Cardiac Output Responses to Exercise

There has been a long standing bias towards cardiovascular and pulmonary physiology to be the main determinants to exercise tolerance and performance. During the late 1990’s and through the early 2000’s, there has been on-going debate to how such a cardiopulmonary bias, when it functions to prevent central nervous system function as an important additional determinant, has hampered progress in exercise physiology. I agree with this realization. This does not mean cardiopulmonary physiology is not important. Rather, it shows that the body is multi-systemic, and that it is illogical to think that one component of this multiple systems response is any more important than any other. Read on and I hope it is all logical!

The determinants and computation of cardiac output is provided in Equation 1.

\[
\text{Cardiac Output (L/min)} = \text{Heart Rate (beats/ min)} \times \text{Stroke Volume (L)}
\]

Equation 1

The volume of research on cardiac output responses to exercise is not large, due mainly to difficulties in the measurement of cardiac output. While stroke volume can be measured using Doppler ultrasound, it is expensive, difficult to do when a subject is exercising, and has some limitations in accuracy due to changing dimensions of the aortic valve during left ventricular systole. Consequently, the Fick equation of Equations 2 and 3 has been used to provide alternate options for the indirect measurement of cardiac output. Note that Equations 2 and 3 differ only in whether VO\(_2\) or VCO\(_2\) is used in the calculation.

\[
\text{Oxygen Consumption (VO}_2; \text{L/min}) = \text{Cardiac Output (Q; L/min)} \times (a - vO_2\Delta) (L/L)
\]

\[
Q = \frac{VO_2}{(a - vO_2\Delta)}
\]

Equation 2

\[
\text{Carbon Dioxide Production (VCO}_2; \text{L/min}) = \text{Cardiac Output (Q; L/min)} \times (v - aCO_2\Delta) (L/L)
\]

\[
Q = \frac{VCO_2}{(v - aCO_2\Delta)}
\]

Equation 3

The Fick equation is useful in that it allows for an alternate method for VO\(_2\) or VCO\(_2\) computation, if cardiac output is known. Conversely, if VO\(_2\) or VCO\(_2\) are known, as can be done using indirect calorimetry, and there is a way to measure arterial and venous \(O_2\) or \(CO_2\) content, then cardiac output can be calculated (see Section on Pulmonary Physiology). Cardiac output can also be measured when certain non-physiological gases are inhaled, such as acetylene and use of a gas mass spectrometer.

I hope you get the point that cardiac output is a difficult measure to make during exercise. However, based on the research that has been done, we do know quite a lot about cardiac output responses to exercise.
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**Steady State Exercise**
As with heart rate, cardiac output increases rapidly during exercise transitions. The relationship between steady state cardiac output and exercise intensity is also linear, and there seems to be a tight relationship between cardiac output and exercise intensity for all individuals, approximating 6 L/L \( \text{VO}_2 \) above the resting cardiac output of between 4.5 to 7 L/min, depending on body size.

![Graphs showing cardiac output, stroke volume, and heart rate for three different subjects](image)

**Figure 1.** Data for three different subjects for heart rate, stroke volume and cardiac output during incremental exercise.

**Incremental Exercise**
Traditionally, it has always been explained that cardiac output increases linearly to \( \text{VO}_2 \text{max} \) and \( \text{Qmax} \) during incremental exercise. However, recent research has shown that in many individuals, cardiac output exhibits a slight curvilinear response approaching \( \text{VO}_2 \text{max} \). In addition, as with stroke volume, there are a variety of profiles in the cardiac output response to exercise. To illustrate this for you, Figures 1 through 3 provide data for heart rate, cardiac output and stroke volume for three different individuals from my research.
### Glossary Words

- **Cardiac output** is the volume of blood pumped by the heart (usually referenced to the left ventricle) per unit time, such as 5 L/min at rest.

- **Fick equation** is the equation describing the computation of either of VO\(_2\) or Q as follows: 
  \[ Q = VO_2 \times (\Delta a-vO_2) \]

- **Acetylene** is a physiologically inert gas often used to estimate cardiac output.

- **Gas mass spectrometer** is an instrument used to quantify gas fractions in air based on the differences in mass between different gases.