Variations in Electrocardiographic Responses during Exercise
Studies of Normal Subjects under Unusual Stresses and of Patients with Cardiopulmonary Diseases

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Precordial electrocardiograms were taken before, during, and after exercise in 20 normal subjects and in 48 patients with cardiopulmonary diseases. Analysis of the findings was based on changes in Q-T interval, alterations in QRS, RS-T and T waves and on presence or absence of premature beats. Whereas in performing standard tests, normal subjects showed no evidence of coronary insufficiency, in about two-thirds of the patients abnormal changes were demonstrable. Definite RS-T depression and changes in Q-T interval were also observed in normal subjects under unusual stresses. The electrocardiographic changes during exertion were discussed and emphasized.

The changes of the Q-T interval during and after exercise in normal subjects, and in patients with cardiopulmonary diseases, have been described in a previous communication.¹ Level walking was done on a motor driven treadmill for 10 minutes, or less if markedly disabled, at a pace of either 1.73 or 2.60 miles per hour. In normal subjects the corrected Q-T interval was prolonged during exercise, shortened during early recovery and then returned to resting value during late recovery. The Q-T:T-Q ratio increased about 40 per cent during exercise and it returned promptly (to resting value) during early recovery. There were no significant changes in the RS-T segment or T wave. In patients with cardiopulmonary diseases, the changes in the Q-T interval showed somewhat different patterns. The frequency of abnormal response in the Q-T interval varied inversely with the duration of exercise. Furthermore, in all the cases in which there was distinct S-T depression during or after exercise, an abnormal response in the Q-T interval was also observed.

Since then, similar studies have been made in normal subjects and in patients walking on the treadmill at 1.73 miles per hour and 10 per cent grade, which is considered as the standard exercise test in this laboratory.² Additional observations were also made in normal subjects with increased work load (20 per cent grade) or induced anoxemia, or both. The purpose of this report is to describe the electrocardiographic changes of the normal subjects under different stresses and to compare them with those obtained in the patients. The cardiorespiratory changes are described separately.³

Methods and Material

The method of taking chest lead electrocardiograms was essentially the same as that described previously.¹ The only difference was that the resting period has been reduced from 10 minutes to 5 minutes, hence consecutive resting electrocardiograms were taken in the second, third, and fourth minutes at rest. During exercise a tracing was taken each minute up to the arbitrary limit of 10 minutes, or for the duration of tolerance as determined by each patient unable to walk 10 minutes. During the 10 minute period of recovery electrocardiograms were obtained in the first three and the last three minutes. The heart rates were

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obtained either by means of an electronic pulse counter, or by measuring the total QRS complexes in six consecutive seconds times 10. The cycle length and the Q-T interval of at least three consecutive complexes in each tracing were measured. The T-Q interval equalled the difference of corresponding cycle length and Q-T interval. The corrected Q-T (Q-Tc) or K is derived from the modified Bazett formula.3

Seven healthy male subjects between the age of 28 and 52 (6 physicians and 1 technician) who walked on the treadmill ergometer under different stresses served as normal controls. The speed of the treadmill was fixed at 1.73 miles per hour; the grade was 0 per cent, 10 per cent and 20 per cent respectively, and the inspired oxygen tension varied between 146 mm. Hg (room air) and 80 mm. Hg (11.3 per cent oxygen). The combination of the grade and inspired oxygen tension for the tests were grouped as follows:

<table>
<thead>
<tr>
<th>Test Group</th>
<th>Grade</th>
<th>Inspired O₂ Tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0%</td>
<td>146 mm. Hg</td>
</tr>
<tr>
<td>II</td>
<td>10%</td>
<td>146 mm. Hg</td>
</tr>
<tr>
<td>III</td>
<td>20%</td>
<td>146 mm. Hg</td>
</tr>
<tr>
<td>IV</td>
<td>10%</td>
<td>104 mm. Hg</td>
</tr>
<tr>
<td>V</td>
<td>20%</td>
<td>104 mm. Hg</td>
</tr>
<tr>
<td>VI</td>
<td>10%</td>
<td>80 mm. Hg</td>
</tr>
</tbody>
</table>

An additional 13 normal subjects (11 men and 2 women) between the ages of 21 and 56 years, were included with those of group II to make a total number of 20 controls and 26 tests (6 subjects walked twice) for the comparison with the patients. Altogether 63 exercise tests with satisfactory electrocardiograms were made on 48 patients. The patients were divided into four groups: (a) arteriosclerotic and hypertensive heart diseases (ASHD and HHD), 10 (15 tests); (b) congenital heart diseases (CHD), 9 (11 tests); (c) pulmonary diseases (PD), 7 (8 tests); and (d) other conditions including thyrotoxicosis, rheumatic heart disease, polycythemia, anemia, 22 (29 tests). Disability of the patients is classified in two broad categories: (a) "none to moderate"—for those who were able to walk for the full 10 minutes, (b) "marked"—for those who were unable to walk 10 minutes.

The criteria of the abnormal response in the electrocardiograms for the standard exercise test were as follows:

1. Q-T patterns: (a) Decrease in Q-Tc during exercise, or increase in Q-Tc during early recovery. (b) Q-T: T-Q ratio greater than 2 during exercise.
2. RS-T and T patterns: (a) Depression of the RS-T segment greater than 1 mm. during exercise or recovery. (b) Marked increase in the voltage, or inversion of the T wave, during exercise.
3. Premature beats: Multiple ventricular premature beats during exercise and early recovery.

Results

Normal Subjects

The mean values of the heart rate, Q-T, and Q-T: T-Q ratio of the 7 normal subjects under different stresses are presented in table 1. The mean values of the Q-Tc and Q-T: T-Q ratio in consecutive minutes for the tests of groups II, III, IV, and V are also plotted in figure 1.

The over-all change of the Q-Tc in all the tests was prolongation during exercise, shortening during early recovery, and returning to resting value, or slight prolongation, during later recovery. The prolongation of Q-Tc during late recovery was more marked with severe stress than with moderate stresses. The Q-Tc pattern of the standard test (group II) was not materially different from that seen in level walking. When the work load was increased, or anoxemia induced, there was a tendency for the Q-Tc to decline during the last four minutes of exercise (fig. 1). The declination was similar to that observed in cases with hypertensive heart disease. This was further supported by the fact that in normal subjects under severe stress (group VI) the systolic blood pressure during exercise may reach 200 mm. Hg.

The Q-T: T-Q ratio varied directly with the heart rate and pulse pressure. The resting Q-T: T-Q ratio of the normal subjects was about 1.0 while breathing air and it was slightly higher when breathing 11.3 per cent oxygen. In groups I and II, the ratio was always less than 2 during exercise and promptly returned to the resting value during early recovery. With increased work load or induced anoxemia the Q-T: T-Q ratio during exercise was either greater than 2, or it did not return promptly to resting value in the first three minutes of recovery. During late recovery the ratio was still high (groups V and VI), although the heart rate was only 100 per minute.

No changes in the RS-T segment were demonstrable in all the normal subjects of the groups I and II. Only one subject of groups III and IV, respectively, showed slight RS-T depression during exercise. Whereas only slight to moderate RS-T depressions occurred during
exercise in all the subjects of group V, a very marked depression (sometimes as much as 4 mm.) was observed in those of group VI. In the latter individuals the RS-T depression occurred on only three occasions. High, peaked T or inverted T waves during exercise were never observed.

Throughout the tests there was no significant change in the QRS complex, nor was any ventricular premature beat recorded.

Representative tracings of a normal subject under different stresses showing the various changes are reproduced in figure 2.
Patients

The incidence of the abnormal electrocardiographic changes in 48 patients with various cardiopulmonary diseases are summarized in table 2, with 20 normal subjects serving as controls.

In the group of patients with arteriosclerotic and hypertensive heart disease, RS-T depressions during and after exercise were most frequently observed, followed by high Q-T: T-Q ratio during exercise. Abnormal Q-Tc was noted in 5 of 15 tests and ventricular premature beats occurred in only one case. In another patient (R. W., case 23) during exercise there was a definite reduction in the voltage of the R waves, and an increase in the amplitude of QS waves. In 2 cases the T wave became high and peaked during exercise.

In patients making up the group with congenital heart disease a characteristic congenital pattern of the Q-Tc change, i.e., decrease during exercise and increase during early recovery, was observed in 8 of 9 cases. The exception was a patient with coarctation of the aorta. High Q-T: T-Q ratio during exercise was noted in 3 cases and the presence of ventricular premature beats in 2 cases. There was no significant change in either RS-T segment or T wave.
In the patients with pulmonary disease, an abnormal Q-T response was observed in 3, high Q-T:Q-T ratio in 2, and RST-T depression in 1 patient.

The patients in the miscellaneous group showed variable responses. High Q-T:Q-T ratios were most frequent, and an abnormal Q-T pattern and RST-T depression were less common. High, peaked T wave during exercise was seen in one case. The electrocardiographic response in patients with compensated rheumatic heart disease was usually normal, except for an occasional high Q-T:Q-T ratio during exercise.

<table>
<thead>
<tr>
<th>Electrocardiographic Changes</th>
<th>No. of Test</th>
<th>Per Cent</th>
</tr>
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<tbody>
<tr>
<td>Abnormal Q-T and normal RST-T</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>Abnormal RST-T and normal Q-T</td>
<td>8</td>
<td>12.7</td>
</tr>
<tr>
<td>Both Q-T and RST-T abnormal</td>
<td>9</td>
<td>14.3</td>
</tr>
<tr>
<td>Both Q-T and RST-T normal</td>
<td>21</td>
<td>33</td>
</tr>
<tr>
<td>Total</td>
<td>63</td>
<td>100</td>
</tr>
</tbody>
</table>

The comparison between the incidence of abnormal Q-T changes and that of abnormal RST-T changes in 48 patients is tabulated in table 3. Whereas in 40 per cent of the tests there were definite changes in Q-T interval without any alteration of RST-T waves, in only 12.7 per cent were there abnormal RST-T changes with normal Q-T response. Both abnormal Q-T and RST-T changes were observed in 14.3 per cent and finally in the remaining 33 per cent there was neither Q-T nor RST-T change.

Furthermore, there was an inverse relationship between the incidence of abnormal electrocardiographic response (both Q-T pattern and RST-T changes) and the duration of exercise. Of patients who walked the full 10 minutes, 19 of 36 tests (52 per cent) showed electrocardiographic abnormalities, whereas of those who walked less than 10 minutes, 23 of 27 tests (85 per cent) were abnormal.

Case reports of 9 patients are briefly presented in the following section with reproduction of the electrocardiograms in figures 3 and 4 for illustration of the types of responses seen.

**Case Reports**

1. G. E. H. This 58 year old man had a history of exertional dyspnea and recurrent lower left chest pain. He was about 25 pounds overweight and quite anxious about his symptoms. Physical examination, x-ray, and resting electrocardiogram were essentially negative. Exercise tolerance for the full 10 minutes showed some increased voltage of the T waves in the chest lead electrocardiogram. This change was considered to represent early coronary insufficiency due to subendocardial ischemia.

2. S. E. This 52 year old physician had been in good health until about one year ago when some exertional substernal discomfort was noticed. His family history was of importance in that his father, two paternal uncles and a younger brother had coronary occlusion. Physical examination was essentially negative except for a few basilar rales. Fluoroscopy of the chest and electrocardiogram at rest were normal. Exercise tolerance test for full 10 minutes showed definite S-T depression in the chest lead electrocardiogram after the fifth minute of exercise and during early recovery. This electrocardiographic change was compatible with the classical features of angina pectoris.

3. R. W. This 53 year old man had a history of pain of angina pectoris for three years, which was definitely benefited by the administration of nitroglycerine. He was about 25 pounds over his ideal weight. Exercise tolerance test for full 10 minutes showed borderline physical fitness index and very marked electrocardiographic changes. During exercise there was a definite reduction in the voltage of the R wave and increase in QS wave. In addition, there was also S-T depression followed by high T wave. The S-T depression persisted for six minutes after exercise. Although the history suggested only angina pectoris, the electrocardiographic changes during exercise simulated an anterior myocardial infarction. This abnormality disappeared with recovery.

4. N. L. This 60 year old woman had recurrent episodes of substernal pain with radiation to the arms for the past eight years. Six years ago she was treated for myocardial infarction. She had been hypertensive for several years. She was able to walk for only six minutes when she became tired, dyspneic and subsequently on sitting down felt a stinging pain in the left shoulder for several minutes. Blood pressure rose to 200/120 at this point. During exercise she exhibited a paradoxic response in the respiratory efficiency. There was a significant depression of the S-T segment in the resting chest lead electrocardiogram, which became more marked during exercise, and persisted for several minutes thereafter. In this patient, an abnormal electrocardiographic finding was accentuated by exertion.
Figs. 3 and 4. These two graphs show illustrative electrocardiographic tracings during rest, exercise, and recovery in 9 patients with various cardiopulmonary diseases. The description of changes is in the text.
(5) D. S. This 52 year old biophysicist had an exercise tolerance test in order to evaluate his physical condition. He had had no symptoms. The only positive physical finding was a slightly high blood pressure, which was 160/118 at rest. Exercise tolerance test for 10 minutes showed some lowering of the T wave in the electrocardiogram during exercise. This was considered to be due to tachycardia, and not significant of disease.

(6) W. C. This 61 year old man complained of exertional dyspnea, and cramps in the calves of his legs for the past three years. He had physical signs of emphysema, confirmed by a grossly increased residual air volume amounting to 56 per cent of the total pulmonary capacity. Although he experienced some pain and dyspnea, he was able to walk for 10 minutes. His chest lead electrocardiogram showed a normal response. There was no evidence of coronary insufficiency in this patient, despite pain and dyspnea on exertion.

(7) R. S. This 36 year old man had an attack of subacute bacterial endocarditis complicating mitral stenosis, in February, 1950, which was treated well with penicillin. Physical examination and fluoroscopy of the chest in March, 1950 showed marked enlargement of the heart, signs of mitral stenosis and auricular fibrillation. He was able to walk for only 6.2 minutes because of excessive fatigue and dyspnea. There was marked hyperventilation with a paradoxic response of respiratory efficiency during exercise. The chest lead electrocardiogram revealed tachycardia and considerable depression of the S-T segment during exercise and early recovery. In common with other patients with auricular fibrillation, there was a marked tachycardia and S-T depression during exercise.

(8) J. M. This 62 year old man had marked exertional dyspnea for the past six years due to emphysema. The residual air volume of 3.6 liters amounted to 64 per cent of the total pulmonary capacity, whereas the vital capacity was reduced to 0.6 liter. He was found to have pulmonary hypertension by cardiac catheterization. His exercise tolerance was grossly impaired by severe dyspnea due to marked hyperventilation. The chest lead electrocardiogram showed some depression of the S-T junction, and an abnormal increase in the Q-T: T-Q ratio during the exertion. He was slightly helped by digitalization, and subjectively claimed even greater benefit from an artificial pneumoperitoneum.

The chest lead electrocardiogram of this patient showed accentuation of the slight S-T depression during exercise.

(9) G. H. This 20 year old woman had been cyanotic since birth, showed some retardation of growth and had frequent infections. In recent years there had been appreciable spontaneous improvement in exercise tolerance, whereas in childhood the patient frequently squatted. Physical examination showed marked clubbing, polythemia, cardiac enlargement, accentuation of second pulmonic sound, a systolic murmur and thrill as well as decrescendo diastolic murmur along left sternal border. Exercise tolerance was markedly impaired because of fatigue, dyspnea, and tachycardia. There was a slight elevation of the T waves in the chest lead electrocardiogram. Exploratory thoracotomy revealed abnormal pulmonary artery, features compatible with tetralogy of Fallot, as well as too many collaterals to warrant attempting further dissections necessary for an artificial anastomosis. Again, the earliest evidence of coronary insufficiency was suggested by the increased voltage of the T waves.

DISCUSSION

The data presented herein was based upon grade walking on a treadmill ergometer at 1.73 miles per hour. This was considered to be a more satisfactory standard exercise test than level walking. In normal controls the precordial lead electrocardiograms showed responses similar to those in normal subjects with level walking.

This report shows that definite changes in the electrocardiograms occurred in normal subjects when the work load was increased further, or when moderate or severe hypoxia was induced. The changes were even more marked with both stresses. Definite RS-T depression, high Q-T: T-Q ratio during exercise and a tendency for the Q-T, to decline during exercise were the most constant findings. During recovery the RS-T depression persisted for a few minutes and the Q-T: T-Q ratio did not return promptly to the resting value.

The patients with acquired heart diseases showed quite similar changes in the electrocardiograms during the standard exercise stress (10 per cent grade walking, 1.73 miles per hour). Although RS-T depressions during and after exercise were most frequently seen in patients with arteriosclerotic and hypertensive heart diseases, this change also occurred in patients of other groups. Likewise, abnormal changes in the Q-T interval were observed in different patients regardless of the underlying diseases. Therefore, the significant electrocardiographic changes were nonspecific for any particular group of patients. Since the electrocardiographic changes in either normal subjects under unusual stresses or in patients with disease were indistinguishable from each other,
it was difficult to differentiate "functional" from "organic" coronary insufficiency. Possibly the use of dihydroergocornine would aid in this differentiation.5

The close relationship between the Q-T:T-Q ratio and the presence of precordial pain has been discussed previously.1 It was suggested that excessive shortening of the duration of diastolic filling (when the Q-T:T-Q ratio was high) might impede the coronary blood flow, especially in patients with arteriosclerotic changes of the coronary arteries. Whereas no normal subjects experienced precordial pain even when the Q-T:T-Q ratio exceeded 2.5 and marked RS-T depression occurred, patients with arteriosclerotic and hypertensive heart diseases frequently complained of precordial pain. There was some evidence in normal subjects under unusual stresses that there may be a redistribution of blood during exercise to spare the vital organs such as the heart.3

The Q-Tc pattern in the congenital heart group was rather unique in that it showed reduction during exercise and increase during early recovery. This was more striking in those cases with cyanosis. So far patients with coarctation of the aorta have been exceptions to this. More cases of congenital heart disease need to be studied, however. Patients with compensated rheumatic heart diseases usually show a normal response in the Q-Tc. Hence this may aid differential diagnosis between these two groups of patients.

The mechanism of the depression of RS-T segment is probably due to injury of the subendocardial layers of the myocardium as a result of reduced coronary blood flow, or anoxia. Recently it was demonstrated conclusively by experimental studies7, 8 and clinical observations9, 10 that the essential change in the electrocardiograms in subendocardial myocardial infarction is a marked RS-T depression in the left precordial leads. The presence of high T wave has also been shown experimentally to be a result of early injury of subendocardial layer11 and clinically, an early sign of myocardial infarction.12 The appearance of a high, peaked T wave during exercise is of particular interest, because it may indicate an early abnormal response that has not been emphasized before. One of the patients in the group with arteriosclerotic and hypertensive heart disease showed a distinct increase in the T wave during exercise, and 10 days later he developed coronary occlusion. Scherf13 has stated that "damage of the inner layers of the myocardium causes depression of the RS-T segment and the T wave as an acute effect and high-positive T waves as an after-effect." Our experience has led us to believe that the appearance of high peaked T wave is probably an acute effect. Should electrocardiogram be taken routinely during exercise, a higher incidence of the high T waves might be observed.

The conspicuous advantages of registering a precordial lead electrocardiogram with a direct writing instrument during treadmill walking can not be overemphasized. A similar study has been applied to the performance of the Master two step test; the results have been uniform and encouraging.14 First, the recording of the chest lead is superior to that of standard leads because marked changes may appear in the former and be absent in the latter.15 Second, important changes in the electrocardiograms may appear only during exercise, and disappear as soon as the exercise has been discontinued, or within two or three minutes.16 These include reduction of the R wave and increase in the QS wave, significant increase in the voltage of the T wave, marked depression in the RS-T segment and multiple ventricular premature beats. Finally the measurement of the Q-T interval as a quantitative measure to differentiate normal from abnormal responses has been found to be helpful in majority of the cases. In normal subjects performing the standard exercise test the pattern response in both Q-Tc and Q-T:T-Q ratio have been described. In patients with various types of cardiopulmonary diseases, the incidence of abnormal responses was quite high. The percentage of abnormal response was even greater in patients with marked disability than in those with no or moderate disability. In some patients there was no alteration of the RS-T segment and T wave, yet the response in Q-T pattern was distinctly abnormal.
ELECTROCARDIOGRAPHIC RESPONSES DURING EXERCISE

SUMMARY

1. Walking on a treadmill at a pace of 1.73 miles per hour and 10 per cent grade has been adapted in this laboratory as a standard exercise test. Minute-by-minute chest lead electrocardiograms were recorded, before, during, and after the exercise. The electrocardiographic response in 20 normal subjects was similar to that observed in level walking, which has been previously described. The criteria of the abnormal responses in the standard test in regard to changes in the Q-T pattern, RS-T and T waves and premature beats have been defined.

2. Abnormal electrocardiographic changes are described in a group of 7 normal subjects walking on the treadmill with increased work load or induced hypoxemia or both. The magnitude of these changes was directly proportional to the severity of the stresses.

3. Standard exercise tests were also performed in a group of 48 patients with various kinds of cardiopulmonary diseases. The electrocardiographic changes obtained from these patients have been analyzed and compared with those of the 20 normal controls. It was found that about two-thirds of the patients showed an abnormal response. The incidence of abnormal electrocardiographic changes varied inversely with the duration of exercise.

4. The electrocardiographic abnormalities in both normal subjects under unusual stresses and patients with cardiopulmonary diseases were comparable. The changes in either group were considered as significant but nonspecific.

5. The advantages of registering chest lead electrocardiograms during exercise have been discussed.

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