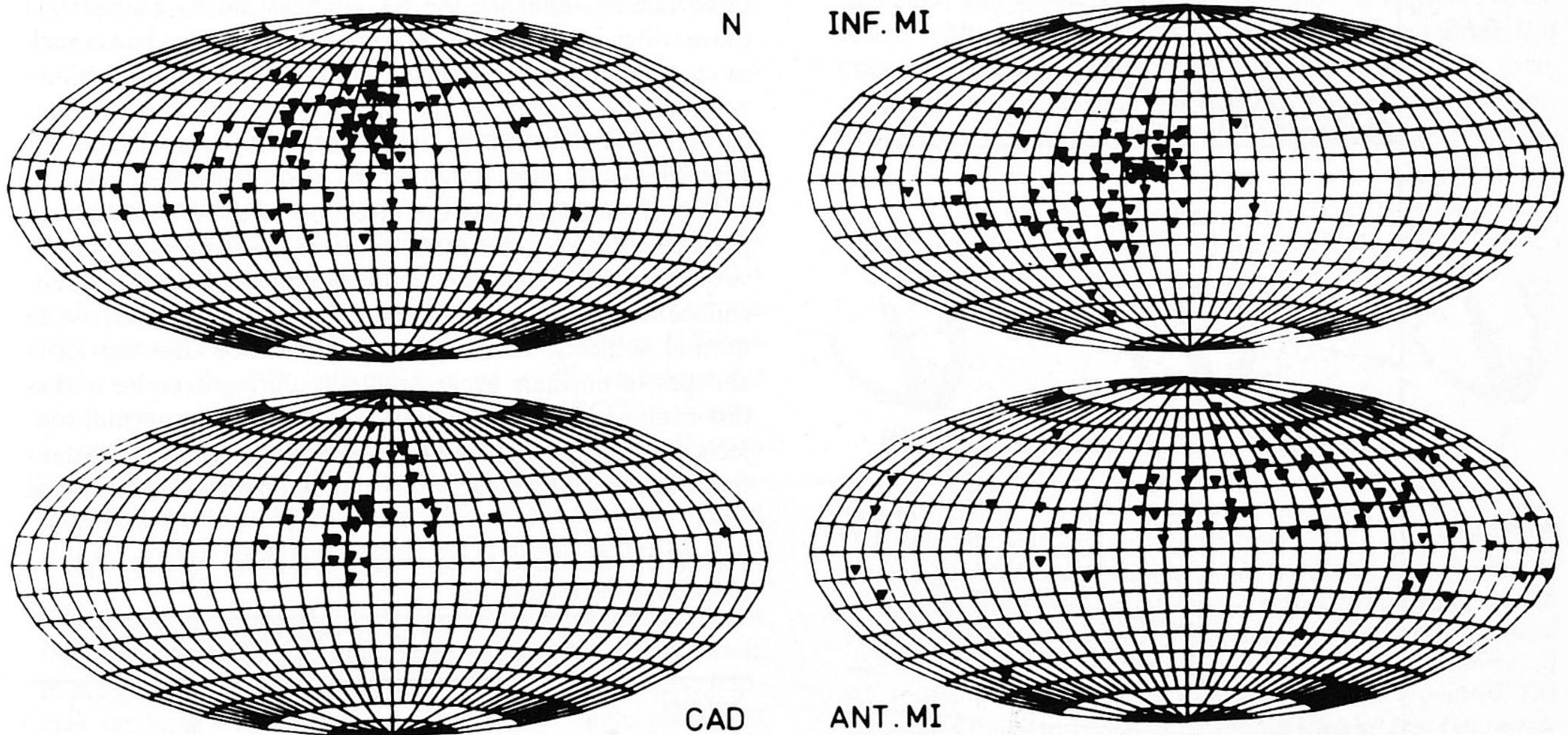


FIGURE 6. Spatial directions of the ST3 changes in 86 normal men (N), in 41 patients with a normal ECG at rest and obstructive coronary artery disease (CAD), in 73 patients with an old inferior wall infarction (INF-MI) and in 71 patients with an old anteroseptal or anterolateral infarction (ANT-MI). Note similar orientations of the Δ ST3 vectors in N and CAD. In ANT-MI the changes were more anteriorly oriented while more inferiorly oriented ST3 changes occurred in INF-MI.

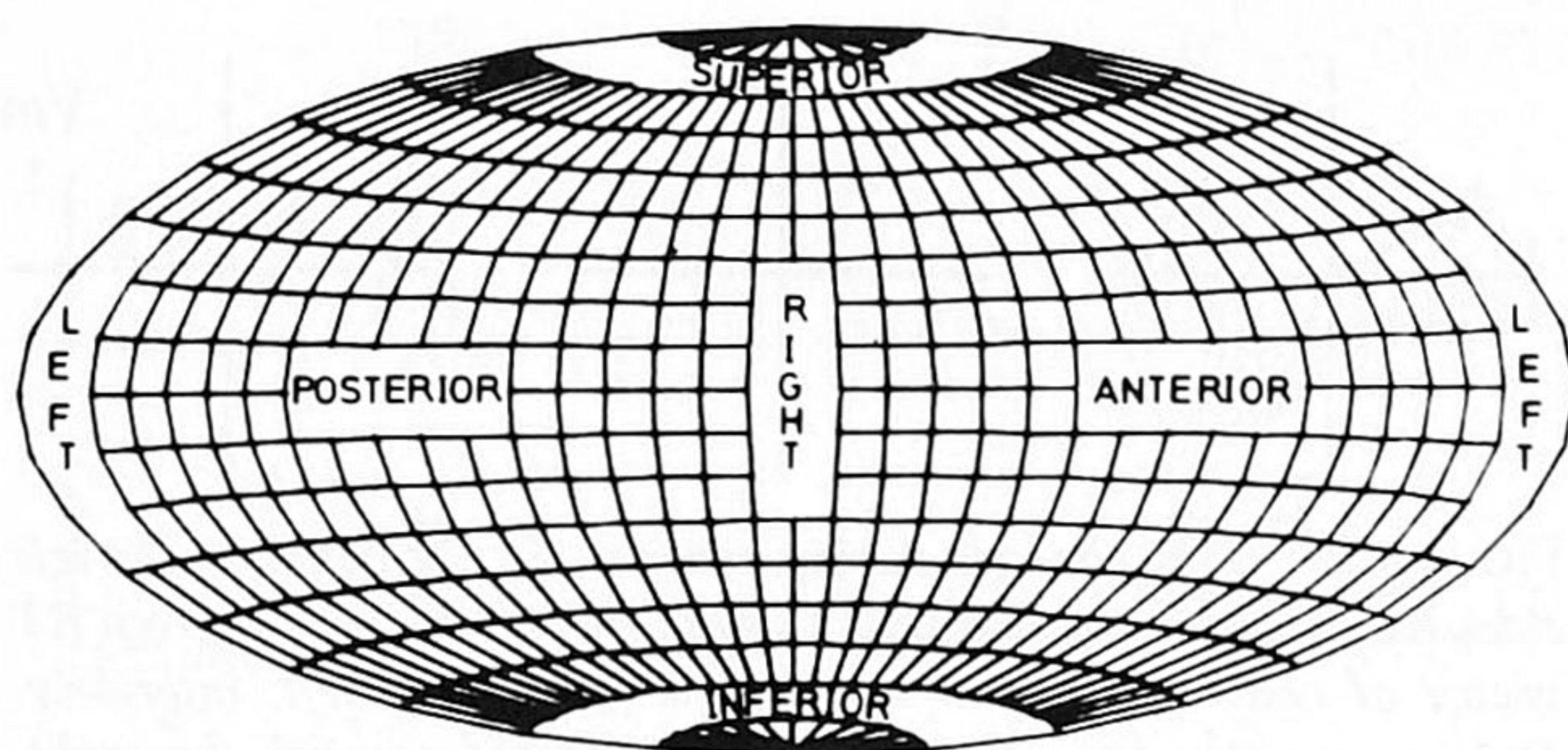


FIGURE 7. Orientation of the different regions on the global projections in figures 6 and 8.

straight lines. In 14 out of 41 patients with a normal ECG and in 21 out of 73 patients with INF-MI the changes were larger than in normal subjects at corresponding heart rates. Surprisingly the magnitudes of the changes in patients with ANT-MI were smaller. In only 11 out of 71 of these patients did the ST3 changes exceed the normal upper limit.

Left Ventricular Dyssynergy

Left ventricular angiograms in RAO positions were available and of sufficient quality in 95 subjects. As the groups were small, all three types of dyssynergy were analyzed together. Normal contraction patterns were observed in 43 patients, and dyssynergy of different degrees was found in 52 individuals. The relation between the contraction pattern and the ECG at rest is presented in table 2.

Forty-one patients out of 52 with dyssynergy had an abnormal QRS complex (79%) as well as eight out of 43 patients without dyssynergy (19%). Eleven patients had no

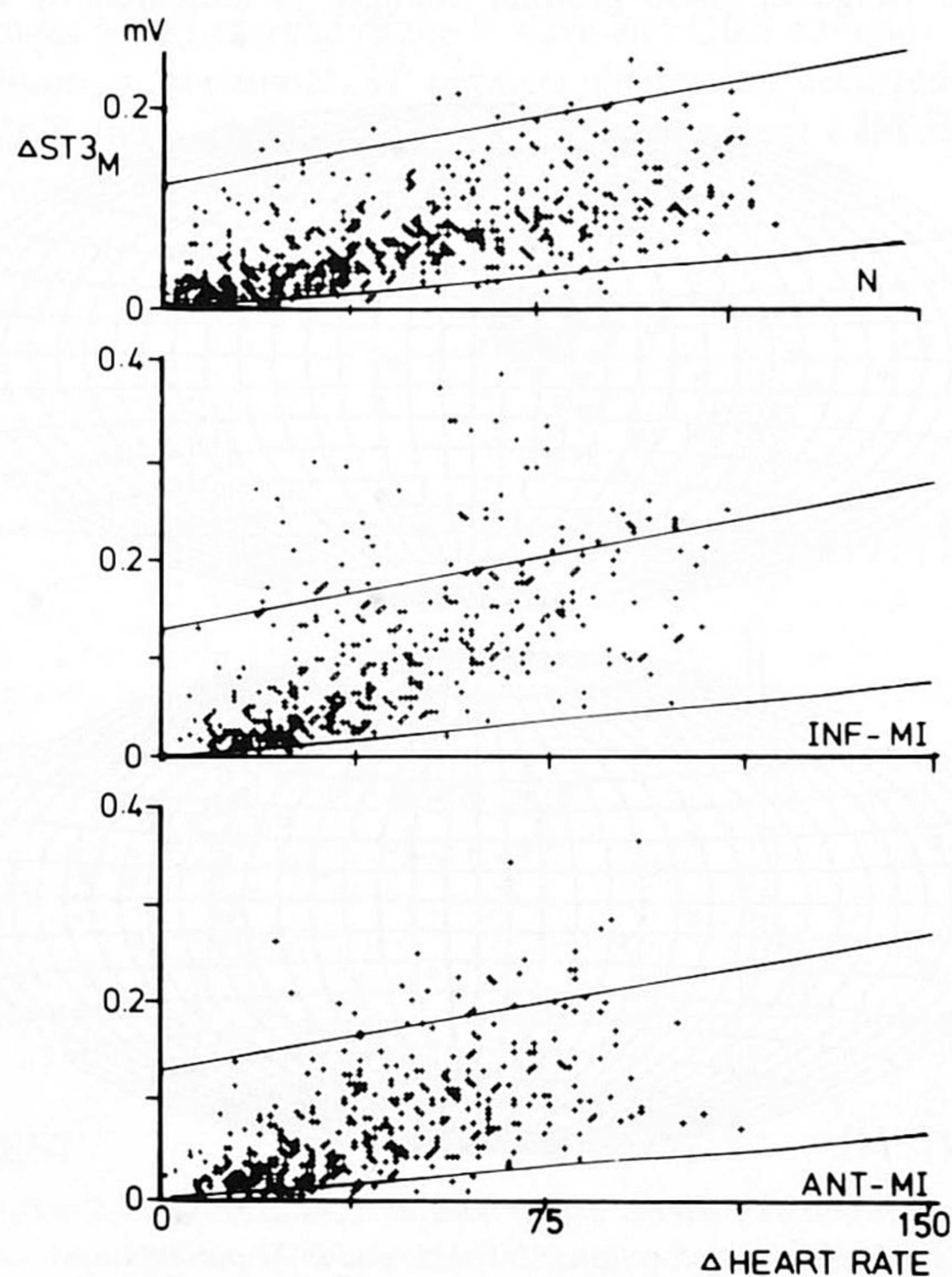


FIGURE 8. Magnitudes of the changes of the ST3 vectors against the heart rate changes during exercise. The lines indicate the boundaries of the measurements from the normal subjects.

TABLE 2. Relation between Left Ventricular Contraction Pattern and ECG at Rest

ECG	LV contraction pattern		Total
	Normal	Abnormal	
Normal	33	8	41
ST	2	3	5
MI	8	41	49
Total	43	52	95

Abbreviations: ST = repolarization disturbances but normal QRS; MI = pattern indicative of an old myocardial infarction.

electrocardiographic evidence of a transmural infarction, although they had an abnormal contraction pattern. However, all six patients with an aneurysm (dyskinesia) had an abnormal QRS complex. In table 3 the areas of left ventricular dyssynergy are correlated with the ECG pattern at rest. Anterior wall and apical dyssynergy appeared to be associated predominantly with anteroseptal or anterolateral infarction patterns in the ECG, while inferior dyssynergy was strongly related to inferior or posterior wall infarction patterns. These findings were in agreement with those reported recently by Miller et al.² and by Hilsenrath et al.¹⁴

Since a relationship exists between the QRS pattern at rest and the spatial orientation of the ST changes during exercise, the same relation could be expected between the ST changes and areas of left ventricular dyssynergy. In fact, in patients with inferior wall dyssynergy the ST changes were more inferiorly oriented than in those with a normal contraction pattern while anterior or apical dyssynergy was present in 14 out of 18 cases with anteriorly or leftward oriented ST3 changes (fig. 9).

Discussion

The results in this and prior studies indicate that at least three factors influence the ST changes during exercise: 1) those which cause the ECG changes in normal subjects such as changes in heart rate, hematocrit, and intracardiac blood volume; 2) changes of the action potential due to myocardial ischemia; and 3) areas with dyssynergy in the left ventricle which are related to the QRS pattern at rest.

It is remarkable that the direction of the ST changes in patients with a normal ECG at rest is the same as in normal subjects (fig. 6). This could indicate that some degree of subendocardial ischemia is present during strenuous exercise in normal subjects. However, the observation that the ECG changes in normals occur gradually during exercise makes this explanation very unlikely. The ST shift in normal subjects may better be explained by changes in the action potential shape at higher heart rates and by temporarily increased

TABLE 3. Localization of Left Ventricular Dyssynergy in Relation to the ECG at Rest

ECG	LV Dyssynergy			Inf
	Diffuse	Ant and/or apex	Inf + apex	
Normal		5	2	1
ST		1	1	1
ANT-MI	5	18	2	1
INF-MI		3	3	9
Total	5	27	8	12

Abbreviations: ant = anterior wall dyssynergy; apex = apical dyssynergy; inf = inferior dyssynergy; diffuse = poorly contracting ventricle in all regions.

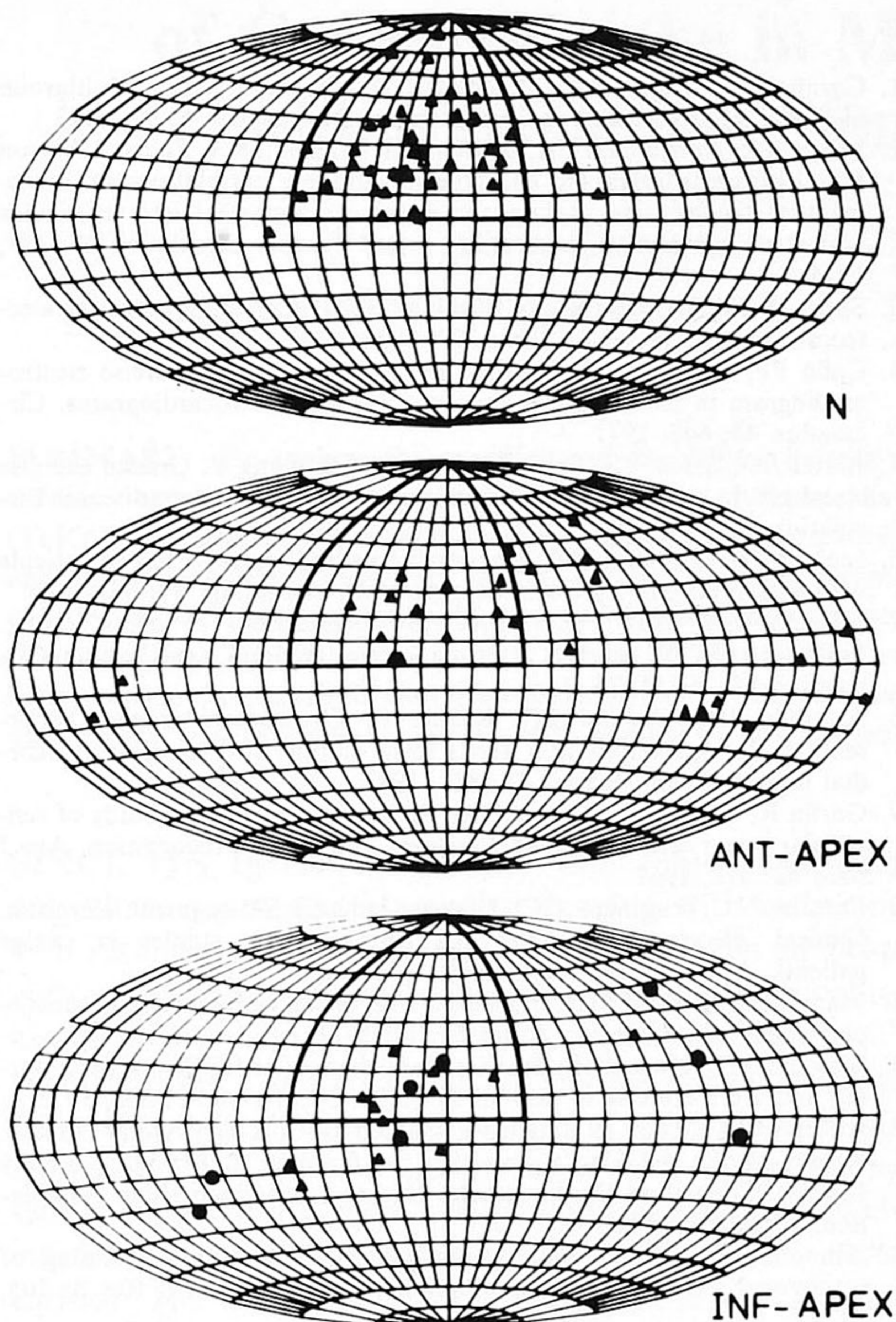


FIGURE 9. Orientation of the Δ ST3 vectors in 43 patients with a normal left ventricular contraction pattern (N), in 27 patients with anterior wall or apical dyssynergy or both, and in 20 patients with inferior wall or inferior wall and apical dyssynergy. The heavy lines mark the zone in which most measurements in N were found. The closed circles in the lower figure indicate the patients with both inferior wall and apical dyssynergy.

hematocrit and/or decreased left ventricular volume during exercise which both diminish the effect of the radially-oriented repolarization forces.¹² This in turn causes a shift of the ST vectors in the opposite direction to that of the T wave at rest; rightward, superiorly, and posteriorly. In patients with CAD, the increased oxygen demand during exercise will cause predominantly subendocardial ischemia.¹⁵ When the level of the PQ segment is used as the reference for amplitude measurements in the X lead ECG, subendocardial ischemia results in an ST shift from epicardium to endocardium. Thus the ST changes in patients with exercise-induced ischemia will have the same spatial orientation, but will be greater than the normal ST-T changes during exercise.

Miller et al.² recently reported a strong relation between the QRS pattern at rest and dyssynergy of the left ventricle in biplane angiograms. Hilsenrath et al.¹⁴ dispute these findings on basis of 230 patients studied by single plane left ventriculography. Nevertheless in their series about 75% of the patients with infarction patterns in the ECG and VCG had dyssynergy of the left ventricular wall which corresponded to the localization of the infarct in the ECG or VCG. The data in our smaller series with single plane

(RAO) left ventricular angiograms are in good agreement with these reports (table 3). Patients with inferior wall dyssynergy had electrocardiographic evidence of an old inferior wall infarction in nine out of 12 cases, while antero-septal or anterolateral infarctions were observed in the ECG of 18 out of 27 patients with apical or anterior wall dyssynergy.

During exercise similar ST shifts were observed in patients with inferior wall infarctions and in patients with inferior dyssynergy. The ST shift in these cases was oriented more toward the posterior and inferior direction than in patients with a normal left ventricular contraction pattern. Patients with antero-septal or anterolateral infarctions exhibited ST shift directed anteriorly, which was also observed in patients with anterior wall or apical dyssynergy.

A schematic explanation of these observations is given in figure 10. Since no relation has been found between the location of isolated coronary artery obstructions and the direction of the ST forces during exercise,⁴ it is likely that ischemia during exercise in patients with an otherwise normal ventricle extends through the entire subendocardial region. The electric forces due to the ischemia in the septum and in the lateral wall should then cancel each other and the resultant force will be directed toward right, posterior and superior (fig. 10, left). When part of the anterior wall and apex is replaced by scar tissue, dyssynergy will appear on the left ventricular angiogram (fig. 10, center). During exercise the ischemic forces in the anterior wall and septum will then be weaker than in the normal contracting ventricle and the resultant force will be more anteriorly oriented. Similarly a more leftward orientation will be observed in lateral dyssynergy (fig. 10, right) and a more inferior orientation in patients with inferior dyssynergy.

It is difficult to assess which part of the ST shift in patients with abnormal QRS patterns is caused by myocardial ischemia, and which is the result of a normal response to exercise. Although these patients all have significant CAD, this does not necessarily mean that they all suffer from myocardial ischemia during exercise. Dysfunction of the coronary circulation in the presence of anatomical lesions may

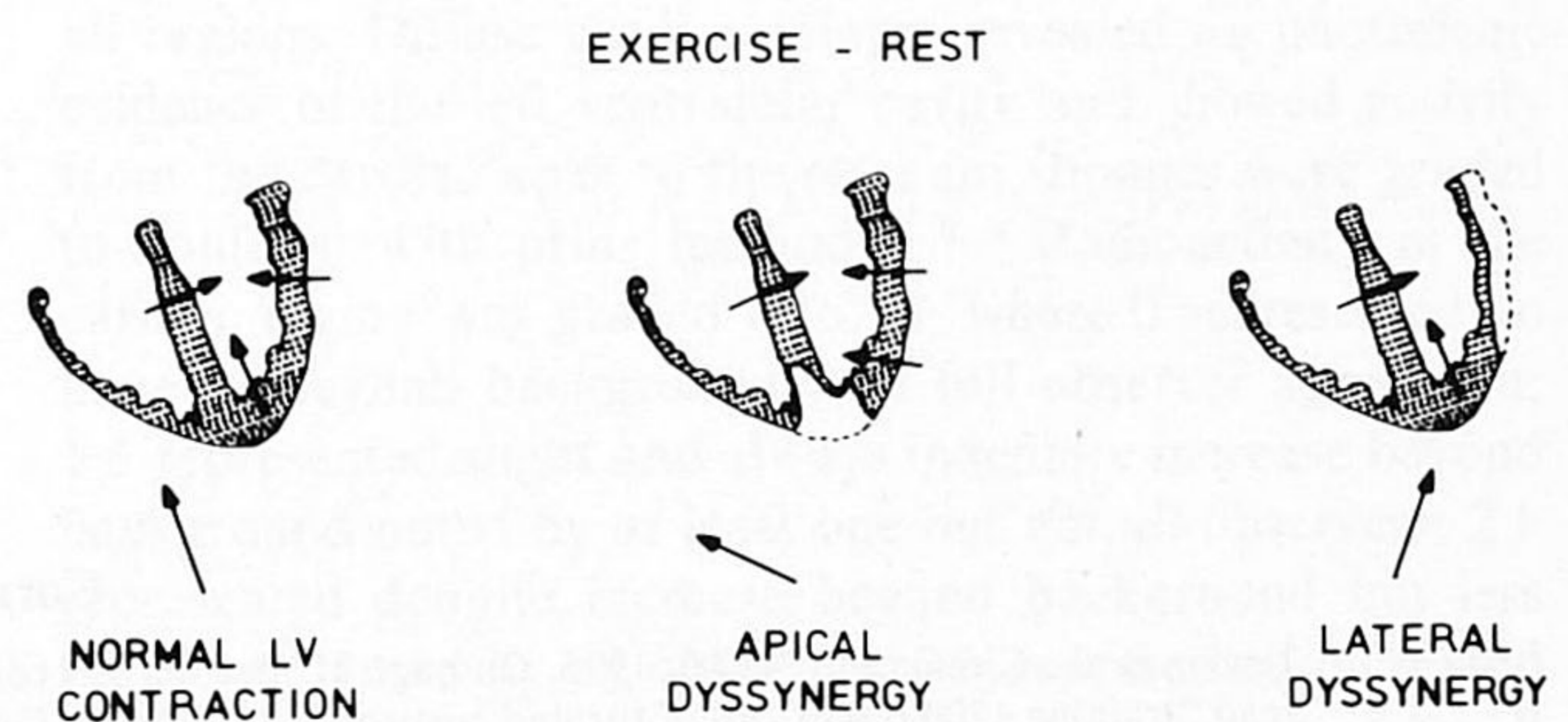


FIGURE 10. Schematic drawing of the ST changes during exercise in patients with CAD and a normal contraction pattern of the left ventricle, patients with apical dyssynergy, and patients with lateral wall dyssynergy. The arrows indicate the repolarization forces of three parts of the left ventricle. The right ventricle is omitted. The resultant ST vector is plotted under each figure. The dyssynergic area is supposed to contain predominantly scar tissue (white areas). Thus the electric forces from these areas are diminished and the forces in other regions of the ventricle dominate. Therefore the ST changes are more anteriorly oriented in apical dyssynergy and are oriented more to the left in lateral wall dyssynergy.

be prevented by either sufficient collateral circulation or by replacement of the heart muscle cells by fibrous tissue. Therefore a normal ST segment during exercise in a patient with an old infarction and with obstructions in the coronary arteries should not be considered a false negative response, unless other signs of coronary artery dysfunction are present.

Several other methods are being developed to detect myocardial ischemia. Increased serum lactate concentrations can be demonstrated in the coronary sinus as early evidence of ischemia,¹⁶ but this method is not practical during a routine upright exercise test. Scanning of the myocardium with radioactive isotopes¹⁷ is more promising, and studies with this method during exercise are now underway. Until the data from these studies become available, a completely independent evaluation of the exercise ECG in patients with abnormal ECGs at rest is not feasible. Therefore, at present the ST changes in patients with an abnormal ECG at rest should be interpreted as a sign of myocardial ischemia only when they are larger than the ST changes in normal subjects at corresponding heart rates. This can be justified by the observation that patients with significant ST changes during exercise after a myocardial infarction have a worse prognosis than patients without further ST depression during exercise.⁷

In conclusion, the ST changes during exercise in patients with an abnormal ECG at rest are partly dependent on the amount of scar tissue present from a previous infarction and partly on its location. Since the direction of the ST changes varies widely, only the magnitude of the changes can be used as an indication of exercise-induced ischemia.

Addendum

In the August 1975 edition of CIRCULATION (54: 209) Cahine, Raizner, and Ishimon reported that ST elevations in leads V₅ or V₆ in 29 patients were associated with an anterior myocardial infarction at rest and with a left ventricular aneurysm, which is in agreement with the present study.

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Correction

Taylor et al.: *Circulation* 54: 20, 1976. On page 21, line 48, left column, "Locarte Fluorimeter"; line 7, right column, same page, should read "training 1200 d.p.m./ml of titrated cortisol (1,2,6,7 ³H-". On page 24, line 14, left column: "Mathews and Saffran¹⁹". In the References: 4: "Eik-Ness"; 8: "Mattox"; 10: "Mikulaj"; 12: "1969".