Comparison of the Electrocardiographic Changes Induced by Maximum Exercise Testing with Treadmill and Cycle Ergometer

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SUMMARY Maximum exercise testing using treadmill walking and cycle ergometry was compared in 40 male patients who had suffered a myocardial infarction in the preceding twelve months. Maximum oxygen uptake was on average 17% greater in the treadmill than the cycle test and maximum heart rate was also higher, but the rate pressure product (RPP) was similar due to a higher blood pressure in the cycle ergometer test. Eleven subjects showed ST-segment depression greater than 1 mm and eight subjects showed ST-segment elevation greater than 1 mm. There was a close relationship \( r^2 = 0.96 \) between the magnitude of ST-segment changes in the two tests. Four subjects showing ST depression of 1 mm in the treadmill test showed depression during the cycle ergometer test which was less than this conventionally "positive" value. In these subjects RPP was lower during cycling than in treadmill walking. With both tests maximum ST-segment changes were measured immediately on stopping exercise: resolution of ST depression was more rapid than ST elevation. The two exercise testing modes are closely comparable in their ability to reveal changes of myocardial ischemia.

MULTISTAGE EXERCISE TESTS using the treadmill or cycle ergometer, as opposed to the single stage Master's two-step test,\(^1\) result in a higher sensitivity of detection of ST-segment depression.\(^2\) \(^5\) Although myocardial ischemia is often induced by the Master's test in subjects with coronary heart disease, the level of work may not be high enough to compromise myocardial oxygen requirements in those with a lesser degree of impaired coronary blood flow. Because of this, several authors have proposed exercise tests to either a symptom-limited maximum\(^6\) \(^7\) or to an end point defined by an age-related heart rate.\(^8\) \(^9\) Despite the ability of treadmill exercise to achieve a higher maximum oxygen uptake (\(\text{VO}_2\) max) than cycle ergometry,\(^10\) \(^11\) it remains to be established whether there is a difference between the two types of exercise in eliciting ST-segment changes. The purpose of this study was to assess differences in the ST-segment changes induced by maximal cycle ergometry and treadmill walking using a conventional exercise protocol in patients following myocardial infarction.

Subjects

Forty male subjects (mean age 47.2 yrs ± 6.0 sd) were studied; all had experienced a myocardial infarction documented by enzyme and electrocardiographic changes within the preceding twelve months (mean 6.1 ± 3.0 months post-infarct). Four subjects had experienced two myocardial infarctions. Cycle ergometry and treadmill testing were performed on separate days and in random order; both tests were conducted in the postabsorptive state. The subjects continued taking any medication, the dosage of which remained unchanged for both tests. Four were taking digoxin and seven propranolol; none were in cardiac failure at the time of the studies. Severe hypertension, diabetes mellitus, and coronary bypass surgery were all exclusions to participation in the cardiac rehabilitation program.\(^12\) Interview, clinical examination, and resting 12 lead electrocardiography were used to ensure that the subjects were in a comparable condition on the two study days. Resting electrocardiographs usually showed evidence of the previous infarction: in two subjects left bundle branch block was also present.

On entry into the study, the subjects gave their informed consent.

Methods

Both tests employed a progressive multistage protocol with exercise being terminated by generalized fatigue, chest pain or other symptoms of exercise intolerance, a significant fall in blood pressure, or rhythm or conduction disturbances. ST-segment depression alone was not used as an indication to terminate the exercise procedure.

Cycle ergometry was performed in the erect position using an electrically braked Elema Schonander EM-370 ergometer regularly calibrated by physical balance. The initial work load was 100 kpm/min (16 watts) with increments of 100 kpm/min each minute.\(^13\) With treadmill testing (Quinton 24–72) the subject walked at a constant speed (80 m/min) throughout the test. The initial work load was a 0% grade and each minute the grade was increased by 2.5%.\(^14\) During the treadmill test the patient was not allowed to hold the handrails. Grade and speed settings were regularly checked.

A standard 12-lead electrocardiogram was recorded in the sitting position prior to and immediately following the exercise test, and at 1, 3, 5, 7 and 10 minutes post-exercise using a three channel Hewlett Packard 1515B recorder. During exercise a CM5 lead was continuously monitored and recorded. A significant ST-segment change was defined by either a 1 mm horizontal or down-sloping depression for at least 0.08 sec\(^4\) or a 1 mm ST-segment elevation of similar duration.\(^5\) The isoelectric point was taken as the junction of the PR segment with the QRS complex. The recorder was calibrated to give a 1 mV/10 mm stylus deflection. All electrocardiograms were examined independently by two observers. ST-segment shift was measured in a minimum of

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five complexes with a magnifying viewer incorporating a measuring scale. Blood pressure was measured by the cuff method at one minute intervals during the test procedure. The subject breathed through a low resistance valve and inspired ventilation was recorded with a Parkinson Cowan CD4 gas meter. Mixed expired gas was continuously sampled and measured for carbon dioxide with an infra-red CO2 analyzer (Capnograph, Godart) and a paramagnetic oxygen analyzer (Rapox, Godart); both analyzers were calibrated with several gases analyzed with the Lloyd Haldane apparatus. The outputs of the analyzers and the CM5 electrocardiograph lead were recorded on a direct writing multichannel recorder (Mingograf 81). Ventilation and mixed expired gas analyses were used to calculate O2 uptake and CO2 output during the last 15-20 seconds of each minute.

A Student's paired t-test was used to test the significance of differences between mean values.

Results

Of the forty subjects tested, 23 (57.5%) performed cycle ergometry first. The mean time (± 1 sd) between tests was 12.4 ± 10.1 days. In 36 subjects complete measurements of oxygen uptake were obtained for both tests. In the remaining four subjects, the oxygen uptake for the final work load was predicted from the cycle ergometer or treadmill settings using a regression equation established in these cardiac patients for both tests (fig. 1). The maximum values of oxygen uptake (V\textsubscript{O\textsubscript{2}}), heart rate (HR), systolic blood pressure (SBP), rate pressure product (RPP), i.e., HR × SBP, and ST-segment change are shown in table 1.

Nineteen subjects showed ST-segment changes related to exercise: two of these patients were taking digitalis and propranolol, and three were taking propranolol alone. Five subjects experienced angina during the final stages of the exercise test, and in four there were associated ST-segment changes (two depression, two elevation). Significant ST-segment depression was observed in 11 subjects with treadmill exercise. In seven of these subjects a similar degree of ST-segment depression occurred with cycle ergometry; in the remaining four subjects the ST-segment depression did not reach the significance level with cycle ergometry (fig. 2). For the eight subjects with ST-segment elevation during exercise, a significant and similar change was observed with both tests (fig. 2). The relationship between the maximum ST-segment changes observed in each subject for the two test methods (fig. 2) showed a coefficient of determination (r\textsuperscript{2}) of 0.96, indicating that less than 4% of the variation between the ST-segment change of the tests remains unaccounted for. In all but one subject, maximum ST-segment change was associated with maximum exercise. The one exception showed a delayed response in both tests, with maximum ST-segment depression occurring 4 minutes postexercise.

The rate at which ST-segment changes resolved showed different trends for depression and elevation (fig. 3). Although the mean ST-segment depression returned to the diagnostic level of 1 mm by approximately 60 sec postexerc-
Table 1. Comparison of Measurements Made during Maximum Exercise for Cycle Ergometry (C) and Treadmill Walking (T)

<table>
<thead>
<tr>
<th></th>
<th>Max VO₂max (ml/kg/min)</th>
<th>Max HR (beats/min)</th>
<th>Max SBP (mm Hg)</th>
<th>Max RPP (mm Hg/min x 10⁻⁴)</th>
<th>ST change (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>T</td>
<td>C</td>
<td>T</td>
<td>C</td>
</tr>
<tr>
<td>All subjects</td>
<td>22.6*</td>
<td>26.5</td>
<td>159</td>
<td>166</td>
<td>194</td>
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<tr>
<td>(N = 40)</td>
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<tr>
<td>Group 1</td>
<td>24.2</td>
<td>28.7</td>
<td>166</td>
<td>171</td>
<td>208</td>
</tr>
<tr>
<td>(N = 21)</td>
<td></td>
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<tr>
<td>Group 2</td>
<td>19.6</td>
<td>23.9</td>
<td>141</td>
<td>153</td>
<td>171</td>
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<tr>
<td>(N = 11)</td>
<td></td>
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<tr>
<td>Group 3</td>
<td>22.2</td>
<td>24.0</td>
<td>164</td>
<td>169</td>
<td>191</td>
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<tr>
<td>(N = 8)</td>
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*Values are mean ± 1 SEM.
Group 1 = no ST-segment change; group 2 = ST-segment depression; group 3 = ST-segment elevation.

The suitability of the RPP as a determinant of MVO₂ and coronary blood flow has been shown both in normal subjects20, 21 and in subjects with coronary heart disease with and without angina.22-26 The indirect cuff method has been established as a reliable alternative to direct intra-arterial blood pressure recording in the measurement of systolic blood pressure for the determination of RPP.24

In this study the mean ST-segment depression produced by maximum exercise testing using two dissimilar types of exercise, cycling and incline walking, was comparable (table 1, fig. 2) in spite of differences between the two tests for maximum VO₂(max), heart rate, and SBP. The similar ST-segment changes (fig. 2) appear to be explained by the similar RPP which implies a comparable maximum MVO₂ for the test methods. A number of comparisons have been made between exercise performance on a cycle ergometer and on a treadmill. In normal subjects VO₂(max) has been found to be 8-12% higher on a treadmill.10, 11 The greater disparity in patients with heart disease,27 amounting to 17% in this study, is unexplained. It may be due to greater motivation and skill required in cycling, but the greater strain falling on a relatively smaller muscle mass, taken with the cardiovascular limitation, may be important in limiting exercise on the cycle ergometer. However, in spite of the difference in VO₂(max) the myocardial stress, as assessed by the RPP and electrocardiographic changes, appeared comparable.

Niederberger and colleagues27 compared measurements made during exercise on a cycle ergometer and treadmill in eight patients with ischemic heart disease. Their findings were similar to ours in that VO₂(max) was about 25% higher during treadmill exercise than with cycle ergometry. At submaximal power, for a given proportion of the treadmill VO₂(max), heart rates, blood pressure and ventilation were higher on the cycle. Similar data were obtained in our study, to be reported separately, which also showed that at a given VO₂ the higher ventilation is due to a higher CO₂ output, secondary to a higher lactic acid production during cycling. Examination of the results presented by Niederberger et al. suggests that at maximum exercise RPP was the same with both testing modes, as found in our study.

When comparing the effects of different maximum exercise tests, it is important that they be comparable in terms of exercise for cycle ergometry and 105 sec postexercise for treadmill testing, these differences were not significant. In contrast to ST-segment depression, ST-segment elevation was of greater magnitude and more sustained during the postexercise recovery period, being in excess of 1 mm for approximately 9 minutes postexercise with both testing methods.

All subjects achieved a higher VO₂(max) 26.5 ± 0.9 ml/kg min (mean ± 1 SEM), during treadmill testing than with cycle ergometry, 22.6 ± 0.8 ml/kg min. Similarly, the maximum heart rate for treadmill testing was 166 ± 2.5 beats/min compared to 159 ± 3.3 beats/min for cycle ergometry (table 1). However, as maximum systolic blood pressure was higher with cycle ergometry, 194 ± 5.8 mm Hg, than with the treadmill, 181 ± 5.0 mm Hg, the resultant maximum RPP of the two test methods were comparable, 313 ± 14.5 × 10⁻² mm Hg/min for the treadmill, and 303 ± 12.7 × 10⁻² mm Hg/min for the cycle.

To identify factors related to electrocardiographic changes, patients were divided into three groups based on the presence or absence of ST-segment change (table 1). For group 1 (no significant ST-segment change) and group 2 (ST-segment depression), the maximum RPP of treadmill testing and cycle ergometry were not significantly different. In group 2 (ST-segment depression), although maximum VO₂(max), heart rate and SBP were significantly different between tests, the RPP and mean ST-segment depression were similar (table 1). In group 3 (ST-segment elevation), despite a similarity of the mean ST-segment elevation, the RPP of the tests, 324 ± 28.4 × 10⁻² mm Hg/min for cycle ergometry and 288 ± 23.4 × 10⁻² mm Hg/min for treadmill, were significantly different due to the lower SBP with treadmill exercise (table 1).

Discussion

The interrelationships of myocardial oxygen consumption (MVO₂) with RPP and ST-segment depression in subjects with coronary artery obstruction are well established. Shift of the ST segment, whether depression16-18 or elevation,19, 19 reflects an imbalance between MVO₂ and oxygen delivery, resulting from coronary obstruction, or may indicate abnormal left ventricular function or left ventricular aneurysm.18

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intensity and duration. Suitably structured tests achieved a good reproducibility of VO₂ max.²⁶ RPP at onset of exercise-induced angina²²,²³ and ST-segment depression/RPP relationship during progressive exercise.²⁶ It has been established for subjects with coronary heart disease that the test duration should be a minimum of 3 to 6 minutes to reach a maximum,²⁶ and an increase in power output by a small and constant amount each minute allows optimal adaptation of cardiorespiratory function during progressive exercise.²¹ In the protocol used in the present study the relationship of oxygen uptake to duration of exercise and to work load was similar for the two test protocols (fig. 1). For treadmill walking at 3 miles/hour, the increment of oxygen uptake/minute for a 2.5% increase in grade was 225 ml/min (2.8 ml/kg/min) which is similar to the increment in oxygen uptake of 175 ml/min (2.2 ml/kg min) for each 100 kpm/min increase in work load with cycle ergometry. The protocol we used in the study was associated with a higher VO₂ in the initial stage of the treadmill protocol than with the cycle, and also a shorter test duration (6.5 ± 1.0 min compared to 8.5 ± 1.2 min). These differences are unlikely to be physiologically important but to achieve strict comparability we now use initial treadmill speeds of 20, 40 and 80 m/min for one min each at zero grade, before increasing the grade to 2.5%.

Although there was no significant difference in mean ST-segment depression and RPP for the two methods, four of the eleven subjects showed differences which were potentially important diagnostically, in that they did not show conventionally significant ST-segment depression with cycle ergometry, whereas the treadmill test produced changes which were at the limit of significance (fig. 2). These four subjects all had a marginally higher RPP with the treadmill, the mean values being 193.5 × 10⁻⁶ mm Hg/min for cycle ergometry, and 219.0 × 10⁻⁴ mm Hg/min for the treadmill, a difference of 12%.

In contrast to ST-segment depression, the pathophysiological significance of ST-segment elevation with exercise is less well defined. Elevation is frequently seen during exercise testing when performed soon after anterior myocardial infarction, the extent of the elevation decreasing with time.²³ The association between ST-segment elevation and proximal coronary artery stenosis is well known,¹⁹ and angiographic studies established an 86% incidence of left ventricular aneurysm.¹⁸ Angina is less frequent in association with ST-segment elevation than with exercise-induced ST-segment depression, perhaps suggesting different underlying mechanisms, such as abnormal ventricular wall motion rather than acute ischemia in ST-segment elevation. The magnitude of ST-segment elevation was approximately twice that of the group with ST-segment depression, but it is unlikely that comparable degrees of ST-segment change for both elevation and depression indicate similar degrees of coronary obstruction.

The time taken for ST-segment elevation to resolve following exercise is longer than for depression (fig. 3). The rapidity with which ST-segment depression resolved after exercise emphasizes the need, first, to obtain high quality electrocardiographic recordings during exercise and second, to record immediately postexercise, i.e., no longer than 15 sec following cessation of exercise.¹⁴ In the group with ST-segment elevation, the time course of resolution was considerably slower, a mean elevation of greater than 1 mm being sustained until 9 minutes postexercise. In only one subject did significant ST-segment change occur maximally during the postexercise recovery period. The occurrence of this variant in only one subject is consistent with previous studies which have shown an incidence of approximately 10% of all cases showing ST-segment depression.¹⁵,¹⁶

In this study a relatively uniform RPP suggested that the myocardial oxygen requirements of maximum exercise were comparable for most subjects. However, those subjects in whom maximum RPP was less during cycle ergometer exercise than treadmill walking also exhibited less ST-segment depression. In these subjects adherence to rigid conventional criteria for evaluating ST-segment change would result in a different diagnostic interpretation. Redwood et al.⁶⁰ and Borer et al.⁶¹ have criticized the use of ST-segment depression alone in the diagnosis of coronary heart disease. Because of the controversy surrounding the interpretive value, Bruce²⁸ and El lstad²⁸ have emphasized the need to interpret ST-segment change in conjunction with abnormal physiological responses and clinical signs. Rifkin and Hoå have recently pointed out that there is a significant incidence of coronary artery pathology in patients showing exercise-induced ST-segment changes which do not reach the present conventional diagnostic limits, and suggest that interpretation of a test result in terms of likelihood or "risk" of coronary artery disease should take the wide spectrum of electrocardiographic changes into account.

Acknowledgment

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References

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Coronary Bypass Graft Fate

Angiographic Grading of 1400 Consecutive Grafts Early after Operation and of 1132 after One Year

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SUMMARY All 1400 coronary bypass grafts, in 409 survivors of 414 patients undergoing 440 consecutive bypass operations, were selectively opacified in multiple cineangiograms prior to hospital discharge and 1132 (81%) were restudied at one year. Grafts were graded A (excellent), B (fair) or O (occluded) by separate assessment of proximal and distal anastomoses and bypass trunks. In early graft studies 89% were patent (A and B), 79% graded A; at one year, 81% were patent, 74% graded A. Circumflex-marginal grafts fared less well early, but similarly late, compared with other grafts. Of all grafts graded B early, 37% became A, 39% remained B and 24% were occluded at one year; 90% of early graded A grafts remained so, 4% became B and 6% occluded; the grading system seems to have had useful predictive value. Distal anastomosis defects dictated early B grading in 81.3% of cases, trunk defects in 12.5% and proximal anastomosis defects in 2.7%. Trunk defects carried a worse prognosis for occlusion than did distal anastomosis defects. Side-to-side, vein-coronary anastomoses had a significantly higher patency rate than terminal end-to-side coronary anastomoses with the same veins.

Coronary bypass grafting will not become definitive treatment for coronary stenosis until its effectiveness in correcting myocardial perfusion deficit has been demonstrated conclusively. Further, apparent relief of ischemia, suggested by historical or functional criteria, requires support by morphologic data. To ensure this, a sufficiently large number of consecutively fashioned grafts must be studied and assessed using criteria more specific than "patent" or "occluded."

Prior to postoperative hospital discharge, we have examined, by selective angiography in multiple planes, all 1400 coronary bypass grafts placed in a series of patients consecutively operated on between 11 November 1971 and 10 November 1976; the only exclusions were grafts of patients dying perioperatively. Our policy is to reexamine coronary bypass grafts, using precisely the same technique, approximately one year after operation. By the time of writing we have already examined 1132 (81%) of the original 1400 grafts. We have devised a simple method for grading the
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