SHORT COMMUNICATION

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Estimation of $\dot{V}O_{2max}$ from the ratio between HR_{max} and HR_{rest} – the Heart Rate Ratio Method

Abstract The effects of training and/or ageing upon maximal oxygen uptake ($\dot{V}O_{2max}$) and heart rate values at rest (HR_{rest}) and maximal exercise (HR_{max}), respectively, suggest a relationship between $\dot{V}O_{2max}$ and the HR_{max}-to-HR_{rest} ratio which may be of use for indirect testing of $\dot{V}O_{2max}$. Fick principle calculations supplemented by literature data on maximum-to-rest ratios for stroke volume and the arterio-venous O_2 difference suggest that the conversion factor between mass-specific $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1}) and HR_{max}·$HR_{rest}$$^{-1}$ is ~15. In the study we experimentally examined this relationship and evaluated its potential for prediction of $\dot{V}O_{2max}$. $\dot{V}O_{2max}$ was measured in 46 well-trained men (age 21–51 years) during a treadmill protocol. A subgroup ($n=10$) demonstrated that the proportionality factor between HR_{max}·$HR_{rest}$$^{-1}$ and mass-specific $\dot{V}O_{2max}$ was 15.3 (0.7) ml·min^{-1}·kg^{-1}. Using this value, $\dot{V}O_{2max}$ in the remaining 36 individuals could be estimated with an SEE of 0.21 l·min^{-1} or 2.7 ml·min^{-1}·kg^{-1} (~4.5%). This compares favourably with other common indirect tests. When replacing measured HR_{max} with an age-predicted one, SEE was 0.37 l·min^{-1} and 4.7 ml·min^{-1}·kg^{-1} (~7.8%), which is still comparable with other indirect tests. We conclude that the HR_{max}-to-HR_{rest} ratio may provide a tool for estimation of $\dot{V}O_{2max}$ in well-trained men. The applicability of the test principle in relation to other groups will have to await direct validation. $\dot{V}O_{2max}$ can be estimated indirectly from the measured HR_{max}-to-HR_{rest} ratio with an accuracy that compares favourably with that of other common indirect tests. The results also suggest that the test may be of use for $\dot{V}O_{2max}$ estimation based on resting measurements alone.

Keywords HR_{max}-to-HR_{rest} ratio · Maximal heart rate · Maximal oxygen uptake · Resting heart rate

Introduction

The maximal rate of oxygen uptake uptake ($\dot{V}O_{2max}$) is an important determinant of cardiorespiratory fitness and aerobic performance (Howley et al. 1995). Direct measurements of oxygen uptake ($\dot{V}O_2$) during maximal work provide the most accurate value for this parameter, and measurements are reproducible with a coefficient of variation of about 2–4% (Howley et al. 1995). Direct measurements of $\dot{V}O_{2max}$ are, however, technically demanding and require access to expensive laboratory equipment and skilled personnel. As a consequence, alternative procedures have been developed in which $\dot{V}O_{2max}$ is estimated from physiological responses during submaximal exercise (e.g. Åstrand and Ryhming 1954; Fox 1973) or from physiological responses in combination with performance measures (e.g. Kline et al. 1987).

Training status is a major determinant of $\dot{V}O_{2max}$. It is well documented that $\dot{V}O_{2max}$ increases with training and that inactivity or cessation of training reduces $\dot{V}O_{2max}$ (e.g. Blomqvist and Saltin 1983). Training, likewise, has been shown to lower resting heart rate (HR_{rest}) (Blomqvist and Saltin 1983) whereas detraining is associated with increased HR_{rest} (Katona et al. 1982). This suggests that one would expect a negative relationship between $\dot{V}O_{2max}$ and HR_{rest}. Whether such a relationship is close enough to merit interest in indirect estimation of $\dot{V}O_{2max}$ is uncertain.

Ageing is associated with decrements in both $\dot{V}O_{2max}$ and HR_{max} (Tanaka et al. 2001). The effect of ageing would therefore suggest a positive relationship between $\dot{V}O_{2max}$ and HR_{max}. If we combine the mentioned influences of training, or ageing, upon the $\dot{V}O_{2max}$ and HR

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response, it appears likely that a positive relationship exists between $\dot{V}O_{2max}$ and the ratio between HR_{max} and HR_{rest} ($HR_{max} \cdot HR_{rest}^{-1}$). Calculations based upon the Fick principle and incorporating literature data for maximum-to-rest ratios for HR, stroke volume and arterio-venous O_2 difference, respectively (see Appendix), suggest that mass-specific $\dot{V}O_{2max}$ may be estimated by multiplying $HR_{max} \cdot HR_{rest}^{-1}$ by a factor of about 15.0. The purpose of the present study was therefore (1) to examine whether this theoretical proportionality factor could be confirmed by experimental data, and (2) to evaluate in a group of well-trained men the limits of agreement (LOA) (Bland and Altman 1986) for prediction of $\dot{V}O_{2max}$ using the experimentally established proportionality factor.

Methods

Subjects

Forty-six healthy well-trained, non-smoking men volunteered to participate in the study. The mean (SD) values for age, height, body mass (BM) and $\dot{V}O_{2max}$ were 29.6 (7.7) years, 182 (6.1) cm, 76.3 (6.5) kg, 4.66 (0.49) $l \cdot min^{-1}$ and 60.9 (5.5) $ml \cdot min^{-1} \cdot kg^{-1}$, respectively. They trained on average 8.7 (2.9) h per week. All subjects provided written informed consent in accordance with the guidelines of the local Ethics Committee. The experiments complied with the standards of the local Ethics Committee.

Study design

The subjects were randomly assigned to either of two groups. One group ($n = 10$) validated the proportionality factor between the mass-specific $\dot{V}O_{2max}$ and the HR_{max}-to-HR_{rest} ratio (theoretical value $\sim$15). The other group ($n = 36$) was used to establish LOA between $\dot{V}O_{2max}$ estimates based upon the HR_{max}-to-HR_{rest} ratio and the above factor, versus direct measurements of $\dot{V}O_{2max}$.

Experimental protocol

Height was measured to the nearest 0.5 cm and BM determined to the nearest 0.1 kg. Exercise experiments were performed on a motor-driven treadmill (Technogym Runrace, Gambettola, Italy). The subjects warmed up for 10 min at a speed and grade selected to impose a heart rate of $\sim$140 $beats \cdot min^{-1}$. The typical initial running speed was 13 $km \cdot h^{-1}$. Speed (first part of the test) and/or inclination (later part) were subsequently increased stepwise every minute by 1 $km \cdot h^{-1}$ or 2% slope, respectively, to exhaustion. The duration of the test ranged 5–10 min. Pulmonary gas exchange and heart rate were monitored continuously during the test. High-intensity and/or high-volume training was avoided for 48 h prior to testing. Resting heart rate was measured over a 5-min period by the subject in the morning the day after the test (supine, while in bed). HR_{rest} ($beats \cdot min^{-1}$ with one decimal) was defined as the lowest value of any 1-min average during the 5-min sampling period. HR_{max} was defined as the highest 5-s average during the treadmill test.

Techniques

Pulmonary gas exchange was measured with an automated metabolic cart system (AMIS 2001, Innovision, Odense, Denmark). Ventilatory flow rate was measured on the inspiratory side with a differential pressure sensor (Pneumotachograph - Lilly type, Innovision A/S, Odense, Denmark.). $\dot{V}O_{2max}$ was defined as the highest $\dot{V}O_2$ measured during any 30-s period. Heart rate was measured with a Polar Electro heart rate monitor (Kempele, Finland). A test was approved as being maximal when at least three of the following four criteria were met: (1) a plateau in $\dot{V}O_2$ despite increased running speed or inclination (increase < 150 $ml \cdot min^{-1}$), (2) R-value ≥ 1.15, (3) ventilatory equivalent for oxygen > 30, and (4) terminal HR within 10 $beats \cdot min^{-1}$ of age-predicted HR_{max}. The HR_{max} was predicted from age using the formula of Tanaka et al. (2001): HR_{max} (age-predicted) $= 208 - 0.7 \cdot age$ in years.

Statistics

Analysis of variance (ANOVA) was performed to analyse differences between group means. Pearson's coefficient of correlation (r) was used to describe the relationship between $\dot{V}O_{2max}$ as well as the mass-specific $\dot{V}O_{2max}$ and selected physiological variables. Bland-Altman plots (1986) were employed to establish the LOA between measured and estimated $\dot{V}O_{2max}$. Operationally, LOA define the range within which 95% of the individual differences between measured and estimated $\dot{V}O_{2max}$ will lie. After calculating the standard error of estimate (SEE) for the differences between measured and estimated $\dot{V}O_{2max}$, a 95% confidence interval (± 1.96 SEE) is determined around the mean difference. As part of the analysis, differences between measured and estimated $\dot{V}O_{2max}$ were plotted against their average and tested for homoscedasticity. Statistical significance was set at $P < 0.05$ for all analyses.

Results

The experimentally determined proportionality factor between mass-specific $\dot{V}O_{2max}$ and $HR_{max} \cdot HR_{rest}^{-1}$ was 15.26 (0.72) $ml \cdot min^{-1} \cdot kg^{-1}$ which is not significantly different from the theoretical value of $\sim$15 $ml \cdot min^{-1} \cdot kg^{-1}$. Highly statistically significant correlations were found between measured $\dot{V}O_{2max}$ and the estimated counterparts using the Heart Rate Ratio Method. Correlation coefficients for $\dot{V}O_{2max}$ in $ml \cdot min^{-1}$ averaged 0.91 ($P < 0.001$; see Fig. 1a) and for mass-specific $\dot{V}O_{2max}$ 0.87 ($P < 0.001$; see Fig. 1b). The average difference between measured and estimated $\dot{V}O_{2max}$ was not significantly different from zero (0.024 $l \cdot min^{-1}$, $P = 0.83$ and 0.28 $ml \cdot min^{-1}$ kg^{-1}, $P = 0.83$). The LOA for individual estimates of $\dot{V}O_{2max}$ averaged 0.41 $l \cdot min^{-1}$ or 5.3 $ml \cdot min^{-1} \cdot kg^{-1}$, corresponding to about 8.7% (see Fig. 2a, b). The magnitude of the differences between measured and estimated $\dot{V}O_{2max}$ was not dependent on the actual level of $\dot{V}O_{2max}$, confirming the homoscedastic nature of the data. Replacement of measured HR_{max} with its age-predicted match in the $\dot{V}O_{2max}$ calculation resulted in larger differences between measured and estimated $\dot{V}O_{2max}$. LOA increased to ± 0.72 $l \cdot min^{-1}$, or 9.2 $ml \cdot min^{-1} \cdot kg^{-1}$, which corresponds to about 15% (see Fig. 2b). Moreover, statistically significant correlations were also found between $BM \cdot HR_{max} \cdot HR_{rest}^{-1}$ and $\dot{V}O_{2max}$ ($r = 0.92$; $P < 0.001$) and between $HR_{max} \cdot HR_{rest}^{-1}$ and mass-specific $\dot{V}O_{2max}$ ($r = 0.86$; $P < 0.001$).

Discussion

By elaborating upon the Fick principle we developed an equation that predicts a relationship between the

Fig. 1a, b **a** Scatter plot between estimated and measured maximal oxygen uptake (l·min^{-1}), **b** Scatter plot between estimated and measured mass-specific maximal oxygen uptake (ml·min^{-1}·kg^{-1}). The *solid lines* depicted are the least-squares derived best-fitting lines
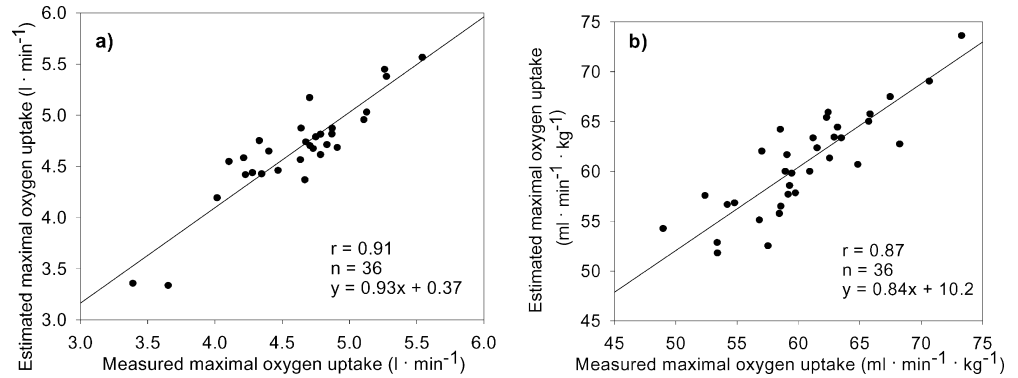
HR$_{max}$-to-HR$_{rest}$ ratio and mass-specific $\dot{V}O_{2max}$. Experimental testing of ten well-trained men demonstrated that the proportionality factor applied in the conversion of HR$_{max}$·HR$_{rest}^{-1}$ to $\dot{V}O_{2max}$ was 15.26 (0.72) ml·min^{-1}·kg^{-1}, a value which is not significantly different from the theoretically assumed value of 15.0 ml·min^{-1}·kg^{-1}. Subsequent testing of 36 trained men demonstrated that individual values for mass-specific $\dot{V}O_{2max}$ (range 49–73 ml·min^{-1}·kg^{-1}) could be obtained with a SEE of 2.72 ml·min^{-1}·kg^{-1}, or ~4.5%. This yields a 95% confidence interval (LOA) for individual estimates of mass-specific $\dot{V}O_{2max}$ of about 8.7%.

In order to evaluate the relative merit of the above method for estimation of $\dot{V}O_{2max}$ we have compared its SEE value with data from some other indirect tests. The Åstrand-Ryhming nomogram test from 1954, which was based upon cycle ergometer testing of 27 male and 31 female subjects, reported SEE values of 7–15%. Fox's (1973) cycle ergometer study which comprised of 87 young men reported SEE to be 6–11%. Kline et al. (1987) tested middle-aged men ($n=83$) and women ($n=86$) using a walking test in combination with anthropometry and arrived at SEE ~10%. Andersen (1995) used a maximal exercise protocol to predict $\dot{V}O_{2max}$ and found SEE to be ~8%. In comparison with these tests the Heart Rate Ratio Method may offer superior accuracy, although attention should be paid to the possible significance of its being based upon a relatively homogenous study group ("well-trained men").

It should be noticed that the regression lines of Fig. 1 cross the line of identity. The slopes of both regression lines are not significantly different from 1 ($P<0.001$).

The point at which the regression line intersects the *y*-axis is significantly different from 0 in Fig. 1b ($P=0.04$) but not in Fig. 1a ($P=0.25$).

Age-predicted versus experimentally determined HR$_{max}$

Instead of experimentally determining HR$_{max}$ as in the above version of the test, HR$_{max}$ may also be predicted from the person's age. Use of a theoretical HR$_{max}$ value rather than an experimental one would facilitate the accomplishment of the test and potentially increase its applicability to groups of individuals where maximal effort may be unwarranted, such as patients or elderly individuals. The accuracy of the $\dot{V}O_{2max}$ estimation was significantly less when age-predicted HR$_{max}$ values replaced the experimental ones in the formula (SEE 7.8% versus 4.5% of the average $\dot{V}O_{2max}$). Thus, the convenience obtained from not having to expose the individual to maximal exercise had a price. It is of note, however, that even with age-predicted HR$_{max}$ values SEE was still comparable with other indirect tests. It may therefore be of interest to further examine its applicability to individuals of different age and training levels.

Standardization of measurement conditions

It should be noted that the SV$_{max}$-to-SV$_{rest}$ ratio is about 1.3 when measured in the supine position (as presumed in the calculation of the proportionality factor), whereas

Fig. 2a, b Limits of agreement (Bland and Altman 1986) for measured versus estimated maximal oxygen uptake using the Heart Rate Ratio Method. **a** HR$_{max}$ is experimentally established as opposed to the age-predicted value (Tanaka et al. 2001) used in **b**. Upper and lower limit of agreement are indicated with *solid lines* while the mean difference is indicated by a *dashed line*
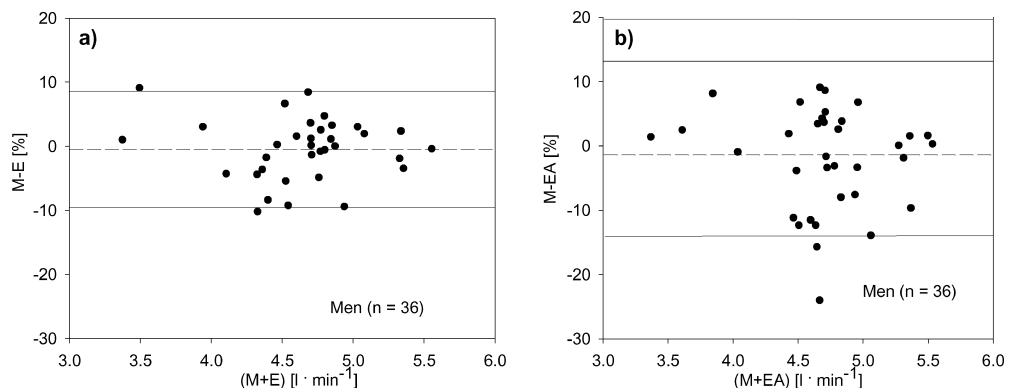
the corresponding value for the standing position would be 1.82 (Chapman et al. 1960). This emphasizes the importance of HR measurements being performed under strictly standardized conditions. Furthermore, it is important to underline that the proportionality factor between mass-specific $\dot{V}O_{2max}$ and the HR_{max}-to-HR_{rest} ratio may vary between groups of individuals since both mass-specific resting $\dot{V}O_{2max}$ and the max-to-rest ratios of SV and the arterio-venous O_2 difference $(CaO_2-C\bar{v}O_2)$ can be influenced by factors such as age, gender and training level. Therefore valid proportionality factors should first be experimentally established before the principle of the Heart Rate Ratio Method is extended to groups other than well-trained men.

Conclusion

In a group of ten well-trained men, the proportionality factor between mass-specific $\dot{V}O_{2max}$ and the HR_{max}-to-HR_{rest} ratio was found to be 15.26 ml·min^{-1}·kg^{-1}, which was in good agreement with the theoretical value. Furthermore, when using this proportionality factor in 36 well-trained men we found that the mass-specific $\dot{V}O_{2max}$ could be estimated from the experimentally determined HR_{max}-to-HR_{rest} ratio with an SEE of 4.5%, which appears to be superior to other common indirect tests. Moreover, when replacing the experimentally determined HR_{max} with an age-predicted one, the mass-specific $\dot{V}O_{2max}$ could be estimated by the Heart Rate Ratio Method with an SEE of 7.8%. The results indicate that the principle of this test may provide a simple and useful tool for $\dot{V}O_{2max}$ estimation.

Appendix

Derivation of an equation for a relationship between $\dot{V}O_{2max}$ and the ratio between HR_{max} and HR_{rest}

According to the Fick principle, $\dot{V}O_{2max}$ may be expressed as the product of cardiac output $(\dot{Q})$ and the arterio-venous O_2 difference $(CaO_2-C\bar{v}O_2)$.

$$\dot{V}O_2 = \dot{Q} \cdot (C_aO_2 - C\bar{v}O_2) \tag{1}$$

Thus, since $\bar{Q}$ is the product of HR and stroke volume (SV), $\dot{V}O_{2max}$ can be expressed as:

$$\dot{V}O_2 = HR \cdot SV \cdot (C_aO_2 - C\bar{v}O_2) \tag{2}$$

When applied to rest $\dot{V}O_{2max}$ can be expressed as:

$$\dot{V}O_{2rest} = HR_{rest} \cdot SV_{rest} \cdot (CaO_2 - C\bar{v}O_2)_{rest} \tag{3}$$

implying that:

$$\frac{\dot{V}O_{2rest}}{HR_{rest} \cdot SV_{rest} \cdot (CaO_2 - C\bar{v}O_2)_{rest}} = 1 \tag{4}$$

During maximal exercise the Fick equation reads:

$$\dot{V}O_{2max} = HR_{max} \cdot SV_{max} \cdot (CaO_2 - C\bar{v}O_2)_{max} \tag{5}$$

By multiplying the right side of Eq. 5 with 1 in the form of Eq. 4 it follows that:

$$\dot{V}O_{2max} = \frac{HR_{max} \cdot SV_{max} \cdot (CaO_2 - C\bar{v}O_2)_{max}}{HR_{max} \cdot SV_{max} \cdot (CaO_2 - C\bar{v}O_2)_{rest}} \cdot \dot{V}O_{2rest} \tag{6}$$

or

$$\dot{V}O_{2max} = \left(\frac{HR_{max}}{HR_{rest}}\right) \cdot \left(\frac{SV_{max}}{SV_{rest}}\right) \cdot \left(\frac{(CaO_2 - C\bar{v}O_2)_{max}}{(CaO_2 - C\bar{v}O_2)_{rest}}\right) \times \dot{V}O_{2rest} \tag{7}$$

This implies that $\dot{V}O_{2max}$ may be calculated as the product of $\dot{V}O_{2max}$ and the ratios of maximal versus resting values of, respectively, HR, SV, and $(CaO_2-C\bar{v}O_2)$.

$\dot{V}O_{2rest}$ is dependent on and increases with the individual's body mass. Åstrand and Rodahl (1986) suggest that, relative to body mass (BM), resting $\dot{V}O_2$ equals about 3.5 ml·min^{-1}·kg^{-1} (one MET), but slightly lower values were reported by McCann and Adams (2002) (3.3 for men and 3.1 for women, respectively). As a compromise we chose 3.4 ml·min^{-1}·kg^{-1} to represent the mass-specific resting $\dot{V}O_2$. Accordingly, $\dot{V}O_{2rest}$ (ml·min^{-1}) may be expressed as 3.4 ml·min^{-1}·kg^{-1} times BM in kg.

$$\dot{V}O_{2max} = \left(\frac{HR_{max}}{HR_{rest}}\right) \cdot \left(\frac{SV_{max}}{SV_{rest}}\right) \cdot \left(\frac{(CaO_2 - C\bar{v}O_2)_{max}}{(CaO_2 - C\bar{v}O_2)_{rest}}\right) \times BM \cdot 3.4ml \cdot min^{-1} \cdot kg^{-1} \tag{8}$$

From a test perspective only the HR_{max}-to-HR_{rest} ratio is readily obtainable. The other two ratios in the equation involve complicated measurements, in fact more complicated than the measurement of $\dot{V}O_2$ itself. Equation 8 suggests, however, that if the max-to-rest ratios of SV and $(CaO_2-C\bar{v}O_2)$ were approximately constant across individuals, $\dot{V}O_{2max}$ per kg BM may be estimated by experimentally determining the HR_{max}-to-HR_{rest} ratio, and multiplying this ratio with these constants and 3.4 ml·min^{-1}·kg^{-1}. Nottin et al. (2002) and Chapman et al. (1960) reported the average $SV_{max} \cdot SV_{rest}^{-1}$ to be 1.28 and 1.29, respectively, in men, when measured in the supine position. Thus, according to the studies mentioned it appears that $SV_{max} \cdot SV_{rest}^{-1}$ may be replaced by a dimensionless value of approximately 1.3.

The arterio-venous oxygen difference increases from rest to maximal exercise. Chapman et al. (1960) found the average ratio between maximal and resting

$(CaO_2 - C\bar{v}O_2)$ to be 3.4 in men. We therefore replaced $(CaO_2 - C\bar{v}O_2)_{max} \cdot (CaO_2 - C\bar{v}O_2)rest^{-1}$ in Eq. 8 with 3.4. Altogether, data from the literature suggest that Eq. 8 may be simplified to the approximation:

$$\dot{V}O_{2\,max} = \left(1.3 \cdot 3.4 \cdot ml \cdot min^{-1} \cdot kg^{-1}\right) \cdot BM(kg) \cdot \frac{HR_{max}}{HR_{rest}}$$
$$= 15.0 \; ml \cdot min^{-1} \cdot BM(kg) \cdot \frac{HR_{max}}{HR_{rest}}, \; or$$

(9)

$$Mass-specific \; \dot{V}O_{2\,max} = \left(15.0 \; ml \cdot min^{-1} \cdot kg^{-1}\right) \frac{HR_{max}}{HR_{rest}}$$

(10)

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