Cardiopulmonary exercise testing in the assessment of exertional dyspnea

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Abstract:

Dyspnea on exertion is a commonly encountered problem in clinical practice. It is usually investigated by resting tests such as pulmonary function tests and echocardiogram, which may at times can be non-diagnostic. Cardiopulmonary exercise testing (CPET) measures physiologic parameters during exercise which can enable accurate identification of the cause of dyspnea. Though CPET has been around for decades and provides valuable and pertinent physiologic information on the integrated cardiopulmonary responses to exercise, it remains underutilized. The objective of this review is to provide a comprehensible overview of the underlying principles of exercise physiology, indications and contraindications of CPET, methodology and interpretative strategies involved and thereby increase the understanding of the insights that can be gained from the use of CPET.

Key words:
Anaerobic threshold, cardiopulmonary exercise test, carbon dioxide output, dyspnea, exercise limitation, oxygen uptake

Rationale for exercise testing

Exertional dyspnea is a common problem in patients with chronic lung diseases. This often leads to respiratory assessments such as spirometry, lung volume assessments, diffusing capacity, arterial blood gas determination, or cardiac assessments such as echocardiography. In essence, information from these tests which are performed in a resting state is used to assess a symptom which occurs with exertion. While this is often useful, exertional symptoms may correlate poorly with resting measurements.[1] Performing physiologic and subjective measurements during exercise often provides more relevant physiologic information and may give a more accurate estimate of functional capacity than testing done at rest in the laboratory. Furthermore, disease is often not confined to one organ system such as the lung, and testing the body's overall physiological response to exercise will provide useful data. This provides the general rationale for exercise testing in the evaluation of exertional dyspnea.

Categories of exercise testing

Several types of exercise tests are commonly performed in the clinical assessment of patients. These can be divided into field and laboratory tests. The former include the timed walk test (e.g., the 6 minute walk test)[2] and the incremental and endurance shuttle walk tests.[3] Besides giving an overall measurement of exercise capacity, these are easy to perform, are related to daily functional activities, and may even predict morbidity or mortality. They do not, however, provide much physiologic information on exercise limitation. Laboratory tests of exercise performance include the incremental and constant work rate cardiopulmonary exercise tests (CPET). Both provide a wealth of physiologic data. Incremental testing provides information on maximal responses and anaerobic threshold. Constant work rate testing, usually performed at a high fraction of maximal work rate is commonly performed before and after an intervention, such as bronchodilator therapy or exercise training.

Cardiopulmonary exercise testing (CPET)

CPET provides a comprehensive assessment of the exercise response, and reflects the influences (including interactions) of the cardiac, respiratory, musculoskeletal and hematological systems.[4] This testing provides data on respiratory gas exchange, including oxygen uptake (V_{O2}), and carbon dioxide output (V_{CO2}), tidal volume (VT) and minute ventilation (V_E), and other variables such as electrocardiographic, blood pressure and oxygen saturation. Testing can be done incrementally or at a constant work rate.

Integration of physiologic information allows for an analysis of the system as a whole,[5] while separate analyses help determine which system(s) limit exercise capacity or are related to exertional dyspnea. In general, CPET enables accurate determination of the physiologic reserves of the heart and lungs as well as functional capacity. Table 1 lists many of the physiologic variables measured during CPET.

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objective of this review is to provide a comprehensible overview of the underlying principles of exercise physiology, indications and contraindications of CPET, methodology and interpretative strategies involved and thereby increase the understanding of the insights that can be gained from the use of CPET.

A brief review of exercise physiology

A working knowledge of exercise physiology is essential to understand the various aspects of CPET. This is schematically illustrated in Figure 1. During exercise, to provide the energy required by the muscles, oxygen (O_2) is inhaled into the lungs, transported by the pulmonary vessels to the heart and delivered to the muscles by the arterial circulatory system. Q_{O2} is the O_2 utilized by the muscles and Q_{CO2} is the carbon dioxide (CO_2) produced by muscles with exercise which is then transported by the venous system to the heart and lungs and then exhaled. Analysis of the measured inspired and expired gases during exercise enables quantification of the oxygen consumed or oxygen uptake (V_{O2}) and the CO_2 generated (V_{CO2}). In steady state, $Q_{O2} = V_{O2}$ and $Q_{CO2} = V_{CO2}$.

Table 1: Parameters measured during CPET

Tidal Volume: VT

Breathing frequency: Respiratory Rate (RR or f)

Minute Ventilation: $V_E = VT \times RR$

Rate of O_2 consumption: O_2 uptake (V_{O2})

Maximal V_{O2}: $V_{O2\ max}$

Rate of CO_2 elimination: CO_2 output (V_{CO2})

Anaerobic threshold: AT

Respiratory Exchange ratio/ Respiratory Quotient (RER/RQ)

Heart Rate Reserve (HRR)

HR *vs.* V_{O2} slope

O2 pulse (V_{O2}/HR)

Ventilatory Reserve (VR)

Maximal ventilation (V_{Emax})

Ventilatory Equivalents for O_2 and CO_2 (V_E/ V_{O2} and V_E/V_{CO2})

End-tidal O_2: $PETO_2$
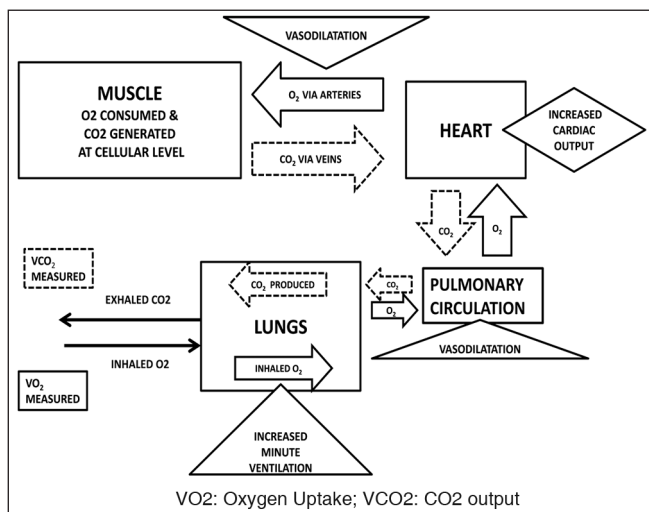
End-tidal CO_2: $PETCO_2$

Dead space/Tidal volume: V_D /V_T

Increased O_2 utilization by the muscles is achieved by increased O_2 extraction from blood perfusing exercising muscles, increased O_2 delivery by dilatation of the arteries, increased cardiac output (by increasing stroke volume and heart rate) and increasing pulmonary blood flow by recruitment of the pulmonary vasculature. As exercise results in increased CO_2 production, it is exhaled by the lungs by an increase in ventilation by a rise in tidal volume (VT) and respiratory rate.

Energy required for exercise is derived from adenosine triphosphate (ATP) which is generated in the cells by 3 processes — aerobic oxidation of glycogen and fatty acids, anaerobic hydrolysis of phosphocreatinine and anaerobic metabolism of glycogen.[6] This is illustrated in Figure 2. In the early phase of exercise, local stores of muscle phosphocreatinine provide energy. Aerobic glycogen and fatty acid metabolism provide the major source of ATP and constitutes the only source during moderate intensity exercise. During heavy or sustained exercise, aerobic metabolism is unable to meet the demand; consequently, anaerobic generation of ATP occurs.

With aerobic metabolism, V_{O2} and V_{CO2} are generated in proportion to the amount of glycogen and fatty acid oxidized, with increase in V_{O2} normally being slightly greater than the increase in V_{CO2}. With anaerobic metabolism, lactic acid generated, is neutralized by bicarbonate (HCO_3), resulting in increased CO_2 production. Hence V_{CO2} rises more than VO_2 in anaerobic exercise. This further burdens the ventilatory system, which must eliminate this excess CO_2.

The effects of increasing exercise intensity on ventilatory and gas exchange parameters are depicted in Figure 3. As work rate increases, V_{O2}, V_{CO2} and minute ventilation (V_E) increases linearly till anaerobic metabolism causes lactic acidosis.[7] Once lactic acidosis develops, HCO_3 buffers lactate and more CO_2 is generated ($H^+ + HCO_3^- = H_2CO_3 = H_2O + CO_2$). Consequently, rise in V_{CO2} is higher than rise in V_{O2} as more CO_2 is produced from HCO_3 buffering of lactic acid. V_E rises at the same rate and in proportion to rise in V_{CO2}. Hence, V_E/V_{CO2} and PET_{CO2} remain unchanged while PET_{O2} and V_E/V_{O2} increases. With continued exercise, with worsening lactic acidosis, ventilation increases markedly to compensate for exercise-induced metabolic acidosis. The rise in V_E is more than the rise in V_{CO2}. So V_E/V_{CO2} increases while PET_{CO2} falls.

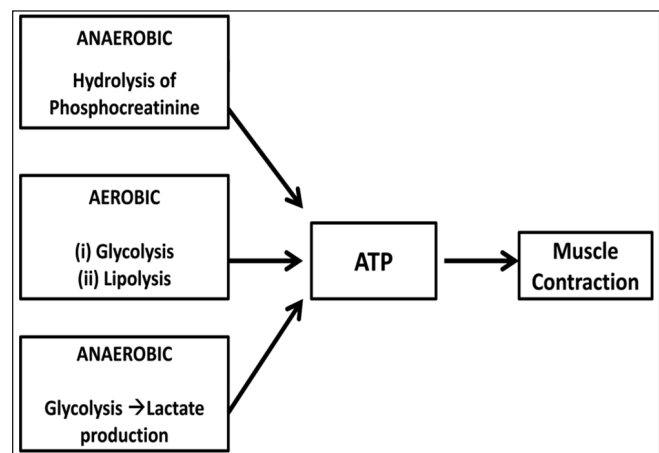**Figure 1:** Physiologic response to exercise

Figure 2: Cell bioenergetics during exercise

With increasing work, the point at which anaerobic metabolism begins is referred to as anaerobic threshold (AT).[8] At AT, V_{O2} does not decrease but V_{CO2} rises due to buffering of lactic acid generated by anaerobic metabolism. In incremental exercise testing, the AT is usually expressed as the V_{O2} at which this process begins. It can be measured directly by demonstrating an increase in lactate in arterial blood or indirectly through its effects on V_{O2} and V_{CO2}: Lactate entering the system is buffered by HCO_3, resulting in an increase in the slope of V_{CO2} and resulting in increased VE. The *indirect* measurement of AT is commonly performed using the V-slope method [Figure 4], which determines when the V_{CO2}–V_{O2} slope abruptly increases.

During exercise, heart rate, respiratory rate, VT and V_E increase. V_{O2} and V_{CO2} rise steadily till anaerobic threshold is reached. With exercise, dead space (V_D) decreases due to increased pulmonary blood flow causing increased recruitment of pulmonary vessels. With increasing workload, V_{O2} peaks and remains constant, even though work intensity continues to increase. Maximal V_{O2} during exercise, which plateaus and remains constant, despite further increases in exercise intensity is V_{O2max}. It serves as an indicator of exercise capacity.[9]

Indications for CPET
CPET is useful in determining the cause of exercise intolerance not diagnosed by history, physical examination, chest radiograph, PFTS and resting electrocardiogram and ECHO.
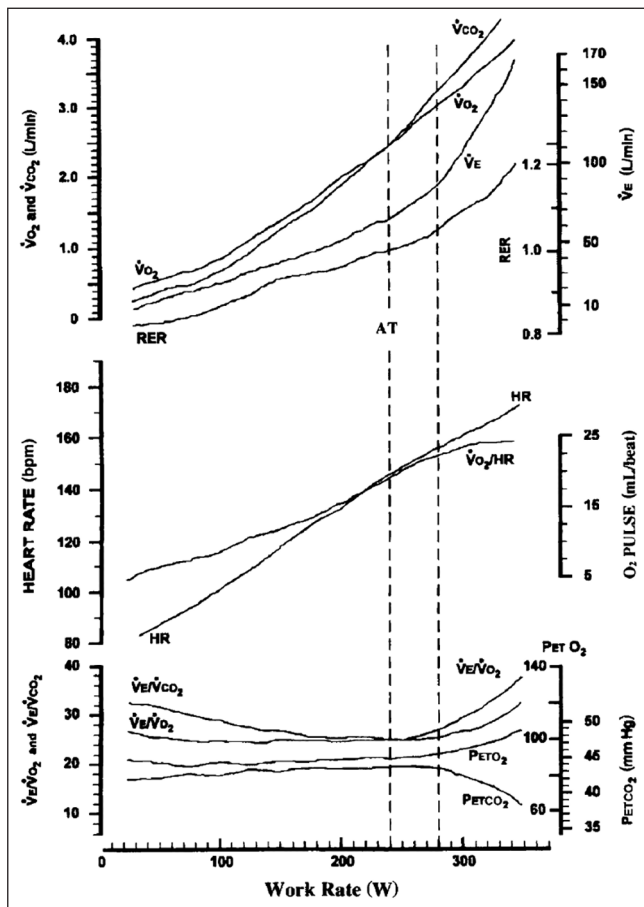

Figure 3: Changes in physiological parameters with exercise (From Weisman: Clinics in Chest Medicine 2001, with permission.)

Common indications for CPET are shown in Table 2. Absolute contraindications for CPET are shown in Table 3. Relative contraindications for CPET include uncontrolled hypertension (SBP > 200, DBP > 120), moderate cardiac valvular stenosis, hypertrophic obstructive cardiomyopathy, high-grade AV block, significant pulmonary hypertension, advanced/ complicated pregnancy, significant dyselectrolytemia and orthopedic or neurologic impediments to exercise.

CPET Methodology

Cycle ergometer or treadmill?
Exercise testing in CPET is usually performed in the laboratory using a stationary cycle ergometer or a treadmill, although newer portable metabolic devices may permit exercise testing in non-traditional laboratory settings such as during activities of daily living.[10] Whether a cycle ergometer or a treadmill is used often depends more on the equipment in the particular laboratory and experience and preference of the testers than the specific clinical indication of the testing. Exercise testing on a cycle ergometer is less likely to be associated with falls. Many consider the electrically braked cycle ergometry the preferred method of testing since it produces less movement artifact, facilitates obtaining arterial blood specimen drawing, provides a smooth increase in load. In addition, it is less affected by weight and gait dynamics which allows for a more accurate estimate of the externally applied work. An important advantage of treadmill testing is that, unlike cycling, walking and running are familiar activities that are incorporated into many activities of

Table 2: Indications for CPET
Evaluation of dyspnea of unclear etiology after routine cardiopulmonary testing
Determination of functional impairment in exercise intolerance
Evaluation of patients with heart disease for cardiac transplantation
Evaluation of patients for lung/ heart-lung transplantation
Evaluation for exercise-induced bronchospasm
Preoperative evaluation prior to lung resection surgery
Assessment of response to therapeutic interventions in patients with lung disease
Evaluation for disability
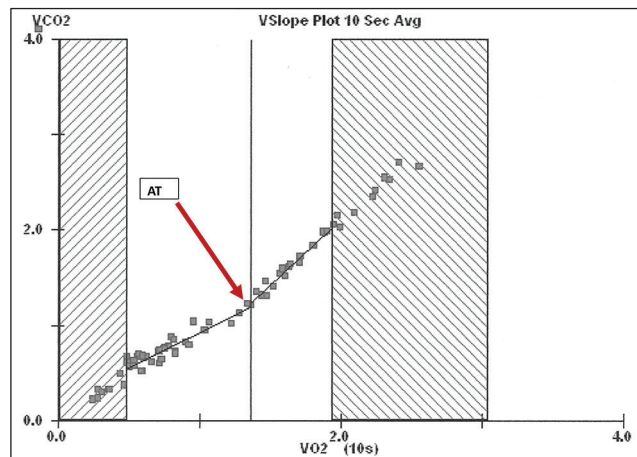Exercise prescription for cardiac and pulmonary rehabilitation

Figure 4: The V-slope method of determining Anaerobic Threshold (AT)

daily living. V_{O2max} in treadmill exercise testing is considerably more affected by body weight with treadmill testing than cycle ergometry.[11,12] Even if workload is estimated using weight, incline and speed, if the patient leans on the handrails this will introduce substantial error in this measurement.

Peak work rate, as expressed by V_{O2}, is about 5-10% higher with treadmill testing than cycle ergometry,[13] probably because more muscles are used. Exercise-induced hypoxemia in COPD patients appears to be more pronounced during treadmill testing than on the cycle ergometer.

Exercise protocols

Most CPET protocols generally fall into two broad categories:
1. Incremental tests up to maximal exercise and
2. Constant work rate test.

These approaches provide different information and have different clinical indications. Incremental exercise testing involves gradually increasing work rate in a continuous or stepwise fashion over time. In cycle ergometer testing, work rate is usually increased by 5-25 watts each minute after a warm-up period of 1-3 minutes of unloaded pedaling. Exercise is usually continued to the point of symptom-limitation unless medical complications (such as chest pain, ECG changes, hemodynamic abnormalities, gait issues) develop. Criteria for terminating CPET[11] include:
1. Chest pain suggestive of angina,
2. Ischemic EKG changes,
3. Complex ectopy or 2nd or 3rd degree AV block,
4. Drop in SBP > 20 mmHg from highest value during test,
5. Uncontrolled hypertension (SBP > 250 mmHg; DBP > 120 mmHg),
6. O_2 desaturation with O_2 saturation <80% or cyanosis and (viii) Dizziness or mental confusion or loss of coordination.

The pre-set rate increase in watts is determined by the exercise physiologist based on the physical state of the patient. In general, a test lasting 8-12 minutes is ideal.[14] This is long enough to provide useful physiologic information yet not so long as to be burdensome to the patient and staff. In severely limited patients, 5 minutes exercise time is reasonable. Incremental treadmill testing is similar in concept, but requires gradual increase in walking speed and incline. Incremental testing provides information on maximal exercise performance

(such as peak VO_2) and potential mechanisms limiting that performance.

A typical protocol for constant work rate cycle ergometer testing is to begin with a 1 to 3 minute period of unloaded pedaling for warm-up, then increase workload abruptly to a high percentage (such as 75%) of that patient's maximal work rate.[11,15] Exercise is generally continued to a symptom-limited maximum. This approach, therefore, requires a prior incremental test to determine maximal work rate and a period of time (usually one or more days) to recover from the first test. The constant work test is useful for determining response to therapeutic interventions such as bronchodilators and pulmonary rehabilitation.

Measurements

As stated earlier, an important advantage of CPET is that it not only determines maximal exercise performance, but also supplies important physiologic information during exercise. This may permit an analysis of physiologic derangement leading to exercise limitation and symptom-generation. The instruments used for measurement of physiologic variables during CPET are shown schematically in Figure 5.[11] Stringent calibration of sensors to minimize errors is extremely important for quality control.

The primary physiologic measurements during CPET include the following physiologic information:
1. Cardiac monitoring: Continuous heart rate, rhythm, and ECG changes
2. Hemodynamic monitoring: Blood pressure at set intervals
3. Breath-by-breath analysis of inspired and expired gas: V_{O2}, V_{CO2}
4. Pneumotachograph: Tidal volume, respiratory rate, V_E, inspiratory capacity (IC)
5. Pulse oximetry: Continuous measurement of oxygen saturation
6. Symptom assessment: Periodic assessments of dyspnea and leg fatigue using a category (Borg) or analog (visual analog) scale.

In selected cases, arterial blood is obtained during exercise testing to provide additional physiologic data. This may include
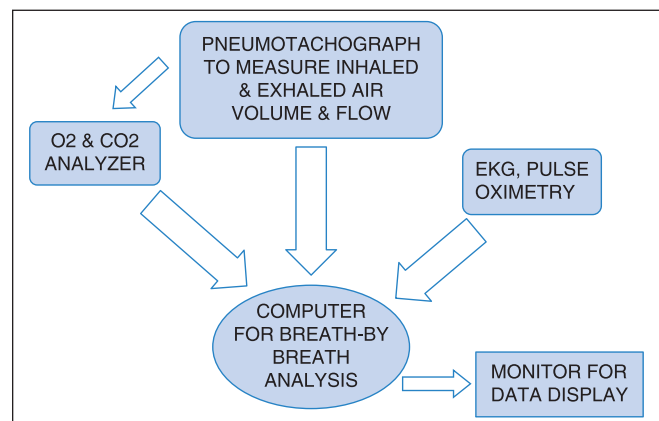1. Arterial blood gas determinations
2. Lactate levels

Table 3: Absolute contraindications for CPET

Acute coronary insufficiency

Syncope

Uncontrolled arrhythmia

Acute myocarditis/pericarditis

Decompensated heart failure

 Acute pulmonary edema

Severe cardiac valvular stenosis

Suspected dissected aneurysm

Resting O2 saturation <85%

Acute Renal failure

Untreated thyrotoxicosis

Acute infection

Mental impairment/inability to follow instructions

Figure 5: Automated system for CPET

Physiologic parameters derived from the above measured data also provide important information. These derived measurements include: Ve/VO$_2$, Ve/VCO$_2$, VO$_{2max}$, O$_2$ pulse (VO$_2$/HR), Work efficiency (δ VO$_2$/δ WR), Anaerobic threshold (AT), Respiratory quotient (R) (VCO$_2$/VO$_2$), Dead space: (VD/VT), P(A-a) O$_2$, Heart Rate Reserve and Breathing Reserve.

In addition to numeric data, composite graphic display of ventilatory and gas exchange parameters can be generated.[16] Computer analysis of physiologic data allows the generation of VO$_2$ and VCO$_2$ on a breath-by-breath basis.[17]

Physiologic variables measured during CPET
The following parameters are important in the interpretation of CPET and are discussed in more detail.

Oxygen uptake (V$_{O2}$):[2,3,18]
This is calculated from the difference between the volume of O$_2$ in the inhaled and exhaled air during exercise per unit of time and in steady state is equal to metabolic O$_2$ consumption. The measurement of V$_{O2}$ is based on the equation:

$V_{O2} = VI \times FIO_2 - VE \times FEO_2$,
where VI = Volume of inhaled air
VE = Volume of exhaled air
FIO$_2$ = Concentration of O$_2$ in the inhaled gases
FEO$_2$ = Concentration of O$_2$ in the exhaled gases

V$_{O2}$ is determined by cellular O$_2$ demand and increases linearly as external work increases. In healthy subjects, a faster rate of increase in work results in a greater amount of work being achieved while peak VO$_2$ achieved is independent of the rate of increase in work.[19] The slope of the relationship between the increase in work *versus* the change in VO$_2$ determined during incremental CPET is unaffected by age, sex or height. A reduction in the value of this relationship is indicative of the abnormalities in O2 transport and utilization.

As work increases, V$_{O2}$ increases until a point where it begins to plateau. This represents the highest attainable V$_{O2}$ for a subject and is known as maximal V$_{O2}$ or V$_{O2max}$. It represents the maximal achievable level of oxidative metabolism involving large muscle groups. If a clear plateau is not obtained during CPET, the highest VO$_2$ attained is the V$_{O2peak}$ and can be used as a substitute for V$_{O2max}$. V$_{O2max}$ (as well as V$_{O2Peak}$) serves as the index of aerobic exercise capacity. V$_{O2max}$ and V$_{O2Peak}$ should be expressed as an absolute value (in Liters/minute) as well as a percentage of predicted, referenced to body weight (in milliliters/kg/minute). A reduced V$_{O2max}$ or V$_{O2Peak}$ reflects reduced exercise capacity which may be due to cardiac, pulmonary, gas exchange, neuromuscular, muscular or effort limitation. However, in obesity, VO$_{2max}$ and VO$_{2Peak}$ are reduced in reference to body weight but the absolute value remains normal.[20]

Carbon dioxide output (VCO$_2$)
This is calculated from the difference between the volume of CO$_2$ in the inhaled and exhaled air during exercise per unit of time and represents metabolic CO$_2$ output. The measurement of V$_{CO2}$ is based on the equation:

$V_{CO2} = VE \times F_{ECO2}$,

where VE = Volume of exhaled air
FE$_{CO2}$ = Concentration of O$_2$ in the exhaled gases

V$_{CO2}$ is affected by the same factors as V$_{O2}$. However, it is more dependent on ventilation due to the increased solubility of CO$_2$ in the blood. Several variables in CPET including the RER/RQ, V$_D$/V$_T$ and ventilatory equivalents are derived from V$_{CO2}$.

Respiratory exchange ratio (RER)
This is derived from the ratio of VCO$_2$/VO$_2$ and corresponds to the gas exchange ratio. In steady state, it equals the Respiratory Quotient (RQ) which represents metabolism at the tissue level. Metabolism predominantly from carbohydrates results in an RQ of 1, while metabolism of protein results in an RQ of 0.8 and from fat, an RQ of 0.7. The production of lactic acid during exercise results in an RER greater than 1, since extra CO$_2$ is introduced into the system from bicarbonate buffering of the acid. Therefore an RER substantially greater than 1 at peak exercise is one marker of maximal effort. Hyperventilation may also cause an RER>1.

Anaerobic threshold (AT)
This represents the VO$_2$ at which anaerobic metabolism sets in during exercise. It can be expressed in L/min or as a percentage of the predicted value of V$_{O2max}$. Direct measurement of AT requires continuous arterial sampling of lactate. However, it can be reasonably estimated from continuous physiologic data. In the modified V-slope method the AT is identified as that point where the slope of the relationship of V$_{CO2}$ to V$_{O2}$ changes. The abrupt increase in VCO$_2$ indicates an increase in the rate of CO$_2$ production from lactate buffering by bicarbonate.[21] In many cases the AT cannot be estimated from physiologic data. In other cases, exercise is limited before the AT is reached, such as in ventilatory-limited COPD patients. Its normal value is >40% of predicted V$_{O2max}$.

Heart rate reserve (HRR)
It is the difference between maximum predicted heart rate and the observed maximum heart rate during CPET. Its normal value is <15. A high HRR may indicate a sub-maximal effort.

VO$_2$-work rate relationship
The relationship between VO$_2$ and work rate at peak work rate is approximately 10 mL/min/watt. Values lower than this suggests abnormalities with oxygen delivery. It may be elevated in obesity.

O$_2$ pulse (VO$_2$/HR)
This is determined by dividing VO$_2$ by HR and is expressed as mL/beat. A low O$_2$ pulse during exercise may indicate a reduced stroke volume or an abnormality in skeletal muscle O$_2$ extraction. A low HR during exercise, such as from beta-blocker medications, may elevate the O2 pulse by decreasing the denominator.

Maximal ventilation (V$_{Emax}$)
Minute ventilation (V$_E$) is the volume of air exhaled from the lungs in 1 min. With exercise, V$_E$ increases due to increase in both tidal volume and respiratory frequency. The normal maximal value of respiratory frequency is less than 60 breaths per minute while the maximal VT is generally less than 60% of the vital capacity.[22] V$_{Emax}$, the maximal ventilation achieved during exercise, reflects ventilatory demand.[23] Abnormalities

in V_{Emax} may indicate respiratory or neuromuscular limitation to exercise.

Ventilatory reserve (VR)

This reflects the difference between the measured or estimated maximal voluntary ventilation (MVV) and the V_{Emax}. MVV is the volume of air that can be breathed per minute at rest with maximal effort. While the MVV can be determined in the lab, it can be reasonably estimated by multiplying the FEV1 by 35. VR is usually determined by the formula: VR= (V_{Emax} /MVV) × 100. Normal values are ≥15% to ≤85%. VR is usually reduced in individuals with ventilatory limitation to exercise, such as patients with obstructive airways disease or interstitial lung disease.

Ventilatory equivalents for O_2 and CO_2 (V_E/ V_{O2} and V_E/V_{CO2})

The ventilatory equivalent for O_2 (V_E/ V_{O2}) is the ratio of V_E to V_{O2}, while the ventilatory equivalent for CO_2 (V_E/V_{CO2}) is the ratio of V_E to V_{CO2}. With increasing exercise, V_E/V_{O2} initially falls, reaches its nadir near the anaerobic threshold, and then rises. V_E/V_{CO2} follows a similar trajectory, but rises after the rise in V_E/V_{O2}, due to compensatory hyperventilation to counter metabolic acidosis. High values of V_E/V_{CO2} are indicative of increased dead space during exercise. If the V_E/V_{O2} and V_E/V_{CO2} do not rise with maximal exercise that indicates high airway resistance or a general increase in pulmonary muscle load. Both increase with hyperventilation.

Dead space to tidal volume ratio (V_D/V_T)

The V_D/V_T reflects the adequacy or efficiency of gas exchange. With exercise, V_D/V_T decreases as tidal volume increase in response to increased metabolic demand and dead space ventilation remains relatively unchanged. An elevated V_D/V_T or absence of reduction in V_D/V_T with exercise suggests pulmonary vascular disease such as pulmonary hypertension.

Interpreting data from CPET

Exercise limitation during CPET is indicated by a reduced VO_{2Peak}. Exercise limitation could be secondary to cardiovascular, ventilatory, gas exchange, or neuromuscular limitation. In addition, physical deconditioning and poor effort are also considerations. Moreover, exercise limitation may result from several of the above limitations, although one factor is usually of more significance than the others.[24] Furthermore, overlap in response patterns to exercise may exist, sometimes making exact distinctions in mechanisms of exercise limitation problematical.

Before interpreting a CPET, it is essential to assess whether patient effort was adequate. Adequate effort is indicated by the following:
1. Attaining maximal predicted heart rate,
2. Attaining maximal predicted minute ventilation (V_E),
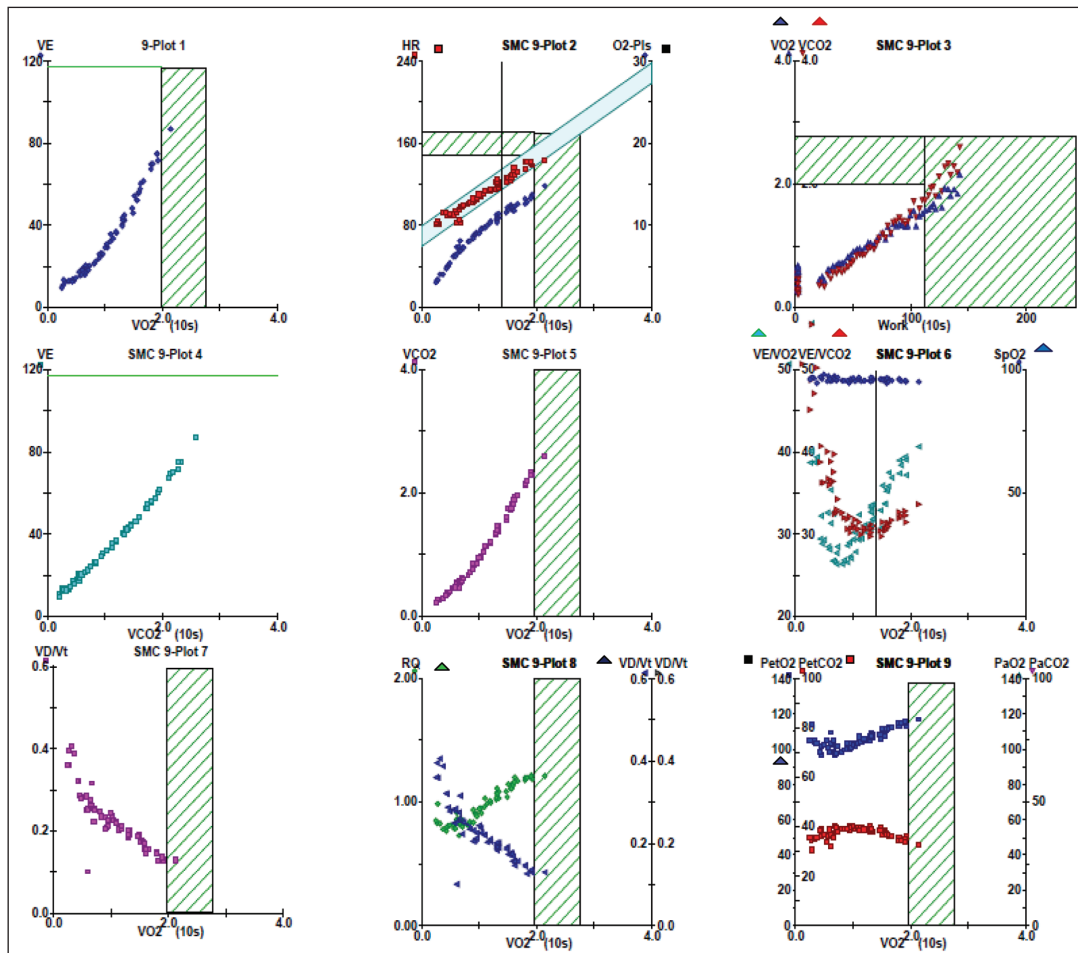3. RQ > 1.15, (iv) patient showing signs of exhaustion.

Figure 6: Graphic display of response to exercise in a normal subject on cardiopulmonary exercise testing

Other conditions, such as significant O_2-desaturation, chest pain, lightheadedness, ECG abnormalities, orthopedic symptoms, or unexpected changes in blood pressure, may limit exercise before maximal effort is attained.

Certain physiologic patterns during exercise may indicate the cause of exercise limitation. The CPET pattern in some common disease states causing exercise limitation is as follows:

CPET pattern in cardiac disease

Exercise capacity is reduced as indicated by a reduced V_{O2max}. Cardiovascular responses are abnormal- heart rate reserve is decreased or absent and O_2 pulse is reduced. Anaerobic threshold (AT) is early onset and less than 40% predicted V_{O2max}. Ventilatory responses are normal, including normal Ventilatory Reserve (V_{Emax}/MVV), normal maximal respiratory rate (<50/minute) and a normal $paCO_2$. In cardiac

disease, gas exchange maybe mildly abnormal, with a mildly reduced dead space (V_D/V_T) at rest and a mildly increased ventilatory equivalents for O_2 and CO_2 (V_E/V_{O2} and V_E/V_{CO2}) at AT.

The effect of exercise on physiologic parameters studied during CPET in a normal subject is shown in Figure 6. The changes in various physiologic parameters with exercise in heart disease (cardiac limitation to exercise) are depicted graphically in Figure 7.

CPET pattern in lung disease

Exercise capacity (V_{O2max}) is reduced. Ventilatory responses are abnormal: Maximal voluntary ventilation (MVV) and Ventilatory Reserve (V_{Emax}/MVV) are reduced; respiratory rate at maximal exercise is increased (>50/minute) and hypercapnia may be present. Cardiovascular responses are normal/borderline abnormal. Heart rate reserve may be increased or normal; O_2
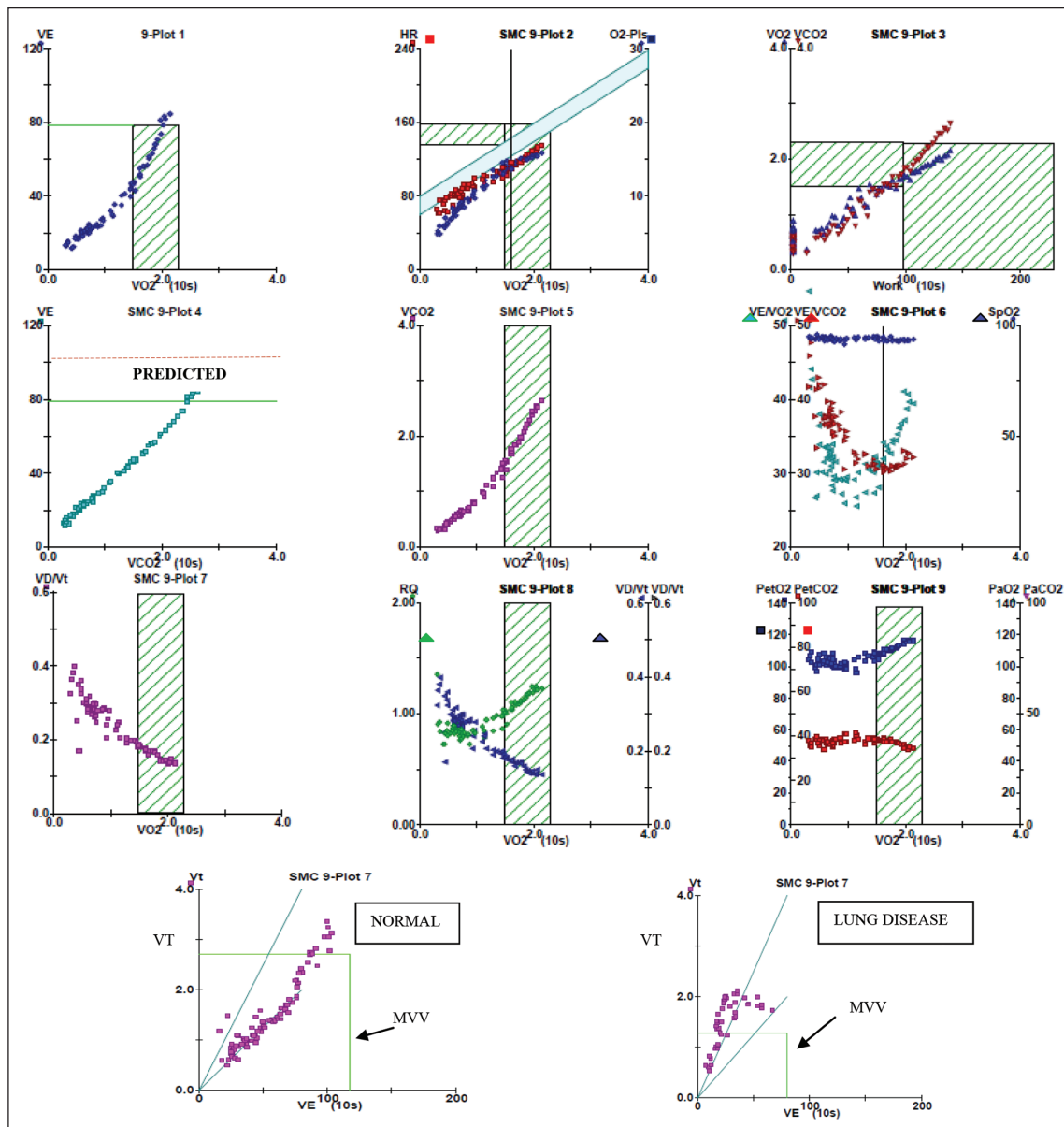

Figure 7: Graphic display of response to exercise in patient with lung disease on cardiopulmonary exercise testing (ventilatory limitation to exercise)

pulse will be normal and AT may be normal or indeterminate. Mild gas exchange abnormalities may be present such as increased dead space (V_D/V_T) at rest with < normal reduction with exercise and ventilatory equivalent for CO_2 and O_2 (V_E/V_{CO2} and V_E/V_{O2}) may be mildly increased with reduced pO_2 or oxygen saturation with exercise. Individuals with ventilatory limitation to maximal exercise may have an increased heart rate reserve at peak exercise because ventilatory limitation may have occurred before cardiovascular limitation set in. The AT may be normal, reduced or indeterminate in individuals with ventilatory limitation. A decrease in end-tidal O_2 (PETO2) and CO_2 (PETO2) also indicates ventilatory limitation. The changes in various physiologic parameters with exercise in lung disease (ventilatory limitation to exercise) are depicted graphically in Figure 8.

CPET pattern in pulmonary vascular disease

Exercise capacity is reduced, with a reduced V_{O2max}. Cardiovascular responses are abnormal with low or absent

heart rate reserve and low O_2 pulse. AT is early onset and reduced to <40% of predicted V_{O2max}. Gas exchange is significantly abnormal with a moderate-to-severely increased dead space-to-tidal volume ratio (V_D/V_T) at rest and no reduction in V_D/V_T with exercise. Ventilatory equivalent for O_2 and CO_2 (V_E/V_{CO2} and V_E/V_{O2}) at AT is markedly increased with a low pO_2/oxygen saturation and a markedly increased A-a gradient. In pulmonary vascular disease, ventilatory responses are normal with a low normal Ventilatory Reserve (V_{Emax}/MVV), respiratory rate at maximal exercise <50/minute and a normal $paCO_2$. The AT may or may not be reduced with gas exchange limitation. The changes in various physiologic parameters with exercise in pulmonary vascular disease (gas exchange limitation to exercise) are depicted graphically in Figure 9.[7]

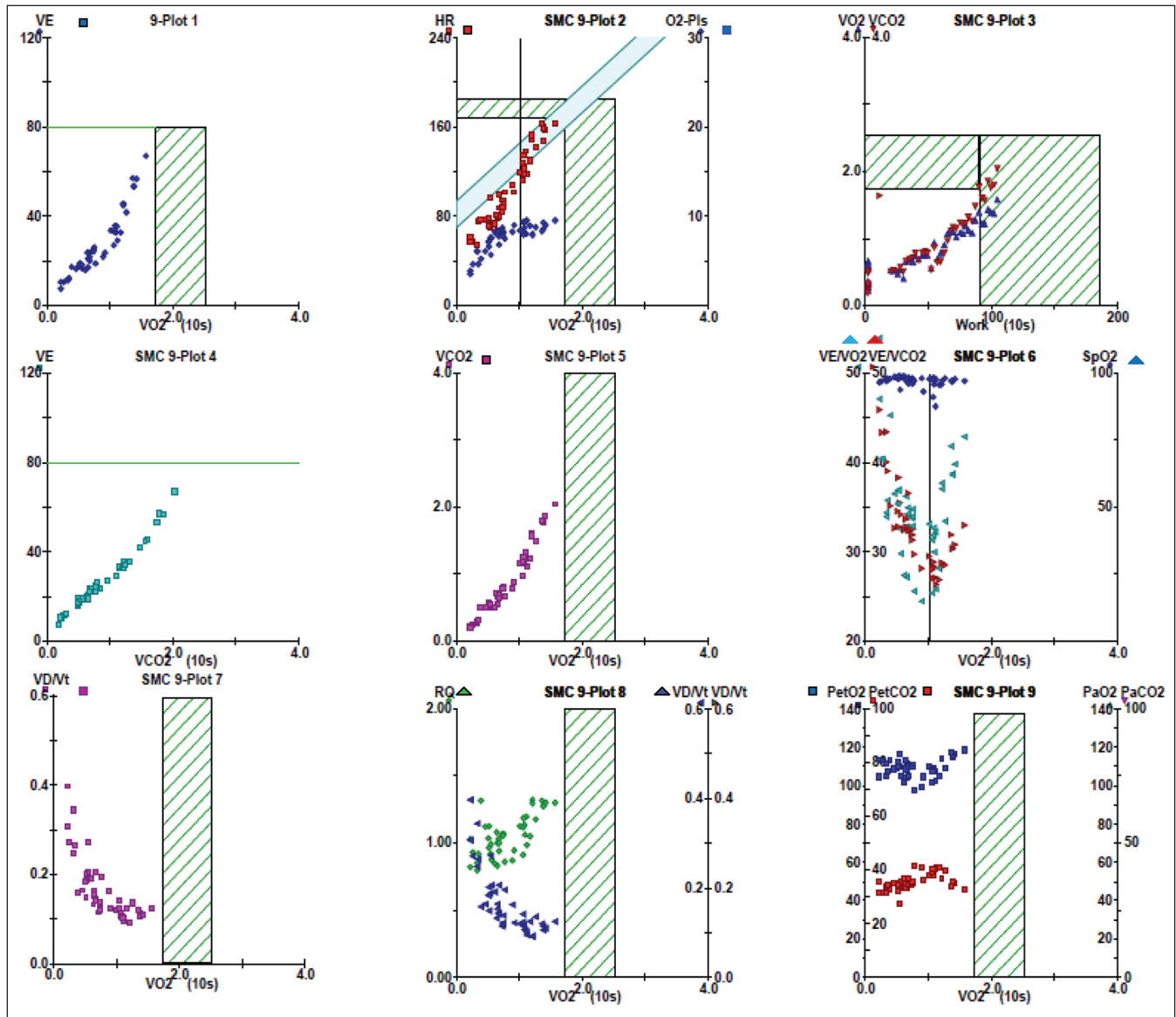Otherwise healthy obese individuals have increased workload during exercise, but often their physiologic patterns are

Figure 8: Graphic display of response to exercise in patient with heart disease on cardiopulmonary exercise testing (cardiac limitation to exercise)
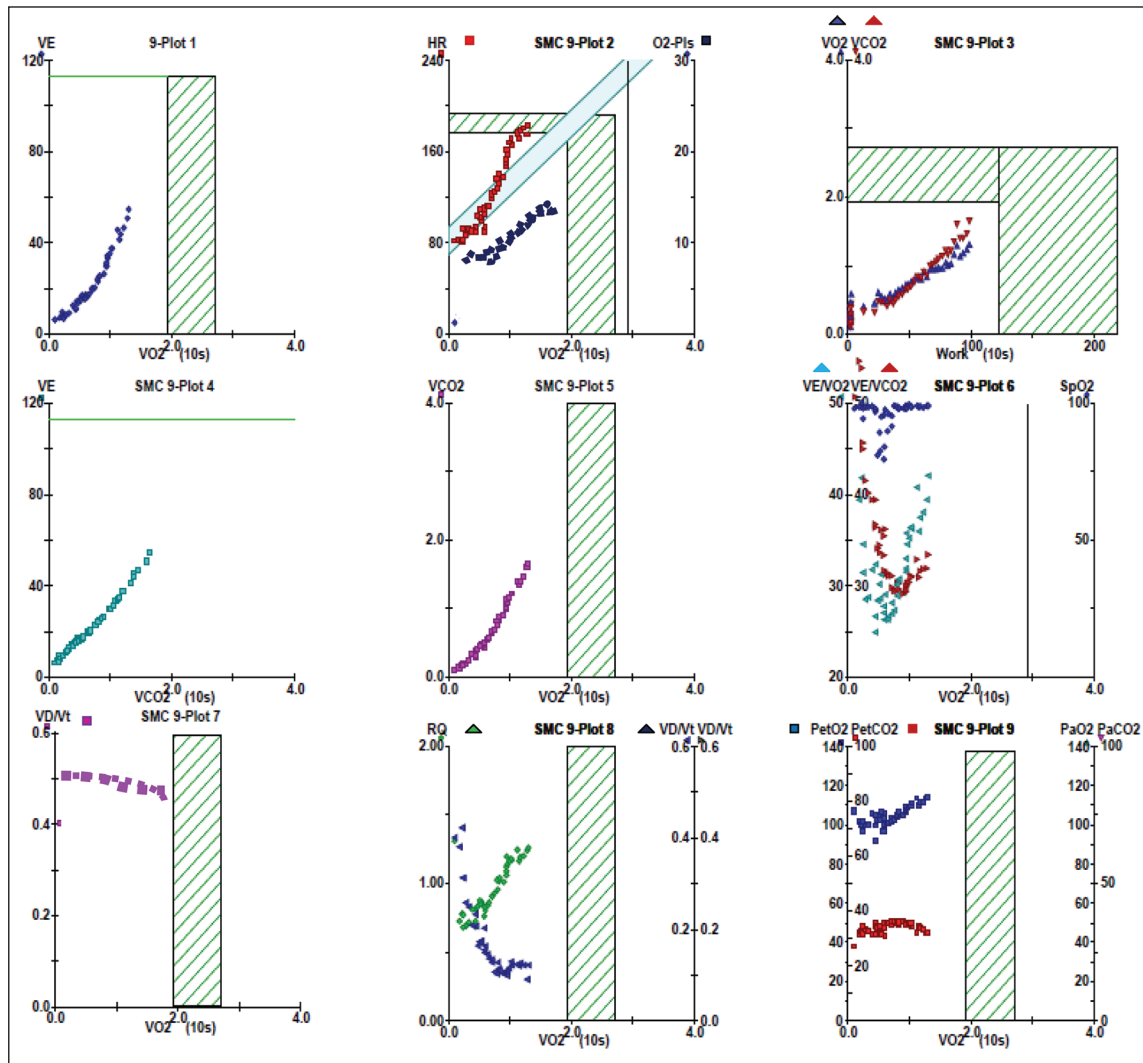
Figure 9: Graphic display of response to exercise in a pattient with pulmonary hypertension on cardiopulmonary exercise testing (gas exchange limitation to exercise)

normal. The peak VO_2 in obesity is normal when expressed as L/min, but is low when expressed as ml/kg/min.[25] Exercise limitation due to physical deconditioning is characterized by reduced V_{O2max} or V_{O2peak}; as such it may be difficult at times to differentiate from disease state limitations. Heart rate reserve may be reduced or absent. AT may be normal or reduced; O_2 pulse is reduced.[4] There is no evidence of ventilatory and gas exchange abnormalities. Suboptimal effort may be suspected by premature cessation of exercise, a reduced V_{O2peak}, a normal or unattained AT, in conjunction with markedly increased heart rate reserve and ventilatory reserve and low RQ. The presence of irregular and erratic breathing patterns and respiratory rates unrelated to increase in work may be a clue to malingering.

Conclusion

The evaluation of exercise symptoms, such as exertional dyspnea, usually begins with tests done at rest, such as spirometry, echocardiography, or radiographic procedures. These assessments often provide useful information relating to the diagnosis of the limitation and its severity. CPET should be considered when there is some discord between the patient's symptoms or stated level of exercise limitation and the baseline diagnostic information. It makes sense to assess symptoms, limitation and physiologic responses during exercise rather than inferring these responses from tests done at rest. CPET adds complementary information to our usual diagnostic testing. The information obtained from CPET can alter the management of an individual patient by identifying the cause of exercise limitation. In some cases, exertional dyspnea may be related to obesity and deconditioning, which can be detected by CPET and help to provide reassurance to patients, as well as prevent further utilization of resources in further testing to determine cause of exercise intolerance.

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