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Indirectly Determined Maximal Cardiac Output in Men and Women With Different Physical Activity

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ABSTRACT

Maximal cardiac output (COmax) is one of the most important functional parameters related to cardiorespiratory capacity (VO2max) and physical fitness. In clinical medicine, low COmax values are a risk factor for imminent heart failure. Conversely, high COmax values are a prerequisite for achieving high performance in sports, especially in endurance disciplines. To determine the COmax, we used our own modification of the COmax calculation from the VO2max values obtained during the spiroergometric examination [Stork, 2010]. Our work is based on the findings of Stringer et al. [1997], which documented a very close correlation between COmax values obtained by calculation and COmax values obtained by the classical method according to Fick's principle.

Subjects: From our 20-year examination database, we included in this study 641 men (M) and 164 women (F) over 19 years of age who completed a stress test on a bicycle ergometer with a graded load to the maximum. To calculate COmax, we used the equation with which we have already worked in several of our earlier studies [Stork, 2010]. We have divided the files into three groups according to different physical activity: group A included well-trained endurance-athletes, who had several years of sports training at the time of the examination. Group B included subjects who engaged in physical activity only in their free time without competing in any sports competition. Subjects with various health problems who either never played any sport at all or ended their sports career many years ago, were included in group C. Movement activity is a condition for the development and maintenance of the adaptive abilities of the cardiorespiratory system. The parameters measured in recreational sportsmen correspond to the average of a healthy average fit population. If physical activity is not part of a healthy lifestyle and, in addition, there are health problems (in our groups C obesity and resting and exertional chest pains are the most common), in many subjects from our groups C the COmax parameters are significantly below average and close to the level characterizing the NYHA-1 to NYHA-2 group according to cardiology classification. The results show, on the one hand, how important factor in health prevention is regular physical activity, and, on the other hand, the applicability of our modified method to determine non-invasively the maximum cardiac output.

Keywords: Cardiac output, Stroke volume, Indirect estimation, Cardiorespiratory capacity, Stress test, Spiroergometry

INTRODUCTION

Cardiac output (*CO*) is a measure of the amount of blood pumped by either ventricle. In resting steady state, the outputs of both ventricles are the same. In a healthy adult male, *CO* is approximately 5 l/min [Bock, 2006]. *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 [Guyton, 2006]. Abnormally low levels of *COmax* can also be an indication of pathology.

The primary function of the heart is to import energy to blood to generate and sustain an arterial blood pressure sufficient to adequately perfuse organs. The heart achieves this by contracting its muscular walls around a closed chamber to generate sufficient pressure to propel blood from the left ventricle, through the aortic valve, and into the aorta. 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*:

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

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* returns 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* in average fit adult subject can vary by a ratio factor of approximately 3, between 60 and 180 beats per minute, while *SV* can vary between 70 and 120 ml, a ratio factor of only 1.7.

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* measurements, 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.

Current invasive procedures for monitoring *CO* increase the potential for complications, including the higher risk of infection and sepsis. Other methods of measuring *CO* exist, but require additional measurements, tests, and/or equipment:

The impedance cardiography is a non-invasive method of measuring *CO*. Impedance changes are due to changes in intrathoracic fluid volume and respiration, so changes in blood volume per cardiac cycle can be measured and used to estimate *SV* and *CO* [White 1990].

The Doppler ultrasound method (**Doppler echocardiography**) uses reflected sound waves to calculate flow velocity and volume to obtain *CO*. From the product of aortic blood velocity and cross-sectional area of the aorta, stroke volume (SV) can be calculated (Rowland 2002).

The **Pulse Pressure** (*PP*) methods measure the pressure in an artery over time to derive a waveform and use this information to calculate cardiac performance. The problem is that any measure from the artery includes the changes in pressure associated with changes in arterial function (compliance, impedance, etc.).

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 [Fick, 1870]. *CO* can be calculated from these measurements: VO_2 consumption per minute using an O_2 gas-analyzer (with the subject re-breathing air) and a CO_2 absorber, the oxygen content of blood taken from the pulmonary artery (representing mixed venous blood) and the oxygen content of blood from a cannula in a peripheral artery (representing arterial blood)

From these values, it is known (2):

$$VO_2 = (CO{*}C_A) - (CO{*}C_V) \tag{2}$$

where C_A is oxygen content of arterial blood and C_V is oxygen content of venous blood and *CO* is:

$$CO = VO_2\ /(C_A - C_V) \tag{3}$$

While considered to be the most accurate method for CO measurement, Fick method is invasive, requires time for the sample analysis, and accurate oxygen consumption samples are difficult to acquire. There have also been modifications to the Fick method where respiratory oxygen content is measured as part of a closed system and the consumed oxygen calculated using an assumed oxygen consumption index which is then used to calculate *CO*. Other modifications use inert gas as tracers and measure the change in inspired and expired gas concentrations to calculate *CO*.

Athletic training, mainly endurance training, evokes significant adaptive changes both in cardiac output and in many other body functions. Maximal oxygen uptake (VO_{2max}) as the highest rate of oxygen consumption during maximal or exhaustive exercise, is considered as the best objective laboratory measure of endurance capacity. It markedly depends on the oxygen transport capacity (cardiac output, red blood cell count, plasma volume) and oxidative capacity of muscles. While measuring of heart rate is practicable method how to evaluate response and adaptability to physical load, assessment of cardiac output was not so easy.

MATERIALS AND METHODS

Study 1

Because both HR and VO_2 can be easily measured during standard incremental cardio-pulmonary exercise testing [Guyton, 2005], both CO and SV could be accurately quantified if the simultaneous arteriovenous O_2 content difference $(C_A - C_V)$ could be estimated [Stringer, 1997; Sullivan, 1989]. For noninvasive CO estimation, exercise tests were performed on an electronically braked cycle 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 samples of expired gas were connected to gas analyzer (O_2 and CO_2 analyzer). All electrical signals from sensors and from gas analyzer were processed in personal computer. From the measured values workload [W] for cycle ergometer or running velocity [km/h] for treadmill, HR [beats/min] and VO_2 [l/min] the CO and also SV were calculated [Stringer, 1998]. The CO was estimated according formula (4):

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

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 stress test (Tab. 1). M1 – top-class cross-country skier, M2 – former top-class cross-country skier, recently jogger, M3 – leisure “hobby” athlete, F1 – top-class triathlete, F2 – young competitive swimmer, F3 – leisure “hobby” athlete.

Table 1. Spiroergometric values of 6 subjects. Sub=Subject M-male F-female, He=Height [cm], We=Weight [kg], VO2m=VO_{2max} [L/min], VO_{2mk}=VO_{2max}/kg [ml/min/kg].

Sub	Age	He	We	VO_{2m}	VO_{2mk}
M1	28	177	70.3	5.75	81.9
M2	49	170	66.7	4.21	63.1
M3	65	166.5	65.2	3.15	39.7
F1	31	168.5	63.2	4.52	71.5
F2	18	171	64.8	4.32	66.7
F3	40	165.5	72	2.69	37.4

Study 2

From our 20-year examination database, we included in this study 641 men (M) and 164 women (F) over 19 years of age who completed a stress test on a bicycle ergometer with a graded load to the maximum. From an extensive database of all persons examined at the Department of Sports Medicine of the University Hospital in Pilsen and at the Department of Sports Medicine of the Medical Faculty of Charles University in Pilsen between 1994 and 2015, the protocols of those examined were selected that provided the necessary data.

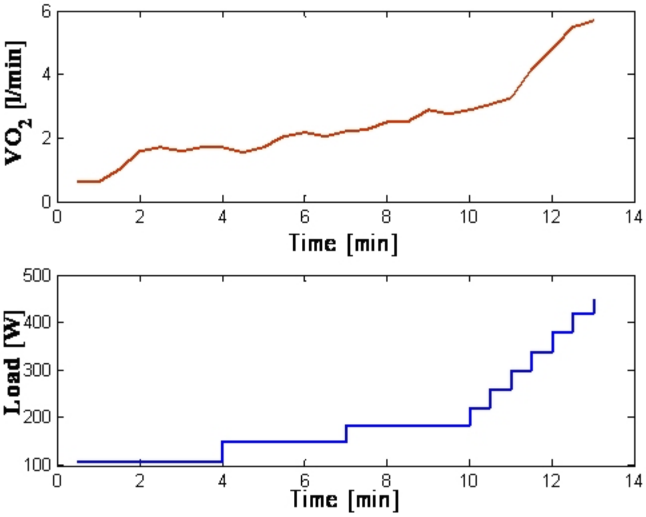

Figure 1: *VO_2* [l/min] and workloads [in W] during stress-test in M1 (top-class cross-country skier) on cycle ergometer.

During each of these complex sports medical examinations, the examined person underwent a stress test on a bicycle ergometer. It consisted of the workload on the bicycle ergometer gradually increased until exhaustion. The procedure was similar to that of the International Biological Program in the 70s of the last century, which was the basis for determining the normatives of physical fitness of the Czechoslovak population [Seliger, 1976]. These normatives are still used in our country, as a similar study has not been carried out since.

The subjects were pedaling on the ergometer 3 times 3 minutes (light, moderate and sub-maximum load), followed by increasing the load every half minute to the maximum, ie until exhaustion. At maximum load, at least two of the following criteria must have been met: the age norm for maximal heart rate (HRmax), RER (respiratory exchange ratio) greater than 1.10, maximum ventilatory equivalent for O2 (VEqO2) greater than 30 l and maximum lactate concentration (LAmax) greater than 10 mmol/l. To calculate COmax, we used the same equation like in Study 1:

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

The files were divided into three groups according to different physical activity: group A included well-trained endurance-athletes, who had several years of sports training at the time of the examination. Group B included subjects who engaged in physical activity only in their leisure time without competing in any sports competition. Subjects with various health problems who either never played any sport at all or ended their sports career many years ago, were included in group C.

RESULTS

Study 1

The VO_2 values, measured during the graded load to the maximum on bicycle ergometer, were used to calculate estimated CO and SV values. Results of those calculations are presented in Fig. 2 for men and in Fig. 3 for women. VO_2 isopleths according to Stringer et al. [1997] experience were used to illustrate the difference in highly trained endurance athlete and less trained or even untrained subjects. The data clearly documented the difference in the heart's pumping efficiency during increasing peripheral tissue needs. 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.

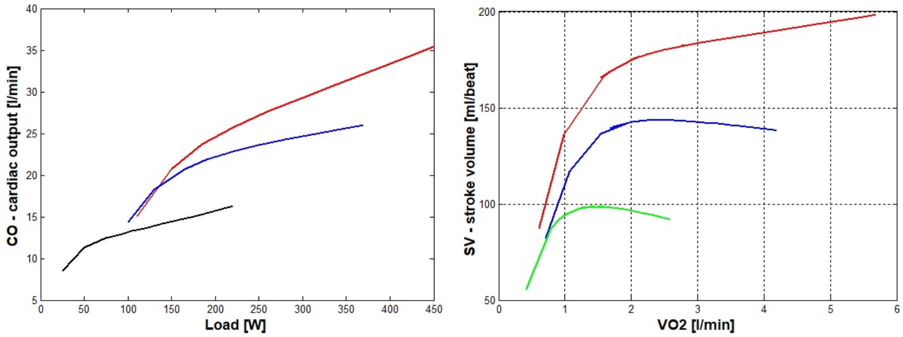

Figure 2: *CO* and *SV* changes during the stress-test in men. Left: *CO* related to workload intensity (Watts) during stress-test. Right: *SV* related to VO_2 during stress-test (red - top class cross-country skier, blue – former top class cross-country skier, now "masters" age group; black (green) - leisure "hobby" athlete).

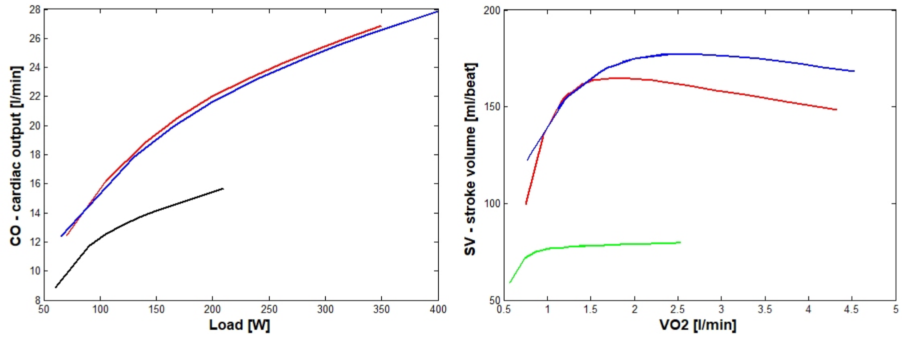

Figure 3: *CO* and *SV* changes during the stress-test in women. Left: *CO* related to workload intensity (Watts) during stress-test. Right: *SV* related to VO_2 during stress-test (blue – top class triathlete, red – young competitive swimmer, F3 – black (green) – leisure time "hobby" athlete).

Study 2

COmax in group M-A (trained endurance athletes) (n = 462, COmax = 28.38 ±4.47 l/min) was significantly higher than in groups M-B (leisure-time athletes) (n = 143, COmax = 19.4±3.7 l/min) and M-C (untrained subjects) (n = 36, COmax = 18.4±5.9 l/min). It was the same with the women's groups. COmax value in group F-A (n = 58, COmax = 20.7±3.7 l/min) was significantly higher than that in groups F-B (n = 88, COmax = 12.8±2.3 l/min) and F-C (n = 18, COmax = 12.1±2.0 l/min). There were no significant differences in both M and F between groups C and D.

The same findings were obtained when comparing maximal stroke volume (SVmax) values. SVmax parameters were significantly higher in the group M-A (trained endurance athletes) compared to the groups M-B (recreational athletes) and M-C (untrained subjects).

When comparing SV in the three groups of women, the results were very similar. The significantly highest values of and SVmax were evident in group F-A in comparison with groups F-B and F.C (see Fig. 4 and Fig. 5).

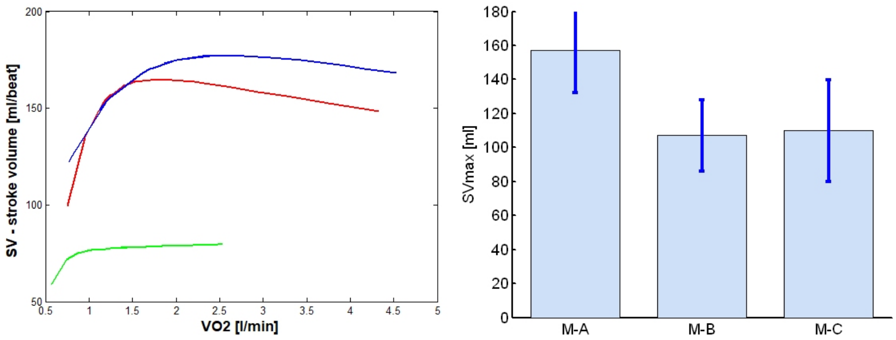

Figure 4: COmax and SVmax values in men with different physical activity (M-A - endurance athletes, M-B - leisure time athletes, M-C - former athletes and subjects with health problems).

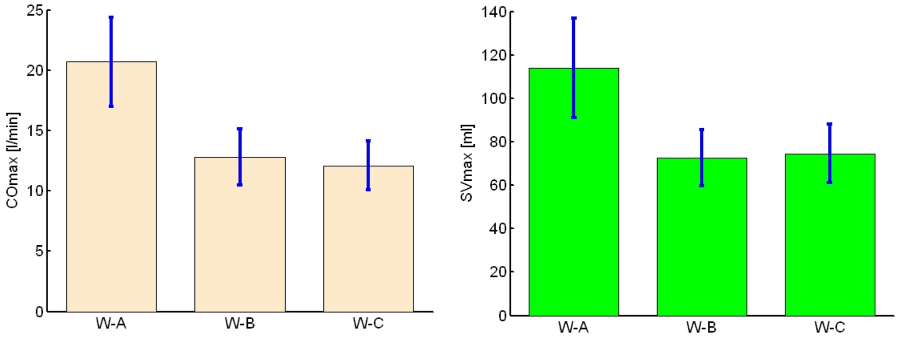

Figure 5: COmax and SVmax values in women with different physical activity (W-A - endurance athletes, W-B - leisure time athletes, W-C - former athletes and subjects with health problems).

DISCUSSION

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 [8, 10]. Having estimated CO and corresponding *HR*, *SV* can be calculated. 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 resting normal cardiac output. When the peripheral tissues demand excessive amounts of blood flow, the nervous signals increase cardiac output [Guyton, 1979]. Our examples document that the time course of these changes is similar in the subjects of very different cardio-respiratory fitness level (see Fig. 2 and 3). 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. Top level endurance athletes can reach outstanding values of *CO* and *SV* at about 40 l/min and 200 ml/beat respectively [Ekblom, 1968]. Hence, this method seems to offer another useful data to evaluate cardio-respiratory capacity and adaptation to physical activity and/or inactivity.

CONCLUSION

Movement activity is a condition for the development and maintenance of the adaptive abilities of the cardiorespiratory system. The parameters measured in recreational sportsmen correspond to the average of a healthy average fit population. If physical activity is not part of a healthy lifestyle and, in addition, there are health problems (in our groups C obesity and resting and exertional chest pains are the most common), in many subjects from our groups C the COmax parameters are significantly below average and close to the level characterizing the NYHA-1 to NYHA-2 group according to cardiology classification. The results show, on the one hand, how important factor in health prevention is regular physical activity, and, on the other hand, the applicability of our modified method to determine non-invasively the maximum cardiac output.

CONFLICT OF INTEREST STATEMENT

The authors have no conflicts to report relative to this work.

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