Radioelectrocardiographic Changes during Strenuous Exercise in Normal Subjects

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The type and amount of exercise recommended for the electrocardiographic diagnosis of coronary artery disease have been a matter of discussion and some controversy. The electrocardiogram has also been studied after extreme effort, such as long-distance running, skiing, rowing, strenuous marching, and other forms of sports. Master and Oppenheimer in 1929 described a standardized two-step exercise test that has gained wide popularity for the diagnosis of coronary artery disease. Other forms of standardized exercise such as walking on a treadmill or riding a bicycle have also been used.

With a few exceptions, most studies on the effect of exercise on the electrocardiogram deal with the period after exercise. The recently introduced radioelectrocardiograph eliminates most of the difficulties of recording electrocardiograms during exercise. We have previously described the changes that occur during the Master two-step test in normal subjects as well as in patients with hypertensive or arteriosclerotic cardiovascular disease and in patients with angina pectoris. Here, are presented the changes that occur in normal individuals during the performance of exercise more strenuous than the Master test.

Material and Methods

One hundred and thirty-five apparently healthy men were used in this study. Most of them were college students, young physicians, and policemen. The ages varied between 17 and 64 years (average 30.3 years); only 24 patients were above the age of 40 years. There were no history and no signs of cardiovascular disease in any of the subjects; the resting 12-lead electrocardiogram was normal in all cases. In all but 10 patients, the exercise consisted of riding a stationary bicycle at 20 to 25 miles per hour for 3 minutes. This exercise was continued in eight patients for 4 to 5 minutes and in two patients for 8 and 10 minutes. Most patients experienced fatigue and some shortness of breath by the end of the test, but none had precordial pain. One subject performed strenuous rowing for 10 minutes.

The radioelectrocardiograph employed in this study has been previously described in detail. The procedure included the recording of a 12-lead electrocardiogram with the conventional machine, taking a 1-lead control tracing in the recumbent and prone positions with the radioelectrocardiograph and obtaining a continuous record during the exercise and 2 to 8 seconds, 1, 3, 5, and 8 minutes after the cessation of exercise. The lead employed in most of the subjects was similar to $V_5$ or $V_6$ (one exploring electrode in the fifth intercostal space, left midaxillary line, and the second electrode over the scapular end of the right clavicle).

The criteria for abnormality have been described previously. The following were considered to be "definitely abnormal": (1) ischemic (flat or downward) ST-segment depression of 1 mm. or more; (2) ST-segment elevation of 1 mm. or more; (3) inversion of a positive or reversion of a negative T wave; (4) marked changes in the width of the QRS complex; (5) appearance of multiple premature beats in couples or runs; and (6) frank inversion of the U wave.

The following were considered as "probably abnormal": (1) ischemic ST-segment depression or T-wave inversion, appearing in a few cycles; (2) biphasic T waves; (3) appearance of U waves of high amplitude; and (4) appearance of a few premature beats as an isolated finding.

Results

Normal ("Physiologic") Changes

Certain electrocardiographic alterations, not included in the criteria for abnormality,
were observed very frequently during and after the period of strenuous exercise and were, therefore, considered to represent the physiologic response to exercise.

**Changes during Exercise**

The most common changes during the period of exercise were sinus tachycardia (observed in all subjects); a marked increase in P-wave amplitude (85 per cent); ST-segment depression of the junction type (75 per cent); and diminished (68 per cent) or increased (9 per cent) amplitude of the T wave (table 1, fig. 1).

The heart rate increased from an average of 73 (68 to 102) to 138 (120 to 182) beats per minute. The tachycardia was of sinus origin in all cases. Respiratory arrhythmias, present in most subjects during the first minute of exercise, tended to diminish or disappear as the heart rate became faster. Ectopic tachycardia did not appear in any of the subjects. The P wave sometimes doubled or even tripled in amplitude during the exercise. This often occurred as soon as 30 seconds after the beginning of exercise, but was usually observed after the first minute. Measurements of the PQ interval were rendered difficult or unreliable because of fusion of the P wave with the preceding T wave, which took place in most patients. The QRS complexes showed no changes in width and insignificant changes in amplitude. Decrease in the amplitude of the R wave and deepening of the S wave were observed not infrequently. ST-segment depression of the junction type usually accompanied the tall P waves. The depression varied between 1 and 5 mm. in different subjects. The T waves were typically flattened during the early phase of exercise (30 to 60 seconds). In some patients, this flattening persisted even immediately after exercise; in others the T waves became normal or taller than the control during the course of exercise. Only 12 patients (9 per cent) had T waves of increased amplitude during exercise without a preceding decrease.

Other less frequent changes during exercise included the appearance of a few ventricular premature beats (2 subjects) and a prolongation of the QT interval (1 subject).

**Changes after Exercise**

Three minutes after the cessation of exercise, the average heart rate was 68 (52 to 116) beats per minute (table 1). The P wave regained its normal amplitude within the first minute of rest in more than half of the cases in which it had been increased during the period of exercise. The ST-segment depression
frequently persisted after the P wave had become normal; 58 per cent of the subjects still showed jST depression of 1 mm. or more after 1 minute of rest. The T wave increased its amplitude above the control in about one third of the cases. In these, a slight diminution of the T-wave amplitude sometimes preceded its return to normal. Less frequent changes included a few ventricular premature beats (1.4 per cent) and prolongation of the QT interval (0.7 per cent).

Abnormal Changes

"Probably Abnormal"

Ischemic ST-segment depression in a few cycles appeared during exercise in four subjects (3 per cent) and after exercise in one subject (0.7 per cent). Inversion of the T wave in occasional cycles was observed only in two subjects (1.4 per cent) during the period of exercise.

"Definitely Abnormal"

Persistent ischemic ST-segment depression of 1 mm. or more or T-wave inversion appeared in 18 patients during, and in 14 patients after, the exercise (13 and 10 per cent, respectively) (figs. 2 to 5). Persistent T-wave inversion was observed less frequently (6 per cent during and 3.7 per cent after exercise). Multiple premature beats were observed in only two patients (1.4 per cent) during exercise.

In summary, electrocardiographic abnormalities were observed in 34 of the 135 subjects (25 per cent) during or after the exercise, or both. Twenty-eight (20.4 per cent) had "definitely abnormal" and six subjects (4.4 per cent) had "probably abnormal" responses (table 2). Eleven of the 28 "definitely abnormal" responses were observed only during exercise, another 11 appeared both during and after exercise and six occurred only after exercise. Five of the six "probably abnormal" responses were observed to 8 seconds after the cessation of exercise. The tracing taken 1 minute after exercise shows tall and peaked T-waves, which become flatter again in the tracing taken 5 minutes after exercise.

Figure 1

Typical (physiologic) electrocardiographic changes during strenuous exercise (riding a bicycle at 25 mph for 3 minutes) in a normal subject. In this and in subsequent figures the tracings during exercise are above and those after exercise are below the double black line. The control tracing is normal. The changes during exercise consist of diminished amplitude of the T wave, increased amplitude of the P wave and junction ST-segment depression (45 and 165 seconds). These changes persisted 2
Table 2
Incidence of "Probably" and "Definitely Abnormal" Responses and Relation of Their Occurrence to the Period of Exercise in 155 Normal Men

<table>
<thead>
<tr>
<th>Number of cases</th>
<th>Per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abnormal responses</td>
<td>28</td>
</tr>
<tr>
<td>Only during exercise</td>
<td>11</td>
</tr>
<tr>
<td>During and after exercise</td>
<td>11</td>
</tr>
<tr>
<td>Only after exercise</td>
<td>6</td>
</tr>
<tr>
<td>Probably abnormal responses</td>
<td>6</td>
</tr>
<tr>
<td>Only during exercise</td>
<td>5</td>
</tr>
<tr>
<td>During and after exercise</td>
<td>1</td>
</tr>
<tr>
<td>Only after exercise</td>
<td>0</td>
</tr>
<tr>
<td>Total abnormal and</td>
<td>34</td>
</tr>
<tr>
<td>probably abnormal</td>
<td></td>
</tr>
</tbody>
</table>

served only during exercise and one occurred both during and after exercise. Therefore, 16 of the total of 34 definitely and probably abnormal tracings (47 per cent) were recorded only during the period of exercise.

An analysis of the group of 34 patients showing electrocardiographic abnormalities during strenuous exercise showed that the average age did not differ significantly from that of the remainder of this group of 101 patients who showed normal responses (32 and 30 years, respectively). Of the 24 subjects aged 40 years or above, however, nine were in the group of 34 patients manifesting abnormal responses (26 per cent) and 15 in the group of 101 patients with normal responses (15 per cent). Moreover, the incidence of an abnormal response in individuals above the age of 40 years was 37 per cent as compared to an incidence of 23 per cent in the group below the age of 40. Therefore, abnormal responses to exercise in the group of subjects above the age of 40 years was 60 per cent higher than that observed in the group of subjects below the age of 40 years.

Discussion

Most of the electrocardiographic changes, considered as "normal" in this study, have been observed and described previously in healthy people as occurring in the period after exercise. The increased amplitude of the P wave, found both during and after exercise, is apparently due to increased venous return to the heart, increased sympathetic activity, and a tendency of the P vector to become more vertical. The junction ST-segment depression is caused mainly by the tachycardia, which leads to a shortening in
the duration of the action current, chiefly during the recovery phase.\textsuperscript{27} As the Ta wave shortens, it must deepen in order to maintain an area equal and opposite to that of the P wave.\textsuperscript{27} This inevitably results in a depression of the ST-segment junction over which the Ta wave is superimposed. The changes in the amplitude of the T wave during and after exercise are due to a multitude of factors. Hyperventilation,\textsuperscript{28} increased sympathetic tone,\textsuperscript{29} and the effect of tachycardia on the myocardium\textsuperscript{27} are probably the most important factors causing the flattening of the T wave during exercise, while increased vagal tone is apparently the most important cause of the increase in amplitude in the period after exercise.

The incidence of changes referred to as "definitely abnormal" during the bicycle exercise test in apparently healthy individuals is much higher than that during the double Master two-step test (as previously reported).\textsuperscript{23-25} Even when age is taken into account, individuals below 40 years showed a 5.5 per cent incidence of definite and probable abnormalities during the Master two-step test and 22.5 per cent during the bicycle test. The incidence of abnormalities for individuals above the age of 40 years is 20 and 37 per cent, respectively, in these two groups. These differences are not surprising since, although direct estimations were not made, the bicycle test involves a much greater energy expenditure over a shorter period of time than the Master two-step test. This was indicated by the much greater degree of fatigue and shortness of breath during the bicycle test, experienced by individuals who performed both this and the Master tests.

Whether or not the amount of exercise per unit of time is a factor of considerable importance for the incidence of the electrocardiographic changes after exercise has been a matter of discussion. This is true for both normal individuals and for patients with coronary artery disease. Some believe that the criteria diagnostic of coronary artery disease do not depend too much on the degree of exercise,\textsuperscript{1,10,27} whereas others attribute a definite significance to the type, degree, and length of exercise.\textsuperscript{12,30-32} A close look at the figures in various studies shows that the mere increase from a single to a double Master two-step test increases somewhat the prevalence of false-positive results and decreases

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Abnormal response to strenuous exercise (riding a bicycle for 3½ minutes) in a 25-year-old normal man. Note normal control tracing. During exercise, note ST-segment depression after 122 seconds of exercise, which continued during the period of exercise and in the tracing taken immediately after exercise. One minute after exercise, the ST-segment depression approached the J type and was somewhat less marked than that observed during exercise; 5 minutes after exercise, the ST-segment depression is almost entirely gone.

even more so the prevalence of false-negative results. Unterman and DeGraff\textsuperscript{33} reported no false-positive results after the single Master two-step test in 31 healthy individuals and a positive test in one of six subjects after the double test. In the series of 200 normal subjects reported by Scherlis et al.,\textsuperscript{34} the incidence of false positives was 4.5 per cent after the single test and 7.5 after the double test. The respective numbers for the series reported by Wener et al.\textsuperscript{35} were 5.4 and 9.3 per cent. Simonson and Keys\textsuperscript{10} compared the changes in 91 healthy adult individuals after two difficult types of exercise (walking on a 5 per cent-grade treadmill at 3 mph for 10 minutes and 47 steps up and down on a single 12-inch step at the rate of 19 ascents per minute) and concluded that definite differ-
double test. Later (1957), \textsuperscript{37} they reported 56.8 per cent positive results after the single test in 200 patients with coronary artery disease and 96.8 per cent after the double Master test. In addition, most of the studies performed after strenuous exercise in athletes have resulted in the finding of definitely abnormal changes in a fairly high percentage of cases.\textsuperscript{2-7}

The significance of the changes considered as abnormal in our and other studies has not been definitely determined. The only follow-up study on a large group of patients is that by Mattingly and Robb,\textsuperscript{38} who found that the ischemic ST-segment depression of 0.5 or more in the post exercise electrocardiogram was the only change bearing a bad prognosis. Whether or not the changes observed during exercise in 20.4 per cent of our group of normal subjects have a similar meaning is not certain at present. It is well known that coronary artery disease may be present in a very high per cent of young and apparently healthy men.\textsuperscript{39, 40} It is also of interest that the abnormal changes were observed more frequently in subjects of the older age group in our series. This conforms well with the observation that apparently healthy patients of the older age group have a higher incidence of abnormalities with the conventional Master two-step test.\textsuperscript{41-43} Nevertheless, other factors such as the lack of training for this particular type of exercise, hyperventilation, and increased sympathetic tone may have contributed to the appearance of abnormal changes.

The results of this and previous studies\textsuperscript{23-25} suggest that although the Master two-step test may be adequate for the diagnosis of coronary artery disease in adult individuals (above the age of 40 years), a more strenuous type of exercise may be necessary in younger patients (below 40 years) who present no anginal symptoms. Preliminary studies indicate that the bicycle exercise test results in an extremely high incidence of positive tests in patients with hypertensive or arteriosclerotic cardiovascular disease. Patients who have had negative responses to the double Master test.

\textbf{Figure 5}

Abnormal response to strenuous exercise in a 29-year-old man. Note the inverted T waves and tall P waves 20 seconds after the exercise was started. Note the disappearance of the inversion at 171 seconds. Because the patient felt quite comfortable, the exercise was continued for 11 minutes. Note the gradual return to normal in the electrocardiogram taken at 3 and 5 minutes after the exercise.
two-step test will frequently exhibit abnormal alterations during a bicycle test. The bicycle test may, therefore, be more adequate than the Master two-step test in the search for latent coronary artery disease in subjects below the age of 40 years. Similarly, it may be more appropriate for the evaluation of the physical fitness in younger individuals.

Summary

The effect of strenuous exercise (riding a stationary bicycle at 20 to 25 mph for 3 minutes) on the electrocardiogram was studied in 135 normal subjects, aged 17 to 64 years. Radioelectrocardiography was used to record the tracings during and after the period of exercise.

The following electrocardiographic alterations during exercise were interpreted as representing a normal physiologic response; sinus tachycardia (100 per cent of the cases), increased P-wave amplitude (85 per cent), ST-segment depression of the junction type, 1 mm. or more (75 per cent), diminished (68 per cent) or increased (9 per cent) T-wave amplitude. A few ventricular premature beats were observed in only two subjects (1.4 per cent). All these changes were observed, although less frequently, in the period after exercise (1 minute after the cessation of exercise).

According to criteria for abnormality described previously, 34 35 of the 135 subjects (24.8 per cent) exhibited abnormal responses to the bicycle exercise test. Sixteen of the 34 "definitely" and "probably abnormal" responses (47 per cent) occurred only during the period of exercise, 12 were observed both during and after the exercise and six occurred only in the postexercise period.

The incidence of abnormalities in the group of subjects in the age group 40 to 64 years was 37 per cent, while that in subjects in the age group 17 to 40 years was 22.5 per cent.

A comparison between the Master two-step and the bicycle tests suggests that the latter may be more diagnostic for the detection of latent coronary artery disease and the evaluation of the state of physical fitness in subjects below the age of 40 years.

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