Maximal Treadmill Stress Testing for Cardiovascular Evaluation

By Myrvin H. Ellestad, M.D., William Allen, M.D., Maurice C. K. Wan, M.D., and George L. Kemp, M.D.

SUMMARY
Experience with a maximal treadmill stress testing procedure which is relatively safe, simple, and reproducible is reported. It has been used in normal persons and cardiac patients with ages ranging from 7 to 83 years. There have been no deaths in our total experience of 4,028 maximal capacity stress tests. Maximal capacity is predicted by the patient's peak predicted pulse rate. Sixty-three per cent of those with ischemic S-T segments did not experience pain of any type.

Additional Indexing Words:
Maximal capacity testing Ischemic S-T changes Peak predicted pulse rates
Monitoring Cardiac diagnosis

Almost 40 years ago Master and Oppenheimer introduced an exercise test for the detection of coronary insufficiency which many still consider to be the standard. The significance of exercise induced S-T segment depression as indicative of coronary insufficiency is accepted by most cardiologists. Master's single and double two-step test is accepted as the standard submaximal stress test, but there has been no uniform acceptance of a protocol for a maximal stress test.

It is the purpose of this paper to describe a method which has evolved in our laboratory and propose it as a standard maximal stress test. The procedure is simple to perform and requires a limited amount of special equipment. Experience with it has been extensive enough to establish norms of performance and to demonstrate its safety.

Methods
The first 1,000 patients referred to the Division of Clinical Physiology, of Memorial Hospital of Long Beach, for maximal treadmill stress testing were chosen for detailed analysis. Information as to their previous health was only known for 284 executives previously examined and thought to be normal by history and resting ECG. Many of the remainder were sent for evaluation of known or suspected angina, and many were sent for screening prior to embarking on a physical fitness program. Careful questioning as to symptoms, medication, and previous cardiac disease was done to rule out unstable coronary insufficiency and congestive failure. In the group were 205 females and 795 males with ages varying between 7 and 83 years.

No special attempt was made to standardize the time of day or the relationship of the last meal.

The patients are prepared by applying gel (Lectrocardiographic Gel) to the Telectrode electrode and affixing these self-adherent electrodes to the upper part of the manubrium sterni and the standard left chest V<sub>5</sub> position (CM-5). The cable attachments are then snapped to the electrodes and the cable is connected to a direct-writing Sanborn electrocardiograph. The electrocardiographic complexes are monitored continually with an oscilloscope. An aneroid sphygmomanometer is placed on the right arm for measurements of blood pressure. A cardiotachometer gives a constant read-out of the heart rate. Oxygen, emergency drugs, and a DC defibrillator are available in the room.

Resting electrocardiograms are taken while the patient is sitting and also while standing, before and after hyperventilation, and are used
Table 1

Ages and Maximal Pulse Rates (MPR)*

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*These figures are based upon regression figures of Robinson. Age groups from 10 to 20 years have been compiled by Astrand and associates, and range of MPR from 210 to 197, respectively.

as a base line for changes occurring during and after exercise. Blood pressure is also taken in the sitting and standing positions. The patient then steps onto a treadmill which has a fixed incline of 10% and walks for 3 min at 1.7 mph, 2 min at 3 mph, 2 min at 4 mph and finally, 3 min at 5 mph. Blood pressure and electrocardiogram are recorded at 1-min intervals during exercise and for a period of 8 min following exercise.

The exercise is terminated if the patient becomes exhausted, if the blood pressure falls significantly, if there is progressive S-T segment depression or pain, or if multiple premature ventricular contractions or ventricular tachycardia occurs. If none of these occur, the patient is urged to continue until he or she reaches at least 95% of the predicted maximal pulse rate. A compilation of maximal pulse rates (MPR) based upon age is listed from studies by Astrand and Norris and their associates (table 1).

Ischemic S-T change in the electrocardiogram occurring during or in the 8-min period of monitoring after maximal exercise stress testing is defined as a 2-mm depression below the isoelectric line lasting for 0.08 sec from the J-point (fig. 1). When the depressed S-T segment is not horizontal but slopes upward, a point 0.08 sec after the J-point is measured, and if it is 2 mm below a line drawn through the P-Q junction, the tracing is read as positive for ischemia. Depressions of lesser magnitude are read as equivocal for ischemia if the S-T segment is concave, but are considered as a normal finding if the S-T segment is convex. T-wave changes by themselves are not considered in the evaluation of ischemic response to exercise if there are no coexisting abnormalities in the S-T segment. Precipitation of frequent premature atrial or ventricular contractions or an increase in these if present at rest as well as runs of ventricular tachycardia during or after exercise are considered equivocal findings not necessarily indicative of myocardial ischemia.

Results

Safety

No deaths occurred during the testing in the 1,000 cases presented herein or from any of the subsequent 3,028 treadmill tests performed in our laboratory. Ventricular asystole and ventricular fibrillation were not seen. Transient ventricular tachycardia, lasting less than 20 sec and reverting spontaneously, occurred nine times. Only one patient required any therapy for ventricular tachycardia. He became slightly hypotensive and diaphoretic and was converted to normal sinus rhythm by DC countershock. Disturbances in A-V conduction were precipitated in only two patients. No patient fell from the apparatus although physical support was frequently needed at the end of walking to assist the patient in sitting down.

Transient vasovagal reactions, that is, mild hypotension and bradycardia in the early recovery period, occurred in less than 1% of the group. Hypotension during or after exercise occurred infrequently and was rarely a problem. Two patients had myocardial infarctions temporally related to the test, but both survived.

The safety of maximal stress testing has been demonstrated not only by this study but also by Bruce and others. It must be emphasized that safety requires continuous observation by an experienced physician. The test can then be terminated in time to avoid trouble, or the patient can be encouraged to continue long enough for us to obtain definitive data. A careful history, and if indicated, a
S-T Segment Change With Exercise

(A) This QRS-T complex demonstrates a normal configuration noted during or after maximal stress. J-point depression is associated with a convex J-X curve. (B) The J-point depression is associated with a slow return of the S-T segment to the base line. By measurement, a point 0.08 sec after the J-point is projected upward to bisect the S-T segment. If this intersection is 2 mm or more below the iso-electric line, the tracing is considered positive for ischemia. The J-X curve is concave. (C) This complex demonstrates the typical ischemic S-T segment depression seen after maximal stress. The S-T segment is depressed 2 mm or more below the iso-electric line and there is usually straightening of the S-T segment.

Figure 1

REPEATABILITY OF MAXIMAL EFFORT & ISCHEMIC S-T CHANGES

Of a total of 25 males who were retested by maximal treadmill exercise within a 90-day period, 92% performed for a similar length of time (within 1 min) and 95% developed S-T segment abnormalities at a similar time interval (within 1 min).

Reproducibility

To evaluate the reproducibility of a patient’s response to maximal treadmill stress testing, 25 males, 40 to 68 years old, had repeat stress tests within 1 to 90 days. Twenty-two of the patients had angina pectoris or a history of myocardial infarction, or both, and three did not. Fifteen patients (60%) performed for an identical time, eight (32%) walked 1 min less or 1 min more than they had on their previous treadmill test, and only two (8%) had a difference in duration of effort greater than 1 min on repeat study. Thus, in 92% the duration of exercise was within 1 min on the repeat study (fig. 2). The hypothesis

resting ECG should be repeated to prevent exercising a patient with recent infarction or unstable angina.
of more than chance reproducibility of performance was tested using the standard normal deviate, Z. The frequency categories were split into performance within 1 min and greater than 1 min, and were significant at less than the 0.01 level.

Twenty-two patients, all of whom had a positive history, exhibited ischemic S-T changes. Fifteen patients (68%) developed ischemic S-T changes at the identical time interval, six (27%) within 1 min of the previous time, and one (5%) had his S-T changes at a time interval greater than 1 min. The onset of ischemic S-T changes was separated by only 1 min or less in 95% of the patients. By splitting the frequency categories into less than 1 min and greater than 1 min, a Z test indicated significant reproducibility (less than 0.01 level of significance).

Incidence of Chest Pain

Of 284 apparently normal executives referred for treadmill stress testing as part of a routine physical examination, 30 (11%) developed ischemic S-T changes, and 10 (3.5%) had equivocal S-T changes during or after exercise. All of the executives were males, aged 30 to 59 years, and in none was heart disease previously suspected. It was surprising that in no instance was chest pain associated with ischemic abnormalities. This executive group will be the subject of a subsequent report.

A detailed analysis of the remaining 718 patients is not presented, since they were referred for various reasons, some of which were not apparent at the time of the test. However, the relationship between positive tests and chest pain in the total group is of interest. Only 88 (37%) of the 236 patients with positive tests had chest pain. Sixty-three per cent had ischemic changes without pain. The females had a 16% higher incidence of chest pain than the males (50% and 34%, respectively) with Z significant at less than 0.01 level. The younger males (31 to 40 years of age) stand out as the group which had the lowest percentage of chest pain (13%). Of the 88 patients who developed chest pain as well as ischemic S-T patterns, 61 (69%) experienced pain within the first 5 min.

Discussion

When considering an exercise stress test, several objectives should be kept in mind: (1) It should be safe, (2) should require a limited amount of special equipment, (3) should not be too time consuming, (4) should be adaptable enough in design so that it does not over stress some and under stress other cardiac patients, (5) should use a familiar form of exercise, and (6) results should be reproducible.9,12-14

The reproducible association between the exercise work load and the onset of S-T segment depression has been documented by Areskag,12 Burkart and their associates,13 and others.9,15 The product of systolic blood pressure multiplied by the pulse rate has been found by others to be even more predictive of the end point in patients with coronary insufficiency.16 It has been our impression that the more severe the disease, the more reproducible the test.

Since the cardiac output and oxygen consumption increase in nearly a linear relationship with the pulse, the peak pulse response allows us to estimate the maximal cardiac output.6-8 Many patients with coronary disease do not reach their predicted maximal pulse rate; however, in those with normal tests only 6% failed to reach a pulse rate of at least 80% of predicted value.

The advantage of our procedure over the Bruce procedure is based mainly on its simplicity and the fact that it takes less time to perform. The 10% incline is kept constant in our test in contrast to their changing inclines. However, if one wishes to study the well-trained athlete, the Bruce test has the advantage of requiring much higher levels of energy expenditure toward the end of the test.

The timing of the work periods has been arbitrarily set for convenience. The initial 3-min period functions as a warm-up and allows the patient to become acquainted with the uphill grade. When the speed reaches 4 mph, some subjects must jog and almost all must do so at 5 mph. It has been suggested that increasing the grade would be a more satisfactory method of increasing the work load,
but we have found that the stretch in the soleus muscles is very uncomfortable for untrained individuals at the higher inclines.

More study on the range of oxygen consumption at each speed is underway, but some preliminary data collected with the Webb metabolic rate monitor are available. At a speed of 1.7 mph the oxygen consumption is equivalent to 4 to 5 times the basal consumption of oxygen, at 3 mph to 6 to 7 times basal, at 4 mph to 9 to 10 times basal, and 5 mph to 15 times basal. \( \text{Vo}_{2}/\text{kg/min} \) for 10 middle-aged males averaged 4.2 at rest, 5 at 1.7 mph, 7 at 3 mph, 9 at 4 mph and 16 at 5 mph.\(^{17}\) These data are consistent with that presented by Gordon,\(^{18}\) Rowell and associates\(^{19}\) and Ford and Hellerstein\(^{20}\) and would suggest that 3 mph at a 10% grade is roughly equivalent to Master's single-step test and 4 mph is equivalent to Master's two-step test. We do not believe that it is practical to strive for a steady state at each work load.

The controversy over ECG criteria for diagnosis of ischemia by exercise has yet to be settled. We have used more stringent criteria for ischemia than those used by Master and Rosenfeld\(^{21}\) in order to avoid false positives as reported by Mattingly.\(^{14}\) Friedberg and associates\(^{22}\) found no false positives only when the S-T segment was depressed 2 mm or more. However, we believe that the criteria listed by us may be established eventually as too strict. Robb and Marks,\(^{23}\) using the standard double Master's test, have shown that even minimal S-T depression is associated with a higher mortality risk. This may not be as valid with maximal stress testing, however, because many young, seemingly healthy males and females have minimal S-T depression with this technic. Sensitivity might also be increased by using more than one ECG lead.\(^{12}\)

It should be stressed that little is known about the specificity and prognostic significance of ischemic S-T changes during and after maximal exercise. A recent paper by Most and co-workers\(^{24}\) supports the view, however, that relative ischemia is the most likely cause.

The infrequent occurrence of pain associated with S-T depression should be considered when the absence of angina is used to rule out the likelihood of coronary insufficiency. Exercise is often prescribed to the point of pain on the grounds that it is a reliable indicator of myocardial ischemia. Our experience indicates that more often than not ischemia, often associated with ventricular irritability, will develop unannounced by pain or any other symptom easily recognizable by the patient.

The fact that the incidence of pain is higher in patients manifesting S-T segment depression early in the test suggests that it may be partly related to the degree of ischemia. In those with S-T depression at or near peak pulse rate it was invariably absent. On the other hand, typical coronary pain in the absence of S-T depression is rare, and we have not seen it more than a few times. While we were able to discover 11% positive ischemic responses to the treadmill stress test in a group of executives without clinical heart disease, in no case were these ischemic changes associated with pain in the chest, even though each man was exercised to his maximal capacity.

Using maximal stress testing in the younger age groups seems particularly important. Sixty per cent of our males, aged 31 to 40 years with positive tests, would have been missed by submaximal testing.

We have used treadmill stress testing to discover subclinical coronary artery disease and to clarify the etiology of chest pain, to evaluate the results of cardiac surgery, and to assess medical management of coronary disease. It may also be helpful in developing exercise prescriptions for patients with coronary disease.*

References


2. Master, A. M., and Rosenfeld, I.: Can the

*Note: Pulse response graphs for untrained normal individuals, male and female, age 20 to 70 years, are available on request from M. H. Ellestad.
amount of S-T segment depression after the "two-step" test be correlated with the severity of ischemic heart disease? Amer J Cardiol 15: 139, 1965.
17. Kemp, G. L.: Rapid analysis of oxygen consumption during treadmill exercise. A.C.C. course, Instrumental Acquisition of Cardiological Data, Memorial Hospital of Long Beach, August 1 to 3, 1968.
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