clinical investigations

An Algorithm for the Interpretation of Cardiopulmonary Exercise Tests*

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We have developed and are using an algorithm for the interpretation of cardiopulmonary exercise tests that are performed in our Pulmonary Diagnostic Service Department. As its decision points, this algorithm uses routinely obtained measurements from the results of these exercise tests, such as $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}E$, SaO_2, HR, and AT. Using the algorithm results in an objective determination of limitation to exercise and allows for the differentiation between pulmonary and cardiac or circulatory limitation. This straightforward technique for arriving at an interpretation of these tests has resulted in a more consistent approach to interpretation and an excellent teaching guide for physicians and technicians. ***(Chest 1990; 97:263-67)***

MVV = maximal voluntary ventilation; AT = anaerobic threshold; VR = ventilatory reserve; HRR = heart rate response;

Exercise testing has been used by cardiologists and pulmonologists for the evaluation of the heart and lungs under the physiologic stress of increasing external workloads. Cardiac stress tests were developed to evaluate possible ischemic changes that may occur as the pressure-pulse product or the modified tension time index is increased.[1] During a cardiac stress test, changes in the ECG and blood pressure are monitored during increasing workloads. Cardiopulmonary exercise tests in addition can help determine other potential limiting factors to exercise: the lungs; or the heart; or both. Thus, in addition to monitoring the ECG and blood pressure, cardiopulmonary exercise tests monitor exhaled oxygen, carbon dioxide, $\dot{V}E$, and arterial blood gas tensions or oxygen saturation (or both).

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Although much has been written regarding the basic physiologic responses to exercise, little information has been provided for a routine and consistent approach to the interpretation of a cardiopulmonary exercise test. One example of an interpretative technique is shown in a recent book by Wasserman and others.[2] We have developed and are currently using a simple algorithm for the interpretation of cardiopulmonary exercise tests. This algorithm is based upon the routinely obtained parameters of $\dot{V}E$, $\dot{V}O_2$, $\dot{V}CO_2$, HR, and SaO_2. With this algorithm, we can evaluate a patient's response to exercise and determine whether there was limitation to exercise because of the lungs, the heart, or both.

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Materials and Methods

Cardiopulmonary exercise tests were ordered by pulmonary physicians in our division and performed on patients with primary pulmonary diseases: chronic obstructive pulmonary disease; diffuse interstitial fibrosis; pulmonary vascular disease; occupational pulmonary disease; primary pulmonary hypertension; etc. Each patient had a full set of standard pulmonary function tests before the exercise test (flow/volume loop; lung volumes; Dco; 15-second MVV using a pneumotachograph-based pulmonary analyzer (Medical Graphics system 1070) and a body plethysmograph (Medical Graphics system 1085).

The cardiopulmonary exercise tests were performed using a treadmill (Marquette Electronics series 1825) and an exercise system analyzer for the analysis of exhaled gases and exhaled ventilation (Medical Graphics system 2001). The protocol used for these studies was either the pulmonary protocol or the low performance protocol as outlined in the manual for the treadmill (Marquette Electronics, Inc). In addition, electrocardiographic monitoring (Eaton Medical Group model G-2700) and noninvasive oximetry (Hewlett-Packard model 47201A) were performed on each patient during the exercise protocol. During the test, blood pressure was also measured using a portable sphygmomanometer. The $\dot{V}E$, respiratory rate, tidal volume, $\dot{V}O_2$, and $\dot{V}CO_2$ were measured on a breath-by-breath basis.

Testing was terminated when the patient signalled exhaustion, fatigue, shortness of breath, leg pain, or chest pain or when ST-segment changes or a cardiac arrhythmia was noted on the 12-lead ECG.

The following parameters were determined for each test and used for the interpretation of the results: $\dot{V}O_2$; $\dot{V}CO_2$; $\dot{V}E$; VR (VR = 1 - [$\dot{V}E$max/predicted MVV]); ventilatory equivalents ($\dot{V}E/\dot{V}O_2$; $\dot{V}E/\dot{V}CO_2$); oxygen saturation; HRR (discussed subsequently); and AT. The AT was expressed as the oxygen consumption at which the $\dot{V}E/\dot{V}O_2$ ratio increases and was determined graphically for each exercise

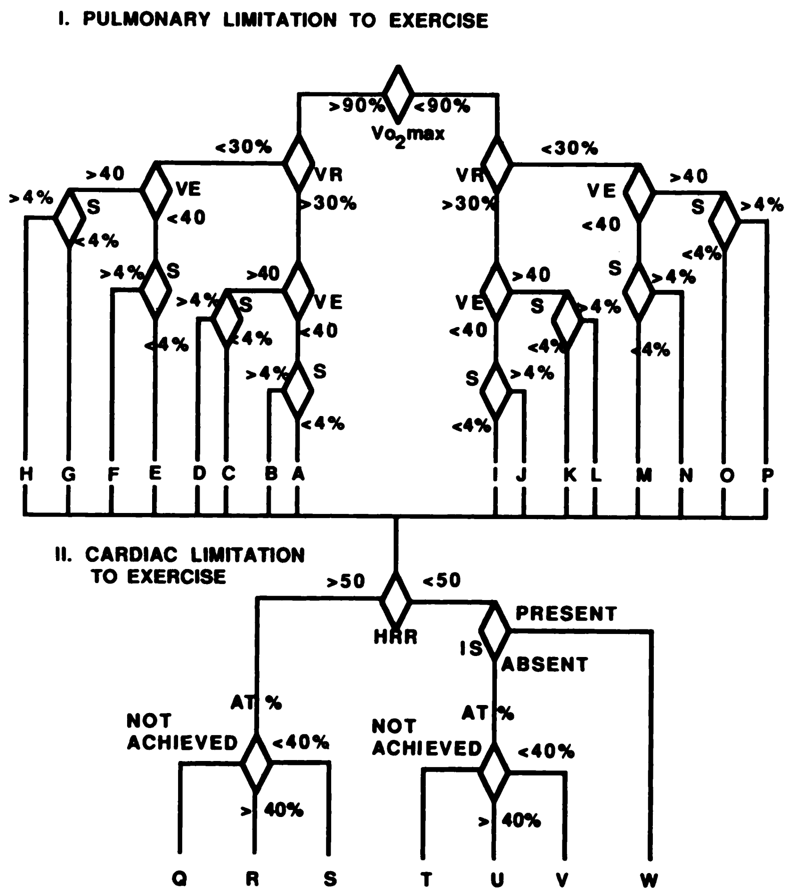

FIGURE 1. Algorithm for interpretation of cardiopulmonary exercise tests. VE, Ventilatory equivalent for carbon dioxide; S, change in SaO_2; IS, ischemic symptoms (chest pain, ST-segment changes, etc); and AT%, ratio of AT to $\dot{V}O_2$max. For explanation of interpretations, A through W, see Table 1.

test.[3]

The algorithm that we used for the actual interpretation of the results of cardiopulmonary exercise tests is shown in Figure 1. In this approach, there were certain parameters that were used as decision points for the evaluation of pulmonary and cardiac or circulatory limitation to exercise. The first parameter that was examined was the $\dot{V}O_2$max. This value for the patient should have been more than 90 percent of the predicted maximal value for that patient. The predicted values for $\dot{V}O_2$max were determined by regression equations and used by Medical Graphics Corp in their equipment.[4] When using separate equations for underweight and normal individuals vs obese individuals, Wasserman et al[2,3] have shown that subjects without pulmonary or cardiac limitation to exercise should achieve approximately 100 ± 10 percent of the predicted $\dot{V}O_2$max. Therefore, we have arbitrarily set 90 percent of predicted $\dot{V}O_2$max as the lower limit of normal. We realize that a more statistically appropriate guide could be used (*eg*, 95 percent confidence interval); however, we have found this limit of 90 percent to be simple to use and easy to teach. If an individual is able to achieve 90 percent or greater of his or her predicted $\dot{V}O_2$max, they may still have some pulmonary or cardiac limitation, but obviously, it would be mild in quality to allow them to achieve close to their predicted $\dot{V}O_2$max. On the other hand, if the patient is not able to achieve 90 percent of his or her predicted $\dot{V}O_2$max, then the pulmonary or cardiac limitation, if present, would be either moderate or severe in quality.

The next decision parameter that we used was the VR:

$$VR = [1 - (\dot{V}E\text{max/pred MVV})] \times 100\%$$

where the $\dot{V}E$max is the maximal minute ventilation achieved with exercise, and the predicted MVV is determined by $41 \times FEV_1$.[5] When an individual without pulmonary limitation exercises to a $\dot{V}O_2$max; he or she will still exhibit some VR. One report suggests that without pulmonary limitation, this reserve should be greater than 30 percent.[6] Patients with pulmonary disease may have no ventilatory reserve left at their $\dot{V}O_2$max. Patients with less than 30 percent VR are said to have a ventilatory mechanical limitation.

The next parameter that we used in our algorithm is the $\dot{V}E\text{max}/\dot{V}CO_2$. This value is a good overall determinant of the efficiency of the lung as a gas exchange unit. Normally, at maximal exercise, this value will be 25 to 35,[4] and values above 40 represent an excessive ventilation that is necessary to overcome the inability of the lung to excrete carbon dioxide due to gas exchange problems. Patients with values of $\dot{V}E\text{max}/\dot{V}CO_2$ of greater than 40 are said to have a gas exchange abnormality; however, another possibility for an increased ventilatory equivalent is any abnormal drive to ventilation such as anxiety. Usually, anxiety at the beginning of an exercise study can result in a ventilatory equivalent that is greater than 40; however, as exercise proceeds, this value will decrease as the drive to ventilation becomes more dependent upon the factors associated with exercise metabolism. This value will also increase again towards maximal exercise. The cutoff value that was chosen (40) should take into account the normal increases in this value with maximal exercise.[4]

Finally, for the determination of pulmonary limitation to exercise, we examined the change in SaO_2 either by arterial blood gas determinations or by noninvasive oximetry. The acccuracy of oximeters in measuring a change in oxygen saturation is ± 2.5 to ± 3.5 percent (95 percent confidence limits).[7] Therefore, a decrease in oxygen saturation of more than 4 percent is considered to be abnormal. In the context of exercise testing, desaturation can occur most commonly in patients with diffusion limitations,[8] although other pulmonary abnormalities, such as shunts or ventilation-perfusion mismatching, may result in exercise-associated desatura-

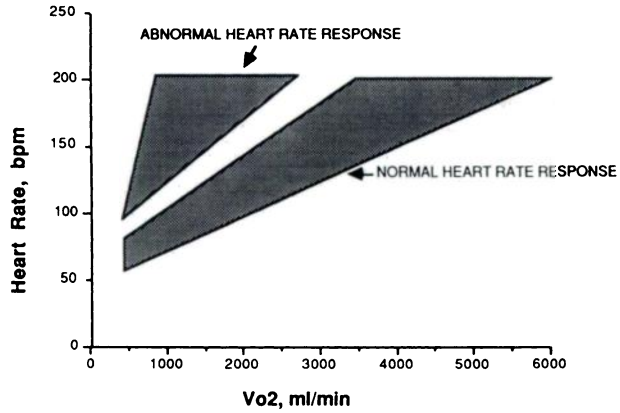

FIGURE 2. Normal and abnormal responses for increase in HR during exercise when plotted against increasing $\dot{V}O_2$max.

tion. Therefore, patients with desaturation with exercise are said to have a diffusion-type limitation.

After establishing whether the patient either does or does not have a pulmonary limitation to exercise, we then determined whether a cardiac or circulatory limitation to exercise may exist. Our first decision parameter for this determination was the HRR. Normally, there should be a linear relationship between oxygen consumption and HR.[9] If there are problems with the heart as a pump (*eg*, a cardiomyopathy), the HRR at any oxygen consumption may be inappropriately increased. As shown in Figure 2, the normal increases in HR with exercise are shown in the lower shaded area. An abnormal increase in HR with exercise is shown in the shaded area above the normal area. We can calculate HRR by the following formula:

$$HRR = (HRmax - HRrest)/\dot{V}O_2max - \dot{V}O_2rest)$$

where HRmax is the heart rate at maximal exercise, HRrest is the heart rate at rest, $\dot{V}O_2$max is the maximal oxygen consumption in liters per minute, and $\dot{V}O_2$rest is the oxygen consumption at rest in liters per minute. Normally, this ratio (HRR) will be 25 to 35 for trained individuals and 35 to 45 for sedentary or untrained subjects. Patients with a cardiomyopathy or deconditioning or other "cardiac pump" problem may have a HRR of more than 50. This value of 50 as a cutoff point between normal individuals and individuals with heart disease or deconditioning was chosen arbitrarily but was based upon the reported data for normal individuals.[9] These values apply only to patients who are not taking a medication that could block the HRR to exercise. For example, if a patient is receiving β-adrenergic blockade, his or her HRR to exercise can be decreased;[10] however, using this parameter, we can also identify patients who did not give a maximal effort and had a reduced $\dot{V}O_2$max. Their HRR will still be normal. Also, patients who did not achieve their $\dot{V}O_2$max because of only ventilatory limitation should also have a normal HRR; however, those patients with both a ventilatory and cardiac or circulatory limitation can be identified by having an increased HRR and a pulmonary limitation to exercise identified by the parameters listed previously.

If the HRR is normal (<50), we then determined if the exercise test was stopped because of electrocardiographic changes (depressed ST segments, arrhythmias, etc) or because of chest pain or hypotension. These all can suggest an ischemic cardiac limitation to exercise (IS = ischemic symptoms).

Finally, we examined the AT. We determined the ratio of the oxygen consumption at the AT with the actual $\dot{V}O_2$max achieved or the predicted $\dot{V}O_2$max. If this ratio is less than 40 percent, this suggests a circulatory or "pump" limitation to exercise. Normally, this ratio is 55 to 60 percent.[4] It can be decreased because the exercising muscles have switched over to anaerobic metabolism at

Table 1—*Interpretative Results Using Algorithm*

I. Pulmonary limitation to exercise
A. No pulmonary limitation or decreased effort or cardiac limitation
B. Mild diffusion-type limitation
C. Mild gas exchange abnormality
D. Mild gas exchange abnormality and diffusion-type limitation
E. Mild ventilatory mechanical limitation
F. Mild ventilatory mechanical limitation and diffusion-type limitation
G. Mild ventilatory mechanical limitation and gas exchange abnormality
H. Mild ventilatory mechanical limitation and gas exchange abnormality and diffusion-type limitation
I. Decreased effort or cardiac limitation
J. Moderate or severe diffusion-type limitation
K. Moderate or severe gas exchange abnormality
L. Moderate or severe gas exchange abnormality and diffusion-type limitation
M. Moderate or severe ventilatory mechanical limitation
N. Moderate or severe ventilatory mechanical limitation and diffusion-type limitation
O. Moderate or severe ventilatory mechanical limitation and gas exchange abnormality
P. Moderate or severe ventilatory mechanical limitation and gas exchange abnormality and diffusion-type limitation
II. Cardiac or circulatory limitation to exercise
Q. Moderate or severe cardiac "pump" limitation (cardiomyopathy; deconditioning)
R. Cardiac "pump" limitation (cardiomyopathy; deconditioning)
S. Cardiac "pump" limitation and circulatory limitation (pulmonary vascular or peripheral vascular disease, or "pump" limitation)
T. Moderate or severe pulmonary limitation (see J through P) or poor effort
U. No obvious cardiac or circulatory limitation
V. Circulatory limitation (pulmonary vascular or peripheral vascular disease, or "pump" limitation)
W. Ischemic heart disease

Table 2—*Use of Algorithm for 52-Year-Old Woman with Suspected Pulmonary Vascular Disease**

Data	Rest	Maximal Exercise
$\dot{V}O_2$, ml/min	280	1,081
$\dot{V}CO_2$, ml/min	240	1,259
$\dot{V}E$, L/min	9.6	62.9
$\dot{V}E/\dot{V}CO_2$	40.3	50.2
SaO_2, %	95	89
HR, bpm	93	153
AT, ml/min	...	428

*Baseline pulmonary function tests: FEV_1, 2.68 L/s (102 percent of predicted); FVC, 3.86 L (111 percent of predicted); and Dco, 12.24 ml/min/mm Hg (46 percent of predicted). Calculations: $\dot{V}O_2$max/$\dot{V}O_2$max predicted = 1,081/1,457 = 74 percent; VR = 1 − ($\dot{V}E$max/predicted MVV) = {1-[62.9/(2.68 × 41)]} × 100 = 41.3 percent; HRR = (HRmax − HRest)/$\dot{V}O_2$max − $\dot{V}O_2$rest) = (153 − 93)/(1.081 − .280) = 74.9; AT% = ($\dot{V}O_2$AT/$\dot{V}O_2$max) or ($\dot{V}O_2$AT/$\dot{V}O_2$max predicted) × 100 percent = (428/1,181) × 100 or (428/1,457) × 100 = 39.6 or 29.4 percent. Using algorithm: L and S: moderate or severe gas exchange and diffusion-type pulmonary limitation and cardiac "pump" and circulatory limitation (compatible with pulmonary vascular disease).

an earlier workload because of the inability of the heart or the circulation to provide the necessary oxygen for aerobic metabolism. If the AT is not reached at all, this suggests that there is either a pure moderate to severe pulmonary limitation to exercise, a mixed pulmonary and cardiac limitation, or poor effort by the patient.

Using the algorithm shown in Figure 1, we were able to arrive at the different interpretative diagnoses that are listed in Table 1. Each letter, A through W, represents the end of a pathway in the algorithm.

Results

Using this algorithm, we have interpreted more than 20 cardiopulmonary exercise tests that were performed in our laboratory. We have found that the interpretation of the tests when using this algorithm not only gave a more consistent result but also was an improvement upon the interpretation by our pulmonary faculty in several instances. An example of the use of the algorithm is shown by interpreting the results of an exercise test for a patient with suspected pulmonary vascular disease (Table 2). In this example, the woman with possible pulmonary vascular disease has normal pulmonary mechanics as part of her baseline pulmonary function tests but a decrease in her value for Dco. By exercise testing, we determine that she was not able to achieve her predicted $\dot{V}O_2max$, but she had a normal VR; however, the patient had an increased $\dot{V}Emax/\dot{V}CO_2$, and she had desaturation with exercise. In addition, she had an abnormal HRR (74.9), and her AT was less than 40 percent of either her $\dot{V}O_2max$ or her predicted $\dot{V}O_2max$. These factors taken together suggest that she has both pulmonary and cardiac limitation to exercise.

Table 3—*Comparison of Use of Our Algorithm with Algorithm of Wasserman et al*[2]*

Case	Our Interpretation	Interpretation of Wasserman et al[2]
1	Normal or decreased effort	Normal
2	Normal or decreased effort	Obesity usually with low breathing reserve
3	Decreased effort	Obesity usually with low breathing reserve
4	Mild ventilatory mechanical limitation	Obesity usually with low breathing reserve
5	Moderate or severe ventilatory mechanical limitation	Obstructive pulmonary disease
6	Moderate or severe ventilatory mechanical limitation and gas exchange abnormality and diffusion-type limitation	Obstructive pulmonary disease
7	Cardiac "pump" limitation (cardiomyopathy; deconditioning)	Early cardiovascular disease
8	Cardiac "pump" limitation (cardiomyopathy; deconditioning)	Obesity usually with low breathing reserve
9	Cardiac "pump" limitation (cardiomyopathy; deconditioning)	Poor effort or musculoskeletal disorder
10	Moderate or severe gas exchange abnormality with cardiac "pump" limitation and circulatory limitation (pulmonary vascular or peripheral vascular disease or "pump" limitation)	Pulmonary vascular disease without right-to-left shunt
11	Moderate or severe gas exchange abnormality and diffusion-type limitation with cardiac "pump" limitation and circulatory limitation (pulmonary vascular or peripheral vascular disease, or "pump" limitation)	Early pulmonary disease; pulmonary vascular disease

We have compared our algorithm with the algorithm provided by Wasserman and others.[2] We have taken 11 representative studies from our laboratory and used our algorithm and the algorithm of Wasserman and associates[2] to obtain interpretations of these tests. The results of this comparison is shown in Table 3 (the example shown in Table 2 is patient 11). We were pleased to find that for nine of the 11 examples, the two algorithms gave quite similar interpretations, especially in suggesting the same organ system that could be limiting. In the two exceptions (patients 8 and 9), we had suggested that some deconditioning or cardiac "pump" limitation could have existed, whereas by the algorithm of Wasserman et al[2] the limitation could have been due to obesity, poor effort, or musculoskeletal disorder. It is possible that both algorithms may be right in these two patients, in that these diagnoses are not mutually exclusive.

Discussion

We have described the use of an algorithm that will simplify the interpretation of a cardiopulmonary exercise test. As its decision points, this algorithm uses parameters that are routinely obtained during the performance of an exercise test that includes the measurement of exhaled gases. This method allows for the interpretation of a cardiopulmonary exercise test in a straight-forward manner, so that an objective assessment of limitation to exercise can be determined. Using this method, we can also differentiate between a pulmonary and a cardiac or circulatory limitation to exercise. Previously, other than the algorithm from Wasserman and colleagues,[2] only general guidelines were available for the interpretation of these exercise tests.[11-13] Use of this algorithm can result in a specific interpretation for the patient based upon objective test results. We believe that this approach will be quite useful for the evaluation of patients with known pulmonary or cardiac disease (or both) or for the patient with unexplained dyspnea, especially when the results are combined with routinely obtained pulmonary function studies. From a teaching perspective, this algorithm has resulted in a greater understanding and more consistent interpretations of cardiopulmonary exercise tests by our medical residents, pulmonary fellows, and pulmonary faculty.

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