Noninvasive Cardiac Output Estimation Based on Oxygen Consumption During Stress Test

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Abstract: Cardiac output (CO) is one of the most important hemodynamic signals to measure in patients with compromised cardiovascular performance. 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 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 stress test. The results for well - trained and untrained persons are also shown.

Key-Words: Cardiac index, cardiac output, stroke volume, heart rate, spiroergometric examination.

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 [1]. *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 [2]. Abnormally low levels of *CO* 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*:

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

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 per 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.

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 requires additional measurements, tests, and/or equipment:

a) Impedance cardiography is a non-invasive method of measuring *CO*, whereby electrodes are placed on the neck and chest to transmit and detect impedance changes in the thorax. 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*, but reliability and reproducibility of measurements are limited. [3].

b) The **Doppler ultrasound method** uses reflected sound waves to calculate flow velocity and volume to obtain *CO* and is a non-invasive, accurate way of measuring *CO* using a handheld transducer placed over the skin.

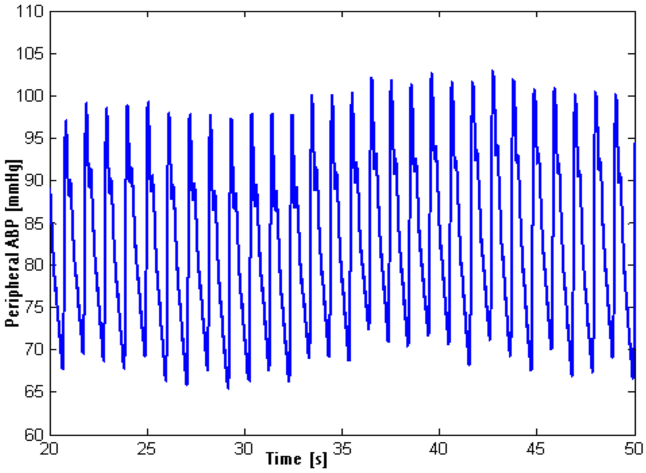

Fig. 1. Peripheral *ABP* waveform.

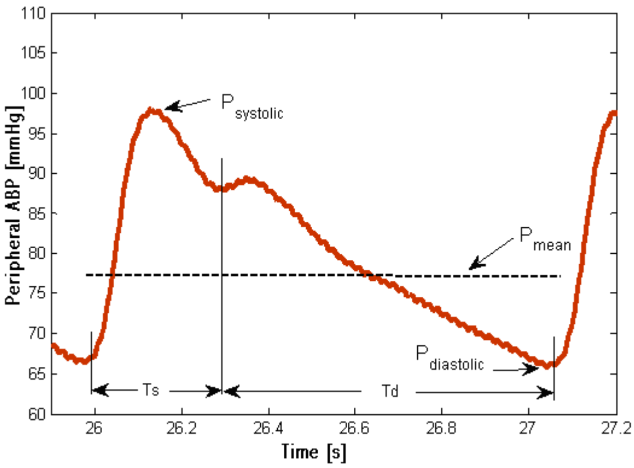

Fig. 2. One period of *ABP* waveforms and important points (Systolic, diastolic and mean blood pressure). *Ts* - systolic time, *Td* - diastolic time.

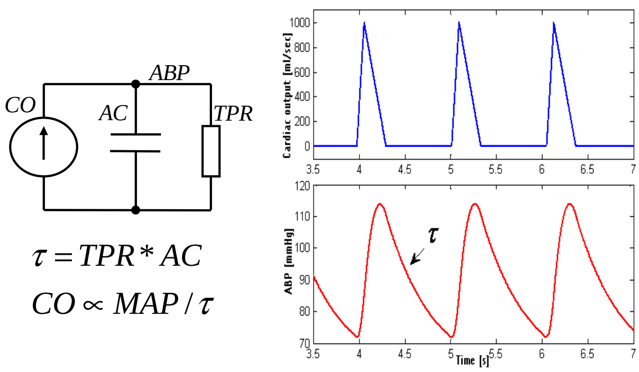

Fig. 3. Simple Winkessel model for *CO* estimation (left) and waveforms (right). *CO* pulses (top) and *ABP* waveforms (bottom). *ABP* decay like pure exponential with time constant τ.

c) The **Pulse Pressure** (*PP*) methods measure the artery blood pressure (ABP) over time to derive a waveform information to calculate cardiac performance (Fig. 1. and 2.) [4-6]. The principle is shown in Fig. 3, where *TPR* is total peripheral resistance and *AC* is arterial compliance [7-8].

The problem is that any measure from the artery includes the changes in pressure associated with changes in arterial function (compliance, impedance, etc.).

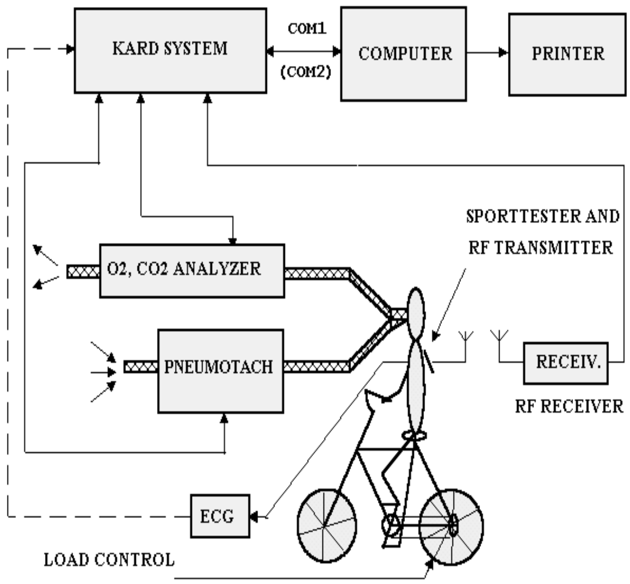

Fig. 4. Block diagram of measuring system for non-invasive CO estimation. The bicycle or treadmill ergometer can be used.

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. *CO* can be calculated from these measurements:

- VO_2 consumption per minute using a spirometer (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).
- The oxygen content of blood from a cannula in a peripheral artery (representing arterial blood).

From these values, it is known (2):

$$VO_2 = (CO*C_A) - (CO*C_V) \qquad (2)$$

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

$$CO = VO_2 /(C_A - C_V) \qquad (3)$$

Sometimes *CO* is expressed as a cardiac index (*Ci*), which is the *CO* divided by the estimated body surface area (*BSA*) in square meters. Several different formulas can be used to estimate *BSA*. One formula is *BSA* [m^2] equals the square root of the (height [cm] times weight [kg] divided by 3600):

$$BSA = (height * weight/3600)^{0.5} \quad [m^2, cm, kg] \qquad (4)$$

and *Ci* is given by (5):

$$Ci = CO / BSA \quad [l/min/m^2, l/min, m^2] \qquad (5)$$

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, 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*.

In this paper, *CO* was estimated noninvasively from oxygen uptake during exercise on cycle or treadmill ergometer.

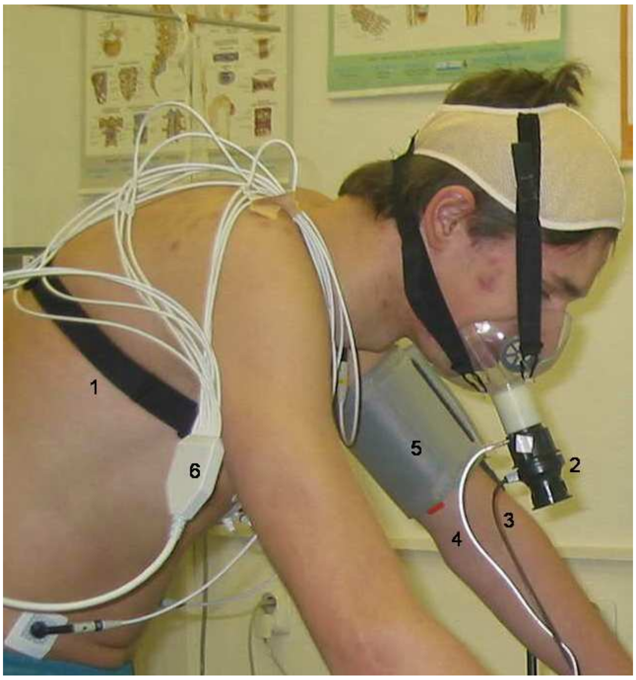

Fig. 5. The physiological parameter measuring: 1-HR belt (Sporttester), 2-turbine for ventilation measuring, 3-cable for ventilation pulses, 4-tube for exhausted gas samples, 5-cuff for blood pressure measuring, 6-cable for ECG electrodes.

2 Methods

Because both *HR* and VO_2 can be easily measured during standard incremental cardio-pulmonary exercise testing [9], both *CO* and *SV* could be accurately quantified if the simultaneous arteriovenous O_2 content difference $(C_A - C_V)$ could be estimated [10, 11].

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 block diagram of measuring system is shown in Fig. 4. The electrical signals from sensors were connected to microcontroller systems (KARD SYSTEM). The samples of expired gas samples 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. Example of measuring (on bicycle regometrer) is shown on Fig. 5. The treadmill can be also used.

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 [12]. Also *SV* and *Ci* were computed. The *CO* was calculated according formula (6):

$$CO = \frac{100 * VO_2}{\left[5.721 + 0.1047 \dfrac{100 * VO_2}{VO_{2MAX}}\right]} \quad [l/min] \qquad (6)$$

Tab. 1. Spiroergometric values of 6 subject. Sub=Subject, M-male, F-female, He=Height [cm], We=Weight [kg], VO2m=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

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 – 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 (see Fig. 6).

3 Results

Fig. 6 illustrates the changes in oxygen consumption (VO_2) step-vise increased workload in standard stress-test in top-class cross-country skier. VO_2 values were used to calculate estimated CO and SV values. Results of those calculations are presented in Fig. 7, 8 and 9 in men and in Fig. 11, 12 and 13 in women. In Fig. 10 VO_2 isopleths according to Stringer´s et al. [11] experience were used to illustrate the difference in highly trained endurance athlete and less trained or even untrained subjects. Higher cardio-respiratory capacity evokes the shift of the VO_2 isopleth to the left.

The data clearly document 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.

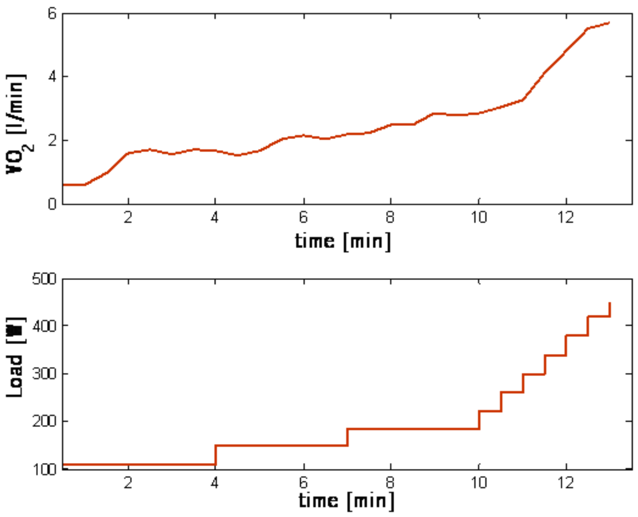

Fig. 6. Workloads [in W] and VO_2 [l/min] during stress-test in M1.

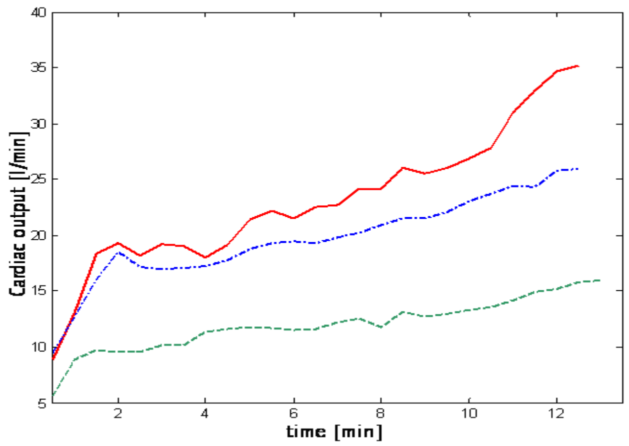

Fig. 7. Changes in cardiac output during the stress-test M1-red, M2-blue (dash-dot), M3-black (dash).

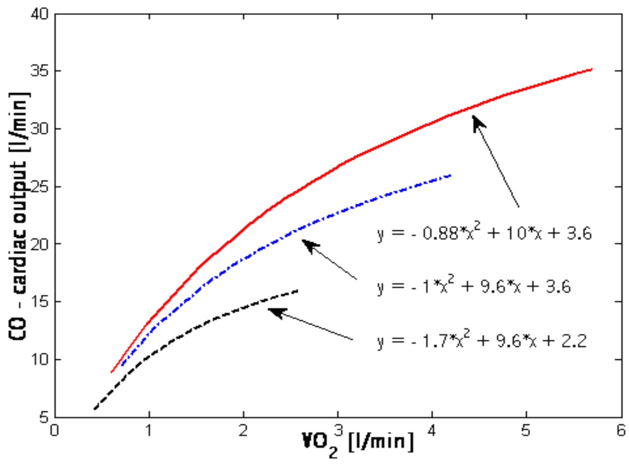

Fig. 8. Cardiac output in relation to VO_2 during stress-test M1-red, M2-blue (dash-dot), M3-black (dash).

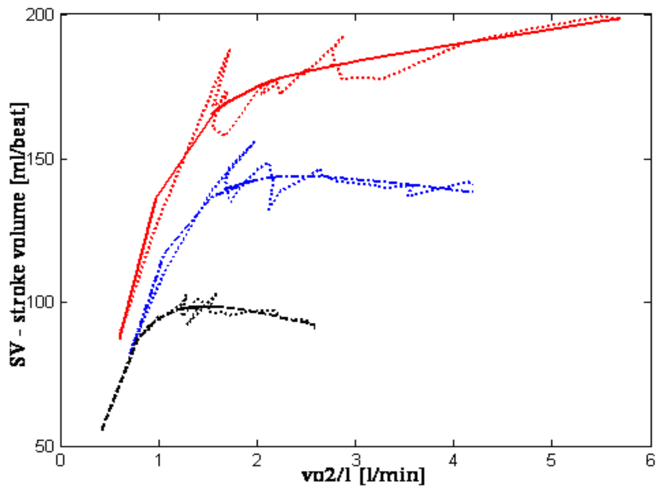

Fig. 9. Stroke volume in relation to VO_2 during the stress-test M1-red, M2-blue (dash-dot), M3-black (dash).

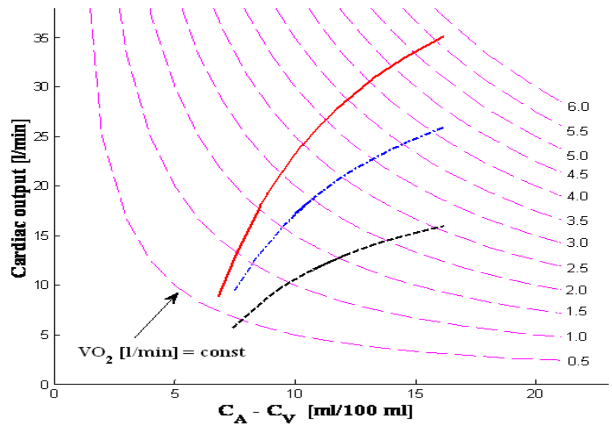

Fig. 10. CO as a function of $(C_A – C_V)$ with superimposed VO_2 isopleths. M1-red, M2-blue (dash-dot), M3-black (dash).

In Fig. 9 and 13 the $SV=f(VO_2)$ is approximated by function (7):

$$y(x) = a*exp(b*x) + c*exp(d*x) \qquad (7)$$

The calculated coefficients for subjects M1-M3 and F1-F3 are shown in Tab.2.

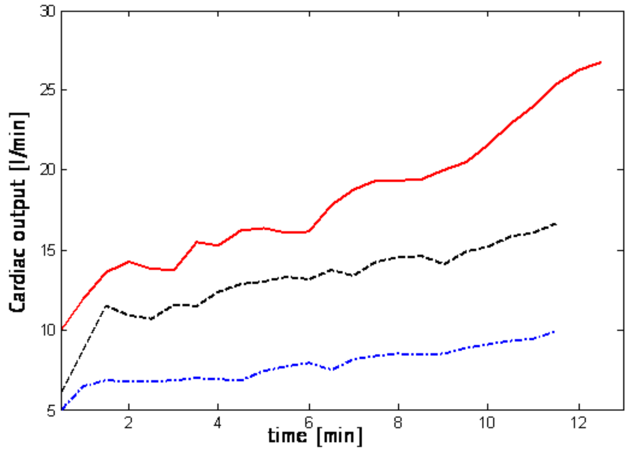

Fig. 11. Changes *CO* during the stress-test F1-red, F2-blue (dash-dot), F3-black (dash).

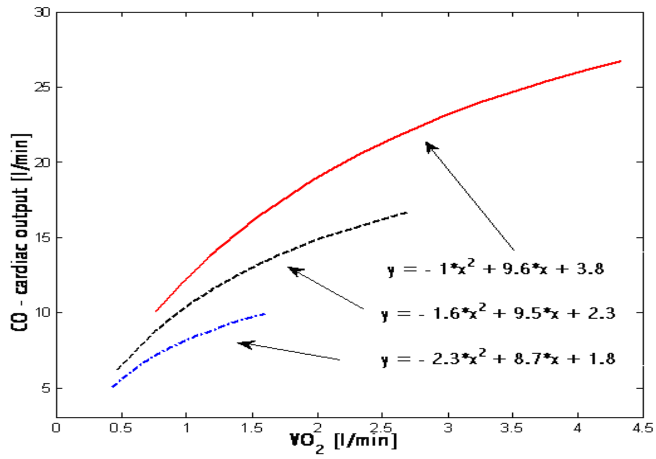

Fig.12. Cardiac output in relation to VO_2 during stress-test F1-red, F2-blue (dash-dot), F3-black (dash).

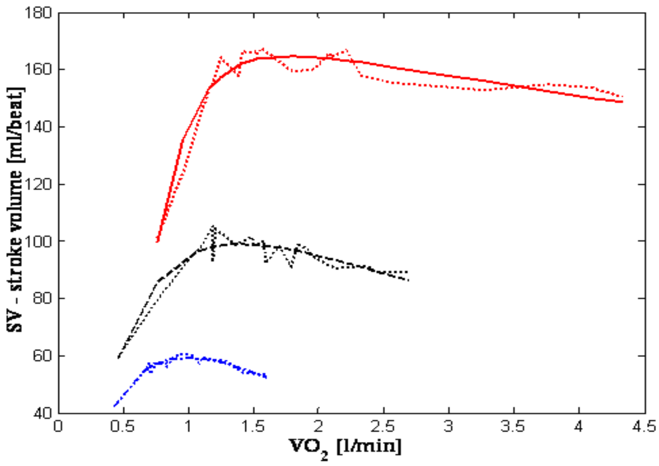

Fig. 13. Stroke volume in relation to VO_2 during the stress-test F1-red, F2-blue (dash-dot), F3-black (dash).

Tab. 2. The coefficients for equation (7).

Sub	a	b	c	d
M1	169.6	0.02761	-309.2	-2.131
M2	157.2	-0.03036	-298	-2.01
M3	117.1	-0.09227	-172.1	-2.623
F1	181.2	-0.0459	-1035	-3.458
F2	-138.9	-2.233	116.6	-0.4516
F3	132	-0.1561	-189.3	-2.351

4 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 [10, 11]. 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 normal cardiac output. When the peripheral tissues demand excessive amounts of blood flow, the nervous signals increase cardiac output [13]. Our examples document that the time course of these changes is very similar in the subjects of very different cardio-respiratory fitness level (see Fig. 7, 8 and 11, 12). 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 [14].

Hence, this method seems to offer another useful data to evaluate cardio-respiratory capacity and adaptation to physical activity and/or inactivity.

5 Conclusions

Cardiac output (*CO*) is one of the most important hemodynamic signals to measure in patients with compromised cardiovascular performance. 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 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 stress test.

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