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Orientation to the cardiopulmonary exercise test

A standard clinical cardiopulmonary exercise test (CPET) acquires continuous measurements of metabolic, cardiovascular, and respiratory parameters over the course of an 8–15 minute effort in which exercise progresses incrementally from minimal movement to a maximal symptom-limited effort. This chapter first describes the equipment needed for these exercise measurements and then discusses the progressive work protocol that is used for all of these clinical studies.

EQUIPMENT REQUIRED FOR A CPET

The integrated commercial systems used for CPET studies incorporate input from several devices, but the measurements

made on exhaled breath during exercise are the defining characteristics of a CPET study. Both the volume of exhaled breath and the concentrations of oxygen and carbon dioxide within that exhaled gas are monitored continuously, so the subject must exercise while breathing through a mouthpiece or mask connected to the measurement system. For systems that perform breath-by-breath measurements of both ventilation and gas exchange, any of several devices incorporated in the exercise mask or mouthpiece can monitor the flow rates within each exhaled breath. In addition, a sampling port for measurements of exhaled oxygen and carbon dioxide concentrations is located in that mask or mouthpiece assembly. The sampling rates for both gas flow and respiratory gas concentration measurements are high enough to permit accurate calculation of breath volume, oxygen uptake, and carbon dioxide output within each exhaled breath. For the simpler systems that do not provide breath-by-breath analysis, the patient's exhaled gas is directed through a mixing box, where volume measurement and respiratory gas concentrations are measured at the distal end of the mixing box. Both types of measurement systems are adequate for the majority of clinical applications, although the breath-by-breath systems can provide additional information on breathing patterns seen in some disease conditions.

In addition to the respiratory gas measurements, integrated CPET systems provide for continuous recording of standard 12-lead ECG for documentation of rate, rhythm, and ST changes during and after exercise. These systems usually can accept input from an automated blood pressure cuff and from a pulse

oximeter. Alternately, manual blood pressure and pulse oximeter measurements can be recorded throughout exercise and recovery (Figure 2.1).

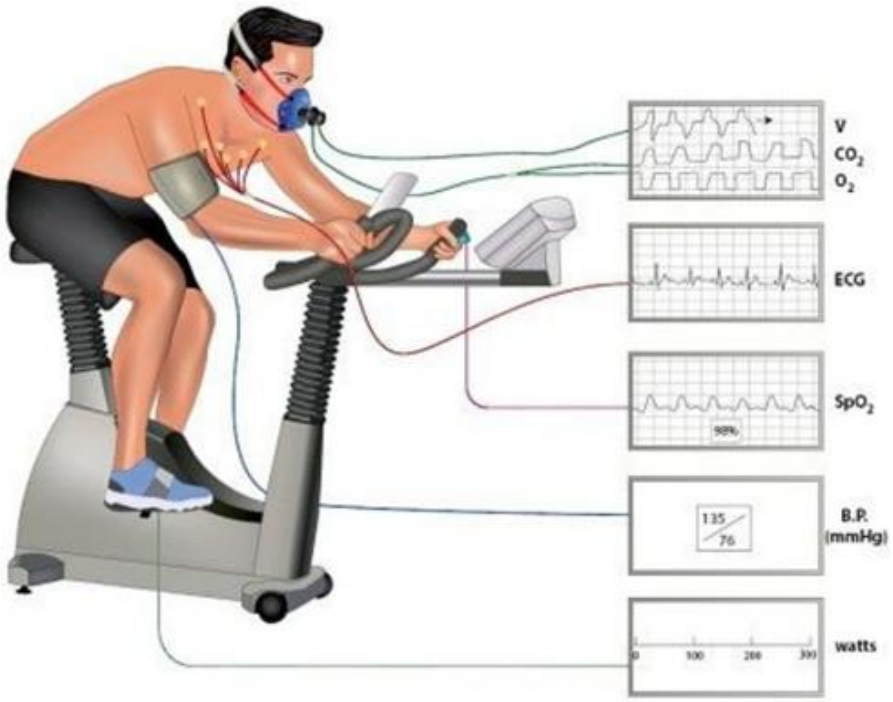

Figure 2.1 Subject on a cycle ergometer outfitted for a CPET, with device for airflow measurement and gas sampling leads attached to mask. Airflow and gas sampling leads are connected to system analysis equipment and computer, along with inputs from ECG, oximeter, blood pressure measurements and ergometer.

THE PROGRESSIVE WORK PROTOCOL

The progressive work protocol used for clinical studies has two characteristics that establish it as a diagnostic tool. First, a standard CPET utilizes an exercise mode that incorporates at least 50% of a subject's muscle mass, a criterion that is most conveniently met by exercise performed on either a cycle ergometer or a treadmill. Second, the progressive work protocol utilizing either ergometer or treadmill should last 8–15 minutes, starting from lowest-level exertion and progressing to a symptom-limited maximal effort.

For either ergometer or treadmill exercise, the rate of increase of progressive exercise stress needs to be adjusted to allow the exercise subject to acquire 8–15 minutes of exercise data. For subjects exercised on a cycle ergometer, the progressive increments in cycling resistance are expressed in terms of watts of power generated. The exercise system setting that determines the rate of watt increase per minute must be adjusted according to subject size, as larger subjects can achieve larger absolute power outputs. To complete a 8–15 minute maximal exercise test, the chosen ergometer power increments must take into account both the subject's size and some estimate of the subject's maximal exercise capacity. For example, small elderly women might work at increments of 10 watts per minute and still be unable to last more than 8 minutes, while a large young male might last over 15 minutes utilizing increments of 25 watts per minute. For treadmill exercise, a standard protocol of increasing speed and grade ordinarily suffices, as subjects exercising on a treadmill are carrying their own body weight, exposing both small and large subjects to size-comparable exercise demands.

However the increments of treadmill speed and grade still may need to be adjusted for estimated exercise capacity to achieve an 8–15 minute test that ends in a symptom-limited maximal exercise effort. Commercial exercise testing systems can automatically run previously selected progressions of ergometer or treadmill work rates during the test.

PRESENTATION OF THE MEASUREMENTS ACQUIRED IN A CPET

The software in integrated exercise systems uses the exercise measurements of gas flow and gas concentrations to calculate breath-by-breath measurements of tidal volume, oxygen uptake, and carbon dioxide output.

Exercise system software ordinarily presents the CPET data acquired throughout a test in a table of 20-second averaged blocks, including oxygen uptake, carbon dioxide output, tidal volume, minute ventilation, respiratory rate, heart rate, end-tidal oxygen, end-tidal carbon dioxide, ECG tracings, blood pressure, oxygen saturation, and power output for ergometer studies or treadmill time for treadmill studies. Ratios useful in test interpretation are calculated from these basic measurements. They include the respiratory "R" ($\dot{V}CO_2/\dot{V}O_2$), oxygen pulse ($\dot{V}O_2$/heart rate), and ventilatory equivalents for oxygen ($\dot{V}E/\dot{V}O_2$) and carbon dioxide ($\dot{V}E/\dot{V}CO_2$). The utility of all these measurements and ratios for test interpretation will be discussed in the following three chapters.

Breath-by-breath plots of oxygen uptake and carbon dioxide output during a progressive work test show substantial

variability, but this variability is primarily attributable to the variability of breath size and does not represent measurement error or variability in muscle metabolism. As this variability of measurements made at the mouth do not represent variability of the metabolic changes in the exercising muscle, the respiratory gas exchange measurements are ordinarily summed in 20-second bins and described in units of milliliter per minute.

POWER OUTPUT AND OXYGEN UPTAKE

Throughout a progressive work test, there is a consistent linear relationship between the oxygen consumption of the exercising subject and the power output achieved. For subjects being exercised on a cycle ergometer with appropriately chosen watt increments, every additional watt of power output is associated with a 10 mL/minute increase in oxygen consumption (Figure 2.2). For treadmill protocols that use a constant walking speed with progressive increases in treadmill grade, the relationship is linear. (Treadmill protocols that incorporate both incremental grade and incremental treadmill speeds also show a linear increase in oxygen consumption, with the exception that the walk-run transition produces a one-time bump in oxygen consumption.)