du foramen ovale dans l'embolie paradoxale—detection par echocardiographie de contraste et test de provocation par la toux. Presse Med **12**:2371, 1983.
22. Higgins JR, Strunk BL, Schiller NB: Diagnosis of paradoxical embolism with contrast echocardiography. AM HEART J **107**:375, 1984.
23. Rodgers DM, Singh S, Meister SG: Contrast echocardiographic documentation of paradoxical embolism. AM HEART J **107**:1270, 1984.
24. Cheng TO: Echocardiogram and paradoxical embolism. Ann Intern Med **95**:515, 1981.
25. Nellessen U, Daniel WG, Matheis G, Oelert H, Depping K, Lichtlen PR: Impending paradoxical embolism from atrial thrombus—correct diagnosis by transesophageal echocardiography and prevention by surgery. J Am Coll Cardiol **5**:1002, 1985.
26. Valdes-Cruz LM, Pieroni DR, Roland JA, Varghese PJ: Echocardiographic detection of intracardiac right-to-left shunts following peripheral vein injections. Circulation **54**:558, 1976.
27. Seward JB, Tajak AJ, Hagler DJ, Ritter DG: Peripheral venous contrast echocardiography. Am J Cardiol **39**:202, 1977.
28. Banas JS Jr, Meister SG, Gazzaniga AB, O'Conner NE, Haynes FW, Dalen JE: A simple technique for detecting small defects in the atrial septum. Am J Cardiol **28**:467, 1971.
29. Johnson BI: Paradoxical embolism. J Clin Pathol **4**:316, 1951.
30. Sasahara AA, Sidd JJ, Tremblay G, Leland OS Jr: Cardiopulmonary consequences of acute pulmonary embolic disease. Prog Cardiovasc Dis **9**:259, 1966.
31. Miller R, Jordon R, Parker R, Edwards J: Thromboembolism in acute and healed myocardial infarction—systemic and pulmonary arterial occlusion. Circulation **6**:7, 1952.
32. Caplan LR, Hier DB, D'Cruz I: Cerebral embolism in the Michael Reese Stroke Registry. Stroke **14**:530, 1983.

Principles of exercise prescription for patients with coronary artery disease

Neil L. Coplan, M.D., Gilbert W. Gleim, Ph.D., and James A. Nicholas, M.D.
New York, N.Y.

Exercise prescription for patients with coronary artery disease should be designed so that exercise is both safe and effective. Exercise, like medication, must be tailored to the individual's needs. Sound exercise prescription requires that the entire patient be considered, including attitude and motivation (Fig. 1). Pathology outside the cardiovascular system may affect the cardiovascular response to exercise. For example, anemia alters the oxygen-carrying capacity of the blood and thereby may change the cardiac output needed to attain a given oxygen consumption.[1] Abnormalities of the musculoskeletal system—such as leg weakness from trauma—are frequently overlooked, but may also significantly affect the cardiovascular response to exercise.

The most commonly used tool for developing an exercise prescription is the treadmill exercise test. This test affords an opportunity to observe the physiologic effects of exercise in a controlled, monitored situation. The information obtained includes heart rate and blood pressure changes during exertion, the workload at which angina or ischemic changes on the ECG occur, the presence of exercise-induced arrhythmia, and the patient's functional capacity (i.e., the duration and intensity of exercise before having to stop). These data are used for diagnosis of cardiovascular disease and development of the exercise prescription.

However, information from the treadmill test alone is frequently not sufficient for determining a complete exercise prescription. There are two basic steps involved in formulating an exercise prescription: (1) determination of optimal exercise intensity and (2) adaptation of the recommendation to include other forms of exercise. The latter requires consideration of the cardiovascular response during different types of exertion. For example, arm exercise results in different hemodynamics and oxygen consumption than exercise with a large component of leg work.[2-4] Static exercise is associated with an

From the Institute of Sports Medicine and Athletic Trauma, and the Division of Cardiology, Lenox Hill Hospital.

Received for publication Jan. 9, 1986; accepted Feb. 10, 1986.

Reprint requests: Neil L. Coplan, M.D., Institute of Sports Medicine and Athletic Trauma, Lenox Hill Hospital, 130 E. 77th St., New York, NY 10021.

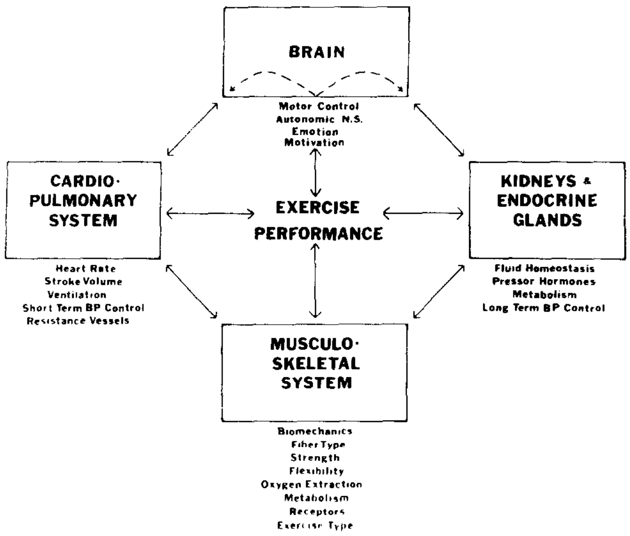

Fig. 1. Factors contributing to exercise performance. (Reproduced with permission from Gleim C, Coplan NL, Nicholas J: Bull NY Acad Sci **62**:211, 1986.)

increase in mean blood pressure, while dynamic exercise usually results in a significant increase in heart rate and oxygen consumption with little elevation of mean blood pressure. The physiologic principles underlying determination of optimal exercise intensity and generalization of the exercise prescription are discussed below.

Determination of optimal exercise intensity. The guidelines for determination of optimal exercise intensity from the treadmill test depend upon the population that is being tested. Patients with coronary artery disease can be divided into two broad groups, those with manifestations of ischemia (i.e., angina, ECG changes, etc.) during exertion and those without these findings. The optimal treadmill exercise intensity in the former group is a level below that at which evidence of ischemia occurs. Determination of the optimal treadmill exercise intensity in the latter group is much more difficult. Methods used include the recommendation that exercise should be done at an intensity that results in a certain percentage of maximal heart rate (i.e., target heart rate of 70% to 85% maximal heart rate) or in a target heart rate corresponding to a certain percentage of maximal oxygen consumption.[5]

Our bias is that the exercise prescription should be based on variables that reflect metabolic changes occurring during exertion. The lactate threshold—the term used to denote the work intensity at which plasma lactate begins to rise during incremental exercise—serves as a useful guideline.[6] Plasma catecholamines and renin begin to rise after incremental exercise surpasses the lactate threshold.[7-9] This pressor hormone response may have deleterious consequences for patients with coronary artery disease, hypertension, or arrhythmias. Indirect evidence suggests that exercise above the lactate threshold increases exertion-related mortality. A recent review of 15 cases of sudden death during cardiac rehabilitation showed that nine of the patients were exercising in excess of 85% of maximum heart rate,[10] and thus were likely to have been at an exercise intensity in excess of the lactate threshold.

The degree of work associated with the lactate threshold is influenced by many factors, including the presence of heart disease, peripheral vascular disease, and the individual's "fitness."[6,11] The lactate threshold does not occur at the same percentage of maximal heart rate in all patients, nor can it be related to the same percentage of maximal oxygen uptake. Consequently, it is difficult to do more than grossly approximate the value by use of a standard percentage of maximal heart rate or maximal oxygen uptake. Accurate determination of the lactate threshold requires additional information.

The best method for determination of the lactate threshold is to sequentially sample lactate during incremental exercise. Ventilatory measurements made during exercise can closely approximate the lactate threshold noninvasively.[6,12,13] Minute ventilation ($\dot{V}_e$), oxygen consumption ($\dot{V}O_2$), and carbon dioxide production ($\dot{V}CO_2$) all increase linearly during the initial stages of exercise. A nonlinear rise in $\dot{V}_e$ and $\dot{V}CO_2$ that is out-of-proportion to $\dot{V}O_2$ occurs at the work intensity corresponding to lactate threshold. This results in an increase in the ventilatory equivalent of oxygen ($\dot{V}_e/\dot{V}O_2$) and end-tidal O_2 at a point at which the ventilatory equivalent of carbon dioxide ($\dot{V}_e/\dot{V}CO_2$) and end-tidal CO_2 are relatively unchanged.

Ventilatory measurements during exercise can be used for deriving an exercise prescription (Fig. 2). An exercise intensity below that associated with the lactate threshold avoids hormonal and metabolic changes that may increase the risk of exercise. An additional benefit is the fact that exercise training below the lactate threshold is characterized by increased endurance capacity.[6,13] Exercise prescription from this method is based on the sum total of the many interacting factors that combine to influence functional capacity. The recommendation is individualized, and serves to minimize the risks and maximize the benefits that can be derived from exercise.

Adapting the exercise prescription to other forms of exercise. After determination of the optimal exercise intensity from the treadmill data, the exercise pre-

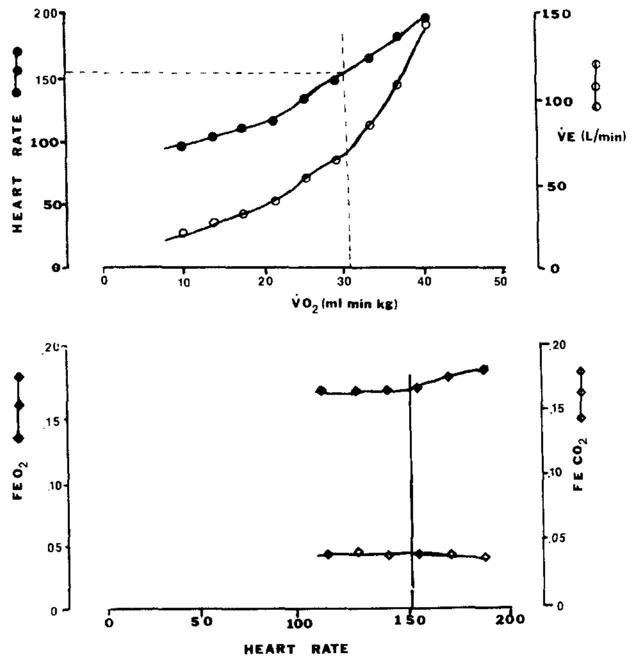

Fig. 2. Use of ventilatory measurements during exercise for determination of target heart rate. The slope of $\dot{V}_e$ vs $\dot{V}O_2$ increases and the percentage of oxygen in expired air increases at the level of activity associated with the lactate threshold. The heart rate at which these ventilatory changes occur, 150 bpm in this patient, can be used as the target heart rate. $\dot{V}O_2$ = oxygen consumption; $\dot{V}_e$ = minute ventilation; FE_{O_2} = fraction of O_2 in mixed expired air; FE_{CO_2} = fraction of CO_2 in mixed expired air.

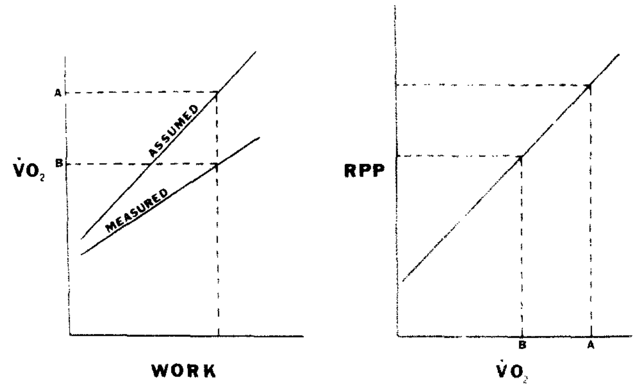

Fig. 3. Relationships of external work to oxygen consumption and oxygen consumption to rate-pressure product. Assumed oxygen consumption, derived from regression equations and based on the amount of work performed, may overestimate actual oxygen consumption. Exercise prescription based on assumed oxygen consumption *(A)* will then result in a higher rate-pressure product than exercise prescription based on measured oxygen consumption *(B)*, and may exceed the threshold for myocardial ischemia. $\dot{V}O_2$ = oxygen consumption; *RPP* = rate-pressure product (heart rate and systolic blood pressure), a correlate of myocardial oxygen consumption.

scription should be adapted to include other forms of exercise. Treadmill time can be related to other activities by use of a common denominator, either the oxygen consumption associated with performing work or the heart rate associated with performing a certain amount of work. Therefore, an exercise prescription is usually made in terms of either a target oxygen consumption or a target heart rate. Each approach has its limitations.

Exercise prescription based on oxygen consumption. Systemic oxygen consumption increases with incremental exercise until the point of maximal oxygen uptake is reached.[14] Maximal oxygen uptake is a measure of cardiovascular fitness, and is a function of maximal cardiac output and peripheral oxygen extraction.

The optimal exercise intensity, derived from treadmill testing, may be generalized to other forms of exercise by comparing the oxygen consumption safely achieved during treadmill exercise with the oxygen consumption that is predicted to be required for performance of other types of exercise (i.e., swimming, tennis, etc.).[5] This method is based on the principle that different types of exercise that elicit the same oxygen consumption will result in a similar cardiovascular response and myocardial oxygen consumption. This implies that equivalent work has an equivalent cardiovascular effect, regardless of how it is achieved. However, the relationship of myocardial oxygen consumption to systemic oxygen consumption (i.e., the efficiency of the circulatory response to exercise[15]) is affected by the type of exercise performed and by the patient's physical conditioning. Static exercise causes a higher heart rate and systolic blood pressure than dynamic exercise at a given work load.[16] Similarly, arm exercise results in higher indices of myocardial oxygen consumption than leg exercise at a similar total body oxygen uptake.[4] Differences in the degree of static/dynamic exercise and arm/leg work between a recreational activity and treadmill exercise may result in a myocardial oxygen consumption that varies from what would be expected based on observations during treadmill testing, and thus must be considered when formulating an exercise prescription.

Physical training improves circulatory efficiency, mainly by enhancing peripheral oxygen extraction.[17-19] This training effect is specific for the trained muscle group.[20,21] For example, the heart rate is lower at any given work level for arm work when the arm is trained; much less, if any, effect is evident for leg work when the arm is trained. Exercise prescription based on a trained muscle group may result in unexpectedly high heart rates if the activity level is generalized to untrained activity. A person in a rehabilitation program involving treadmill exercise may increase his treadmill exercise time substantially, yet continue to have angina when performing activities involving nontrained muscle groups.

Oxygen uptake during treadmill work is either measured directly or is approximated by use of regression equations (assumed oxygen consumption).[22] Exercise prescription based on an assumed oxygen consumption lacks precision. Assumed oxygen consumption may vary significantly from the actual measured oxygen consumption, and usually overestimates the real oxygen consumption.[23-25] Fig. 3 shows the effect this can have on exercise prescription. A recommendation of activity level based on a falsely elevated assumed oxygen consumption may result in a mycardial oxygen consumption that exceeds the threshold for ischemia. Measurement of ventilatory gases during the treadmill test eliminates this source of error.

Exercise prescription based on target heart rate. Many of the problems noted above can be avoided if generalization of the exercise prescription is made in terms of a target rate. This is based on the concept that exercise can be safely performed as long as the exercise heart rate does not exceed that which has been demonstrated to be safe during treadmill exercise. Activity level is guided by the heart rate response to whatever kind of exercise the patient wants to perform.

A generalized exercise prescription based on target heart rate is limited by the fact it only reflects the relationship between heart rate and myocardial oxygen consumption during ong type of exercise. Other forms of exercise may vary in the way the factors that contribute to myocardial oxygen consumption (i.e., heart rate, systolic blood pressure, left ventricular volume, and contractility) respond to exercise. Exercise that evokes similar heart rates but different systolic blood pressures will result in different myocardial demand. Thus, a patient may exceed the threshold for ischemia if the target heart rate determined from the treadmill is reached during arm exercise. It may be necessary to modify the target heart rate based on the hemodynamic response associated with the type of exercise the patient wants to do.

The target heart rate derived from ventilatory measurements also must be modified according to exercise type. The lactate threshold may vary significantly for different exercise modalities.[26] The result is that a target heart rate below lactate threshold on the treadmill may be above lactate threshold for another form of exercise. Once again, modification of the target heart rate is needed to achieve the most effective and practical exercise prescription.

Regardless of how the recommendation is formulated, it must be individualized to the patient's condition and needs. This may require determination of optimal exercise intensity based on a test that reflects the activity the patient wants to perform, rather than generalizing the recommendation from one standard test. Further alterations may be needed as a function of changes in the patient's underlying disease, medication, or training effect.

SUMMARY

Exercise performance is determined by the interaction of many systems. Cardiac disease, noncardiovascular pathology, physical training, and the hemodynamic response to the type of exercise the patient wants to perform should all be considered when developing an exercise prescription. There are two stages for deriving a complete exercise prescription, determination of optimal exercise intensity from an exercise test and adaption of the recommendation to include other forms of exercise. The recommendation is usually based on a target oxygen consumption or a target heart rate derived from a treadmill test, but both of these methods may be of limited effectiveness. Ventilatory measurements during exercise, which reflect metabolic changes, are a useful adjunct. The exercise prescription must be individualized to the patient's needs, and may have to be modified so that exercise intensity remains within acceptable limits.

REFERENCES

1. Zabetakis PM, Gleim GW, Pasternack FL, Seraniti A, Nicholas JA, Michelis MF: Long-term duration submaximal exercise conditioning in hemodyalysis patients. Clin Nephrol **18**:17, 1982.
2. Schwade J, Blomqvist CG, Shapiro W: A comparison of the resonse to arm and leg work in patients with ischemic heart disease. Am Heart J **94**:203, 1977.
3. Wahren W, Bygdeman G: Onset of angina pectoris in relation to circulatory adaption during arm and leg exercise. Circulation **44**:432, 1971.
4. Balady GJ, Weiner DA, McCabe CH, Ryan TJ: Value of arm testing in detecting coronary artery disease. Am J Cardiol **55**:37, 1985.
5. American College of Sports Medicine: Guidelines for graded exercise testing and exercise prescription. Philadelphia, 1980, Lea & Febiger.
6. Wasserman K: The anaerobic threshold measurement to evaluate exercise performance. Am Rev Respir Dis **129**:S35, 1974.
7. Lehman M, Keul J, Huber J, Da Prada M: Plasma catecholamines in trained and untrained volunteers during graduated exercise. Int J Sports Med **2**:143, 1981.
8. Lehman M, Schmid P, Keul J: Plasma catecholamine and

blood lactate cumulation during incremental exhaustive exercise. Int J Sports Med **6**:78, 1985.
9. Gleim GW, Zabetakis PM, DePasquale EE, Michelis MF, Nicholas JA: Plasma osmolality, volume, and renin activity at the "anaerobic threshold." J Appl Physiol **56**:57, 1984.
10. Mead WF, Pyfer HR, Trambold JC, Frederick RC: Successful resuscitation of two near simulaneous cases of cardiac arrest with a review of fifteen cases occurring during supervised exercise. Circulation **53**:187, 1976.
11. Davis JA, Frank MH, Whipp BJ, Wasserman K: Anaerobic threshold alterations caused by endurance training in middle aged men. J Appl Physiol **46**:1039, 1979.
12. Caiozzo VJ, Davis DA, Eccis JF, Azus JL, Vandagriff R, Prietto CA, McMaster WC: A comparison of gas exchange indices used to detect the anaerobic threshold. J Appl Physiol **53**:1184, 1982.
13. Davis JA: Anarobic threshold: Review of the concept and directions for future research. Med Sci Sports Exerc **17**:8, 1985.
14. Astrand P: Quantification of exercise capability and evaluation of physical capacity in man. Prog Cardiovasc Dis **19**:51, 1976.
15. Redwood DR, Rosing DR, Epstein SE: Circulatory and symptomatic effects of physical training in patients with coronary-artery disease and angina pectoris. N Engl J Med **286**:959, 1972.
16. Asmussen E: Similarities and dissimilarities between static and dynamic exercise. Circ Res **48**:(suppl I):I3, 1981.
17. Detry JR, Roussear M, Vandenbronche G: Increased arteriovenous oxygen difference after physical training in cornonary heart disease. Circulation **44**:109, 1971.
18. Paterson DH, Shephard RJ, Cunningham D: Effects of physical training upon cardiovascular function following myocardial infarction. J Appl Physiol **47**:482, 1979.
19. Amsterdam EA, Laslett LJ, Dressendorfer RH, Mason DT: Exercise training in coronary heart disease: Is there a cardiac effect? AM HEART J **101**:870, 1981.
20. Clausen JP: Circulatory adjustments to dynamic exercise and effect of physical training in normal subjects and in patients with coronary artery disease. Prog Cardiovasc Dis **18**:459, 1976.
21. Clausen JP, Klausen K, Rasmussen B: Central and peripheral circulatory changes after training of the arms or legs. Am J Physiol **225**:295, 1970.
22. Bruce RA, Kusumi F, Hosmer D: Maximal oxygen uptake and nomographic assessment of functional aerobic impairment in cardiovascular disease. AM HEART J **85**:546, 1973.
23. Miller MS, Singer DJ, Ribisl PM: Influence of beta blockade, cardiovascular fitness, and cardiovascular disease upon oxygen consumption during graded exercise (abstr). Med Sci Sport Ex **16**:189, 1984.
24. Smith J, Borysyk L, Dressendorfer RH, Gordon S, Timmis GC: Oxygen requirements during submaxmal graded treadmill exercise in coronary heart disease patients (abstr). Med Sci Sport Exerc **16**:189, 1984.
25. Ragg KE, Murray RF, Karbonit LM: Errors in predicting functional capacity from a treadmill exercise stress test. AM HEART J **100**:581, 1980.
26. Davis JA, Vodak P, Wilmore JH, Vodak J, Kurtz P: Anaerobic threshold and maximal aerobic power for three modes of exercise. J Appl Physiol **41**:544, 1976.