

# **Interpreting an Exercise Test**

**Douglas R. Knight, MD, PhD**

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Introduction

Exercise test report

    Protocol

    Functional capacity

    Blood pressure

    Breathing pattern

    Pulse oximeter

Case studies

Terminology

References

## INTRODUCTION

**Objectives.** Clinicians order an exercise test to evaluate the function of the cardiorespiratory system. The purpose of this web-site is to explain the exercise test. The INTRODUCTION presents the rationale for employing progressive exercise to exhaustion as a stimulus of cardiorespiratory function. The next section, entitled EXERCISE TEST REPORT, explains the analysis of exercise test data. The FICK CALCULATOR- and CASE STUDY- sections describe the interpretation of test findings. Italicized words are defined in the section on TERMINOLOGY.

**Exercise test.** The subject is asked to perform progressive *dynamic exercise* to exhaustion while connected to the 12-lead electrocardiogram, a blood pressure cuff, the pulse oximeter, and a mouthpiece or face mask. The mouthpiece or face mask is used to measure the subject's *respiratory gas exchange*.

**Cardiorespiratory system.** The *cardiorespiratory system* is a group of organs that collectively transfer oxygen (O<sub>2</sub>) and carbon dioxide (CO<sub>2</sub>) between the atmosphere and *mitochondria*. Mitochondrial respiration transforms O<sub>2</sub> into CO<sub>2</sub>, water, and energy. A portion of the energy is stored in *ATP* and the rest is released as heat. The cardiorespiratory system is linked to the *neuromuscular system* at the *sarcomere*, which produces muscle contraction by extracting energy from ATP. During exercise, the greatest portion of the body's demand for O<sub>2</sub> resides in the total volume of muscle mitochondria [Weible, 1984].

*Respiratory gases*, O<sub>2</sub> and CO<sub>2</sub>, are transported through the cardiorespiratory system by the integrated processes of breathing, blood flow, and diffusion. The diffusion of respiratory gases across the alveolar wall is so rapid that unsaturated hemoglobin becomes saturated with O<sub>2</sub> as blood flows through pulmonary capillaries. Consequently, the rate of O<sub>2</sub> uptake ( $\dot{V}O_2$ ) by unsaturated hemoglobin increases with the blood flow ( $\dot{Q}$ ) through pulmonary capillaries [West, 1995; Gallagher, 2000].

**Functional capacity.** The *functional capacity* of an organ system is its maximal limit of performance under conditions of stress which do not cause structural damage. Progressive exercise to exhaustion stimulates the cardiorespiratory system to operate at functional capacity as determined by the assessment of respiratory gas exchange during

exercise. The  $\dot{V}O_2$  increases directly with the power output of working muscles by approximately 10 ml O<sub>2</sub>/min/watt above baseline exertion. At maximal exertion, working muscles consume nearly 85% of the maximal  $\dot{V}O_2$  [Poole, 1992]. The maximal  $\dot{V}O_2$  ( $\dot{V}O_{2max}$ ) is reproducible in serial exercise tests and represents the cardiorespiratory system's functional capacity for O<sub>2</sub> transport.

**Fick principle.** The *Fick principle* enables clinicians to calculate blood flow by injecting a known amount of tracer between two vascular sampling sites which differ in their steady-state blood concentration of the tracer substance. Equation 1 illustrates the use of O<sub>2</sub> as a tracer to calculate the cardiac output [Godfrey; 1974; Jones, 1997].

$$\dot{Q} = \frac{\dot{V}O_2}{CaO_2 - C\bar{v}O_2}$$

**Eq. 1: Fick principle.**  $\dot{Q}$  is the flow of blood between sample sites.  $\dot{V}O_2$  is the body's rate of O<sub>2</sub> uptake. The  $CaO_2$  and  $C\bar{v}O_2$  are respective concentrations of O<sub>2</sub> in samples of arterial (subscript a) and mixed venous (subscript  $\bar{v}$ ) blood.

Equation 2 illustrates the use of the Fick principle to predict and interpret the cardiorespiratory response to maximal exertion [BarOr, 1983; Gallagher, 2000].

Arrhythmia, abnormal Stroke volume

Lung dysfunction, Anemia, Right-to-left shunt

Muscle dysfunction, Left-to-right shunt

$$\dot{V}O_{2max} = \dot{Q} (CaO_2 - C\bar{v}O_2)$$

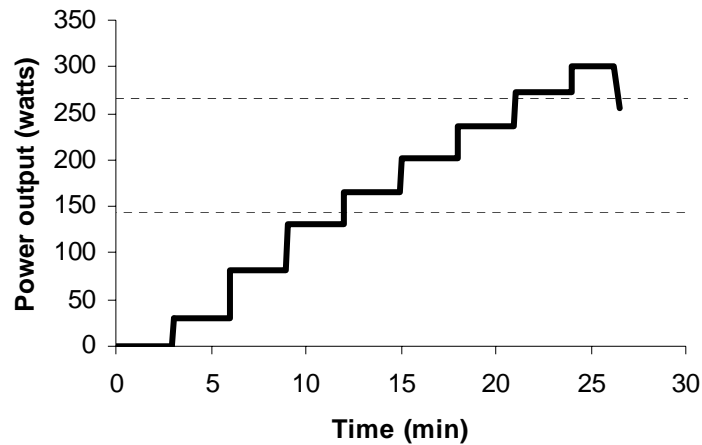
**Eq. 2: Applications of the Fick principle.**  $\dot{V}O_{2max}$  represents the functional capacity for O<sub>2</sub> transport. The callouts identify abnormalities that might reduce  $\dot{V}O_{2max}$ .

**PREDICTION:** Suppose that  $\dot{V}O_2$  increases from minimal 0.3 liters/min to maximal 3 liters/min in a healthy adult subject. The corresponding increase in cardiac output can be

predicted from the formula,  $\dot{Q} = 6\dot{V}O_2 + 4$  [Godfrey; 1974; Jones, 1997]. The  $\dot{Q}$  should increase from 6 to 22 liters/min as  $\dot{V}O_2$  increases from 0.3 to 3 liters/min. Substitution of these numbers into Eq. 2 reveals that  $(CaO_2 - C\bar{v}O_2)$  would increase from 5.2 to 13.6 ml  $O_2$  /dl blood. Thus, the 10-fold increase in  $\dot{V}O_2$  predicts a nearly 4-fold increase in  $\dot{Q}$  and 2.5-fold increase in  $(CaO_2 - C\bar{v}O_2)$ .

INTERPRETATION: The callouts in Eq. 2 classify abnormalities of the heart, lungs, blood, and skeletal muscle that can reduce the  $\dot{V}O_{2max}$ . Habitual exercise can induce structural changes of tissues and organs that improve the efficiency of the cardiorespiratory system [Wagner, 2005]. Consequently, one of the abnormalities listed with Eq. 2 might not reduce the  $\dot{V}O_{2max}$  if there are compensatory changes in remaining elements of the cardiorespiratory system. For example, the slow heart rate caused by congenital heart block might be compensated by an increase in ventricular stroke volume [see Case Study #2].

## EXERCISE TEST REPORT: PROTOCOL



**Fig. 1: Protocol.** The power output of progressive, graded exercise to exhaustion is plotted as a line graph. In this example, the exercise time is 26.5 minutes and the maximal power output is 300 watts. The normal limits of power output are shown as dashed lines intersecting the Y axis at 144 and 267 watts.

**Performance.** Muscles convert the energy stored in ATP to heat and work.

Muscular work is performed by displacing an object against various forces of resistance. The rate of work with respect to time is called power. Walking is a form of weight-bearing exercise in which leg muscles displace the whole body against the forces of inertia, friction, and gravity. The power output of walking uphill on a treadmill is calculated as the lifting power for vertical displacement of body weight. Cycling is a form of non weight-bearing exercise in which leg muscles pedal against resistance. The power output of a cycle ergometer is calculated from flywheel speed and braking resistance.

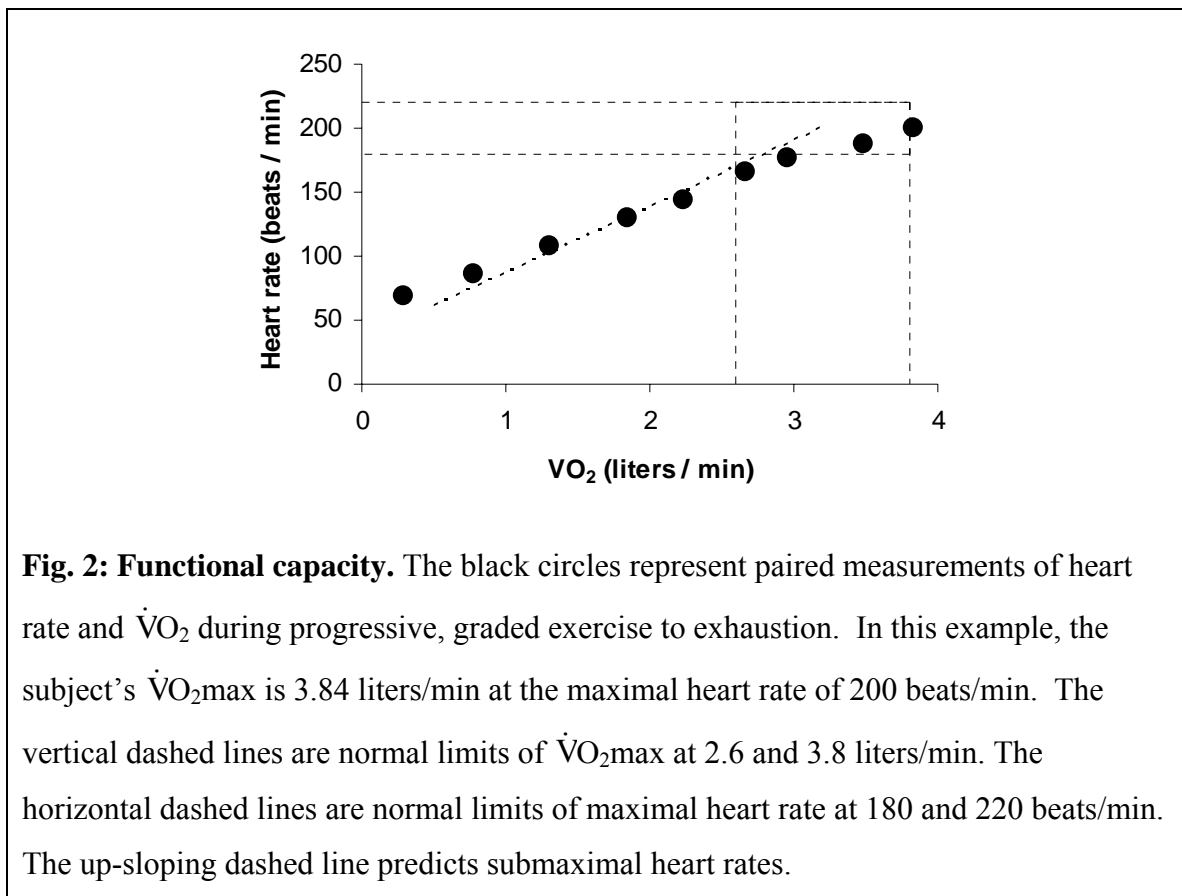
**Strategy.** Exercise laboratories use the treadmill or cycle ergometer to measure the performance of progressive exercise to exhaustion. The progression might be linear or graded. In the graded protocols named for Dr.'s Bruce and James, each grade of exercise is designed to last 3 minutes to ensure that  $\dot{V}O_2$  is measured in a steady-state or nearly

steady-state condition during the 3<sup>rd</sup> minute. Measurements of blood pressure, heart rate, and O<sub>2</sub> saturation of hemoglobin are also made during the 3<sup>rd</sup> minute [Washington, 1994].

**Interpretation.** Figure 1 illustrates the graded increase in power output with respect to time. The subject was an endurance trained athlete who performed the “James 3” protocol on a cycle ergometer. Exhaustion occurred at the terminal drop in power output. The subject’s maximal power output of 300 watts exceeded normal limits. **CONCLUSION:** The subject has an exceptional capacity for dynamic exercise. **OTHER PROPERTIES:** The area under the line graph is the subject’s total work in units of joules.

**Obesity.** Subjects who exceed the upper limit of normal *body mass index (BMI)* are considered obese. Skinfold measurements are helpful in estimating the percentage of body fat and confirming the presence of obesity. An obese subject might fatigue faster than the lean subject of same gender and age when both perform the same exercise test with an identical lean body mass. Both subjects have the same predicted  $\dot{V}O_2\text{max}$  for lean body mass, yet the obese subject exerts more energy at any given power output of cycle exercise by pedaling with heavier legs. During treadmill exercise, the obese subject works at higher power output in any stage of the protocol due to greater body weight. The endurance times of treadmill and cycle exercise are not reliable indices of cardiorespiratory fitness since the obese subject is expected to reach  $\dot{V}O_2\text{max}$  earlier than the lean subject.

## EXERCISE TEST REPORT: FUNCTIONAL CAPACITY



**Strategy.** The functional capacity of the cardiorespiratory system is determined by measuring the body's  $\dot{V}O_{2\max}$ . The subject must perform strenuous dynamic exercise to ensure the absorption of  $O_2$  by hemoglobin at maximal pulmonary blood flow. The  $\dot{V}O_{2\max}$  is measured as the numerical difference between oxygen's inflow and outflow through the upper airways during maximal exertion. The criteria for maximal exertion are: 1) a heart rate of at least 90% predicted maximal value, and 2) a *respiratory exchange ratio* of at least 100% predicted value. Exercise test data that reach the normal limits of maximal heart rate and  $\dot{V}O_{2\max}$  provide compelling evidence for a normal functional capacity. The normal  $\dot{V}O_{2\max}$  indicates that the subject has a normal cardiorespiratory system or compensated disease of the cardiorespiratory system

[Godfrey, 1974]. A subnormal  $\dot{V}O_{2\max}$  indicates the condition of submaximal exertion, sedentary lifestyle, or decompensated disease.

**Interpretation.** Figure 2 illustrates the important relationship of heart rate to  $\dot{V}O_2$ . The subject was an endurance trained athlete who performed graded exercise to exhaustion. The maximal heart rate was within normal limits, which implies that the cardiac output was maximal. The subject's  $\dot{V}O_{2\max}$  exceeded normal limits and therefore revealed an exceptionally high functional capacity of the cardiorespiratory system.

The submaximal heart rates nearly coincided with the up-sloping prediction line except at the onset and end of exercise. Deviations of heart rate from the prediction line might be caused by an arrhythmia or another abnormality of the cardiorespiratory system [see Eq. 2 in the INTRODUCTION].

**PREDICTED LIMITS:** The normal limits of  $\dot{V}O_2$  were set at 80%-120% of the predicted  $\dot{V}O_{2\max}$ . The predicted  $\dot{V}O_{2\max}$  was derived from studies of healthy populations based on the factors of gender, age, standing height, and body weight [Jones, 1997; Cooper, 1984].

The normal limits of heart rate were set at 90%-110% of the predicted maximal heart rate. The predicted maximal heart rate is 200 beats/min at ages below 22 years; otherwise, it is the numerical value of 220 minus the age in years for subjects at least 22 years old [Rowland, 1996].

**UP-SLOPING PREDICTION LINE:** The construction of the up-sloping prediction line was based on the simplifying assumption that the ventricular stroke volume is constant during progressive exercise to exhaustion. The maximal  $\dot{Q}$  was predicted at  $\dot{V}O_{2\max}$  with the formula  $\dot{Q} = 6\dot{V}O_2 + 4$  [Godfrey; 1974; Jones, 1997]. The stroke volume was estimated by dividing the predicted maximal heart rate into the maximal  $\dot{Q}$ . The heart rate at any submaximal  $\dot{V}O_2$  was then predicted by dividing the estimated stroke volume into the formula  $\dot{Q} = 6\dot{V}O_2 + 4$ . In Fig. 2, the estimated stroke volume was 116 ml based on a predicted  $\dot{V}O_{2\max}$  of 3.2 liters/min and a predicted maximal heart rate of 200 beats/min.

CONCLUSION: In Fig. 2, the subject's exceptional functional capacity at maximal cardiac output indicates that the cardiorespiratory system is either free of disease or contains a defect that is exceptionally well compensated.

**What if  $\dot{V}O_2\text{max}$  is subnormal?** If the  $\dot{V}O_2\text{max}$  is less than 80% of its predicted value, the likely cause is an ERROR IN PREDICTION, SUBMAXIMAL EXERTION, HABITUAL LACK OF EXERCISE, or DECOMPENSATED DISEASE.

ERROR IN PREDICTION: Predictions of  $\dot{V}O_2\text{max}$  are erroneously high for obese subjects when based on actual body weight. We routinely correct for this error by predicting the  $\dot{V}O_2\text{max}$  based on an ideal body weight derived from population data for the BMI. For underweight subjects, it is more appropriate to predict  $\dot{V}O_2\text{max}$  from actual body weight. If you suspect an error in prediction, compare the subject's BMI to the BMI of the appropriate reference population [Kuczmarski, 1994; Shils, 1994; CDC, 2003].

SUBMAXIMAL EXERTION: Submaximal exertion might be detected by the subject's failure to achieve the following criteria for maximal exertion [Rowland, 1996]:

- maximal Heart Rate within 90-110% of predicted value.
- maximal Respiratory Exchange Ratio at least 100% of predicted value
- secondary criteria [e.g., maximal ventilation (Fig. 4)]

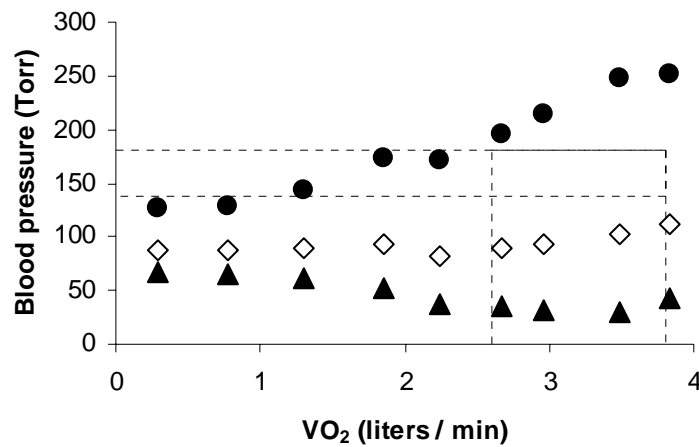
It's occasionally useful to extrapolate the linear heart rate data of Fig. 2 toward higher values with the aid of a straight edge. If the extrapolated data fall within the normal limits of  $\dot{V}O_2\text{max}$  and maximal heart rate, the subject's effort might be submaximal due to poor motivation or discomfort. If the extrapolated data reside in the zone of subnormal  $\dot{V}O_2\text{max}$  or submaximal heart rate, the subject's effort might be limited by habitual lack of exercise or decompensated disease.

HABITUAL LACK OF EXERCISE: A sedentary lifestyle can reduce cardiorespiratory function to the extent that  $\dot{V}O_2\text{max}$  is subnormal at normal maximal heart rate. Habitual inactivity produces abnormal muscle function and low stroke volume [Eq. 2 in INTRODUCTION].

DECOMPENSATED DISEASE: Abnormalities of decompensated disease are outlined in the callouts from Eq. 2. An arrhythmia may produce the slow, erratic, or rapid increase

in heart rate that undershoots or exceeds normal limits of maximal heart rate. The exercise ECG must be used to confirm the arrhythmia.

## EXERCISE TEST REPORT: BLOOD PRESSURE



**Fig. 3: Blood pressure.** Blood pressures were taken from the right brachial artery during graded exercise to exhaustion. The data are plotted as systolic pressure (black circles), calculated mean arterial pressure (white diamonds), and diastolic pressure (black triangles). In this example, the subject's maximal systolic pressure is 250 Torr and the  $\dot{V}O_{2\max}$  is 3.84 liters/min. The normal limits of maximal systolic pressure are shown as dashed lines intersecting the Y axis at 137 and 181 Torr. The normal limits of  $\dot{V}O_{2\max}$  are plotted as dashed lines intersecting the X axis at 2.6 and 3.8 liters/min.

**Strategy.** The *mean arterial pressure* could rise directly with cardiac output by about 4-fold at maximal exertion unless checked by the compensatory decrease in systemic vascular resistance. The systemic vascular resistance normally decreases during progressive exercise to exhaustion [Dlin, 1986; ATS, 2003; Rowland, 1996]. Hypertension blunts the normal decrease in systemic vascular resistance.

The increase in mean arterial pressure is reflected by changes of systolic and diastolic blood pressure measured from a large artery. The systolic pressure should increase to normal maximal limits during progressive exercise to exhaustion. Endurance trained athletes might have an elevated systolic pressure due exceptional cardiac output. Patients with hypertension might have an elevated systolic pressure due to elevated systemic vascular resistance. Failure of the systolic pressure to increase at all or to reach

the lower limit of normal at maximal exertion is presumptive evidence for a low cardiac output of any cause [ATS, 2003]. The diastolic pressure normally stays constant or declines during progressive exercise [Dlin, 1986; Rowland, 1996].

**Interpretation.** Figure 3 illustrates the blood pressure of an endurance trained athlete in response to progressive exercise. Systolic blood pressure exceeded the upper limit of normal on 4 successive measurements. Diastolic blood pressure decreased from 68 to 30 Torr. Consequently, there was a progressive widening of the pulse pressure. The mean arterial pressure increased by 1.3-fold from 87 to 112 Torr and the  $\dot{V}O_2$  increased by 13-fold from 0.3 to 3.8 liters/min.

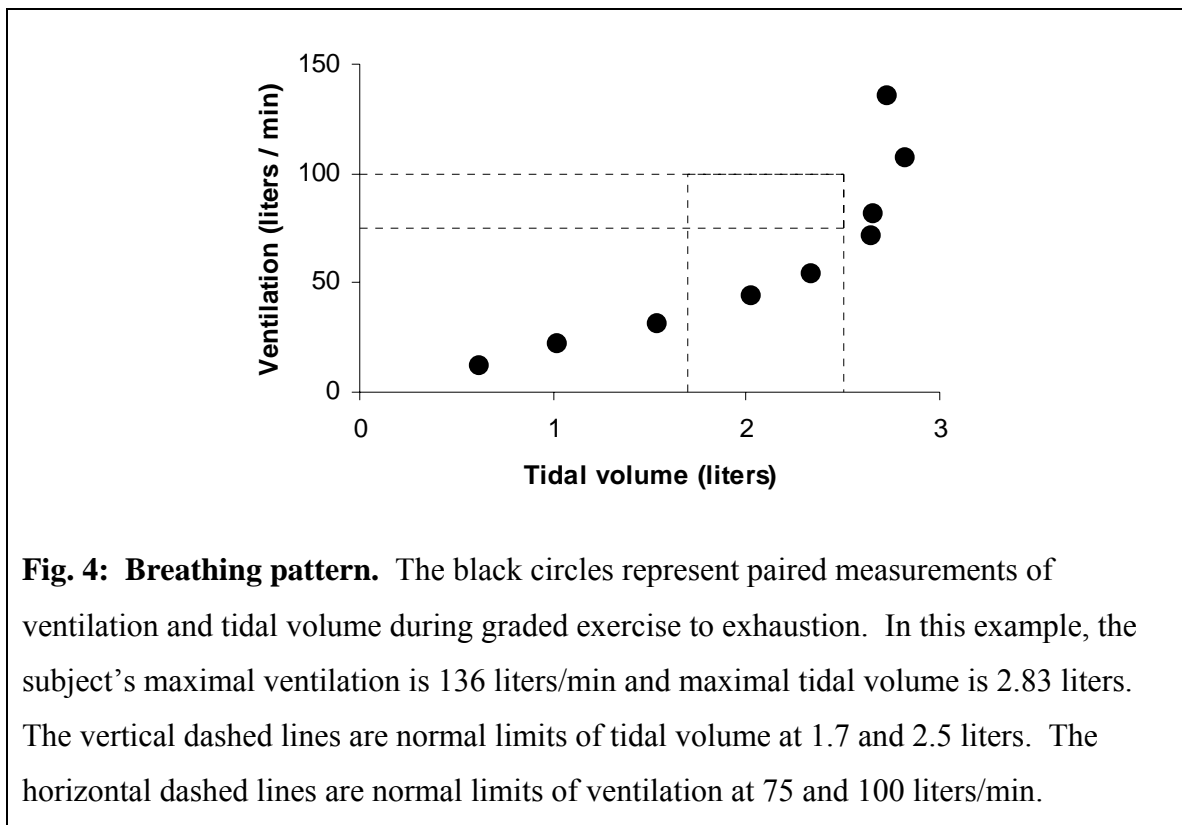
**SLOPE:** The slope of the graph is an index of the systemic vascular resistance, which is the quotient of systemic perfusion pressure divided by cardiac output. The calculated mean arterial pressure is representative of the perfusion pressure and the  $\dot{V}O_2$  is representative of the cardiac output. For example, the slope of the graph decreased from 290 Torr·min/liter at  $\dot{V}O_2$  0.3 liters/min to 29 Torr·min/liter at  $\dot{V}O_2$  3.8 liters/min. This implies a 10-fold decrease in systemic vascular resistance.

**PREDICTED LIMITS:** The normal limits for systolic pressure depend on age, gender, anthropometrics, and population characteristics [Alpert, 1982; Kenney, 1995].

**CONCLUSION:** In Fig. 3, the subject's exceptionally high systolic blood pressure is better explained by an increase in cardiac output than by an elevated systemic vascular resistance. The decrease in diastolic pressure signified a decrease in systemic vascular resistance to accommodate the increasing cardiac output. Furthermore, the modest increase in mean arterial pressure relative to multifold increase in  $\dot{V}O_2$  indicates that the systemic vascular resistance decreased by 10-fold during progressive exercise.

**Safety.** Failure of the systolic pressure to increase during the early stages of exercise is an indication to stop the exercise test and reassess the patient. The risk of myocardial injury and sudden death is high in patients with low cardiac output due to severe cardiovascular obstructive disease (e.g., severe valvular stenosis) or myocardial disease (e.g., ischemia, cardiomyopathy) [ATS, 2003; Washington, 1994].

## EXERCISE TEST REPORT: BREATHING PATTERN



**Strategy.** The breathing response to dynamic exercise correlates more closely with the body's rate of  $\text{CO}_2$  release ( $\dot{V}\text{CO}_2$ ) than its  $\dot{V}\text{O}_2$ . Ventilation increases with  $\dot{V}\text{CO}_2$  by the expansion of tidal volume and increase in breathing rate.

**Intpretation.** Figure 4 illustrates the following properties of the normal breathing pattern during progressive exercise to exhaustion [ATS, 2003; Hey, 1966]:

- The breathing rate is the slope of the graph.
- The initial increase in ventilation is primarily due to an increase in tidal volume. The maximal tidal volume is expected to reach 40-60% of the predicted *forced vital capacity (FVC)* [Hey, 1966; Gallagher, 2000; Bar-Or, 1983].
- At nearly maximal tidal volume, the ventilation continues to increase by the progressive increase in breathing rate. The maximal ventilation is expected to reach 60-80% of the predicted *maximal voluntary ventilation (MVV)*.

PREDICTED LIMITS: The normal limits of maximal ventilation are 60-80% of the predicted MVV. The normal limits of maximal tidal volume are 40-60% of the predicted FVC. The MVV and FVC are predicted on the basis of age, height, and gender [Grimby, 1963; Kory, 1961; Morris, 1976; Polgar, 1971].

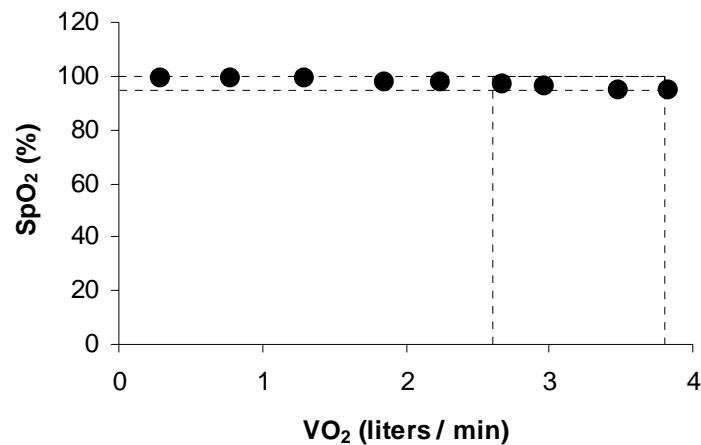
CONCLUSION: The maximal tidal volume and maximal ventilation of Fig. 4 are exceptionally high.

**Significance.** Exceptional lung function at maximal exertion will increase the tidal volume above normal limits. Either an error in the prediction of FVC, a submaximal exertion, or the mechanical limitation of breathing might decrease the maximal tidal volume below normal limits [Gallagher, 2000].

The maximal ventilation of endurance trained athletes might exceed normal limits with an exceptional increase in breathing rate during maximal exertion. Submaximal effort reduces the maximal ventilation by limiting the metabolic drive of breathing. Heart disease and lung disease might reduce the maximal ventilation or change the breathing pattern in one of several ways [ATS, 2003]:

1. Symptom-limitation of exercise.
2. Abnormal control of breathing.
3. Abnormal mechanics of breathing.

## EXERCISE TEST REPORT: PULSE OXIMETER



**Fig. 5. Pulse oximeter.** Readings of the pulse oximeter were taken during graded exercise to exhaustion. The black circles represent the O<sub>2</sub> saturation of arterial hemoglobin measured by the pulse oximeter (SpO<sub>2</sub>). In this example, the subject's minimal SpO<sub>2</sub> is 95% and the  $\dot{V}O_{2\max}$  is 3.84 liters/min. The normal range of SpO<sub>2</sub> is displayed by dashed lines that intersect the Y axis at 95 and 100%. The normal range of  $\dot{V}O_{2\max}$  is displayed by dashed lines that intersect the X axis at 2.6 and 3.8 liters/min.

**Strategy.** A perfectly functioning lung saturates all of the hemoglobin with O<sub>2</sub> during the passage of mixed venous blood through pulmonary capillaries. But the lung and hemoglobin are not perfect systems. Firstly, the pulmonary capillary outflow is never 100% saturated with O<sub>2</sub> because nearly 1% of the hemoglobin's binding sites are either occupied by carbon monoxide or exist as nonreactive methemoglobin. Secondly, a normal right-to-left shunt from the bronchial circulation and cardiac thebesian veins dilutes a small portion of the pulmonary capillary outflow with unsaturated hemoglobin. Thirdly, an imperfect match between capillary blood flow and alveolar ventilation renders some regions of the pulmonary circulation so poorly ventilated as to prevent full saturation [West, 1995]. Fourthly, maximal exertion can diminish the O<sub>2</sub> saturation of arterial hemoglobin ( $SaO_2$ ) by widening the alveolar-to-arterial pO<sub>2</sub> gradient or thermally shifting the O<sub>2</sub> dissociation curve rightward. The net effect of these imperfections is twofold: Firstly, a pO<sub>2</sub> gradient normally exists between the alveoli and arterial blood that varies from 10 Torr during submaximal exertion to 25 Torr during maximal exertion.

Secondly, the  $SaO_2$  is always less than 100% when carefully measured from blood samples in the chemistry laboratory [Dempsey, 1999]. The  $O_2$  saturation might be 100% when measured by pulse oximetry due to differences in methodology. The measurement of  $SaO_2$  by pulse oximetry is reported as the  $SpO_2$ . Exercise induced arterial hypoxemia occurs at  $SpO_2 \leq 95\%$ . The severity of hypoxemia is mild at 95-94%, moderate at 93-88%, and severe below 88% [Dempsey, 1999].

**Interpretation.** Figure 5 illustrates the measurement of  $SpO_2$  from an endurance trained athlete during progressive exercise to exhaustion. Normally, the  $SpO_2$  exceeds 95% throughout the test. CONCLUSION: There was mild exercise induced arterial hypoxemia during maximal exertion as indicated by the 95%  $SpO_2$  at  $\dot{V}O_{2max}$ .

**Hypoxemia.** The mechanism of mild hypoxemia in an athlete at maximal exertion is not known. Athletes might have an inadequate ventilatory response to maximal exertion when dynamic compression of the airways constrains airflow. The mild hypoxemia of an athlete at maximal exertion is not conclusive evidence for lung disease [Dempsey, 1999].

The fundamental causes of exercise induced arterial hypoxemia are an inadequate ventilatory response to exertion and mechanisms that widen the alveolar-to-arterial  $pO_2$  gradient. Lung disease and heart disease widen the alveolar-to-arterial  $pO_2$  gradient by an inequality of ventilation-perfusion, limitation of diffusion, or right-to-left shunt [Dempsey, 1999].

Arterial blood gases are not routinely measured for the diagnosis of respiratory insufficiency during exercise. Insufficient gas exchange can be detected by blood gases that show an alveolar-to-arterial  $pO_2$  gradient  $>25$  Torr and an arterial  $pCO_2 >38$  Torr at maximal exertion [Dempsey, 1999].

**Hyperoxic challenge.** Supplemental  $O_2$  might correct the arterial hypoxemia that results from an inequality of ventilation-perfusion or the limitation of diffusion, but is not expected to correct the hypoxemia due to right-to-left shunt. Consequently, patients with arterial hypoxemia might perform dynamic exercise better when breathing supplemental  $O_2$  from an hyperoxic gas mixture. It's useful to determine this outcome by repeating the exercise test with hyperoxic breathing gas. The potential effects of hyperoxia are 1) the correction of  $SpO_2$  during exercise, and 2) the increase in total time or power output of the exercise protocol.

## Case study #1, Endurance-trained athlete

### History of case #1.

A 13 year old male volunteered to participate in a research project. He habitually trained for competitive bicycle racing.

### Indication for exercise test of case #1.

Determine if the subject is qualified for the research project.

**Predictions:**  $\dot{V}O_{2\max} = \dot{Q}_{\max} (CaO_2 - C\bar{v}O_2)$

1.  $\dot{Q}_{\max}$  might be increased in response to athletic training.
2.  $(CaO_2 - C\bar{v}O_2)$  might be increased due to exceptional  $O_2$  extraction by the muscles.
3.  $\dot{V}O_{2\max}$  might exceed the predicted normal limits

### Laboratory data of case #1.

Height 176 cm, Weight 66 kg, Ideal weight 63 kg.

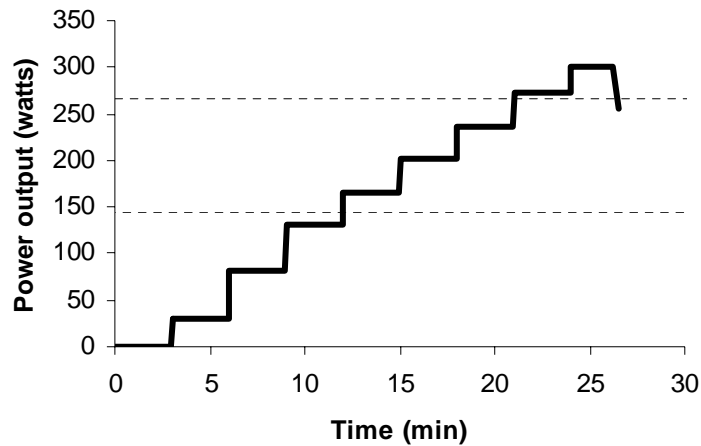
Body mass index (BMI): 21.3 kg/m<sup>2</sup>, 105 % of predicted.

ECG: Normal sinus rhythm. No arrhythmia during exercise.

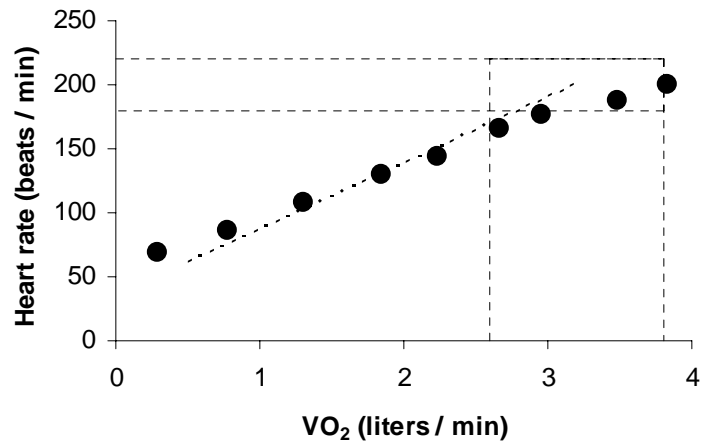
PFT's: Forced vital capacity 132% of predicted value.

### Table for the maximal exertion of case #1.

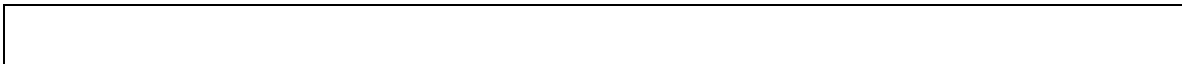
	observed	predicted	Percentage of predicted
Maximal heart rate	207 beats/min	200 beats/min	104 %
Respiratory exchange ratio	1.08	1	108 %
$\dot{V}O_{2\max}$	3.84 liters/min	3.20 liters/min	120 %

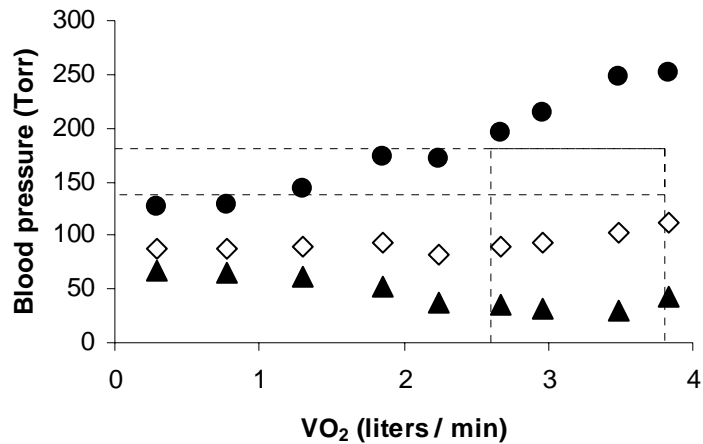


**Graph for exercise protocol of case #1.** The power output of progressive, graded exercise to exhaustion is plotted as a line graph. The normal limits of power output are shown as dashed lines intersecting the Y axis.

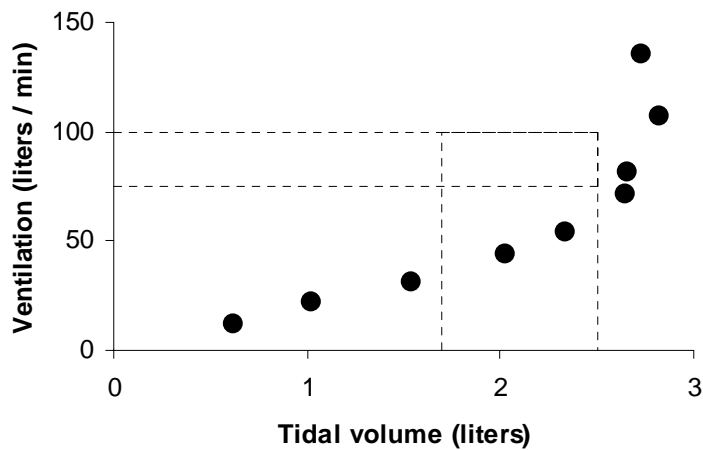


**Graph for functional capacity of case #1.** The black circles represent paired measurements of heart rate and  $\dot{V}O_2$  averaged at 30-s intervals during progressive, graded exercise to exhaustion. The vertical dashed lines are normal limits of  $\dot{V}O_{2max}$ . The horizontal dashed lines are normal limits of maximal heart rate. The up-sloping dashed line predicts submaximal heart rates.

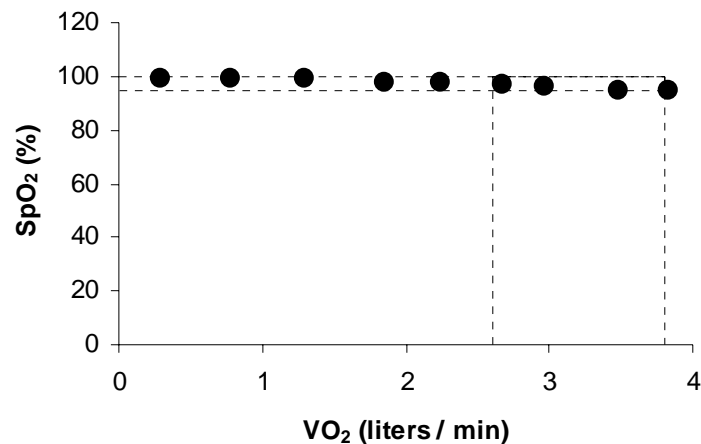




**Graph for blood pressure of case #1.** Blood pressures from the right brachial artery are plotted as systolic pressure (black circles), calculated mean arterial pressure (white diamonds), and diastolic pressure (black triangles). The normal limits of maximal systolic pressure are shown as dashed lines intersecting the Y axis. The normal limits of  $\dot{V}O_2$ max are plotted as dashed lines intersecting the X axis.



**Graph for breathing pattern of case #1.** Black circles represent paired measurements of ventilation and tidal volume averaged at 30-s intervals during progressive, graded exercise to exhaustion. Vertical dashed lines are normal limits of tidal volume. Horizontal dashed lines are normal limits of ventilation.



**Graph for pulse oximetry of case #1.** Black circles represent the O<sub>2</sub> saturation of arterial hemoglobin (SpO<sub>2</sub>) during progressive, graded exercise to exhaustion. Normal range of SpO<sub>2</sub> is displayed by dashed lines that intersect the Y axis at 95 and 100%.

### **Summary of Findings.**

Laboratory data: Forced Vital Capacity was 132% of predicted value.

Anthropometric data: Actual body weight was 105% of ideal body weight.

Maximal exertion table: Subject satisfied the criteria for maximal exertion.  $\dot{V}O_{2max}$  was 120% of predicted value (exceptionally high).

Protocol graph: Maximal power output exceeded the upper limit of normal.

Functional capacity graph: Submaximal heart rates matched the predicted values.

Maximal heart rate was 104% of predicted value.  $\dot{V}O_{2max}$  exceeded the upper limit of normal.

Blood pressure graph: Systolic blood pressure exceeded the upper limit of normal on 4 successive measurements. Diastolic blood pressure decreased from 68 to 30 Torr.

Consequently, there was progressive widening of the pulse pressure.

Breathing pattern graph: Tidal volume and ventilation increased to exceptionally high values.

SpO<sub>2</sub> graph: Decreased from 99% at the start to 95% (mild hypoxemia) at the end of exercise.

Reason for stopping exercise: Muscle fatigue.

**Analysis**

$$\dot{V}O_{2\max} = \text{max heart rate} \cdot \text{stroke volume} \cdot (\text{CaO}_2 - \text{C}\bar{\text{v}}\text{O}_2)$$

The exercise test satisfied criteria for maximal exertion. The cardiorespiratory functional capacity was exceptionally high due to an increase in stroke volume or widening of  $(\text{CaO}_2 - \text{C}\bar{\text{v}}\text{O}_2)$  by athletic training. The exceptionally high systolic blood pressure is explained by an increase in cardiac output or systemic vascular resistance. Athletes can develop high systolic pressures as a result of endurance training, not as the result of pre-existing hypertension [Dlin, 1986].

**Impression.**

1. The cardiorespiratory functional capacity is exceptionally high, which is consistent with endurance training for competitive bicycle racing.
2. The elevated systolic blood pressure is likely due to endurance training and does not exclude this subject from participation in the research study.

**Case study #2, Bradycardia,  
studied by Dr. Wayne H. Franklin, M.D., and presented with his permission.**

**History of case #2.**

A 13 year old male presented with the diagnoses of a dual-orifice mitral valve, trivial mitral regurgitation, and congenital heart block. He was not treated with medicine or a pacemaker.

**Indication for exercise test of case #2.**

Determine the cardiorespiratory functional capacity. Evaluate for evidence of complex ventricular ectopy in combination with congenital 3<sup>rd</sup> degree heart block as an indication for pacemaker therapy.

**Predictions:**  $\dot{V}O_{2\max} = \dot{Q}_{\max} (CaO_2 - C\bar{v}O_2)$

4.  $\dot{Q}_{\max}$  will be subnormal unless compensated by an increase in stroke volume. Atrial rate will match the predicted heart rate. Ventricular heart rate will be subnormal and stimulated by circulating catecholamines [Taylor, 1974; Manno, 1983]. Trivial mitral regurgitation might not decrease the stroke volume.
5.  $(CaO_2 - C\bar{v}O_2)$  might increase to compensate for subnormal  $\dot{Q}_{\max}$ .
6.  $\dot{V}O_{2\max}$  will be subnormal without compensatory increases in stroke volume and  $(CaO_2 - C\bar{v}O_2)$  [Taylor, 1974; Manno, 1983].

**Laboratory data of case #2.**

Height 161.5 cm, Weight 45 kg, Ideal weight 52.4 kg.

Body mass index (BMI): 17.3 kg/m<sup>2</sup>, 86 % of predicted.

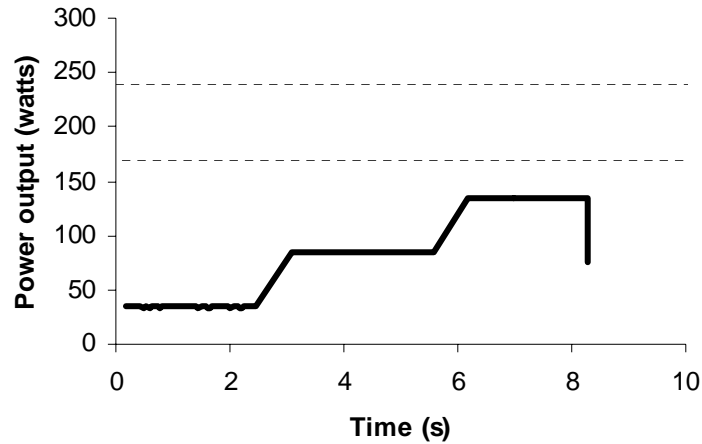
ECG: 3<sup>rd</sup> degree heart block with atrial rate 80- and ventricular rate 50 beats/minute.

During exercise, there were transient episodes of bigeminy at ventricular rates 60- and 85 beats/min. Maximal heart rates were 188- (atrial) and 102 (ventricular) beats/min.

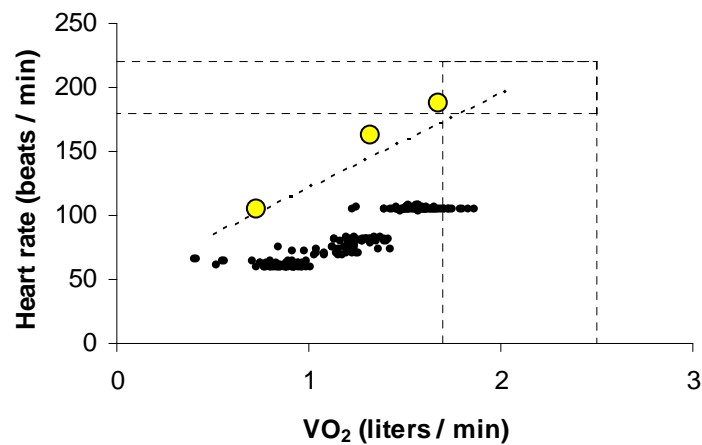
Cardiac output: Stroke volume was 148 ml at rest and 140-168 ml during exercise.

**Table for the maximal exertion of case #2.**

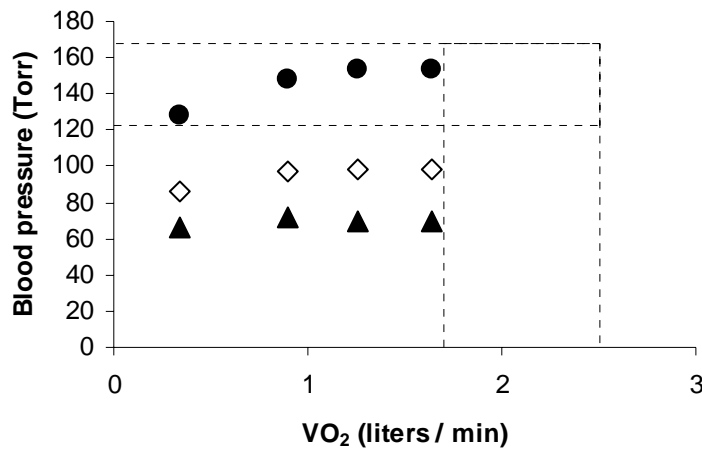
	observed	predicted	Percentage of predicted
Maximal atrial rate	188 beats/min	200 beats/min	94 %
Maximal ventricular rate	102 beats/min	200 beats/min	51 %
Respiratory exchange ratio	1.17	1	117 %
$\dot{V}O_2$ max	1.64 liters/min	2.07 liters/min	79 %



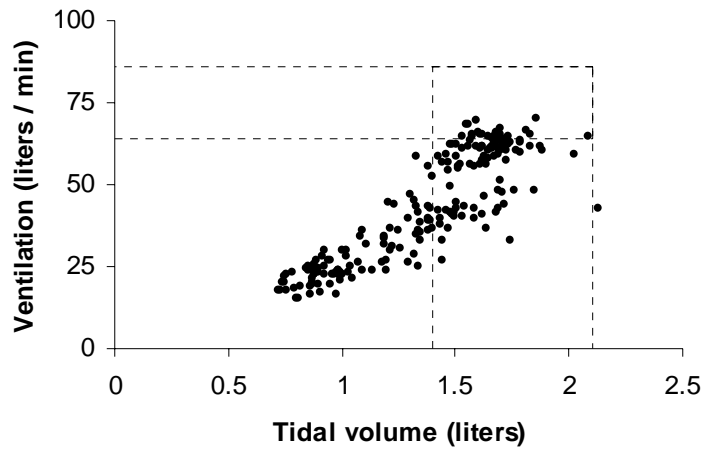
**Graph for exercise protocol of case #2.** The power output of progressive, graded exercise to exhaustion is plotted as a line graph. The normal limits of power output are shown as dashed lines intersecting the Y axis.



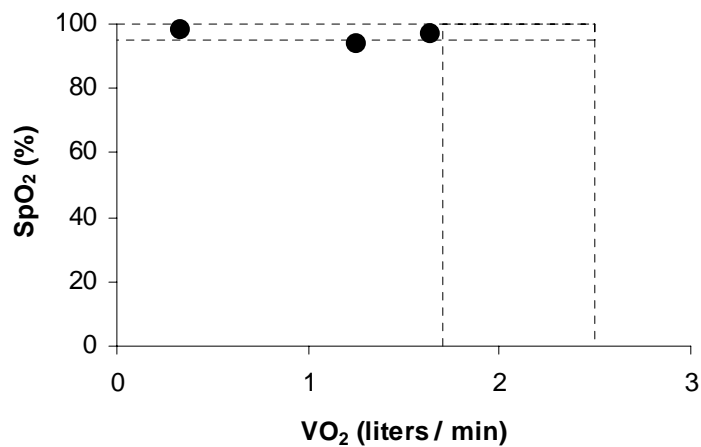
**Graph for functional capacity of case #2.** The black circles represent paired measurements of ventricular rate and  $\dot{V}O_2$  for each breath during progressive, graded exercise to exhaustion. The yellow circles are several paired measurements of atrial rate and  $\dot{V}O_2$ . The vertical dashed lines are normal limits of  $\dot{V}O_{2max}$ . The horizontal dashed lines are normal limits of maximal heart rate. The up-sloping dashed line predicts submaximal heart rates.



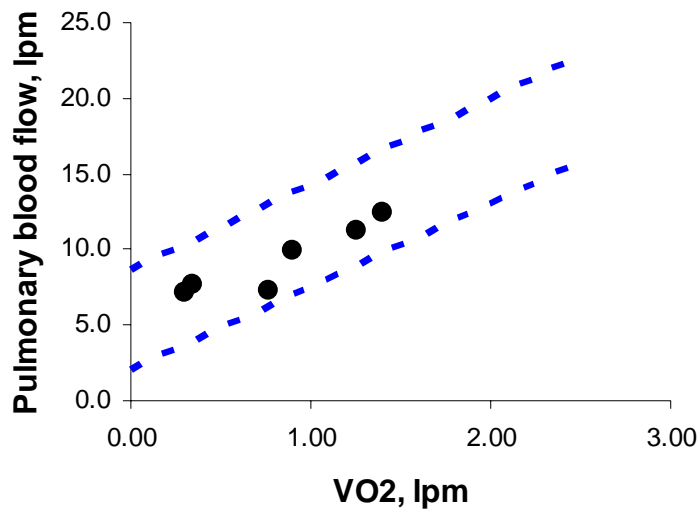
**Graph for blood pressure of case #2.** Blood pressures from the right brachial artery are plotted as systolic pressure (black circles), calculated mean arterial pressure (white diamonds), and diastolic pressure (black triangles). The normal limits of maximal systolic pressure are shown as dashed lines intersecting the Y axis. The normal limits of  $\dot{V}O_{2max}$  are plotted as dashed lines intersecting the X axis.



**Graph for breathing pattern of case #2.** Black circles represent paired measurements of ventilation and tidal volume for each breath during progressive, graded exercise to exhaustion. Vertical dashed lines are normal limits of tidal volume. Horizontal dashed lines are normal limits of ventilation.



**Graph for pulse oximetry of case #2.** Black circles represent the  $O_2$  saturation of arterial hemoglobin ( $SpO_2$ ) during progressive, graded exercise to exhaustion. Normal range of  $SpO_2$  is displayed by dashed lines that intersect the Y axis at 95 and 100%.



**Graph for Cardiac output of case #2.** Data are plotted from 2 exercise tests performed in 1995 and 1997. The black circles represent paired measurements of pulmonary blood flow and  $\dot{V}O_2$  during progressive, graded exercise to exhaustion. Pulmonary blood flow was measured by the acetylene re-breathing technique. The blue dashed lines are normal limits of blood flow.

### Summary of Findings.

Laboratory data: Resting ECG showed complete heart block. Exercise stimulated transient episodes of ventricular bigeminy.

Anthropometric data: Underweight for age and height.

Maximal exertion table: Atrial rate 188 beats/min and respiratory exchange ratio 1.17 satisfy the criteria for maximal exertion. The 30-s averaged  $\dot{V}O_{2max}$  was 79% of its predicted value.

Protocol graph: Maximal power output was below normal limits.

Functional capacity graph: Atrial rates matched the predicted heart rates. Ventricular rates were below normal limits and slower than the atrial rates. Single-breath  $\dot{V}O_2$  increased to within normal limits of  $\dot{V}O_{2max}$ .

Blood pressure graph: Systolic blood pressure increased to normal limits. Diastolic blood pressure was constant.

Breathing pattern graph: Single-breath tidal volumes and ventilations increased to normal limits.

SpO<sub>2</sub> graph: SpO<sub>2</sub> transiently decreased to 94% during submaximal effort and returned to normal limits during maximal effort.

Cardiac output graph: Normal pulmonary blood flow. Derived stroke volume was 148 ml at rest and 140-168 ml during exercise.

### **Analysis**

$$\dot{V}O_{2\max} = \text{max heart rate} \cdot \text{stroke volume} \cdot (CaO_2 - C\bar{v}O_2)$$

The exercise test satisfied criteria for maximal exertion. The mildly subnormal  $\dot{V}O_{2\max}$  is explained by the reduced ventricular heart rate. At reduced heart rate, the pulmonary blood flow was maintained within normal limits by a compensatory increase in ventricular stroke volume.

### **Impression.**

3. The cardiorespiratory functional capacity was mildly subnormal due to 3<sup>rd</sup> degree heart block. There was a compensatory increase in ventricular stroke volume.
4. The exercise electrocardiogram demonstrated complete heart block and episodes of ventricular bigeminy.

**Case study #3, Acyanotic heart disease,  
referred by Dr.'s Curt J. Daniels, M.D., and Stephen C. Cook, M.D., and presented  
with their permission.**

**History of case #3.**

A 28 year old woman with diagnoses of familial restrictive cardiomyopathy and atrial flutter was referred to the exercise laboratory for an evaluation of exertional dyspnea. There was a family history of sudden cardiac death. She took a beta-blocker drug (Sotalol), anticoagulant therapy, diuretics, and birth control tablets.

**Indications for exercise test of case #3.**

Determine the exercise capacity and evaluate the breathing response to exercise.

**Predictions:**                       $\dot{V}O_{2max} = \dot{Q}_{max} (CaO_2 - C\bar{v}O_2)$

7.  $\dot{Q}_{max}$  might decrease due to the combined effect of low stroke volume and bradycardia. Restrictive cardiomyopathy should decrease the stroke volume and beta-blocker therapy should slow the maximal heart rate.
8.  $(CaO_2 - C\bar{v}O_2)$  might be decreased by habitual limitation of physical activity.
9.  $\dot{V}O_{2max}$  might be decreased by the combined reductions of  $\dot{Q}_{max}$  and  $(CaO_2 - C\bar{v}O_2)$ .

**Laboratory data of case #3.**

Height 168.5 cm, Weight 81 kg, ideal weight 70.8 kg.

Body mass index (BMI): 28.5 kg/m<sup>2</sup>, 114 % of predicted.

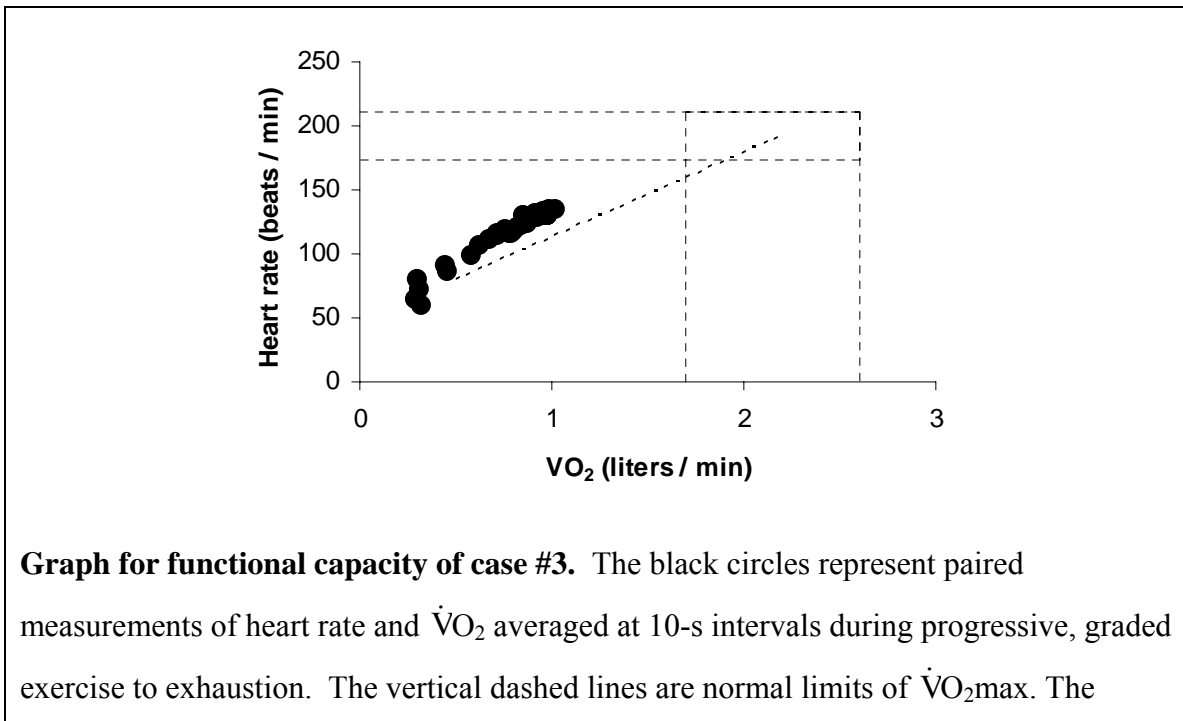
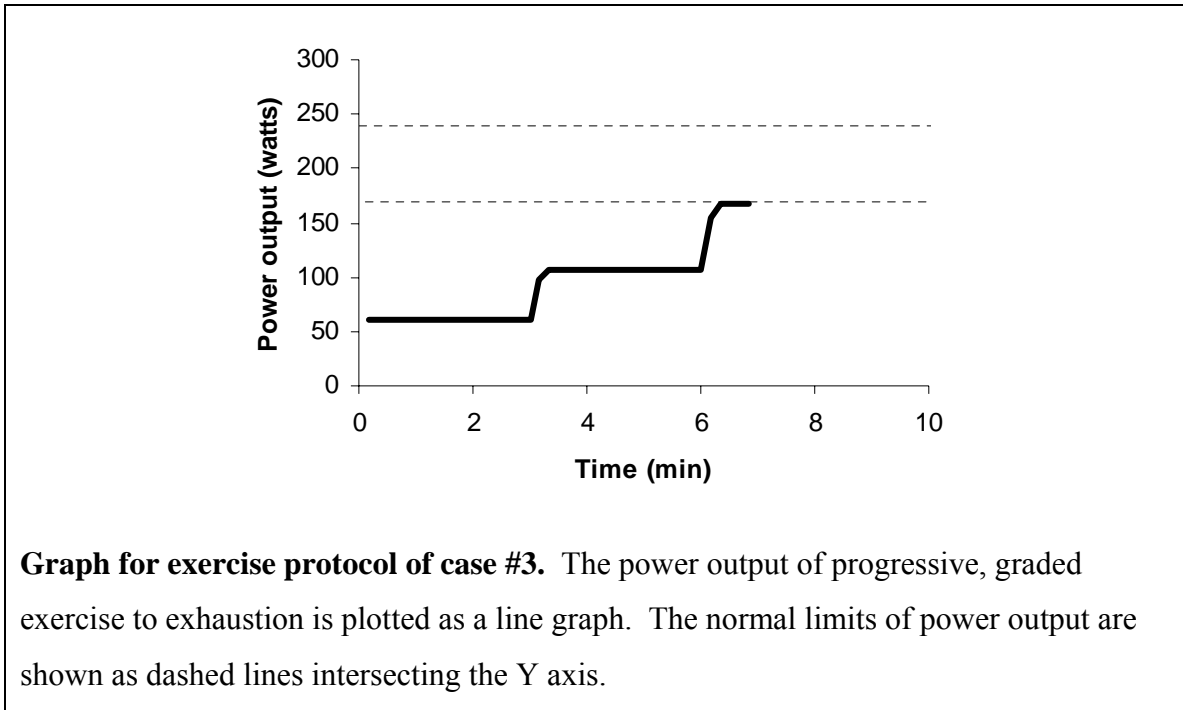
ECG: normal sinus rhythm, biatrial enlargement, incomplete right bundle branch block. 1-2 mm depression of the ST segment during exercise.

PFT's: Forced vital capacity was 84% of predicted. Lung function was not diminished after exercise.

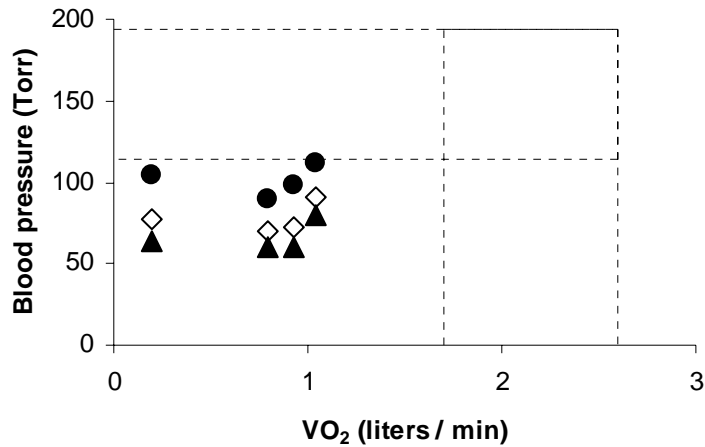
**Table for the maximal exertion of case #3.**

	observed	predicted	Percentage of predicted
Maximal heart rate	136 beats/min	192 beats/min	71 %

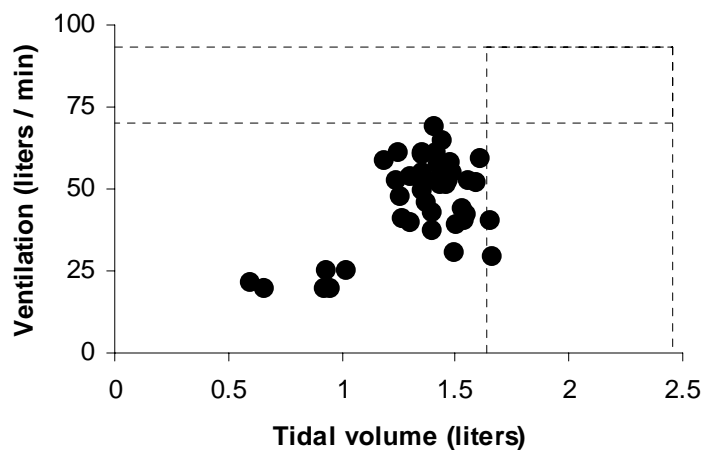
Respiratory exchange ratio	1.13	1	113 %
$\dot{V}O_{2max}$	1.04 liters/min	2.15 liters/min	48 %



horizontal dashed lines are normal limits of maximal heart rate. The up-sloping dashed line predicts submaximal heart rates.

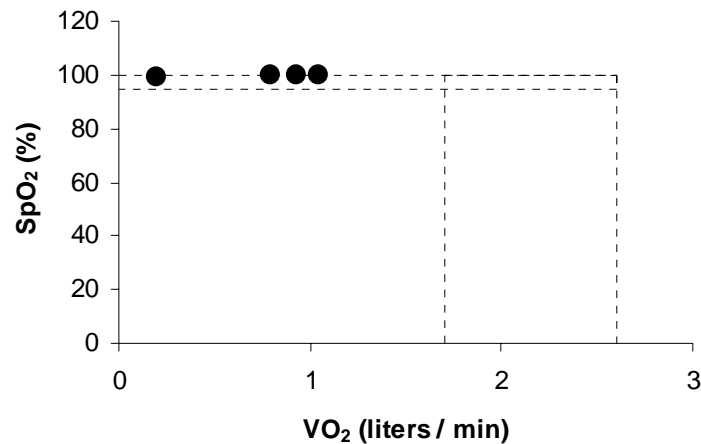


**Graph for blood pressure of case #3.** Blood pressures from the right brachial artery are plotted as systolic pressure (black circles), calculated mean arterial pressure (white diamonds), and diastolic pressure (black triangles). The normal limits of maximal systolic pressure are shown as dashed lines intersecting the Y axis. The normal limits of  $\dot{V}O_2$ max are plotted as dashed lines intersecting the X axis.



**Graph for breathing pattern of case #3.** Black circles represent paired measurements of ventilation and tidal volume averaged at 10-s intervals during progressive, graded

exercise to exhaustion. Vertical dashed lines are normal limits of tidal volume.  
Horizontal dashed lines are normal limits of ventilation.



**Graph for pulse oximetry of case #3.** Black circles represent the O<sub>2</sub> saturation of arterial hemoglobin (SpO<sub>2</sub>) during progressive, graded exercise to exhaustion. Normal range of SpO<sub>2</sub> is displayed by dashed lines that intersect the Y axis at 95 and 100%.

### **Summary of Findings.**

Laboratory data: Pre-exercise ECG showed a normal sinus rhythm with biatrial enlargement. Exercise ECG revealed a 1-2 mm depression of the ST segment. Post-exercise lung function studies showed no evidence of exercise-induced bronchoconstriction.

Anthropometric data: Body weight was 114% of ideal weight.

Maximal exertion table: Conflicting evidence of maximal exertion (maximal heart rate 71% of predicted, respiratory exchange ratio 113% of predicted).  $\dot{V}O_{2\max}$  was 48% of predicted (moderately subnormal).

Protocol graph: Maximal power output was below the lower limit of normal.

Functional capacity graph: The submaximal heart rates tended to be higher than predicted. The maximal heart rate and  $\dot{V}O_{2\max}$  were below normal limits.

Blood pressure graph: Systolic blood pressure increased to the lower limit of normal. The pulse pressure did not increase. There was a terminal up-slope of the mean arterial

pressure with respect to  $\dot{V}O_2$ , which was consistent with a terminal increase in systemic vascular resistance.

Breathing pattern graph: The tidal volume was subnormal at maximal ventilation. The maximal ventilation approached lower limits of normal.

SpO<sub>2</sub> graph: Normal.

Reason for stopping exercise: The symptoms of dizziness and shortness of breath were associated with an end-tidal PCO<sub>2</sub> at abnormally low values of 21-23 Torr.

### **Analysis**

$$\dot{V}O_{2\max} = \text{max heart rate} \cdot \text{stroke volume} \cdot (CaO_2 - C\bar{v}O_2)$$

The subnormal maximal heart rate might be due to the symptom-limitation of exertion or beta blocker therapy. The maximal respiratory exchange ratio reflects either an inappropriate hyperventilation due to exertion dyspnea or the respiratory compensation of lactic acidosis due to reduced cardiac output (beta blocker therapy or restricted stroke volume). The subnormal  $\dot{V}O_{2\max}$  can be explained by the symptom-limitation of exertion or reduced cardiac output. A reduced cardiac output would lower the mean arterial pressure unless there were a compensatory increase of the systemic vascular resistance. Restrictive cardiomyopathy might mimic other forms of chronic heart failure in which dyspnea is due to an inappropriate hyperventilatory response to exercise [Mancini, 2000].

### **Impression.**

5. The cardiorespiratory functional capacity is moderately subnormal. It's uncertain whether the functional capacity is limited by symptoms of exertion dyspnea or reduced cardiac output.
6. The terminal symptoms of breathlessness and dizziness support the patient's history of exertion dyspnea. The abnormally low end-tidal PCO<sub>2</sub> (21-23 Torr) and normal SpO<sub>2</sub> indicate an exceptional hyperventilatory response of undetermined cause.
7. There was an asymptomatic 1-2 mm depression of the ST segment during exercise.

## Case study #4, Severe lung disease

### History of case #4.

A 32 year old man was referred to the exercise laboratory with diagnoses of chronic bronchitis, bronchiectasis, and pulmonary insufficiency. He recovered completely from a surgical lobectomy of one lung. He took medications for bronchodilator (Albuterol, Terbutaline), antibiotic (Zithromex), antacid (Prilosec), and bone resorption-inhibitor (Fosamax) effects.

### Indication for exercise test of case #4.

Determine the cardiopulmonary functional capacity as part of an evaluation for lung transplantation

**Predictions:**  $\dot{V}O_{2max} = \dot{Q}_{max} (CaO_2 - C\bar{v}O_2)$

10.  $\dot{Q}_{max}$  might be decreased by a reduction in stroke volume due to chronic pulmonary hypertension and habitual limitation of physical activity [Gallagher, 2000].
11.  $(CaO_2 - C\bar{v}O_2)$  might be decreased by hypoxemia and habitual limitation of physical activity. Progressive pulmonary failure during exercise would lower the  $CaO_2$ . Habitual inactivity might increase the  $C\bar{v}O_2$  [Gallagher, 2000]
12.  $\dot{V}O_{2max}$  might be decreased by combined reductions of  $\dot{Q}_{max}$  and  $(CaO_2 - C\bar{v}O_2)$ .

### Laboratory data of case #4.

Height 164 cm, Weight 64.5 kg, Ideal weight 69.3 kg.

Body mass index (BMI): 24 kg/m<sup>2</sup>, 93 % of predicted.

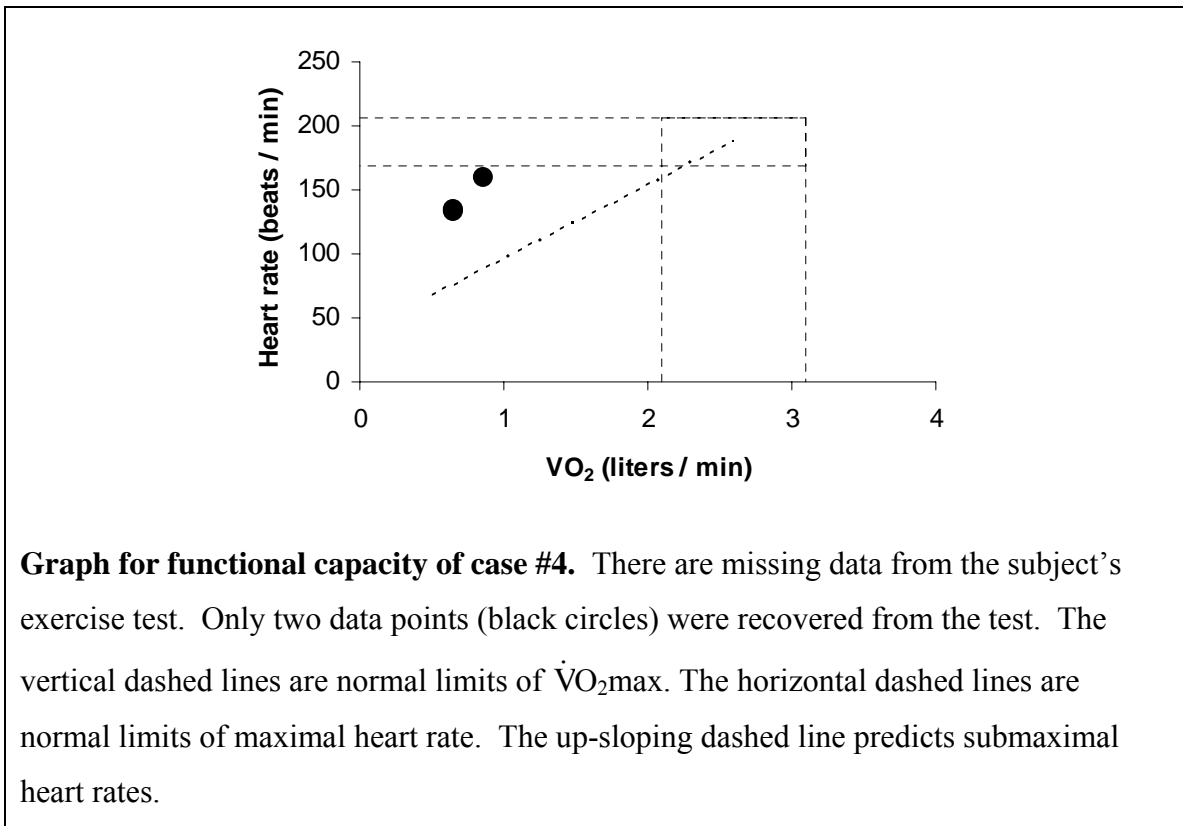
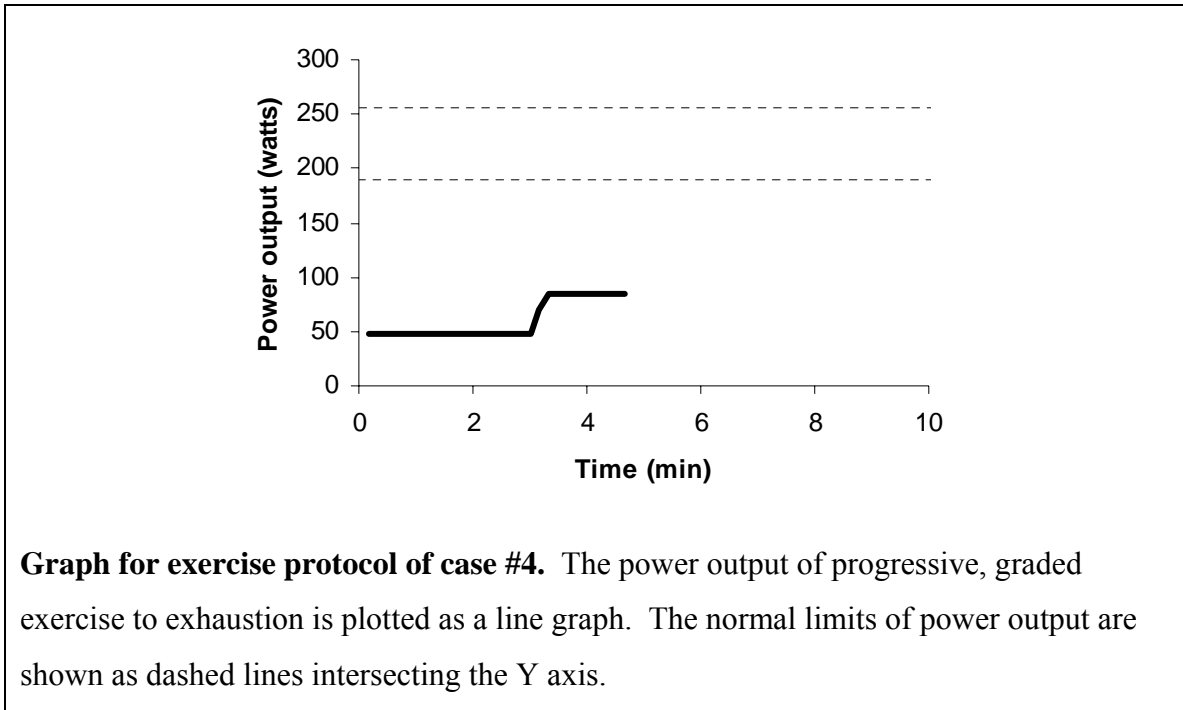
ECG: Normal sinus rhythm.

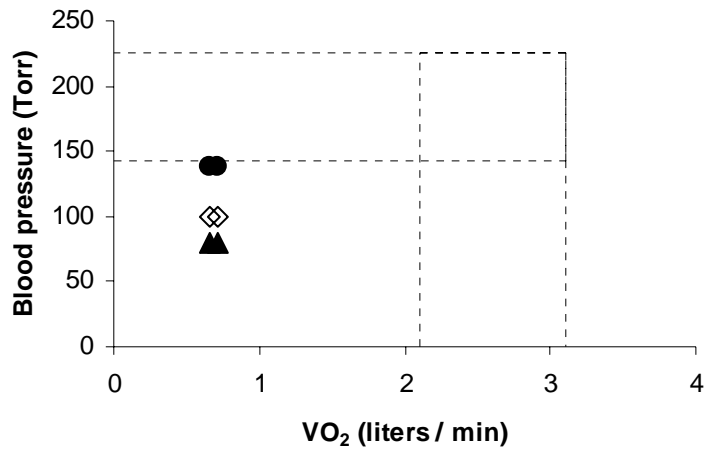
PFT's: Severe obstructive lung disease.

### Table for the maximal exertion of case #4.

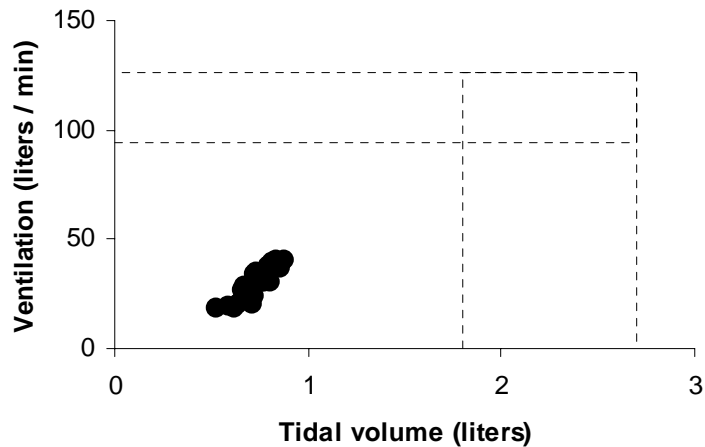
	observed	predicted	Percentage of predicted
<b>Maximal heart rate</b>	160 beats/min	188 beats/min	85 %

Respiratory exchange ratio	1.06	1	106 %
$\dot{V}O_{2max}$	0.84 liters/min	2.49 liters/min	34 %

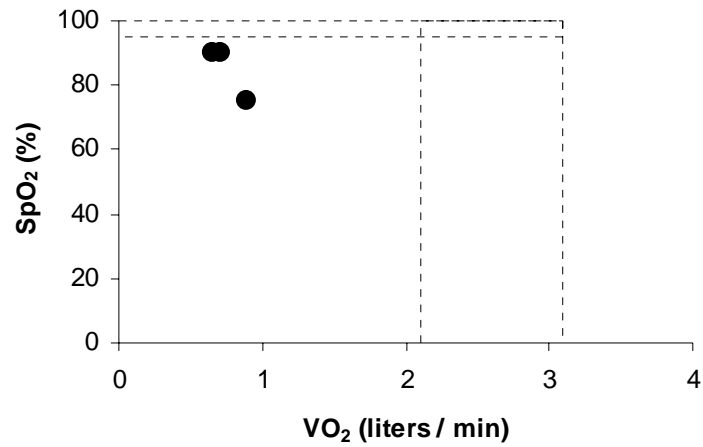




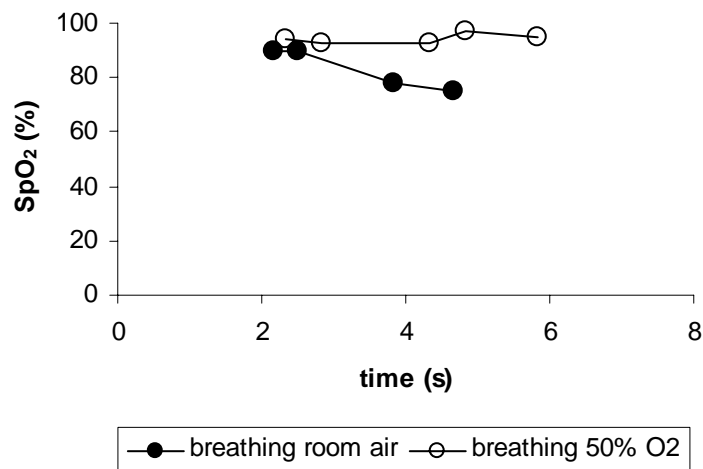
**Graph for blood pressure of case #4.** Blood pressures from the right brachial artery are plotted as systolic pressure (black circles), calculated mean arterial pressure (white diamonds), and diastolic pressure (black triangles). The normal limits of maximal systolic pressure are shown as dashed lines intersecting the Y axis. The normal limits of  $\dot{V}O_2$ max are plotted as dashed lines intersecting the X axis.



**Graph for breathing pattern of case #4.** There are no missing data. Black circles represent paired measurements of ventilation and tidal volume averaged at 10-s intervals during progressive, graded exercise to exhaustion. Vertical dashed lines are normal limits of tidal volume. Horizontal dashed lines are normal limits of ventilation.



**Graph for pulse oximetry of case #4.** Black circles represent the O<sub>2</sub> saturation of arterial hemoglobin (SpO<sub>2</sub>) during progressive, graded exercise to exhaustion. Normal range of SpO<sub>2</sub> is displayed by dashed lines that intersect the Y axis at 95 and 100%.



**Graph for re-test of case #4.** The subject repeated the same graded exercise test to exhaustion to determine the effect of supplemental O<sub>2</sub>. He breathed 21% O<sub>2</sub> (room air) during the 1<sup>st</sup> test and 50% O<sub>2</sub> (balance N<sub>2</sub>) during the 2<sup>nd</sup> test.

### **Summary of Findings.**

Laboratory data: Severe obstructive lung disease.

Anthropometric data: Body weight was 93% of predicted value.

Maximal exertion table: Maximal heart rate was 85% of predicted value and did not satisfy the criteria from maximal exertion.  $\dot{V}O_{2max}$  was 34% of predicted value.

Protocol graph: Maximal power output was below normal limits.

Functional capacity graph: Heart rate data were shifted above the predicted line of submaximal heart rates.

Blood pressure graph: Systolic blood pressure was below normal limits.

Breathing pattern graph: The maximal tidal volume and ventilation were remarkably subnormal.

SpO<sub>2</sub> graph: The SpO<sub>2</sub> progressively decreased from 90% (moderate hypoxemia) to 75% (severe hypoxemia).

Retest graph: The breathing of 50% O<sub>2</sub> during a 2<sup>nd</sup> exercise test maintained the SpO<sub>2</sub> at 93-97%. The subject exercised longer in the 2<sup>nd</sup> test.

Reason for stopping exercise: Shortness of breath and hypoxemia. The end-tidal PCO<sub>2</sub> progressively increased from 32 Torr at onset of exercise to 46 Torr at end of exercise.

### **Analysis**

$$\dot{V}O_{2max} = \text{max heart rate} \cdot \text{stroke volume} \cdot (\text{CaO}_2 - \text{C}\bar{v}\text{O}_2)$$

The exercise test did not satisfy criteria for maximal exertion. Linear extrapolation of the heart rate data to maximal limits indicates that  $\dot{V}O_{2max}$  was severely subnormal. There was pulmonary failure in the 1<sup>st</sup> exercise test (subnormal ventilation, subnormal tidal volume, progressively severe hypoxemia, progressive hypercapnia, dyspnea) that was partially reversed by breathing hyperoxic gas in the 2<sup>nd</sup> exercise test (mild hypoxemia). Ventricular dysfunction and skeletal myopathy potentially contributed to the severely reduced functional capacity [Gallagher, 2000].

**Impression.**

8. The cardiorespiratory functional capacity is severely subnormal due to respiratory complications of chronic lung disease. Ventricular dysfunction and skeletal myopathy cannot be excluded from contributing to the reduction of functional capacity.
9. There is progressive pulmonary insufficiency during exercise. The correction of severely depressed SpO<sub>2</sub> with supplemental O<sub>2</sub> indicates that lung disease is causing the progressive hypoxemia.

**Case study #5, Cyanotic heart disease,  
referred by Dr.'s Curt J. Daniels, M.D., and Stephen C. Cook, M.D., and presented  
with their permission.**

**History of case #5.**

A 51 year old man received palliative open-heart surgery at age 21 years and corrective heart surgery at age 39 years for repair of the Tetralogy of Fallot. At age 46 years, an exercise test was ordered for the evaluation of his fatigue. The  $\dot{V}O_{2max}$  was 1.11 liters/min and there was exercise-induced arterial hypoxemia. The findings were consistent with Eisenmenger's syndrome. He takes medications for antacid (Prevacid), antihyperlipidemic (Lipitor), and antihypertensive (Lisinopril) effects .

**Indication for exercise test of case #5.**

Re-evaluate the patient's cardiorespiratory functional capacity and exercise-stress electrocardiogram.

**Predictions:**  $\dot{V}O_{2max} = \dot{Q}_{max} (CaO_2 - C\bar{v}O_2)$

13.  $\dot{Q}_{max}$  might be decreased by a low stroke volume or reduced maximal heart rate. Stroke volume should be decreased by right ventricular scarring and chronic volume overload of both ventricles [Paridon, 1993; Perrault, 1989].
14.  $(CaO_2 - C\bar{v}O_2)$  might be decreased by exercise-induced arterial hypoxemia and self-limitation of physical activity. Progressive right-to-left shunt should decrease the  $CaO_2$  [Paridon, 1993; Perrault, 1989]. Habitual inactivity might raise the  $C\bar{v}O_2$  [Mancini, 2000].
15.  $\dot{V}O_{2max}$  might be subnormal due to residual effects of heart disease and open heart surgery. Patients with successful repairs can have a normal  $\dot{V}O_{2max}$  due to compensatory mechanisms [Godfrey, 1974; Perrault, 1989].

**Laboratory data of case #5.**

Height 168 cm, Weight 76.7 kg, Ideal weight 79.4 kg.

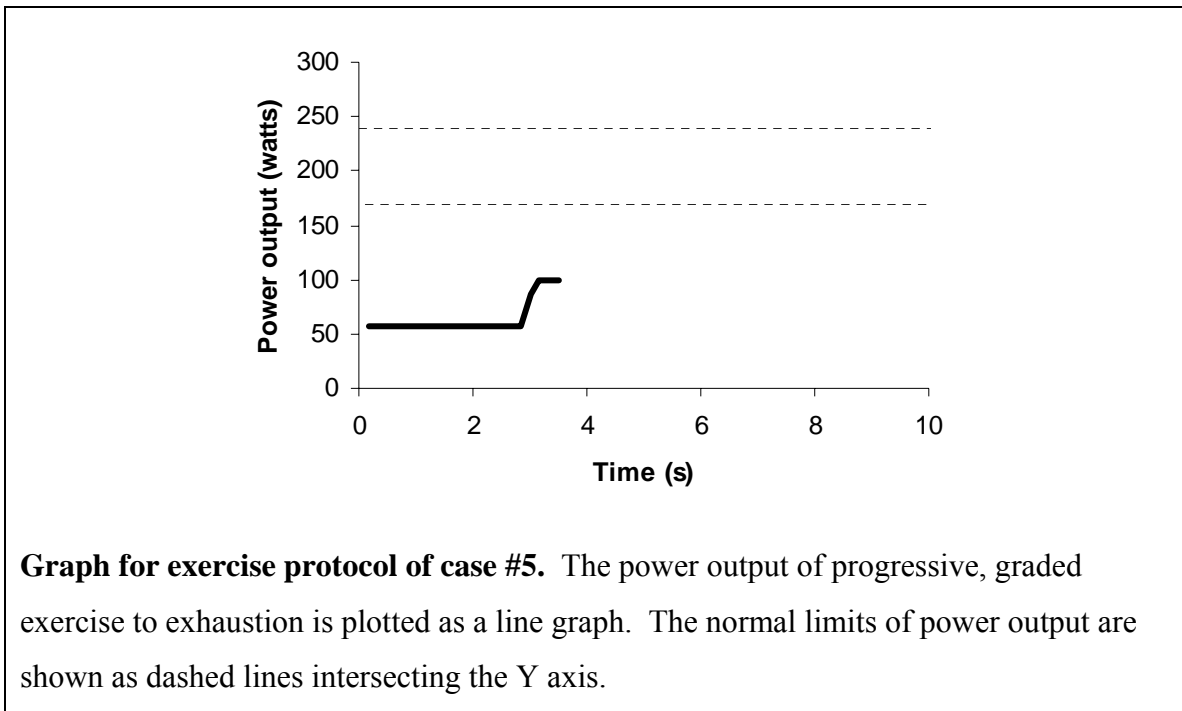
Body mass index (BMI): 27.2 kg/m<sup>2</sup>, 97% of predicted.

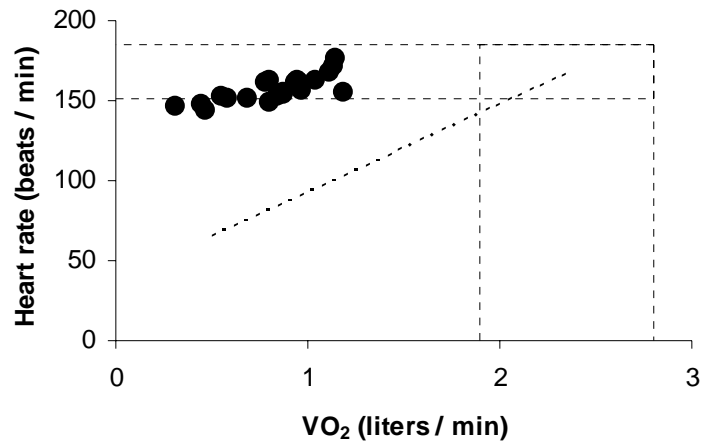
ECG: First degree heart block and right bundle branch block at rest. Triplet premature ventricular contractions appeared during exercise.

PFT's: Forced vital capacity 96% of predicted value.

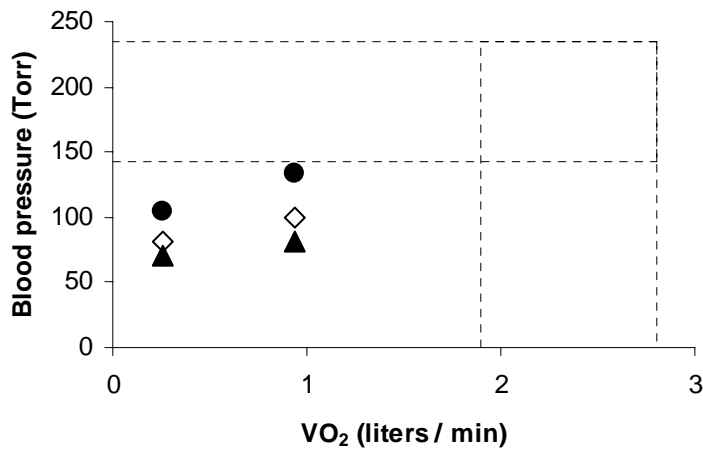
**Table for the maximal exertion of case #5.**

	Observed	predicted	Percentage of predicted
Maximal heart rate	176 beats/min	168 beats/min	105 %
Respiratory exchange ratio	1.16	1	116 %
$\dot{V}O_{2max}$	1.15 liters/min	2.36 liters/min	49 %

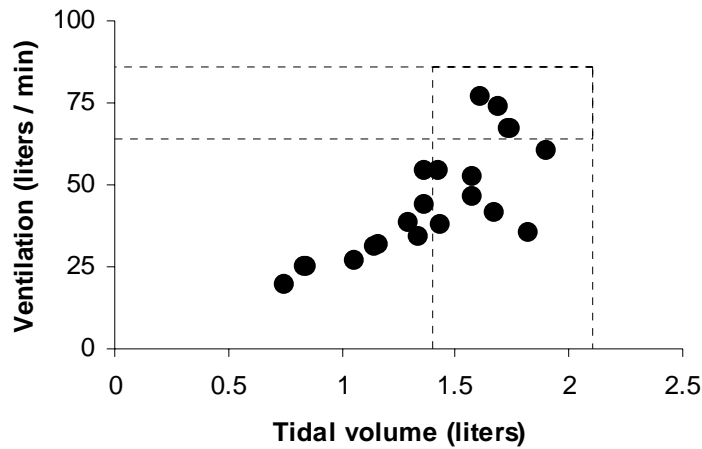




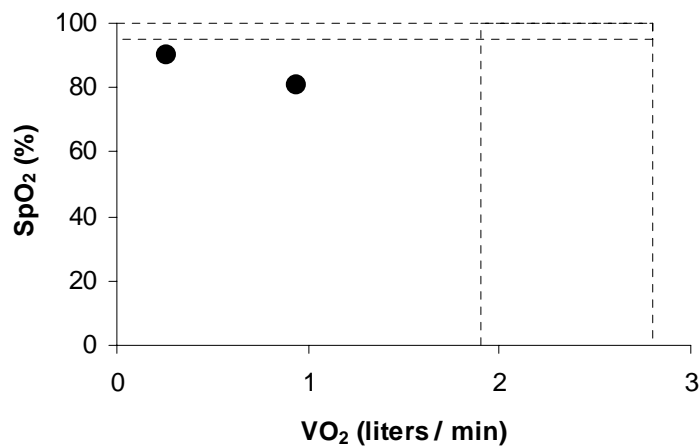
**Graph for functional capacity of case #5.** The black circles represent paired measurements of heart rate and  $\dot{V}O_2$  averaged at 10-s intervals during progressive, graded exercise to exhaustion. The vertical dashed lines are normal limits of  $\dot{V}O_{2max}$ . The horizontal dashed lines are normal limits of maximal heart rate. The up-sloping dashed line predicts submaximal heart rates.



**Graph for blood pressure of case #5.** Blood pressures from the right brachial artery are plotted as systolic pressure (black circles), calculated mean arterial pressure (white diamonds), and diastolic pressure (black triangles). The normal limits of maximal systolic pressure are shown as dashed lines intersecting the Y axis. The normal limits of  $\dot{V}O_{2max}$  are plotted as dashed lines intersecting the X axis.



**Graph for breathing pattern of case #5.** Black circles represent paired measurements of ventilation and tidal volume averaged at 10-s intervals during progressive, graded exercise to exhaustion. Vertical dashed lines are normal limits of tidal volume. Horizontal dashed lines are normal limits of ventilation.



**Graph for pulse oximetry of case #5.** Black circles represent the O<sub>2</sub> saturation of arterial hemoglobin (SpO<sub>2</sub>) during progressive, graded exercise to exhaustion. Normal range of SpO<sub>2</sub> is displayed by dashed lines that intersect the Y axis at 95 and 100%.

**Summary of Findings.**

Laboratory data: Triplet premature ventricular contractions appeared during exercise.

Anthropometric data: Normal body weight.

Maximal exertion table: Maximal heart rate and respiratory exchange ratio satisfied the criteria for maximal exertion.  $\dot{V}O_{2\max}$  (1.15 l/min) was 49% of predicted value (moderately subnormal).

Protocol graph: The maximal power output was below normal limits

Functional capacity graph: Maximal heart rate was within normal limits.  $\dot{V}O_{2\max}$  was below normal limits. The heart rate increased exceptionally rapidly in relationship to  $\dot{V}O_2$ .

Blood pressure graph: Maximal systolic blood pressure was below normal limits. Diastolic pressure increased during exercise.

Breathing pattern graph: The tidal volume and ventilation increased to normal limits.

SpO<sub>2</sub> graph: SpO<sub>2</sub> fell from 90% (moderate hypoxemia) to 72% (severe hypoxemia).

### **Analysis**

$$\dot{V}O_{2\max} = \text{max heart rate} \cdot \text{stroke volume} \cdot (\text{CaO}_2 - \text{C}\bar{\text{v}}\text{O}_2)$$

This test satisfied the criteria for maximal exertion and reproduced the  $\dot{V}O_{2\max}$  of the patient's previous exercise test. The subnormal  $\dot{V}O_{2\max}$  might be explained by hypoxemia, reduced cardiac output, or skeletal myopathy [Mancini, 2000]. The low power output was consistent with any of these mechanisms. Exercise stimulated the rapid progression to severe hypoxemia despite a normal breathing pattern. The severe hypoxemia was consistent with a residual right-to-left shunt 12 years after corrective open heart surgery.

### **Impression.**

10. The cardiorespiratory functional capacity is 4 % greater today than 5 years ago as determined by the slight increase in  $\dot{V}O_2\text{max}$ . Today's  $\dot{V}O_2\text{max}$  is moderately subnormal due to uncompensated, residual effects of repaired Tetralogy of Fallot.
11. The exercise-induced arterial hypoxemia is consistent with a vascular right-to-left shunt.
12. Nonsustained ventricular tachycardia appeared as triplet contractions during exercise.

## TERMINOLOGY

*ATP:* Adenosine triphosphate carries free energy in its phosphoanhydride bonds. The hydrolysis to adenosine diphosphate releases about 7 kilocalories of energy per mole of ATP.

*BMI:* The ratio of body weight to the squared value of body height, as expressed in units of  $\text{kg/m}^2$ .

*Body mass index:* see BMI.

*Cardiorespiratory system:* The group of structures that transfer  $\text{O}_2$  and  $\text{CO}_2$  between the atmosphere and mitochondria. The system includes cardiovascular, pulmonary, and cellular structures.

*Dynamic exercise:* The use of limb muscles to move an object through space. By comparison, static exercise is the use of limb muscles to support an object in space.

*Exercise capacity:* The capacity for dynamic exercise is best expressed in units of maximal work or maximal power output.

*Fick principle:* The principle that blood flow can be calculated by injecting a known amount of tracer between sampling sites which differ in the steady-state blood concentration of tracer. Measurements of  $\dot{V}\text{O}_2$  and the blood concentration of  $\text{O}_2$  take advantage of  $\text{O}_2$  as a physiological tracer substance.

*FVC:* The maximal volume of air released from fully inflated lungs during a single forced expiration.

*Forced vital capacity:* see FVC.

*Functional capacity:* The maximal performance of an organ system without incursion of structural damage.

*MVV:* The total volume of air expired during a rapid succession of deep breaths over a brief time period, typically 12 seconds.

*Maximal voluntary ventilation:* see MVV.

*Mean arterial pressure:* Calculated as the sum of diastolic blood pressure plus  $\frac{1}{3}$  pulse pressure.

*Mitochondrion:* A subcellular structure that transfers free energy from digested food to ATP by oxidative phosphorylation. Oxidative phosphorylation requires molecular oxygen.

*Neuromuscular system:* The network of neural and cellular structures that transmit electrical signals between the brain and sarcomere for purposes of stimulating a muscle contraction or transmitting feedback information to the central nervous system.

*pCO<sub>2</sub>:* The partial pressure of CO<sub>2</sub> in gas or liquid.

*pO<sub>2</sub>:* The partial pressure of O<sub>2</sub> in gas or liquid.

*Pulse pressure:* The difference between systolic and diastolic blood pressure.

*Respiratory exchange ratio:* The quotient of  $\dot{V}CO_2$  divided by  $\dot{V}O_2$  based on measurements of respiratory gas exchange at the mouth.

*Respiratory gas exchange:* The flow of O<sub>2</sub> and CO<sub>2</sub> between the atmosphere and mitochondria.

*Respiratory gases:* O<sub>2</sub> and CO<sub>2</sub>.

*SaO<sub>2</sub>:* The saturation of hemoglobin by O<sub>2</sub> in a sample of arterial blood.

*SpO<sub>2</sub>:* The saturation of hemoglobin by O<sub>2</sub> in arterial blood as measured noninvasively by the pulse oximeter.

*Sarcomere:* A subcellular structure of striated muscle that contains protein filaments. The hydrolysis of ATP by myosin filaments converts potential energy to muscle contraction.

$\dot{V}CO_2$ : The flow of CO<sub>2</sub>. The flow of CO<sub>2</sub> out of the body is called the CO<sub>2</sub> release.

$\dot{V}CO_2$ : The flow of O<sub>2</sub>. The flow of O<sub>2</sub> into the body is called the O<sub>2</sub> uptake.

$\dot{V}O_{2max}$ : A measurement of the functional capacity of the cardiorespiratory system; the highest time-averaged  $\dot{V}O_2$  (e.g., 30 s) that occurs when progressive exercise increases the heart rate to at least 90% of predicted maximum and the respiratory exchange ratio to at least 100% of predicted value.

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