Cardiac Output Estimation Based on Oxygen Consumption during Exercise Test on Bicycle Ergometer

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Abstract. *Cardiac output (CO) is a cardinal parameter of cardiovascular state, and a fundamental determinant of global oxygen delivery. Historically, routine clinical measurement of CO has been limited to critically-ill patients, often with invasive indicator dilution methods such as thermodilution. A variety of cardiac output estimators have been developed over the past hundred years. The estimator evaluated in this paper is based on oxygen uptake measured during exercise test to estimate cardiac output and use heart rate (HR) to obtain also stroke volume (SV). Most important is that estimation is noninvasive and can be used during the exercises test. The results for well – trained, medium trained and untrained persons are also shown.*

Keywords: Cardiac output, stroke volume, heart rate, spiroergometric exercise test

1. Introduction

Cardiac output is a measure of the amount of blood pumped by either ventricle. In steady state, the outputs of both ventricles are the same. In a healthy adult male, *CO* is approximately 5 L/min. *CO* can vary, however, according to the body's physiological needs; for example, a well-trained athlete, while exercising, can increase *CO* to up to 30 L/min to increase the rate of transport of oxygen, nutrients, and wastes [1]. Abnormally low levels of *CO* can also be an indication of pathology. Each time the left ventricle contract, a volume of blood is ejected into the aorta. This *SV*, multiplied by the number of beats per minute (*HR*), equals the *CO*:

$$CO = SV*HR \qquad \text{[ml/min, ml/min/beat, beats/min]} \qquad (1)$$

CO indicates how well the heart is performing this function. *CO* is regulated principally by the demand for oxygen by the cells of the body. If the cells are working hard, with a high metabolic oxygen demand then the *CO* is raised to increase the supply of oxygen to the cells, while at rest when the cellular demand is low, the *CO* return to baseline. *CO* is regulated not only by the heart as it pumps, but also by the function of the vessels of the body as they actively relax and contract thereby increasing and decreasing the resistance to flow. When *CO* increases in a healthy but untrained individual, most of the increase can be attributed to an increase in *HR*. Increased sympathetic nervous system activity, and decreased parasympathetic nervous system activity can also increase *CO*. *HR* can vary by a factor of approximately 3, between 60 and 180 beats/ minute, while *SV* can vary between 70 and 120 ml, a ratio factor of only 1.7 ml. The ability to accurately measure *CO* is important in clinical medicine as it provides for improved diagnosis of abnormalities, and can be used to guide appropriate management. *CO* measurement, if it were accurate and non-invasive, would be adopted as part of every clinical examination from general observations to the intensive care ward, and would be as common as simple blood pressure measurements are now. Such practice, if it were adopted, may revolutionize the treatment of many cardiovascular diseases including hypertension and heart failure. This is the reason why *CO* measurement is now an important research and clinical focus in cardiovascular medicine [2].

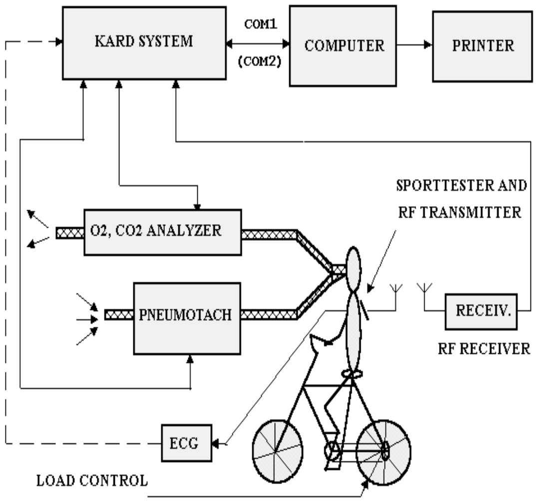

Fig. 1. Block diagram of measuring system for non-invasive *CO* estimation. The bicycle or treadmill ergometer can be used.

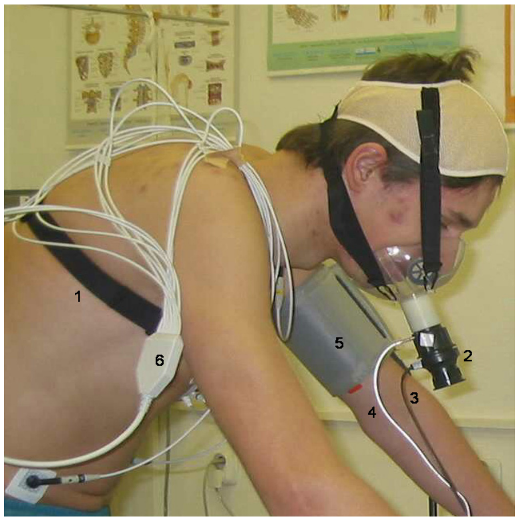

Fig. 2. The physiological parameter measurement: 1-*HR* belt (Sporttester), 2-turbine for ventilation measuring, 3-cable for ventilation pulses, 4-tube for exhausted gas samples, 5-cuff for blood pressure measuring, 6-cable for ECG electrodes.

The Fick method derives *CO* through calculating oxygen consumed over a given period of time by measuring oxygen consumption per minute with a spirometer, oxygen concentration of venous blood from the pulmonary artery, and oxygen concentration of arterial blood from a peripheral artery. Sometimes *CO* is expressed as a cardiac index (*Ci*), which is the *CO* divided by the estimated body surface area (*BSA*) in square meters.

$$BSA = (height * weight/3600)^{0.5} \qquad [m^2, cm, kg] \qquad (2)$$

The *Ci* is given by (5).

$$Ci = CO / BSA \qquad [l/min/m^2, l/min, m^2] \qquad (3)$$

Calculating the *Ci* normalizes *CO* to individuals of different size. A normal range for *Ci* is 2.6 to 4.2 l/min/m^2. While considered to be the most accurate method for *CO* measurement, Fick method is invasive. In this paper, *CO* was estimated noninvasively from oxygen uptake during exercise on cycle or treadmill ergometer.

2. Methods

Because both *HR* and VO_2 can be easily measured during standard incremental cardio-pulmonary exercise testing [1], both *CO* and *SV* could be accurately quantified if the simultaneous arteriovenous O_2 content difference $(C_A - C_V)$ could be estimated [3, 4]. For noninvasive *CO* estimation, exercise tests were performed on an ergometer (or treadmill) controlled by computer. Subjects were familiarized with the apparatus and performed a continuous incremental symptom-limited maximal test for determination of VO_{2max} and lactic acidosis threshold (*LAT*). The block diagram of measuring system is shown in Fig. 1. The electrical signals from sensors were connected to microcontroller systems. The samples of expired gas samples were connected to gas analyzer (O_2 and CO_2 analyzer). All measured signals were processed in personal computer. Example of measuring (on bicycle regometrer) is shown on Fig. 2. From the measured values workload [W] for cycle ergometer or [km/h] for treadmill, *HR* [beats/min] and VO_2 [l/min] the *CO* was estimated [3, 4]. Also *SV* and *Ci* were computed. The *CO* was calculated according formula (4):

$$CO = \frac{100 * VO_2}{\left[5.721 + 0.1047 \frac{100 * VO_2}{VO_{2MAX}} \right]} \qquad [\text{l/min}] \qquad (4)$$

Table 1. Spiroergometric values of 6 subjects. Sub=Subject, M-male, F-female, He=Height [cm], We=Weight [kg], $VO_{2m}=VO_{2max}$ [l], $VO_{2mk}=VO_{2max}/kg$ [ml/min/kg]

Sub	Age	He	We	VO_{2m}	VO_{2mk}
M1	28	177	70.3	6.75	81
M2	49	170	66.7	4.2	63
M3	65	166.5	65.2	3.15	39.7
F1	31	168.5	63.2	4.33	68.5
F2	11	156.5	42.8	1.6	37.5
F3	40	165.5	72	2.69	37.4

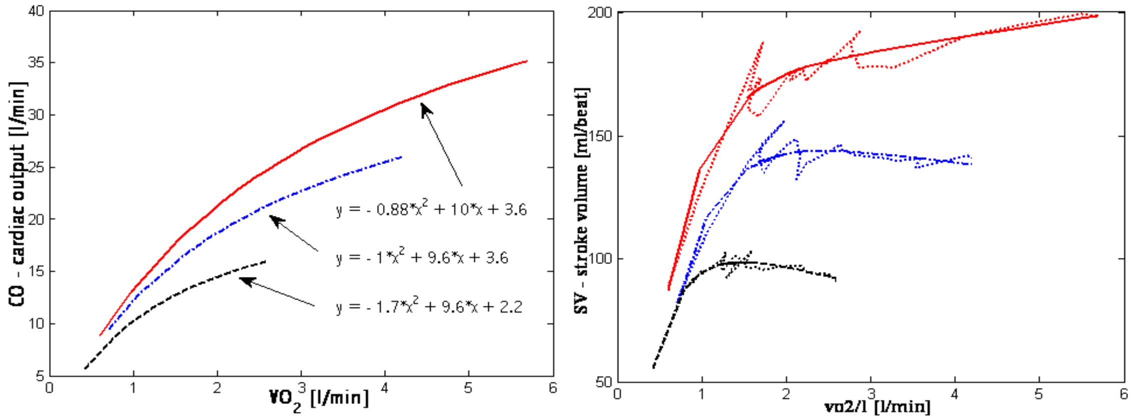

Fig. 3. *CO* in relation to VO_2 during stress-test M1-red, M2-blue (dash-dot), M3-black (dash), (left). *SV* in relation to VO_2 during the stress-test M1-red, M2-blue (dash-dot), M3-black (dash), (right).

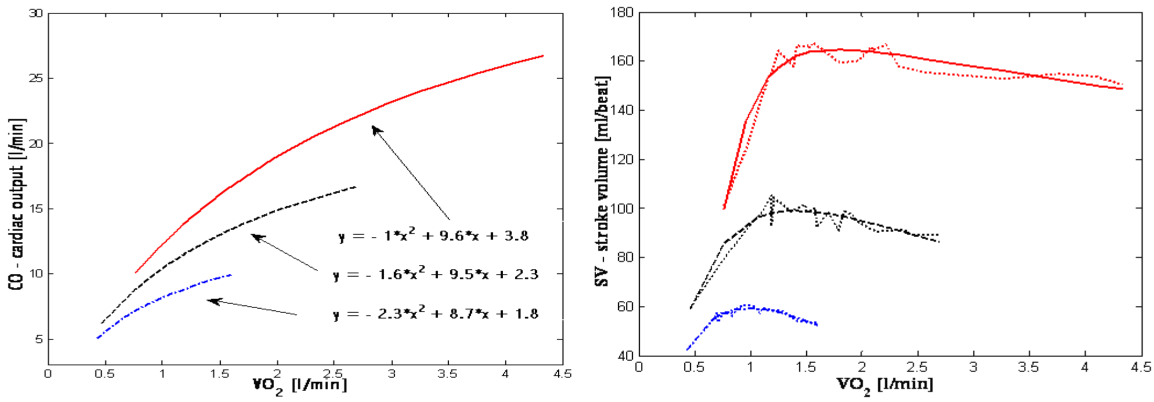

Fig. 4. *CO* in relation to VO_2 during stress-test F1-red, F2-blue (dash-dot), F3-black (dash), (left). *SV* in relation to VO_2 during the stress-test F1-red, F2-blue (dash-dot), F3-black (dash), (right).

3. Results

Six subjects (3 men and 3 women) of our data-base with very different athletic background were used to demonstrate the dynamics of *CO* and *SV* during standard spiroergometric test (Table 1). M1 – top-class cross-country skier, M2 – leisure „hobby” athlete, M3 – pre-surgery patient, F1 – top-class triathlete, F2 – young swimmer, F3 – leisure „hobby” athlete. The test used 3 three-minute sub-maximal worming-up workloads followed by step-vise increased workload up to the exhaustion. Results (*CO* and *SV* in relation to VO_2 [l/min]) are presented in Fig. 3 for men and in Fig. 4 for women. Higher cardiac output as a function of higher stroke volume plays important role in increased transporting capacity of blood for oxygen and enables well trained subject to achieve significantly higher physical performance.

4. Discission

A totally noninvasive determination of *CO* and *SV* during exercise would be very useful in healthy subjects as well as in patients with various degrees of cardiac insufficiency. This can provide a simple and low-cost assessment of cardiac function in response to exercise. Although it is generally assumed that *CO* increases linearly with VO_2, the pattern of variation in VO_2 and *CO* as maximal O_2 consumption is approached has not been extensively investigated and may vary among individuals. According to Frank-Starling mechanism the amount of blood that the heart pumps works up to a limit of 3 times the normal cardiac output. When the peripheral tissues demand excessive amounts of blood flow, the nervous signals increase cardiac output [2, 3, 4]. Our examples document that the time course of these changes is very similar in the subjects of very different cardio-respiratory fitness level. However, these findings still need to be proved in the groups of subjects of different lifestyle, different athletic background, men and women, and even patients. Our pilot study indicates that top level endurance athletes can reach outstanding values of *CO* and *SV* at about 40 l/min and 200 ml/beat respectively. Hence, this method seems to offer another useful data to evaluate cardio-respiratory capacity and adaptation to physical activity and/or inactivity.

5. Conclusions

A variety of cardiac output estimators have been developed over the past hundred years. Stringer et. al. [3] proved that the data of oxygen uptake during exercise can be used to estimate noninvasively cardiac output. They used Fick´s principle for *CO* estimation during exercise, and these results correlated with direct VO_2 measurements. Using their results we calculated *CO* in our subjects [4]. Estimation is noninvasive and can be used during the stress test.

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