Measurement of Cardiac Output during Exercise

There are a variety of reasons why the clinician would want to measure cardiac output. In the intensive care unit (ICU), life-threatening hypoperfusion states may be subject to manipulation. Outside the ICU, low cardiac output may limit the quality of life.

A functional definition of heart failure is a cardiac output insufficient for metabolic needs. Implicit in this is the magnitude of these needs. For the paralyzed patient on a ventilator, the metabolic needs are minimal and the presence of a line in the pulmonary artery allows the measurement of cardiac output by thermodilution or other techniques. For the patient outside the ICU, the metabolic needs are greater, particularly with exercise. Cardiac ultrasonography can provide detailed information about cardiac function at rest but, for technical reasons, cannot do so during exercise. For the patient with shortness of breath on mild exertion, the measurement of cardiac output during exercise could yield useful information, especially if done relatively noninvasively.

The measurement of cardiac output during exercise can be achieved by three main techniques. The oldest and least used is the dye-dilution method. A second is to measure pulmonary blood flow by the uptake of nonresident gases. Briefly, during exercise, a subject is switched for 10 to 15 s into a rebreathing system containing a soluble and an insoluble gas. By using the rate of disappearance of the soluble gas from the closed system, the pulmonary blood flow can be calculated. This technique is completely noninvasive and easy to use, but has a major limitation. In the presence of even relatively mild lung disease, the disappearance of the soluble gas is more dependent on slow diffusion into poorly ventilated regions than on uptake by the pulmonary circulation.

A third method is based on the Fick principle, known since 1870. This principle states that the arrival of oxygen at the right side of the heart plus the oxygen that entered the blood via the lungs must equal the oxygen transported away from the left side of the heart. Said mathematically:

\[
\dot{Q} \times \text{CaO}_2 + \dot{V}_O_2 = \dot{Q} \times \text{CVO}_2,
\]

where \(\dot{Q}\) is cardiac output, \(\text{CVO}_2\) is mixed venous oxygen content, \(\dot{V}_O_2\) is the oxygen uptake in the lungs, and \(\text{CaO}_2\) is arterial oxygen content. Solving for \(\dot{Q}\),

\[
\dot{Q} = \frac{\dot{V}_O_2}{\text{CaO}_2 - \text{CVO}_2}.
\]

The \(\dot{V}_O_2\) can be measured by using the ventilation and the inspired and expired oxygen concentrations. From the oxygen dissociation curve and the \(\text{PaO}_2\), the \(\text{CaO}_2\) can be derived (alternatively, the saturation can be measured and the content derived from the hemoglobin concentration or the content can be measured directly). The problem lies with determination of the \(\text{CVO}_2\), which usually requires a sample of right ventricular or, preferably, pulmonary artery blood, which means cardiac catheterization and relative invasiveness.

If oxygen uptake could be blocked briefly by having the subject breathe from a bag containing a low concentration of oxygen, the lungs could be used as a tonometer to equilibrate the oxygen tension in the bag-lung system during the first few seconds before recirculation occurred. From the partial pressure of oxygen in the system, the \(\text{CVO}_2\) can be derived noninvasively. This "indirect" Fick principle works both in theory and in practice, but, particularly during exercise, the rebreathing of very hypoxic mixtures, even for a short time, is unpleasant and not without danger.

The Fick equation can be rewritten for carbon dioxide as follows:

\[
\dot{Q} = \frac{\dot{V}_C0_2}{\text{CVO}_2 - \text{CaCO}_2}.
\]

In this situation, the measurement of the venous \(\text{CO}_2\) content requires rebreathing from a bag containing \(\text{CO}_2\) and oxygen. This brief period of hypercapnic hypoxia, while not pleasant, is well tolerated even after the requisite steady-state exercise conditions have been achieved, usually considered to be at least 5 min of work at the same level of intensity. Furthermore, unlike the nonresident gas techniques, areas with poor ventilation have local partial pressures of \(\text{CO}_2\) that approach the \(\text{PCO}_2\). Hence, even in the presence of severe lung disease, rebreathing is relatively unaffected by poor intrapulmonary gas mixing. A variation of the technique described by Defares and modified by Heigenhauser and Jones is to have the patient rebreathe from a bag containing 4 percent \(\text{CO}_2\) and 96 percent \(\text{O}_2\) and then estimate the \(\text{PCO}_2\) by an exponential extrapolation.

The accuracy of both the "equilibrium" and the "exponential" rebreathe techniques depends on the ability to measure both \(\text{VCO}_2\) and the arterial-venous
CO2 content difference accurately. Since the metabolic demands increase with exercise, the measurement of VCO2 can be made more accurately. The CO2 content difference also increases with exercise (or hypoperfusion), minimizing small errors in measuring either component. The rebreathe technique has been validated in children and adults, both with and without lung disease, and in patients with hypoperfusion in the ICU. However, one of the problems with the steady-state requirement is that repeated measurements at different levels of work are not easy for sick patients in poor condition unless one resorts to several testing sessions.

To overcome this, there has been recent interest in non-steady-state measurements of cardiac output. In seven normal subjects during an incremental exercise test, McKelvie and colleagues demonstrated that cardiac output could be measured with the same degree of accuracy as during steady-state conditions. In the current issue of Chest (see page 1118), Lands and colleagues, who studied 14 patients with cystic fibrosis ranging in severity from mild to severe and 14 normal control subjects, convincingly demonstrated that the exponential technique used during progressive exercise yields results comparable to those obtained with the equilibrium technique during steady-state exercise. They used a totally noninvasive methodology deriving PaCO2 from the end-tidal PCO2 adjusted for the breathing pattern. Their values for cardiac output in relation to Vo2 clearly fit what would be expected from the literature. This raises the possibility of monitoring cardiac output noninvasively over several levels of effort.

Much of the interest in the indirect CO2 Fick principle for measuring cardiac output during exercise was generated in the 1970s by the group at Hammer smith Hospital in London. In North America it has generally been propagated by either expatriates or disciples of that group. It is of interest that one of the best-known exercise groups in North America alludes to the technique but does not really describe it or advocate it in its recent textbook. Part of the reason for this may be that the equilibrium technique requires considerable experience for the operator to make the correct choices of the initial concentration of CO2 and volume of the rebreathe bag. Furthermore, errors in the technique are not intuitively obvious; as a result, the less experienced operator may end with patently incorrect results and not know why. Finally, the physiology is still not completely understood.

Sampling of arterial blood during an equilibrium rebreathe maneuver has shown a small discrepancy between the PvCO2 measured in the bag and the simultaneous PaCO2, the PCO2 in the bag being higher. While this can be adjusted by using the "downstream" correction factor, there has been no satisfactory explanation as to why it exists and there is controversy as to whether the correction should be used in children. The methodology of Lands et al, while not explaining the physiology of the downstream correction, is considerably simpler to use than the equilibrium technique. This technique should easily lend itself to automation and may lead to increased use of the measurement of cardiac output during exercise.

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Carbon Dioxide Narcosis
Pathological or "Pathological"?

In 1820, Henry Hill Hickman placed a puppy in an enclosed glass jar. After the dog's breathing became labored and ceased, Dr Hickman was able to amputate one of its appendages, following which the dog regained consciousness. Dr Hickman was able to replicate this experiment several times. He concluded that increased CO2 (rather than acidosis or hypoxemia) caused loss of consciousness and suggested that rendering humans hypercarbic would be suitable anes-