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HOW ENDURANCE ATHLETES BREATHE DURING INCREMENTAL EXERCISE TO FATIGUE: INTERACTION OF TIDAL VOLUME AND FREQUENCY

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ABSTRACT

Carey, DG, Pliego GJ, Raymond RL. How Endurance Athletes Breathe During Incremental Exercise to Fatigue: Interaction of Tidal Volume and Frequency. *JEPonline* 2008;11(4):44-51. The purpose of this study was to evaluate the acute responses of tidal volume (TV), respiratory rate (RR) and ventilation (V_E) to incremental cycle ergometry (CE) and treadmill(TM) exercise in trained athletes. Triathletes (N=16, 10 male, 6 female) underwent VO_2 max testing on CE and TM. Breakpoints were analyzed with a macro designed to select breakpoints by the least squared error method, and slope significance assessed by linear regression ANOVA. V_E max was significantly greater for CE (157.5 ± 29.4 vs. 145.7 ± 27.5 l/min, CE vs. TM, respectively). The greater V_E for CE was the result of a greater RR for CE (51.7 ± 6.7 vs. 48.3 ± 5.7 breaths/min CE vs. TM, respectively). For both CE and TM testing V_E and RR were significantly correlated to VO_2 max. TVmax was unrelated to VO_2 max for both CE and TM. TV response patterns were highly variable, with 37.5% of subjects displaying either a plateau or downward deflection at breakpoint and 62.5% displaying either a linear or upward deflection at breakpoint. Chi square analysis indicated no difference in response pattern between CE and TM, and TV response was not related to VO_2 max. In subjects displaying a breakpoint or downward deflection in TV, RR increased exponentially to facilitate an increase in V_E . The ability to ventilate large volumes of air at maximal exercise is important in attaining high VO_2 max values. However, neither TVmax nor the TV pattern appears important in attaining high VO_2 max values.

Key words: Ventilation, VO_2 max, Respiratory Rate.

INTRODUCTION

As the metabolic requirement of exercise increases, the lungs must supply both the working skeletal muscles and the respiratory muscles with adequate oxygen to meet the demand. At the beginning of incremental exercise, ventilation (V_E) is stimulated primarily by mechanoreceptors (proprioceptors and muscle spindles) located in the exercising muscle that send signals to the respiratory centers of the brain to increase primarily the volume (tidal volume; TV) but also the rate (respiratory rate; RR) of breathing(1). This occurs prior to the production of metabolic waste products (decrease in pH, increase in CO_2 , H^+ ions). As intensity of exercise increases, non-metabolic CO_2 that is produced when respiratory exchange ratio (RER) exceeds 1.0 leads to an increase in H^+ ion production by the following formula:



H^+ ions contribute to a decrease in pH and interfere with the force of muscle contraction. The carotid bodies located at the bifurcation of the common carotid arteries serve to “taste the blood” for substances known to disturb acid-base balance (CO_2 , H^+ ions, etc.) and increase ventilation accordingly (respiratory buffering of metabolic acidosis). Those individuals who have had the carotid bodies resected have shown a blunted ventilatory response to CO_2 accumulation (2).

As intensity increases, the metabolic demand for oxygen increases linearly. However, prior to fatigue, ventilation increases exponentially to maintain alveolar oxygen ($P_{\text{A}}\text{O}_2$) and, therefore, arterial oxygen pressure ($P_{\text{a}}\text{O}_2$). Since ventilation is the product of tidal volume (TV) and respiratory rate (RR), the athlete may choose any combination of these 2 variables to increase ventilation. The general recommendation has been to choose a combination of TV and RR that seems natural to the athlete. However, there is some evidence that maintaining a higher TV and lower RR may result in both lower metabolic and respiratory demands for oxygen (3) thereby increasing efficiency and improving performance. Just as V_E increases exponentially during incremental exercise to exhaustion, the work of breathing increases exponentially, with the respiratory muscles requiring from 10-18% (4,5,6) of whole body oxygen consumption when VO_2max is reached. In addition to the O_2 requirements of ventilatory muscles, 14-16% of cardiac output is diverted away from exercising muscle to the respiratory muscles (7). In highly fit athletes, arterial hypoxemia has occurred (8), possibly due to high cardiac output and decreased transit time of red blood cells through the pulmonary vasculature. In addition to the high metabolic demands of the lungs, there is also evidence that the mechanical ability of the respiratory muscles to contract is reached (5) or exceeded (9). However, this has been refuted (4,10). It is contended that, like metabolic requirements, mechanical limitations of ventilatory muscles are reached only in highly fit athletes (11)

As exercise intensity increases, the athlete chooses some combination of TV and RR that supposedly maximizes breathing efficiency and minimizes respiratory muscle demand. Dempsey (11) has provided an excellent review of the mechanics and physiology of the respiratory system during exercise. He states “a carefully selected combination of increased frequency and tidal volume must be achieved, taking into account the need to minimize dead space ventilation (i.e., the increase in breathing frequency should not be excessive). At the same time, this combination protects against excessive increase in TV, which would require excessive generation of subatmospheric intrathoracic pressures and therefore a large amount of work by the inspiratory muscles...the result is, with few exceptions, a nearly perfect and highly efficient ventilatory response to exercise” (p. 255).

Most studies have reported a plateauing of TV prior to exhaustion (5,12-13). A plateau in TV occurs because the work of breathing at both high end-inspiratory volumes and low end-expiratory volumes

needed to increase TV is excessive and inefficient. Regardless of the dynamics of TV, RR at some point in incremental exercise increases exponentially, with many studies reporting that this exponential increase occurs at the anaerobic threshold and may serve as a marker for AT(14-16). While it seems important to be able to exchange high volumes of air (V_E) to maintain P_aO_2 and hemoglobin saturation, it has been reported that endurance athletes may have a lower ventilatory equivalent for CO_2 (V_E/V_{CO_2}) than non-athletes (17). It is hypothesized that this desensitization to CO_2 and its ability to increase V_E in athletes may be an adaptation to training and confers an advantage to the athlete in performance (17).

From the results of previous research, it would appear that, when tidal volume reaches a critical level, where further increases would result in an O_2 -inefficient breathing pattern, increases in V_E would be attained solely by increased RR. It is hypothesized that TV plateaus at this critical level and exponential increases in V_E are due to increases in RR. The primary objective of this study is to examine the interaction of TV and RR during incremental exercise to exhaustion in competitive triathletes. The pattern of response from incremental cycle ergometer and treadmill exercise will be compared.

METHODS

Subjects

Subjects (N=16, 10 male, 6 female) were recruited through an advertisement placed on a popular local website visited by triathletes. Participation in a minimum of 2 triathlons over the past year was criteria for inclusion. Training and racing histories were compiled for subjects for the previous 2 years. Subjects had competed in 10.3 ± 6.2 triathlons consisting of: sprint; 4.0 ± 1.7 ; Olympic, 1.9 ± 1.1 , half Ironman® distance; 1.4 ± 0.3 , and Ironman® distance; 3.0 ± 2.7 over the 2-year period. Training hours/week (13.2 ± 6.1) was divided between running (4.0 ± 1.4), cycling (5.1 ± 2.2), swimming (3.0 ± 2.1) and "other" (1.1 ± 0.6). Descriptive data as well as VO_{2max} testing results indicated subjects were 33.9 ± 6.4 years of age, weighed 76.3 ± 12.3 kg, had $14.1 \pm 5.4\%$ body fat, and had VO_{2max} values of 68.4 ± 11.1 ml/kg/min. Approval for this study was granted by the Institutional Review Board (IRB) of the University of St. Thomas prior to data collection. Subject read and signed consent forms prior to the initial test.

Procedures

Subjects reported to the lab on 3 separate occasions in the post-absorptive state without having trained the previous 24 hours. While the 3 occasions consisted of a cycle maximal oxygen consumption (VO_{2max}) test, treadmill VO_{2max} test, and a 30-minute time trial, only the results of the cycle and treadmill VO_{2max} test will be discussed here. Height (nearest cm.) and weight (nearest kg.) were measured using a Seca 220 scale (Seca Corporation, Hamburg, Germany). Height and weight were measured in shorts and socks immediately prior to VO_{2max} assessment. Percent fat was assessed by hydrostatic weighing using a load cell and digital indicator (Ohaus Corporation, Florham Park, NJ) immediately following their initial VO_{2max} test. Subjects were instructed not to ingest food 3 hours prior to the test and avoid strenuous exercise 24 hours previously.

The cycle ergometer (CE) test was performed on the Lode Excalibur Sport (Electramed Corporation, Netherlands). Subjects adjusted seat height and handlebar distance to their specifications prior to testing. The VO_{2max} test began at 25 watts and increased 25 watts per minute. In an effort to standardize the test, subjects were instructed to maintain a cadence of 90-100 rpm as long as possible. The test was terminated when cadence dropped below 50 rpm. Subjects attained a mean maximal wattage of 367.2 ± 59.8 watts, resulting in a mean duration of 14.7 ± 2.4 minutes. The treadmill™ VO_{2max} test was performed on a Quinton Q55xt and followed a modified Bruce protocol.

The Bruce protocol was modified to result in smaller increases of speed and grade every minute, as opposed to the standard Bruce protocol with larger increases in work output every 3 minutes. Heart rate was recorded every minute of the test and at exhaustion using a Polar Vantage XL Heart Rate Monitor (Polar Electro, Woodbury, New York). Gas analysis (V_E , TV, RR) was performed with the Medical Graphics VO2000 Metabolic Measurement System using 30-second averaging. A bi-directional differential pressure pneumotach assessed volume measurements, while a galvanic fuel cell and infrared analyzer determined O_2 and CO_2 , respectively. This system has been previously validated (18). VO_{2max} was taken as the highest VO_2 achieved during any 30-second increment. All subjects attained at least 2 of the following 3 criteria for attainment of VO_{2max} : 1) an increase of less than 200 ml O_2 /min over the final 2 stages of the test, 2) 95% or greater predicted maximal heart rate, 3) a maximal respiratory exchange ratio (RER) of 1.1 or greater.

Statistical Analyses

Linear regression analysis of variance was used to assess significance of slopes. Breakpoints in continuous variables were determined by a macro using the least squared errors method. Paired and independent Student *t*-tests were used to assess differences between groups. Chi square analysis assessed differences in ventilatory response patterns. Pearson correlation determined relationships between variables. Alpha was set at $P < .05$ for all analyses.

With sample size of 16, using a meaningful difference in means of 4 ml/kg/min, and estimating a standard deviation of 4 ml/kg/min for a homogeneous sample, power was determined to be 78.1. Power analysis was performed using Minitab.

RESULTS

Comparison between CE and TM

Table 1 gives maximal values for TV, RR, and V_E for both the cycle ergometer (CE) and treadmill (TM). No significant difference in TV max ($t=0.33$, $p=0.749$) was observed. However, V_E max was significantly greater on CE than TM ($t=2.73$, $p=0.016$). While RR max was not significantly greater for CE compared to TM, The higher V_E max for CE may be explained by a greater RR max in favor of CE (51.7±6.7 breaths/min) compared to TM (48.3±5.7 breaths/min, $t=2.06$, $p=0.057$). High V_E max values were significantly correlated to both TVmax ($r=0.795$, $p=0.000$) and RR max ($r=0.672$, $p=0.004$) for CE. For TM, high V_E max values were also significantly correlated to high TVmax ($r=0.747$, $p=0.001$) but not high RR max ($r=0.423$, $p=0.103$)

Table 1. Maximal respiratory values

<i>Variable</i>	<i>CE</i>	<i>TM</i>
<i>TV max(ml)</i>	3196±468	3179±505
<i>RR max</i>	51.7±6.7	48.3±5.7
<i>VE max</i>	157.5±29.4	145. ±27.5

Response patterns for TV

Table 2 lists the percentage of tests displaying various patterns of TV response from beginning of exercise to fatigue. A “plateau” implies that the slope of data points after the breakpoint in linearity was not significantly different ($p > .05$) from a zero slope. “Linearity” implies that all data points are best represented by a single straight line. “Upward deflection” indicates a significant positive slope ($p > .05$) of the data points after the breakpoint, while “downward deflection” implies a significant negative slope ($p < .05$) after the breakpoint. Chi square analysis shows no difference in expected and observed outcomes per cell ($X^2=4.267$, $p=0.234$), indicating no relationship between pattern of TV response and mode of VO_{2max} testing (CE vs. TM).

Table 2. Patterns of response for TV during incremental exercise

<i>Pattern</i>	<i>CE</i>	<i>TM</i>
Plateau	37.5% (n=6)	25.0% (n=4)
Linear	31.3% (n=5)	62.5% (n=10)
Upward deflection	18.8% (n=3)	12.5% (n=2)
Downward deflection	12.5 (n=2)	0.0% (n=0)

the total of 32 VO_{2max} tests, 12 (37.5%) displayed either a plateau or downward deflection, while 20 (62.5%) displayed either a linear or upward deflection pattern. The mean VO_{2max} (69.0 ± 11.2 ml/kg/min) for the “plateau/downward deflection” group was not significantly different from VO_{2max} (68.4 ± 12.8 ml/kg/min) of the “linear/upward deflection” group ($t=0.14$, $p=0.890$).

TV breakpoint compared to VE and RR breakpoints

For those tests in which either a plateau or downward deflection in TV occurred, this breakpoint in TV was compared to the V_E and RR breakpoints. This analysis will determine if the exponential increase in V_E begins precisely when both TV has reached a maximal value and RR increases exponentially. Table C gives the breakpoints for TV, V_E and RR as a percentage of V_{O_2} max. No significant difference was found for any pairwise comparison (TV vs. RR: $t=0.11$, $p=0.917$) (TV vs. V_E : $t=0.37$, $p=0.722$) (RR vs. V_E : $t=0.84$, $p=0.418$) (Table 3). Figure 1 displays the simultaneous increase in V_E and RR with the TV plateau.

Table 3. Breakpoints in TV, RR and VE as % VO_{2max} during incremental exercise

<i>Variable</i>	<i>Mean \pm SD</i>
TV	73.9 ± 14.2
RR	73.5 ± 6.8
VE	72.3 ± 8.3

Contribution of ventilatory parameters to VO_{2max}

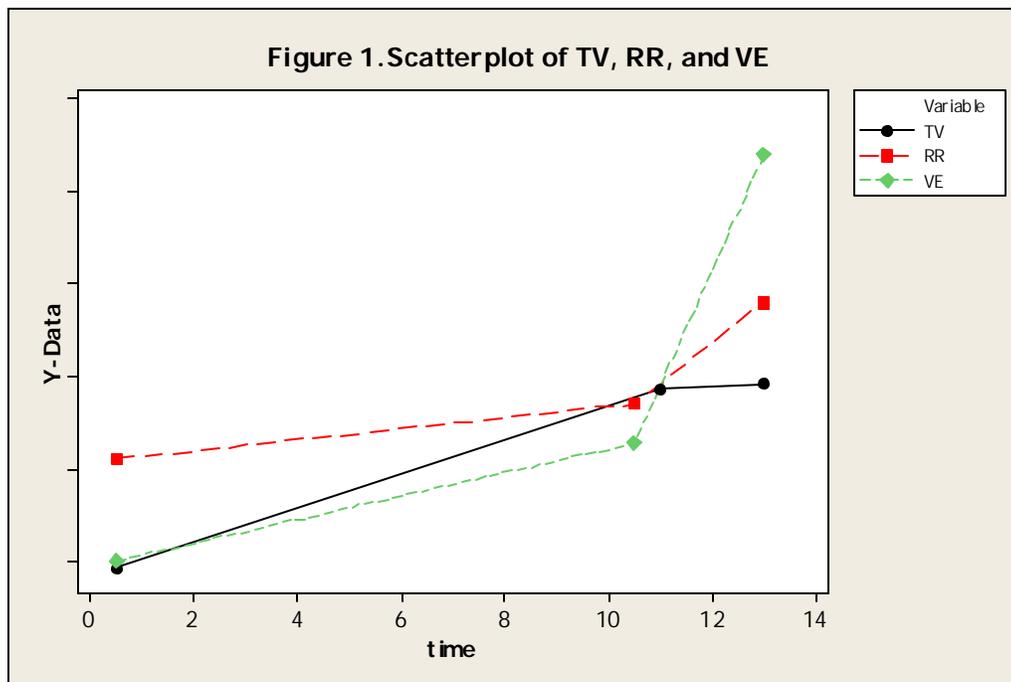
In an effort to determine if V_{Emax} , TV_{max} , and RR_{max} contribute to greater aerobic capacity, these variables were correlated to VO_{2max} . V_{Emax} was significantly related to VO_{2max} for both CE ($r=0.515$, $p=0.041$) and TM ($r=0.532$, $p=0.034$). RR_{max} also was significantly related to VO_{2max} for both CE ($r=0.605$, $p=0.013$) and TM ($r=0.611$, $p=0.012$). However, TV_{max} was not significantly related to VO_{2max} for either CE ($r=0.177$, $p=0.512$) or TM ($r=0.115$, $p=0.672$).

DISCUSSION

Comparison of maximal values between CE and TM

Greater V_E max values for CE compared to TM observed here is in agreement with results reported elsewhere (19,20). However, others have found no difference in maximal V_E for CE and TM (21,22). The discrepancy may be explained by both the level and type of training performed by the subjects. Our subjects and those of Schneider (20) and Dengel (19) were experienced triathletes, while subjects in the study by Hermansen (21) were described as “55 healthy male subjects”, which included the full range of training from competitive endurance athletes to “untrained students”. It is possible that local muscle pain and fatigue experienced on CE may cause a premature termination of exercise in non-athletes. Zhou et al. (22) reported a 13.3 l/min greater V_E for CE than TM in “recreational triathletes” (169.8 ± 10.4 vs. 156.5 ± 6.4), but this difference was not significant ($p > .05$).

In an effort to determine if pattern of response affected VO_{2max} , those subjects who displayed a pattern in which TV continually increased during the test (linear and upward deflection) were compared to subjects who displayed either no increase or actual decrease in TV following the breakpoint (plateau and downward deflection). It might be hypothesized that the former patterns may convey an advantage in achieving high VO_{2max} values. Of

Figure 1. Relationship between TV, RR, and VE breakpoints

A higher V_E max for CE than TM may be a result of greater afferent input from a smaller muscle mass to maintain a given level of O_2 consumption. Indeed, in this study the ventilatory equivalent for O_2 (V_E/VO_2) for CE was 30.9 ± 4.2 compared to 28.4 ± 3.9 ($t=1.74$, $p=0.092$) for TM, supporting the concept that the smaller muscle mass used in CE compared to TM requires a higher V_E to maintain a given O_2 consumption.

Our non-significant difference in RRmax for CE compared to TM is contrary to the results of others, who have found significantly higher RRmax for CE (20). While not significant ($p>0.05$), the mean difference of 3.4 breaths/min (51.7 ± 6.7 vs. 48.3 ± 5.7) probably contributed to a significantly greater V_E for CE than TM. The difference may possibly be explained by the concept of entrainment, in which the rhythm of exercise affects breathing pattern (23). The relatively high rpm's (90-100 rpm) for CE maintained in this study may have resulted in a greater RR and hyperventilation. Our finding of no difference in TVmax is supported by the results of others (20).

Response patterns for TV

Our finding of a continued increase in TV from beginning of exercise to fatigue in 62.5% of our tests is contrary to results reported elsewhere, in which a plateau in TV is reached (5,12). It has been theorized that the athlete will continue to increase TV until a critical volume is reached, above which the mechanical work of breathing and the O_2 cost of ventilation becomes excessive and inefficient. At this point, further increases in V_E would be attained only by an increase in RR, with TV plateauing. We observed this pattern in only 6 subjects (37.5%) for CE and 4 subjects (25%) for TM, leading us to conclude that breathing pattern and interaction of RR and TV are highly variable between endurance athletes.

Our finding of no relationship between VO_{2max} values in subjects who plateaued or exhibited a downward deflection in TV (69.6 ± 11.5 ml/kg/min) and VO_{2max} in subjects who exhibited a linear or upward deflection in TV (67.4 ± 10.3 ml/kg/min) would indicate that TV pattern is inconsequential in attainment of VO_{2max} . These results are somewhat conflicting with "the carefully selected combination of increased frequency and tidal volume" that produces "a nearly perfect and highly efficient ventilatory response to exercise" described by Dempsey (11). If this is indeed an accurate description of ventilation during exercise, (1) why is the TV response so variable among subjects? Why is there no relationship between TV response and VO_{2max} if one pattern is efficient and minimizes respiratory work, while the others must not? Further research is needed to clarify the role of TV and RR in producing an optimal V_E response to incremental exercise.

Finally, in those subjects exhibiting a plateau or downward deflection in TV, this breakpoint occurred identical to the RR and V_E breakpoint. Others (25) have also reported the simultaneous occurrence of the TV plateau and anaerobic threshold. We are not, however, proposing that this breakpoint may serve as a marker of the anaerobic threshold primarily because this breathing pattern occurred in a relatively small percent of our subjects (37.5%). Further research is needed to both identify TV patterns and explain the variability in such patterns, although it appears that this variability does not affect VO_{2max} .

Contribution of ventilatory parameters to VO_{2max}

The finding of a significant relationship between VO_{2max} and V_E max even in this homogeneous group of athletes would indicate that the ability to ventilate large volumes of air is a pre-requisite to attainment of high VO_{2max} values. High V_E becomes a necessity because of the widening of the alveolar-arterial oxygen difference, thus creating a greater demand for alveolar ventilation to maintain arterial O_2 pressure and saturation (11). In fact, oxygen demands of exercising muscle may exceed the ability of the lungs to maintain arterial O_2 pressure, resulting in hemoglobin desaturation (24). We have found that this high V_E is attained either by an exponential increase in RR only (37.5%) or by a combination of an exponential increase in RR and linear increase in TV (62.5%).

CONCLUSIONS

From the results of this study, several conclusions are warranted. First, neither the TV pattern nor the maximal value for TV were related to VO_{2max} , indicating that the pattern and volume of TV is inconsequential in attainment of VO_{2max} . Second, when TV plateaus during incremental exercise, this plateau seems to coincide with both the V_E and RR breakpoints. However, this plateau was observed in only 6 subjects (37.5%) for CE and 4 subjects (25.0%) for TM. Third, the higher V_E max attained in CE compared to TM is due primarily to a greater RR max. Fourth, a high correlation between V_E max and RR max compared to VO_{2max} would indicate that these two ventilatory parameters are related to, and may be pre-requisites to high VO_{2max} values.

Our original hypotheses that a critical TV would be reached, after which further increases in V_E are attained solely by increases in RR, is not supported by these results. During incremental exercise to fatigue, individuals should adopt a natural breathing pattern. However, this may or may not apply to submaximal prolonged exercise performed by endurance athletes.

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