CARDIOPULMONARY EXERCISE TESTING FOR VO₂MAX DETERMINING IN SUBJECTS OF DIFFERENT PHYSICAL ACTIVITY

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Abstract
Cardiopulmonary exercise testing (CPET) provides assessment of the integrative exercise responses involving the pulmonary, cardiovascular, haematopoietic, neuropsychological, and skeletal muscle systems, which are not adequately reflected through the measurement of individual organ system function. This non-invasive, dynamic physiological overview permits the evaluation of both submaximal and peak exercise responses, providing the doctor with relevant information for clinical decision making. CPET is increasingly being used in a wide spectrum of clinical applications for the evaluation of undiagnosed exercise intolerance and for the objective determination of functional capacity and impairment. Its use in patient management is increasing with the understanding that resting pulmonary and cardiac function testing cannot reliably predict exercise performance and functional capacity and that overall health status correlates better with exercise tolerance than with resting measurements. CPET involves measurements of respiratory oxygen uptake (VO₂), carbon dioxide expenditure (VCO₂), and pulmonary ventilation during a step-wise increased physical workload up to the maximum (or symptom-limited level in patients) on ergometer. In this paper the principle of CPET is described and results for VO₂max and VO₂max/kg of almost 3000 measurements in subjects of different physical activity are presented. These values characterizing cardiorespiratory capacity of the subjects were compared to the values of maximal performance achieved during stress test on bicycle ergometer (Wmax and Wmax/kg) and regression equations for VO₂max – Wmax and VO₂max/kg – Wmax/kg were calculated.

Keywords
cardiopulmonary exercise testing, VO₂max, bicycle ergometer, regression equations, measuring system

Introduction
Cardiopulmonary exercise testing (CPET) provides assessment of the integrative exercise responses involving the pulmonary, cardiovascular, haematopoietic, neuropsychological, and skeletal muscle systems, which are not adequately reflected through the measurement of individual organ system function. This non-invasive, dynamic physiological overview permits the evaluation of both submaximal and peak exercise responses, providing the doctor with relevant information for clinical decision making. CPET is increasingly being used in a wide spectrum of clinical applications for the evaluation of undiagnosed exercise intolerance and for the objective determination of functional capacity and impairment. Its use in patient management is increasing with the understanding that resting pulmonary and cardiac function testing cannot reliably predict exercise performance and functional capacity and that overall health status correlates better with exercise tolerance than with resting measurements. CPET involves measurements of respiratory oxygen uptake (VO₂), carbon dioxide expenditure (VCO₂), and pulmonary ventilation during a step-wise increased physical workload up to the maximum (or symptom-limited level in patients) on ergometer. In this paper the principle of CPET is described and results for VO₂max and VO₂max/kg of 2777 measurements in competitive athletes and active but not competing subjects. W₁₇₀ and W₁₇₀/kg characterize physical working capacity. W₁₇₀ is the estimated performance in watts, corresponding to the heart rate 170 beats/min [74, 75].

VO₂max and VO₂max/kg values were directly obtained during 2777 measurements in competitive athletes and active but not competing subjects. W₁₇₀ and W₁₇₀/kg characterize physical working capacity. W₁₇₀ is the estimated performance in watts, corresponding to the heart rate 170 beats/min [74, 75].

The normatives of cardiorespiratory capacity for different age groups of male and female endurance athletes (Group A), team sport players (Group B) and...
other sports (group C) were established, and compared to normatives for Czech population based on the International Biological Program (IBP) results [62]. Group D in our study included subjects performing sport and physical activity in their leisure time, however, did not participate in any competitive sport (so called "hobby" athletes).

The most favorable values of cardiorespiratory capacity (both VO2max; VO2max/kg and W170; W170/kg) were found in the group A athletes (endurance trained) – both males and females. Their level highly exceeded the values of untrained Czech IBP population and also those obtained in control group D in this study.

The highest correlation was found between VO2max and Wmax and between VO2max/kg and Wmax/kg. This high correlation was very similarly high in the whole sample of 2777 examinations, in the sample of men (n=2015) and sample of women (n=762) and also in all age-groups in different athletic groups A to D.

It was proved that VO2max and VO2max/kg values could be calculated according to the maximal performance attained on bicycle ergometer [73]. During spioregometric examination the values of stroke volume and cardiac output can also be calculated [52, 64]. These values represent additional data closely correlating with the adaptive changes of circulatory system.

Regular aerobic endurance exercise could reduce biological age of active individuals by 10 to 20 years with a correspondingly decreased likelihood of becoming dependent when a senior and an expressive improvement in the quality of the final years of life [7, 57, 71]. VO2max and VO2max/kg values represent important health quality marker. They also offer feedback information, positive and/or negative, about the effectiveness of physical activity influencing its development. Thus, aerobic fitness level has been strongly and positively associated with reduced disease and mortality rates, good quality of life, performance level, and functional ability.

Exercise capacity and oxygen uptake measuring principles

Peak exercise capacity is defined as “the maximum ability of the cardiovascular system to deliver oxygen to exercising skeletal muscle and of the exercising muscle to extract oxygen from the blood”. Consequently, exercise tolerance is determined by three factors: pulmonary gas exchange; cardiovascular performance, including the peripheral vascular tree; and skeletal muscle metabolism.

Understanding the Fick equation is of paramount importance for appreciating the utility of functional exercise testing. At rest, the Fick equation states that oxygen uptake (VO2) equals cardiac output times the arterial minus mixed venous oxygen content:

\[ \text{VO}_2 = \text{SV} \cdot \text{HR} \cdot (\text{CaO}_2 - \text{CvO}_2) \]  

where SV is the stroke volume, HR is the heart rate, CaO2 is the arterial oxygen content, and CvO2 is the mixed venous oxygen content. Oxygen uptake is often normalised for body weight and expressed in units of ml O2·min⁻¹·kg⁻¹. One metabolic equivalent (MET) is the resting oxygen uptake in a sitting position and equals 3.5 ml·min⁻¹·kg⁻¹.

This reflects the maximal ability of a person to take in, transport and use oxygen. It defines that person’s functional aerobic capacity. VO2max has become the preferred laboratory measure of cardiorespiratory fitness and is the most important measurement during functional exercise testing. In healthy people, a VO2 plateau occurs at near maximal exercise. This plateau in VO2 has traditionally been used as the best evidence of VO2max. It represents the maximal achievable level of oxidative metabolism involving large muscle groups.

Cardiopulmonary exercise testing measuring principles

Several different methods exist for measuring ventilation and respiratory gas parameters during exercise. Some clinical systems rely on breath-by-breath analysis techniques because they provide the best measures of the metabolic response to exercise.

The block diagram of measuring system is shown in Fig. 1. The 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 VO2max and lactic acidosis threshold (LAT).

A non-rebreathing valve is connected to a mouth-piece to prevent mixing of inspired and expired air. Oxygen and carbon dioxide gas analysers are usually incorporated in a “metabolic cart” designed specifically for functional testing. Respiratory volumes are computed by integrating the air flow signals over the time of inspiration and expiration. Average minute volumes are derived from the breath-by-breath data multiplied by the respiratory rate [65].

Many different protocols are used for functional testing. The purpose of the test and the functional capabilities of the patient determine the choice of protocol. In evaluating patients with congestive heart failure (CHF), both bicycle and treadmill protocols have been used. The rate of workload progression is somewhat arbitrary, although it has been suggested that optimal exercise duration for functional assessment on the bicycle is between 8 and 17 minutes. Bicycle work is quantified in watts (W) or in kilopondmetres/min (kpm/min; 1 W = ~ 6 kpm·min⁻¹). The initial workload for patients with CHF is usually 20–25 W and in-
creased by 15–25 W every 2 minutes until maximal exertion (symptom limited maximum) is reached. Alternatively, the workload can be computer controlled for electronically braked bicycle ergometers, and a ramp protocol (eg. 10 W·min⁻¹) is often used.

Testing protocol in our laboratory was based on the testing protocol used in the IBP [42, 62]. In healthy and average fit subjects three submaximal workloads of 3-min duration were used. The first workload corresponded approximately to 1 W·kg⁻¹ body weight of the subject, the second workload to 1.5 W·kg⁻¹ body weight and the third workload to 2 W·kg⁻¹ body weight respectively. After 9 minutes warming up the workload was consecutively increased every half minute by 20 to 30 W (dependant on body weight and age of the subjects) until exhaustion. In highly fit subjects the initial warming up submaximal workloads were 1.5 W·kg⁻¹, 2 W·kg⁻¹ and 2.5 W·kg⁻¹ of body weight respectively.

Oxygen uptake (VO₂) is determined by cellular O₂ demand up to some level that equates to maximal rate of O₂ transport, which then is determined by that maximal rate of transport. As VO₂ increases with increasing external work, one or more of the determinants of VO₂ approach limitations (eg, stroke volume, heart rate, or tissue extraction), and VO₂ versus work rate may begin to plateau. This plateau in VO₂ has traditionally been used as the best evidence of VO₂max. The main determinants of a normal VO₂max are genetic factors [10, 11], quantity of exercising muscle, age, gender and body size [5]. Other important factors are previous training and patient motivation. VO₂max should be expressed in absolute values (l·min⁻¹) and as a percentage of the predicted value. VO₂ can increase from a resting value of about 3.5 ml·min⁻¹·kg⁻¹ (about 250 ml·min⁻¹ in an average person) to VO₂max values about 15 times the resting value (30–50 ml·min⁻¹·kg⁻¹). Athletes may attain values over 20 times their resting values (up to 90 ml·min⁻¹·kg⁻¹).

The ratio of carbon dioxide output/oxygen uptake (VCO₂/VO₂) is called the respiratory exchange ratio (RER). Under steady state conditions, the RER equals the respiratory quotient (RQ). The RQ value is determined by the fuels used for metabolic processes. RQ of 1.0 indicates covering the metabolic demands exclusively by carbohydrates, while RQ 0.7 indicates metabolism only by free fatty acids. Normal resting values of RQ~0.8 indicates that metabolic demands are by third covered by carbohydrates and by two thirds by free fatty acids. During step-wise increased workload RQ increases up to 1.0 and more due to higher utilization of carbohydrates in muscle metabolism and buffering processes connected to metabolic acidosis.
evoked by near maximal and/or maximal intensity workload.

Example of HR and VO₂ dependence on workload intensity is shown in Fig. 3 and 4.

![Graph showing HR and VO₂](image1)

**Fig. 3**: Workloads [in W] and corresponding HR (heart rate) and VO₂ [l/min] during CPET (male ice hockey player, 18 years).

![Graph showing HR and VO₂](image2)

**Fig. 4**: Workloads [in W] and corresponding HR (heart rate) and VO₂ [l/min] during CPET (male cyclist, 57 years).

**Indications for terminating CPET**

Symptoms during step-vice increased workload up to the maximum during ergometer stress test can rarely result in premature test termination. There are several absolute indications for termination of an exercise test, such as: suspicion of a heart attack, onset of moderate-to-severe angina (chest pain), drop in systolic blood pressure below standing resting pressure, signs of poor perfusion, including pallor, cyanosis, or cold and clammy skin, severe or unusual shortness of breath, CNS symptoms e.g. ataxia, vertigo, visual or gait problems, or confusion, serious arrhythmias e.g. second/third degree AV block, atrial fibrillation with fast ventricular response, increasing premature ventricular contractions or sustained ventricular tachycardia, and also technical inability to monitor the ECG. Cardiac arrhythmias are usually not an indication to stop the test unless sustained tachyarrhythmias develop. Other indications for CPET terminating might be any chest pain that is increasing, physical or verbal manifestations of shortness of breath or severe fatigue, wheezing, leg cramps or intermittent claudication, hypertensive response (SBP>260 mm Hg; DBP>115 mm Hg) and others.

![Graph showing VO₂max and Wmax](image3)

**Fig. 5**: Group MEN-all (n=2015). Relation between VO₂max and Wmax, R=0.89.

![Graph showing VO₂max/kg and Wmax/kg](image4)

**Fig. 6**: Group MEN-all (n=2015). Relation between VO₂max/kg and Wmax/kg, R=0.89.
Oxygen uptake estimation

Bicycle ergometer is nowadays a very common device for testing fitness level of the subject. However, accurate estimation of the VO2max is exclusively dependent on direct availability to analyze O2 and CO2 content in the expired air. Equipment for O2-CO2 analysis is relatively expensive and mostly only in specialized stress test laboratories available. It was the purpose of this study to find the possibility for accurate indirect determination cardiorespiratory capacity without need for the O2-CO2 anylysis. Hence, the values of direct VO2max and VO2max/kg were compared with other fitness values, obtained without the need for the O2-CO2 anylysis: W170 and W170/kg, and Wmax and Wmax/kg.

The highest correlation was found between the values of VO2max and Wmax, and between VO2max/kg and Wmax/kg. Fig. 5 and Fig. 6 illustrate this correlation in the group of 2015 healthy men. Regession equations were calculated to obtain approximate values of VO2 and VO2max indirectly without any need for additional equipment. Similarly, the regression equation could be calculated for individual age subgroups in each group of different level of physical aktivity (for example see Table 1 and 2).

There are other approaches for VO2 estimation [27]. According to the Fick principle, eq. (1), VO2max may be expressed as the product of cardiac output (Q) and the arterio-venous O2 difference

\[ VO_2 = Q \cdot (C_aO_2 - C_vO_2) \]

Thus, since Q is the product of HR and stroke volume (SV), VO2max may be expressed as

\[ VO_2 = HR \cdot SV \cdot (C_aO_2 - C_vO_2) \]

When applied to rest VO2rest can be expressed as:

\[ VO_{2rest} = HR_{rest} \cdot SV_{rest} \cdot (C_{aO_2} - C_{vO_2})_{rest} \]

implying that

\[ \frac{VO_{2rest}}{HR_{rest} \cdot SV_{rest} \cdot (C_{aO_2} - C_{vO_2})_{rest}} = 1 \]

During maximal exercise the Fick equation reads:

\[ VO_{2max} = HR_{max} \cdot SV_{max} \cdot (C_{aO_2} - C_{vO_2})_{max} \]

By multiplying the right side of eq. 6 with 1 in the form of eq. 5 it follows that:

\[ \frac{VO_{2max}}{VO_{2rest}} = \frac{HR_{max} \cdot SV_{max} \cdot (C_{aO_2} - C_{vO_2})_{max}}{HR_{rest} \cdot SV_{rest} \cdot (C_{aO_2} - C_{vO_2})_{rest}} \]

therefore

\[ VO_{2max} = \frac{HR_{max}}{HR_{rest}} \cdot \frac{SV_{max}}{SV_{rest}} \cdot \frac{(C_{aO_2} - C_{vO_2})_{max}}{(C_{aO_2} - C_{vO_2})_{rest}} \cdot VO_{2rest} \]

\[ (8) \]

VO2rest is dependent on and increases with the individual’s body mass. Relative to body mass (BM), resting VO2rest equals about 3.5 ml·min⁻¹·kg⁻¹ (one MET), but slightly lower values were reported by other researchers (e.g. 3.3 for men and 3.1 for women, respectively [27]). As a compromise is possible take 3.4 ml·min⁻¹·kg⁻¹ to represent the mass-specific resting VO2max. Accordingly, VO2rest may be expressed as 3.4 ml·min⁻¹·kg⁻¹ times BM in kg.

\[ VO_{2max} = \frac{HR_{max}}{HR_{rest}} \cdot \frac{SV_{max}}{SV_{rest}} \cdot \frac{(C_{aO_2} - C_{vO_2})_{max}}{(C_{aO_2} - C_{vO_2})_{rest}} \cdot 3.4 \cdot BM \]

\[ (9) \]

From a simplified test only the HRmax to HRrest ratio is readily obtainable. The other two ratios in the equation involve complicated measurements, in fact more complicated than the measurement of VO2 itself. The average SVmax/SVrest is approximately 1.29 when measured in the supine position. Thus, according the SVmax/SVrest may be replaced by a dimensionless value of approximately 1.3. The arterio-venous oxygen difference increases from rest to maximal exercise. It was found the average ratio between maximal and resting \((C_{aO_2} - C_{vO_2})_{max} / (C_{aO_2} - C_{vO_2})_{rest}\) to be approx. 3.4. Therefore \((C_{aO_2} - C_{vO_2})_{max} / (C_{aO_2} - C_{vO_2})_{rest}\) can be replaced with 3.4.

Altogether, based on previous derivation suggest that eq. 9 may be simplified to final approximations

\[ VO_{2max} = 1.3 \cdot 3.4 \cdot 3.4 \cdot BM \cdot \frac{HR_{max}}{HR_{rest}} \]

\[ (10) \]

or for VO2max/kg is

\[ VO_{2max/kg} = 15.0 \cdot BM \cdot \frac{HR_{max}}{HR_{rest}} \] (ml·min⁻¹·kg⁻¹)

\[ (11) \]

Estimation VO2max according another approach [68] can be calculated according:

\[ VO_{2max} = 125.7 - (0.476 \cdot \text{age}) + (7.686 \cdot \text{sex}) - (0.451 \cdot \text{BM}) + (0.179 \cdot W_{max}) - (0.415 \cdot HR_{max}) \]

\[ (12) \]

where sex is 1 for male and 0 for female, BM weight (kg), Wmax is maximal workload (W) and HRmax is maximal heart rate (beats per minute).
Several other attempts with different accuracy were used for indirect calculation of VO$_{2\text{max}}$ [16, 40, 43].

**Tab. 1: Examples of regression equations for group A – well trained men, for individual age subgroups (R = correlation coefficient; N = number of subjects).**

<table>
<thead>
<tr>
<th>Group: age &lt;16 year</th>
<th>R</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO$<em>{2\text{max}}$ =0.013· W$</em>{\text{max}}$ -0.54</td>
<td>0.87</td>
<td>189</td>
</tr>
<tr>
<td>VO$<em>{2\text{max}}$/kg =16.13· W$</em>{\text{max}}$/kg -26.8</td>
<td>0.60</td>
<td>189</td>
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</table>

<table>
<thead>
<tr>
<th>Group: 17&lt; age &lt;25 year</th>
<th>R</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO$<em>{2\text{max}}$ =0.016· W$</em>{\text{max}}$ -2.23</td>
<td>0.71</td>
<td>218</td>
</tr>
<tr>
<td>VO$<em>{2\text{max}}$/kg =16.39· W$</em>{\text{max}}$/kg -32.6</td>
<td>0.66</td>
<td>218</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Group: 26&lt; age &lt;40 year</th>
<th>R</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO$<em>{2\text{max}}$ =0.016· W$</em>{\text{max}}$ -0.8</td>
<td>0.72</td>
<td>191</td>
</tr>
<tr>
<td>VO$<em>{2\text{max}}$/kg =15.15· W$</em>{\text{max}}$/kg -15.3</td>
<td>0.84</td>
<td>36</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Group: age &gt;55 year</th>
<th>R</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO$<em>{2\text{max}}$ =0.014· W$</em>{\text{max}}$ -1.55</td>
<td>0.72</td>
<td>191</td>
</tr>
<tr>
<td>VO$<em>{2\text{max}}$/kg =12.2* W$</em>{\text{max}}$/kg -6.83</td>
<td>0.79</td>
<td>191</td>
</tr>
</tbody>
</table>

**Tab. 2: Examples of regression equations for group A – well trained women, for individual age subgroups (R = correlation coefficient; N = number of subjects).**

<table>
<thead>
<tr>
<th>Group: age &lt;16 year</th>
<th>R</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO$<em>{2\text{max}}$ =0.012· W$</em>{\text{max}}$ -0.20</td>
<td>0.82</td>
<td>200</td>
</tr>
<tr>
<td>VO$<em>{2\text{max}}$/kg =15.4· W$</em>{\text{max}}$/kg -19.1</td>
<td>0.64</td>
<td>200</td>
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<table>
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<tr>
<th>Group: 17&lt; age &lt;25 year</th>
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<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO$<em>{2\text{max}}$ =0.014· W$</em>{\text{max}}$ -0.69</td>
<td>0.80</td>
<td>62</td>
</tr>
<tr>
<td>VO$<em>{2\text{max}}$/kg =12.5· W$</em>{\text{max}}$/kg -10.4</td>
<td>0.81</td>
<td>62</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Group: 26&lt; age &lt;40 year</th>
<th>R</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO$<em>{2\text{max}}$ =0.014· W$</em>{\text{max}}$ -0.8</td>
<td>0.81</td>
<td>31</td>
</tr>
<tr>
<td>VO$<em>{2\text{max}}$/kg =11.7· W$</em>{\text{max}}$/kg -8.6</td>
<td>0.84</td>
<td>31</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Group: 41&lt; age &lt;55 year</th>
<th>R</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO$<em>{2\text{max}}$ =0.011· W$</em>{\text{max}}$ -0.28</td>
<td>0.95</td>
<td>13</td>
</tr>
<tr>
<td>VO$<em>{2\text{max}}$/kg =10.5· W$</em>{\text{max}}$/kg -5.47</td>
<td>0.94</td>
<td>13</td>
</tr>
</tbody>
</table>

**Example:**

Male triathlete, age 20 years, body weight = 64.7 kg

Measured values:

\[
W_{\text{max}} = 440 \text{ (W)}; \quad VO_{2\text{max}} = 4.98 \text{ (l min}^{-1})\]

\[
W_{\text{max/kg}} = \frac{440}{64.7} = 6.80 \text{ (W kg}^{-1})\]

\[
VO_{2\text{max/kg}} = 16.39 \times \frac{4.98}{64.7} = 78.85 \text{ (ml min}^{-1} \text{ kg}^{-1}\text{ beats} \text{ min}^{-1})\]

**VO$_{2\text{max}}$ and age**

Edwardsen et al. [20] demonstrated that the VO$_{2\text{max}}$ relative to body mass (VO$_{2\text{max/kg}}$) decreased 8% per decade. The decline had already started after the first age cohort (20–29 years) and was linear throughout all age cohorts until the last one (70–85 years). VO$_{2\text{max}}$ was about 25% higher in men than in women. Rogers et al. [58] found that the sedentary subjects’ VO$_{2\text{max}}$ declined by an average of 12% per decade. The master athletes’ VO$_{2\text{max}}$ decreased by 5.5% decline per decade. These findings provided evidence that the age-related decrease in VO$_{2\text{max}}$ of master athletes who continue to engage in regular vigorous endurance exercise training is approximately one-half the rate of decline seen in age-matched sedentary subjects.

The decline of VO$_{2\text{max}}$ and VO$_{2\text{max/kg}}$ was observed also in all age groups in our study. The highest values in both men and women were achieved by endurance trained athletes, followed by game sport athletes and other athletes. VO$_{2\text{max}}$ and VO$_{2\text{max/kg}}$ in the groups of...
non-competitive sportsmen (and sportswomen) was significantly lower than in all athletic groups and the age-related decline was faster. Compared to the values, valid like normatives for Czecho-slovak population [62], the data of the „non-competitive“ groups both men and women are almost identical (see Fig. 7 to Fig. 10). They prove that non-competitive sporting activity is effective for maintaining the average level of fitness, however, does not evoke higher level of cardiorespiratory capacity.

Fig. 8: \( \text{VO}_2\text{max/kg} \) (ml·min\(^{-1}\)·kg\(^{-1}\)) in different age groups in men (A-red – endurance athletes, B-blue – game sports, C-green – other athletes, D-black – non-competitive athletes, dash line – IBP values).

Fig. 9: \( \text{VO}_2\text{max/l/min} \) in different age groups in women (A-red – endurance athletes, B-blue – game sports, C-green – other athletes, D-black – non-competitive athletes, dash line – IBP values).

Discussion

Oxygen consumption (\( \text{VO}_2 \)) is considered the most accurate variable to measure the intensity of physical activity, and it can be measured directly in the laboratory with metabolic carts or respiratory gas analysers. Portable devices are available for field measurements, but they can be used only for limited periods of time and for limited number of subjects. Therefore, many efforts have been made to find more feasible ways to estimate \( \text{VO}_2 \) in field studies.

Maximal oxygen uptake or consumption (\( \text{VO}_2\text{max} \)) means the maximal capacity of an individual to perform aerobic work. It is the product of cardiac output and arteriovenous oxygen difference at exhaustion, and represents the golden standard measure for a person’s aerobic fitness [63].

Aerobic fitness is related to a person’s ability to perform dynamic, moderate-to-high intensity physical activity with large muscle groups for prolonged periods. Thus, it expresses the abilities of both cardiorespiratory and muscular systems to transport and utilize oxygen. It is one of the most fundamental measures of human physiology with remarkable health, wellbeing, life quality, work ability, and performance-related associations.

In addition to oxygen consumption (\( \text{VO}_2 \)), the energy cost of physical activities can be expressed as metabolic equivalents (MET; Metabolic Equivalent of Task). MET is defined as the ratio of metabolic rate (and therefore, the rate of energy consumption) during a specific physical activity to a resting metabolic rate. One MET is defined as 1 kcal·kg\(^{-1}\)·hour\(^{-1}\) or \( \text{VO}_2 \) equal to 3.5 ml·min\(^{-1}\)·kg\(^{-1}\), and it is roughly equivalent to the energy cost of sitting quietly.

Individual \( \text{VO}_2\text{max} \) values can range from about 10 ml·min\(^{-1}\)·kg\(^{-1}\) in cardiac patients to over
stress and even depression. Exercise plays an important role in treating obesity and the chances for developing type 2 diabetes and insulin sensitivity and glucose metabolism, reducing them can also lead to an increase in self-esteem. Finding time to exercise several times per week triggers the release of endorphins, which can elevate mood. It would be extremely beneficial to measure VO2max accurately in real-life. VO2max is a marker of optimal health. If it's critical decrease is diagnosed in time, numerous later health problems could be efficiently prevented. While laboratory tests require expensive equipment and trained personnel, and are thus difficult and expensive to perform, simple estimation of maximal performance on the treadmill ergometer could predict VO2max with sufficient accuracy.

Conclusion

The most important marker of cardiorespiratory capacity is VO2max. Also the concept of so called “fitness age” is based on the knowledge of personal VO2max. If somebody's VO2max is below average compared to age normative, his fitness age is actually greater than his chronological age.

On the other hand, a better-than-average VO2max could mean that fitness age is younger than subject's age in years. It's possible to improve VO2max by proper training, which means that the fitness age can actually get younger.

The primary problem with using VO2max to gauge longevity is that very few people know what theirs is, and finding out typically requires high-tech testing on a bicycle and/or treadmill ergometers and analyzing expired air for O2 and CO2 content. Our results on large cohorts of subjects demonstrate that simple bicycle ergometer with accurate measurement of performance reached by step-wise increased workload can offer reliable data (Wmax and Wmax/kg), which can be used for calculation VO2max and VO2max/kg with sufficient enough exactness. Regression equations for men and women and also for different age groups can be used for this purpose.

Fitness age may predict premature death better than risk factors like overweight, high blood pressure, or smoking. If the subject is not satisfied with his fitness age, he is motivated to improve it by regular training program. The recommendation regarding physical activity are available from principle guidelines, however, general practitioner and/or sports medical doctor should give personalized advice about the optimal volume, form and intensity.

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References

ORIGINAL RESEARCH


Appendix

Tab. 3: Example of different values obtained from the whole cohort of all 2777 examinations (men and women) (HR = heart rate; BPs = systolic blood pressure; BPd = diastolic blood pressure; VC = vital capacity; FEV1 = forced expiratory volume per second; METs-max = maximal metabolic equivalent; Wmax = maximal performance; VO2max = maximal O2 consumption; VCO2max = maximal CO2 expenditure; W170 = physical working capacity; VEmax = maximal pulmonary ventilation; BFmax = maximal breathing frequency; RERmax = maximal respiratory exchange ratio).

<table>
<thead>
<tr>
<th>Metric</th>
<th>Mean</th>
<th>Median</th>
<th>Max</th>
<th>Min</th>
<th>Std</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (cm)</td>
<td>173.6</td>
<td>175.5</td>
<td>202.0</td>
<td>125.5</td>
<td>10.9</td>
<td>2777</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>68.1</td>
<td>69.5</td>
<td>145.6</td>
<td>20.6</td>
<td>15.2</td>
<td>2777</td>
</tr>
<tr>
<td>Age (years)</td>
<td>23.6</td>
<td>19.0</td>
<td>95.0</td>
<td>7.0</td>
<td>12.3</td>
<td>2777</td>
</tr>
<tr>
<td>Fat (%)</td>
<td>14.4</td>
<td>13.9</td>
<td>53.0</td>
<td>1.5</td>
<td>6.0</td>
<td>2547</td>
</tr>
<tr>
<td>HRrest (beats/min)</td>
<td>66.6</td>
<td>66.0</td>
<td>122.0</td>
<td>34.0</td>
<td>13.2</td>
<td>2777</td>
</tr>
<tr>
<td>BPs (torr)</td>
<td>120.6</td>
<td>120.0</td>
<td>200.0</td>
<td>75.0</td>
<td>14.8</td>
<td>2770</td>
</tr>
<tr>
<td>BPd (torr)</td>
<td>73.0</td>
<td>71.0</td>
<td>115.0</td>
<td>30.0</td>
<td>10.8</td>
<td>2770</td>
</tr>
<tr>
<td>VC (ml)</td>
<td>4528</td>
<td>4575</td>
<td>8270</td>
<td>1370</td>
<td>1064</td>
<td>1958</td>
</tr>
<tr>
<td>FEV1 (ml)</td>
<td>3800</td>
<td>3820</td>
<td>6250</td>
<td>1340</td>
<td>799</td>
<td>1846</td>
</tr>
<tr>
<td>METs-max</td>
<td>15.0</td>
<td>15.0</td>
<td>29.8</td>
<td>5.6</td>
<td>3.3</td>
<td>2777</td>
</tr>
<tr>
<td>Wmax (watt)</td>
<td>325.6</td>
<td>330.0</td>
<td>610.0</td>
<td>70.0</td>
<td>104.6</td>
<td>2777</td>
</tr>
<tr>
<td>Wmax/kg (W)</td>
<td>4.79</td>
<td>4.89</td>
<td>8.80</td>
<td>1.23</td>
<td>1.16</td>
<td>2777</td>
</tr>
<tr>
<td>VO2max (l/min)</td>
<td>3.60</td>
<td>3.60</td>
<td>6.90</td>
<td>0.80</td>
<td>1.10</td>
<td>2777</td>
</tr>
<tr>
<td>VCO2max (l/min)</td>
<td>4.24</td>
<td>4.30</td>
<td>8.80</td>
<td>0.90</td>
<td>1.35</td>
<td>2777</td>
</tr>
<tr>
<td>VO2max/kg (ml)</td>
<td>52.9</td>
<td>53.5</td>
<td>82.6</td>
<td>19.5</td>
<td>11.6</td>
<td>2777</td>
</tr>
<tr>
<td>VO2max/TFmax (ml/min)</td>
<td>19.53</td>
<td>19.55</td>
<td>41.13</td>
<td>4.22</td>
<td>6.19</td>
<td>2777</td>
</tr>
<tr>
<td>W170 (watts)</td>
<td>199.6</td>
<td>193.7</td>
<td>494.5</td>
<td>34.3</td>
<td>76.0</td>
<td>2777</td>
</tr>
<tr>
<td>W170/kg (watts)</td>
<td>2.9</td>
<td>2.8</td>
<td>6.7</td>
<td>0.9</td>
<td>0.8</td>
<td>2775</td>
</tr>
<tr>
<td>HRmax (beats/min)</td>
<td>186.2</td>
<td>187.0</td>
<td>230.0</td>
<td>115.0</td>
<td>11.8</td>
<td>2777</td>
</tr>
<tr>
<td>VEmax (l/min)</td>
<td>110.2</td>
<td>109.3</td>
<td>219.0</td>
<td>27.7</td>
<td>33.2</td>
<td>2777</td>
</tr>
<tr>
<td>BFmax (breaths/min)</td>
<td>47.4</td>
<td>48.0</td>
<td>60.0</td>
<td>22.0</td>
<td>8.2</td>
<td>1354</td>
</tr>
<tr>
<td>RERmax</td>
<td>1.09</td>
<td>1.08</td>
<td>1.19</td>
<td>0.87</td>
<td>0.05</td>
<td>2774</td>
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