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Correlation of maximal respiratory exchange ratio with anaerobic power and maximal oxygen uptake in anaerobic trained athletes

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection.

Abstract

Background and Study Aim: The respiratory exchange ratio (RER) is the ratio of the amount of carbon dioxide produced (VCO2) to the amount of oxygen uptake (VO2) is important. It indirectly informs about the predominant metabolic pathway to provide the energy needed during exercise. The relationship of maximal RER with aerobic and anaerobic capacity in athletes remains unclear. The purpose of this study was to investigate the relationship between maximal RER and anaerobic power and maximal oxygen uptake (VO_{2max}) in anaerobic trained athletes.

Material and Methods: Thirteen male alpine skiers (age 18.1 ± 3.1 years) competing in national and international competitions participated in the study. Athletes first performed an incremental treadmill run test to determine their VO_{2max} (ml/kg/min), maximal RER (VCO_2 / VO_2) and maximal running speed (km/h). After 48 hours, the athletes performed the Wingate anaerobic test to determine peak power, mean power, minimum power, and fatigue index. Pearson correlation coefficients were used to examine the relations between variables.

Results: Maximal RER was positively correlated with peak power ($r = 0.587$, $p < 0.035$), mean power ($r = 0.656$, $p < 0.015$) and minimum power ($r = 0.674$, $p < 0.012$). Maximal RER did not significantly correlate with fatigue index ($p > 0.05$). Maximal RER was negatively correlated with the VO_{2max} ($r = -0.705$, $p < 0.007$) and maximal running speed ($r = -0.687$, $p < 0.01$).

Conclusions: Maximal RER may be useful for evaluating anaerobic capacity in anaerobic-trained athletes. Measuring the maximal RER values of athletes during incremental exercise may provide information about physiological adaptations in response to physical training.

Keywords: anaerobic capacity, aerobic capacity, wingate test, incremental exercise

Introduction

The ratio of carbon dioxide produced (VCO_2) to the amount of oxygen (VO_2) used is known as the respiratory exchange ratio (RER). In addition to blood lactic acid, the RER is widely used to assess physiological metabolism in athletes [1]. The RER indirectly informs about the predominant metabolic pathway to provide the energy needed during exercise [2].

The RER changes depending on whether the exercise intensity is above or below the anaerobic threshold and increases with exercise intensity [3, 4]. RER values less than 1.00 mean that energy requirement meets predominantly by aerobic metabolism during exercise. Steady-state RER values measured at rest and exercise intensities below the anaerobic threshold typically range from 0.7 to 1.0, depending on the ratio of substrate utilization to obtain energy [3, 5]. A high RER value indicates predominantly carbohydrate utilization, while a low RER value indicates lipid oxidation [3, 6].

A RER value of about 1.00 represents the highest exercise intensity at which the respiratory system maintains a physiological steady state [7]. Lactic acid produced as a result of the anaerobic glycolysis during exercise disassociates into lactate and hydrogen ions (H^+), and H^+ is buffered by both bicarbonate and non-bicarbonate buffers [8]. The relationship between VCO_2 and VO_2 during an incremental exercise is characterized by a relatively linear relationship up to a certain intensity of exercise [9, 10]. When anaerobic glycolysis begins to predominate energy production, VCO_2 increases faster than VO_2, resulting in an increase in RER [10, 11]. The RER value rises above 1.00 due to non-metabolic CO_2 production from buffering of excess H^+ with bicarbonate in addition to the CO_2 produced by aerobic metabolism [11, 12]. At exercise intensities above the anaerobic threshold (RER > 1.00), hyperventilation occurs so that additional CO_2 produced by buffering excess H^+ can be removed from the body [10, 11]. Therefore, a RER value above 1.00 during exercise indicates predominantly anaerobic metabolism is utilized [11, 12].

RER is used as one of the simplest non-invasive methods to determine the anaerobic threshold [13]. The RER method used to assess the anaerobic threshold is based on the observation that a part of the expired CO_2 is derived from the body bicarbonate pool because of lactic acid accumulation during exercise [10]. Anaerobic threshold values based on RER have been shown to be associated with athletic performance [14, 15]. RER has been shown to provide information about physical fitness at exercise intensity above the anaerobic threshold in trained and untrained healthy men [3]. RER values are also used to provide an index of whether the exercise intensity is too high to be sustained throughout the exercise [16]. A RER value above 1.10 is considered a

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good indicator of achieving maximum effort in healthy individuals [16-18]. During incremental exercise, RER can provide a prediction of maximal oxygen uptake (VO_{2max}) in untrained and trained individual [19]. The peak RER can also be used to assess exercise capacity and metabolic responses in individuals with reduced exercise tolerance [20].

Considering that the RER exceeds 1.0 at exercise intensities above the anaerobic threshold, it has been interpreted that high RER values may be important in high-intensity short-distance efforts [9, 15]. During high-intensity exercise, blood lactate concentration has been shown to be the most important determinant of RER in athletes [21]. Blood lactate concentration can be used to estimate aerobic and anaerobic capacity as it reflects the balance between lactate production and removal [8]. It has been shown that there is a significant relationship between anaerobic performance and post-exercise lactate concentration [22, 23]. The increase in CO_2 and thus the RER has been found to be quantitatively related to the magnitude of the increase in lactic acid [12]. Therefore, the maximal RER measured during incremental exercise may be related to anaerobic capacity in athletes.

The association of the maximal RER with aerobic and anaerobic capacity has not been clearly established. The purpose of this study was to investigate the relationship between maximal RER measured during incremental exercise and anaerobic power and VO_{2max} in anaerobic-trained athletes.

Material and Methods

Participants

Thirteen male alpine skiers (mean ± SD; age 18.1 ± 3.1 years, height 174 ± 3.6 cm, body mass 67 ± 9.5 kg) competing in national and international competitions volunteered to participate in the study. Measurements were performed following the approval of the Ethics Committee and carried out in accordance with the Declaration of Helsinki. All testing and training procedures were fully explained, and written informed consent was obtained for each participant. All athletes performed two tests 48 hours apart, consisting of the incremental treadmill test and the Wingate test. To avoid unnecessary fatigue accumulation, the athletes were not allowed to perform any training the day before each test.

Incremental Treadmill Test

Incremental running test was performed on a motorized treadmill (h/p/Cosmos Quasar med, Nussdorf-Traunstein, Germany). Throughout all tests, breath-by-breath gas measurements were taken using an indirect calorimetric system (Quark PFT Ergo, Cosmed Srl, Rome, Italy) which was calibrated before each session to the manufacturer's instructions. The heart rate was recorded continuously using a wireless HR monitor (S610i, Polar, Finland). Breath-by-breath data were smoothed using a five-step average filter and then reduced to 15 s stationary averages. Maximal oxygen uptake (VO_{2max}), maximal respiratory exchange ratio (RER) and maximal running speed were determined during the incremental treadmill test.

Each athletes performed a standardized warm-up consisting of a 5-min run at their own pace followed by about 3-min stretching. Following the warm-up period, athletes performed a progressive protocol with an initial speed of 7 km/h with speed increments of 1 km/h at a constant 5% incline every minute until they could no longer keep the running pace. The athletes were instructed to run until voluntary exhaustion and given strong verbal encouragement throughout the test to elicit their best performance. Achievement of VO_{2max} was considered as the attainment of at least two of the following criteria: 1) a plateau in oxygen uptake (VO_2) despite increasing speed, 2) an HR within ten beats per minute of age-predicted maximum HR (220 – age), and 3) a respiratory exchange ratio (RER) above 1.10. The VO_{2max} was defined as the highest 15-s VO_2 value reached during the test.

Wingate Anaerobic Test

The Wingate anaerobic test was performed on a computerized cycle ergometer (Monark 824E, Monark, Sweden) in standard version [24]. The athletes completed a warming up of 5 minutes cycling at a pedaling rate of 60–70 rpm including two unloaded maximal sprints of 5 seconds each, performed at the end of the 3rd and the 5th minutes. Following the initial warm-up period, the athletes performed about 3-min stretching. The athletes were instructed to pedal as fast as possible. Following the warm-up period, the athletes pedaled at maximal (all-out) effort for 30s on a cycle ergometer against resistance corresponding to 7.5% of their body mass. Athletes were verbally encouraged to maintain a pedaling rate as high as possible for 30 seconds. Peak power (watts), mean power (watts), minimum power (watts) and fatigue index (percent) were calculated with Monark Anaerobic test computer software program.

Statistical Analysis:

Data are reported as the means ± standard deviation (SD). Statistical significance was accepted at $p < 0.05$. The assumption of normality was assessed through the Shapiro-Wilk test. Pearson correlation coefficients were used to examine the relations between variables. Almost perfect (r = >0.9), very large (r = 0.7-0.9), large (r = 0.5-0.7), moderate (r = 0.3-0.5), small (r = 0.1-0.3) or trivial (r = <0.1) of association were defined [25]. Simple linear regression analysis was used to determine the success of prediction (Sigma Plot 12.0, Systat Software Inc., Chicago, USA). IBM SPSS 21 software (IBM SPSS Statistics 21 Inc., Chicago, IL) was used for the statistical analyses.

Results

The results obtained during incremental treadmill test and Wingate anaerobic test are shown in Table 1. Linear regression analyses of the relationship between maximal RER and Wingate anaerobic test variables are given in figure 1.A, B and C. Maximal RER was largely positively correlated with peak power ($r = 0.587$, $p < 0.035$), mean power ($r = 0.656$, $p < 0.015$) and minimum power ($r = 0.674$, $p < 0.012$). Maximal RER did not significantly correlate with fatigue index ($r = – 0.074$, $p > 0.05$).

Figure 1.D shows the linear regression analysis of the relationship between maximal RER and VO_{2max}. Maximal RER was very largely and largely negatively correlated with the VO_{2max} ($r = -0.705$, $p < 0.007$), and maximal running speed ($r = -0.687$, $p < 0.01$), respectively.

Table 1. Mean values for variables determined from incremental treadmill test and Wingate anaerobic test. Mean ± SD

Variables	Mean ± SD
VO_{2max} (ml/kg/min)	54.2 ± 6
Maximal running speed (km/h)	14.3 ± 0.6
Maximal RER (CO_2/O_2)	1.19 ± 0.03
Peak power (Watts)	601.6 ± 123.6
Mean power (Watts)	454.9 ± 80.1
Minimum power (Watts)	266.8 ± 49.9
Fatigue index (%)	55.3 ± 3.4

Discussion

We examined whether maximal RER measured during incremental exercise was related to anaerobic power and VO_{2max} in anaerobic-trained athletes. The main results of this study indicated that maximal RER was positively correlated with the peak power, mean power and minimum power. This finding suggests that the higher the maximal RER, the better the anaerobic capacity in anaerobic-trained athletes. In addition, higher maximal RER was associated with lower VO_{2max} and maximal running speed during the incremental exercise. Maximal RER may be useful for estimating anaerobic capacity in anaerobic-trained athletes.

Above the anaerobic threshold, RER kinetics reflect additional CO_2 production as a result of H^+ buffering associated with lactic acid increase and compensatory hyperventilation for metabolic acidosis [9, 11]. The association between increased blood lactate concentration and decrease in intracellular pH [26] has been documented to occur with a decrease in power [27]. A peak RER value between 1.10 and 1.20 is considered a good indicator of achieving maximum effort in healthy individuals during incremental exercise [17]. In the present study, the maximal RER measured during incremental exercise was related to the peak power, mean power and minimum power of the Wingate anaerobic test. Anaerobic power and capacity are the best indicator of athletic performance in alpine skiing, which race duration varies between 45 seconds and 3 minutes [28]. Anaerobic capacity in alpine skiing is commonly evaluate using the Wingate

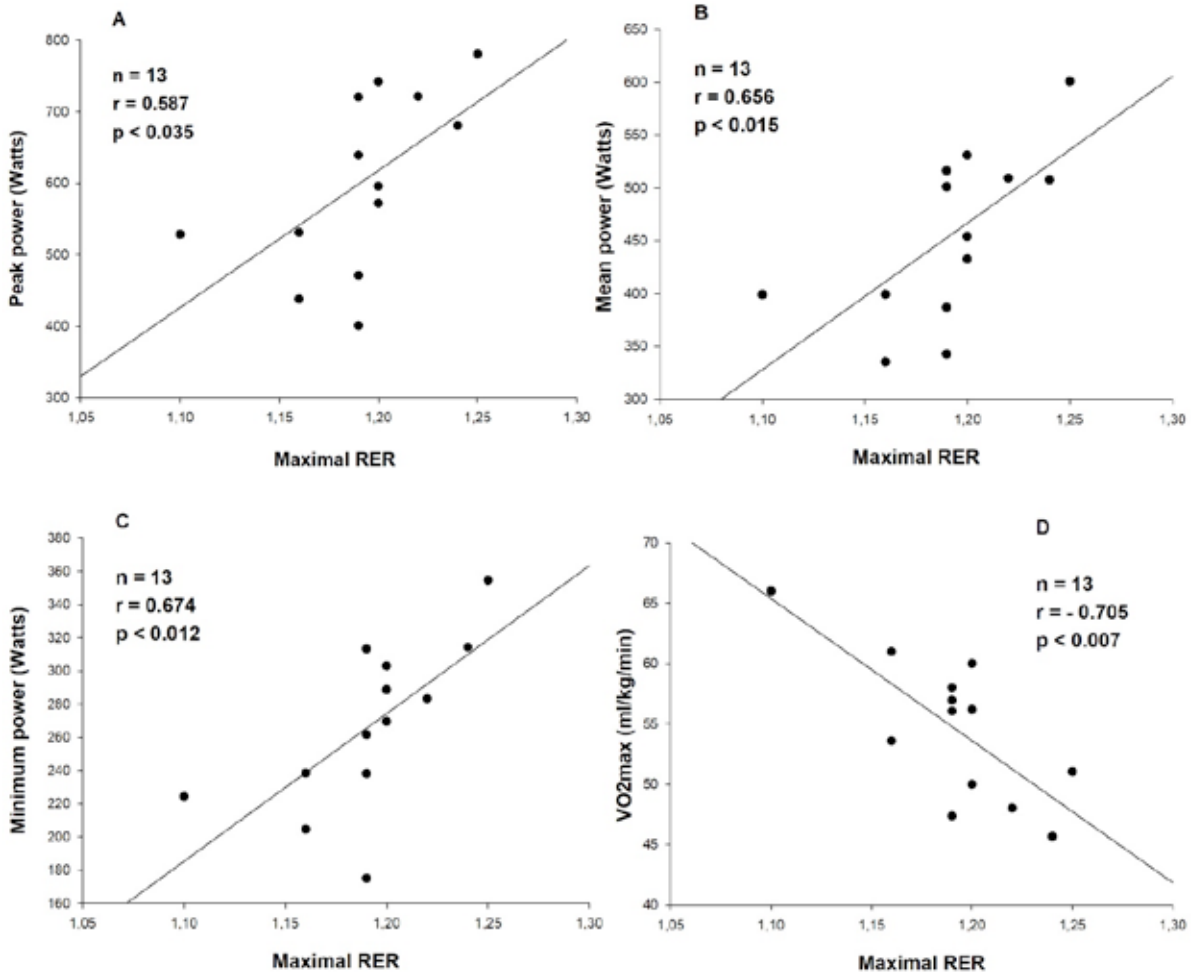

Figure 1. Correlation between A) peak power and maximal RER, B) mean power and maximal RER, C) minimum power and maximal RER, and D) VO_{2max} and maximal RER in all subjects.

anaerobic test [29, 30]. The Wingate anaerobic test, consisting of 30 seconds of maximum cycle exercise, is performed to determine the athletes' ability to maintain their maximal anaerobic power and high-power output [31]. It has been shown that 80% of the energy turnover during Wingate anaerobic test is derived from anaerobic metabolism dominated by glycolysis [33]. Maximal RER may be useful for determining the glycolytic capacity in anaerobic trained athletes. We did not directly measure blood lactate levels in our study. On the other hand, the maximal RER is likely to reflect the rate of lactic acid accumulation [12]. During high-intensity exercise at 70% of peak power output (80% VO_{2peak}), plasma lactate concentration has been shown to be the most important determinant of RER in trained cyclists [21]. The higher RER value may be explained by the higher demand of anaerobic glycolysis during the incremental exercise test and thus the higher lactic acid concentration. It has been shown that the subjects who achieved the best performance in the repeated sprint test were achieved higher lactate concentrations [22]. A close correlation has been found to be between the post-competition blood lactate concentration and the velocity maintained over 400-m and 800-m top-level competitions [23]. Besides the post-exercise blood lactate concentration [23], maximal RER values may also be used to evaluate the anaerobic capacity of athletes.

A RER value above 1.10 has been proposed as evidence of attainment of VO_{2max}, which is known as an indicator of aerobic capacity [17, 18]. In the current study, maximal RER was statistically negatively related to VO_{2max} and maximal running speed measured during the incremental exercise. Similar to our results, Ramos-Jiménez et al. showed that VO_{2max} was negatively correlated with RER measured during three different exercises at below, within, or above the lactate threshold [3]. A negative correlation between relative blood lactate change and VO_{2max} during incremental exercise has been reported [8]. RER response during maximal incremental exercise may be affected by different types of physical training [19]. In our study, the subject profile consists of alpine skiers. In alpine skiing, the physical capacity of the athlete is closely related to the ability to perform high-intensity exercise and develop high power output [30]. For this reason, the traditional training of alpine skiers includes anaerobic exercises such as plyometric training, speed, change of direction and resistance training [33]. During incremental exercise, anaerobic-trained athletes have been shown to have a greater lactate increase after the anaerobic threshold than endurance-trained athletes, despite having lower VO_{2max} [8]. In our previous study, we observed higher maximal RER values in alpine skiers compared to endurance athletes, despite a lower VO_{2max} and shorter running time to exhaustion during incremental exercise [34]. Higher RER values may mean that anaerobic-trained athletes utilized a greater proportion of anaerobic metabolism at higher intensity during exercise than aerobic-trained athletes. Anaerobic training increases intracellular and extracellular buffer capacity [35], which may contribute to a higher increase in RER values [36].

Maximal RER values may also be related to the genetic makeup of the athlete. Fast-twitch fiber-dominant muscle has a higher buffering capacity of H^+ than slow-twitch fiber-dominant muscle [37]. RER has been shown to be inversely related to the proportion of slow-twitch muscle fibers during exercise [38]. A high RER reflects a direct respiratory response to arterial acidosis as well as an indirect stimulation of chemosensitive fibers by local metabolic changes [16]. When the buffering systems are saturated, H^+ can no longer be compensated by the circulation, causing a drop in blood pH and, as a result, the accumulation of H^+ stimulates hyperventilation [8, 11]. A high muscle buffer capacity may allow anaerobic glycolysis to be longer utilization before the performance-limiting pH level is reached [37].

After the anaerobic training period, blood lactate concentrations may increase more than before the training period during exhaustive exercise due to increased muscle buffer capacity and glycolytic enzymes [39]. It has been shown that athletes who regularly perform anaerobic training have a greater muscle buffering capacity than endurance athletes or untrained subjects [8]. During anaerobic exercise training, large accumulation of lactic acid may improve buffer capacity [35, 39], providing a stimulus for the adaptation of muscle pH regulatory systems [31]. Reducing the inhibitory effects of H^+ in muscle cells by anaerobic training may lead to the improvement of the athlete's ability to perform high-intensity exercise for a longer period [31]. The magnitude of the RER increase at heavy exercise intensities is likely to depend on the rate of buffering [12]. After a period of anaerobic training, the H^+ release and buffering capacity of the muscles has been shown to be increases [40]. In our previous study, after a 6-week period of anaerobic training, maximal RER values during incremental exercise increased by 5.6 % compared to the pre-training period, which may be due to enhanced buffering capacity [36]. On the other hand, endurance training to improve aerobic capacity increases oxidative enzyme activity while decreasing RER values [41]. Presumably, the anaerobic training stimulus may increase glycolytic and buffering capacity as contributing factor to anaerobic capacity. Therefore, it is likely that RER during incremental exercise may increase in relation to anaerobic capacity in anaerobic-trained athletes.

Conclusions

The results of the present study indicated that higher maximal RER was associated with higher anaerobic power, while lower aerobic capacity in anaerobic-trained athletes. Maximal RER may be important for determining anaerobic capacity in anaerobic-trained athletes. Measuring the maximal RER values of athletes during incremental exercise may help evaluate their physiological characteristics and physiological adaptations in response to physical training. Further research is necessary to determine the relationship between anaerobic capacity and maximal RER and lactate concentration in athletes.

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Conflict of interest

Authors declare no conflict of interest.

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