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A COMPARISON OF METHODS TO DETERMINE VENTILATORY EFFICIENCY IN ATHLETES

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Abstract

Introduction: Human ventilatory efficiency is quantified during exercise using the slope of the linear relationship between minute ventilation ($\dot{V}E$) and carbon dioxide output ($\dot{V}CO_2$), and the oxygen uptake efficiency slope (OUES). However, limited data compare the ventilatory efficiency of trained subjects using different exercise modalities.

Methods: In endurance trained males (*n* = 12, age range 18-25 years), ventilatory efficiency and OUES were quantified during incremental exercise up to maximal oxygen uptake ($\dot{V}O_2$max) on (1) a rowing ergometer; (2) a treadmill; (3) a cycle ergometer. Data were compared using a one-way analysis of variance, and where appropriate, a post-hoc *t*-test.

Results: Mean (SD) ventilatory efficiency was 28.41 (3.88), 27.59 (5.09), and 26.72 (6.51), and mean (SD) OUES was 4.96 (0.99), 4.31 (0.94), and 5.39 (1.01) for the rowing ergometer, treadmill, and cycle ergometer, respectively. Mean (SD) $\dot{V}O_2$max was 57.76 (6.39), 55.60 (6.44), and 62.88 (9.06) ml Kg^{-1} min^{-1} for the rowing ergometer, treadmill, and cycle ergometer, respectively. A higher $\dot{V}O_2$max and OUES ($P < 0.03$) were measured during cycle ergometry compared to other modalities.

Conclusions: In endurance trained males, measures of ventilatory efficiency appear to be independent of exercise modality, although $\dot{V}O_2$max and OUES may be higher if cycle ergometry is used.

Key words: *ventilatory efficiency, oxygen uptake efficiency slope, ergometers,* $\dot{V}O_2$*max*

Introduction

The slope of the linear relation between carbon dioxide production ($\dot{V}CO_2$) and minute ventilation ($\dot{V}E$), when measured during incremental exercise, quantifies ventilatory efficiency [1]. Typical values for adults range from 19 – 30 [2, 3] and a steeper slope (e.g. $\geq$ 34) suggests ventilatory inefficiency consistent with certain cardio-respiratory disorders [4-6]. Oxygen uptake ($\dot{V}O_2$) may also be expressed as a function of $\dot{V}E$, and this relationship is modelled by: $\dot{V}O_2 = a \, Log_{10} \dot{V}E + b$, where 'a' represents the oxygen uptake efficiency slope (OUES) [7-9]. Adult values range from 3 – 5 where higher values indicate an increased oxygen uptake efficiency. These slopes quantify tolerance to physical exertion in both healthy subjects and patient cohorts with reduced aerobic exercise capacity [10], and can be used to quantify responses to training [11-14].

The physiological systems which support the ability to perform physical work are typically scrutinised during whole body exercise of increasing intensity [15]. Ventilatory efficiency and the OUES are commonly measured using standardised treadmill protocols and/or stationary ergometers; however, limited data report any differences in slope calculation when different ergometers are used. Therefore, the aim of this study was to determine if there were differences in ventilatory efficiency and the OUES of trained athletes when measured using 3 different exercise modalities. It was hypothesised that each type of exercise would evoke similar $\dot{V}O_2$max, and demonstrate similar measures of efficiency.

Methods

With institution ethical approval, trained endurance athletes, ($n = 12$) performed three incremental cardiopulmonary exercise tests to volitional exhaustion, on three different days at least 1 week apart. Tests were performed on a stationary cycle ergometer, a stationary rowing ergometer, and a motorised stationary treadmill. Subjects were all male, endurance trained athletes, age range 18-25 years, all of whom had >3 years history of endurance training. Subject were recruited at local competitions (National and Club events) and all were either triathletes or multi-sport competitors. Each subject was medically screened for conditions which may adversely affect their response to maximal exercise, and were excluded if this was not satisfactory.

On each occasion and on the selected ergometer, each subject performed an initial 10 minute warm-up at a self -selected exercise intensity during which they were instrumented with the expired gas collection mouthpiece and heart rate monitor. Subjects then exercised at an increasing intensity until test termination, and for all tests, duration was between 10 and 15 min with the starting intensity at a level which increased heart rate to approximately 140 beats per min (determined during initial familiarisation trials). On the treadmill, gradient was increased by 1% and speed by 1 km hr^{-1} each minute, on the cycle ergometer, cadence was maintained between 80 and 100 rpm and power was increased at 20 Watts min^{-1}; and on the rowing ergometer, power was increased by 20 Watts min^{-1} using a combination of increasing both stroke rate and resistance.

On each ergometer, subjects performed a continuous incremental test to volitional exhaustion. Heart rate was continuously monitored (S610, Polar Electro, Finland), and throughout the test, exhaled air was collected and analysed for oxygen and carbon dioxide content using an on-line gas analyser (AD Instruments, Australia). Subjects breathed through a mouthpiece connected to a pneumotach (MLT1000L Respiratory Flow Head, AD Instruments, Australia) – the mouthpiece and pneumotach added approximately 100 ml to the total ventilatory dead space of each subject. The fractional content of O_2 and CO_2 in the air flowing through the pneumotach was dried (MLA6024 AD Instruments, Australia) and continuously sampled (response time approximately 100ms) throughout inhalation and exhalation using the gas analyser (ML206 AD Instruments, Australia). The O_2 transducer used absorption spectroscopy at λ760nm and the CO_2 transducer used an infrared sensor. The analyzer was calibrated with samples of known O_2 and CO_2 gas mixtures prior to testing each subject. The length of the sampling lines from the pneumotach to analyzer were minimized to reduce the signal offset – in subsequent data analyses the chart recorder O_2 and CO_2 data streams were time shifted such that the initial changes from typical room air coincided with the start of exhalation, as defined by a continuous positive deflection in ventilatory flow.

Ventilatory flow was integrated to determine volume, and this signal was calibrated using a 3L calibration syringe (Hans Rudolph, USA). Before each test, the pneumotach signal was reset to zero when disconnected from the subject. Values for tidal volume (VT) and breathing frequency (Bf) were used to determine minute ventilation ($\dot{V}E$) in L min^{-1} ATPS. Values of $\dot{V}E$ were converted to L min^{-1} BTPS using appropriate formulae. The mixed expired fractional content of O_2 and CO_2 (%FO_2 and %FCO_2 respectively) and the expired end-tidal fractional content of O_2 and CO_2 (%$F_{ET}O_2$ and %$F_{ET}CO_2$ respectively) were recorded. Oxygen uptake ($\dot{V}O_2$) and carbon dioxide output ($\dot{V}CO_2$) were calculated from $\dot{V}E$ STPD x FO_2 or FCO_2 respectively. An estimate of physiological dead space (VD) was obtained using VD = VT (1-FCO_2/ $F_{ET}CO_2$), and this was used to calculate the VD/VT ratio. Ventilatory equivalents for CO_2 and O_2 are reported as the quotients of $\dot{V}E : \dot{V}CO_2$ and $\dot{V}E : \dot{V}O_2$ respectively, where $\dot{V}E$ is in L min^{-1} BTPS and both $\dot{V}CO_2$ and $\dot{V}O_2$ are in L min^{-1} STPD.

Tests were terminated when the subject could no longer continue (volitional fatigue), and had reached a plateau in their heart rate response to the exercise. At test termination, the maximum heart rate of all subjects was within 10% of their age predicted maximum (220 – age), and analysis of the exhaled gases indicated that all subjects achieved a respiratory exchange ratio of >1.1.

Statistical analysis

For all tests, $\dot{V}E$ was plotted as a function of $\dot{V}CO_2$ and modelled with linear regression, where $\dot{V}E = a \dot{V}CO_2 + b$. The slope constant of this regression line was used as the measure of ventilatory efficiency. For all subjects, $\dot{V}O_2$ was plotted as a function of $\dot{V}E$ and modelled by a logarithmic function, where: $\dot{V}O_2 = a \operatorname{Log}_{10} \dot{V}E + b$. The slope constant of this regression line was used as the measure of oxygen uptake efficiency (OUES). Data for each ergometer (rowing, cycle, and treadmill) were compared using a one-way analysis of variance, and if $P < 0.05$, data were compared with a post-hoc paired samples *t*-test.

Results

All subjects completed the exercise test and summary statistics are shown in table 1.

In all tests, the linear associations between $\dot{V}E$ and $\dot{V}CO_2$, and between $\log_{10}\dot{V}E$ and $\dot{V}O_2$ were quantified using linear regression. For all tests, the coefficient of determination was consistently >0.85, and there was no indication of a closer linear fit between variables for any of the ergometers.

Representative examples of the ventilatory response to exercise are shown in Figure one. In this figure, the

Table 1. *Summary statistics [mean (SD)] for ventilatory efficiency ($\dot{V}E$ vs. $\dot{V}CO_2$), oxygen uptake efficiency slope (OUES), and maximum oxygen uptake ($\dot{V}O_2max$), in 12 trained endurance athletes. * denotes significantly higher than rowing and treadmill values, (P<0.03, post-hoc paired sample t-test following one-way ANOVA).*

	$\dot{V}E$ vs. $\dot{V}CO_2$	OUES	$\dot{V}O_2max$ (ml·Kg^{-1}·min^{-1})
Rowing	28.41	4.96	57.76
	(3.88)	(0.99)	(6.39)
Treadmill	27.59	4.31	55.60
	(5.09)	(0.94)	(6.44)
Cycle	26.72	5.39*	62.88*
	(6.51)	(1.01)	(9.06)

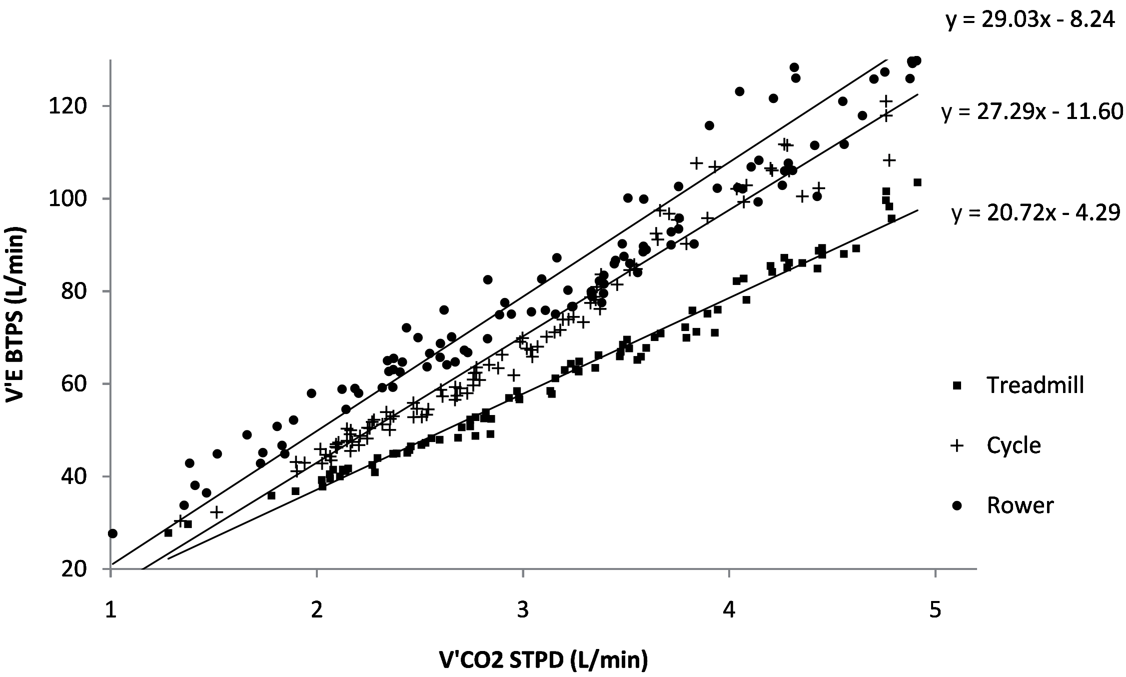

Fig. 1. *Representative example of the relationship between minute ventilation ($\dot{V}E$) and carbon dioxide output ($\dot{V}CO_2$) in an endurance trained athlete, when an incremental test to $\dot{V}O_2max$ was performed on three separate occasions using a treadmill, cycle ergometer, and rowing ergometer. Coefficients of the regression lines quantify the ventilatory efficiency.*

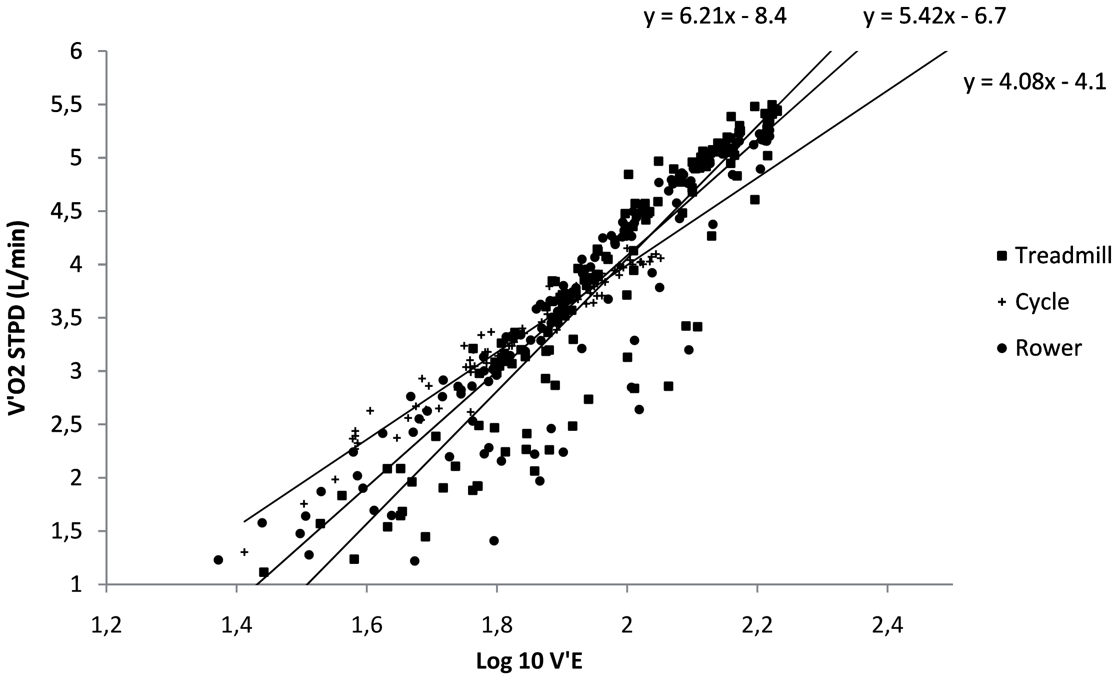

Fig. 2. *Representative examples of the relationship between Log10 minute ventilation ($\dot{V}E$) and the oxygen uptake ($\dot{V}O_2$) in an endurance athlete, when an incremental test to $\dot{V}O_2max$ was performed on three separate occasions using a treadmill, cycle ergometer, and rowing ergometer. Coefficients of the linear regression equations quantify the oxygen uptake efficiency slope.*

relationship between $\dot{V}E$ and $\dot{V}CO_2$ is shown for three exercise modalities and the regression equation coefficients are 29.03, 27.29, and 20.72 for the rowing ergometer, cycle ergometer, and treadmill respectively. These data suggest that the athlete was most efficient (lowest coefficient) using the treadmill compared to the other modalities, however, this did not translate into a higher maximal oxygen uptake for this individual on the treadmill.

Figure two shows the relationship between the Log_{10} $\dot{V}E$ and the $\dot{V}O_2$ for an individual athlete using three different exercise modalities, on three separate occasions. The regression coefficients are 6.21, 5.42, and 4.08 for the treadmill, cycle ergometer, and rowing ergometer respectively. These data suggest that the athlete was most efficient on the treadmill (higher coefficient) when compared to the other modalities, although this did not translate into a higher maximum oxygen uptake recorded using the treadmill.

Discussion

The main findings of this study were: firstly, that for the group, the slope of the linear relationship between $\dot{V}E$ and $\dot{V}CO_2$ was not different when different ergometers were used; and secondly, that for the group, the OUES and $\dot{V}O_2max$ were higher when tests were performed on a cycle ergometer compared to either a treadmill or rowing ergometer. Data presented in this study are novel and help to progress our understanding of human exercise and sport science. The choice of testing protocol for determination of measures of efficiency is of interest to coaches who train and test multi-sport athletes, and the data further suggest that ventilatory efficiency slope is robust and more consistent than the oxygen uptake efficiency slope. Again, for coaches and multi-sport athletes, these data suggest that the exercise type chosen for a test may yield different results for certain aspects of cardiopulmonary efficiency (e.g. OUES), but not for others (e.g. ventilatory efficiency). Coaches who design training and testing regimens for multi-sport athletes may thus need to incorporate protocols which use a variety of exercise types in order to quantify any translation of physiological improvement between modalities.

Novel data from this study suggest that although measures of $\dot{V}O_2max$ may be different when measured using a particular ergometer, ventilatory efficiency when determined by the slope of $\dot{V}CO_2$ vs. $\dot{V}E$ remain the same. There are numerous reports comparing treadmill and cycling protocols for the determination of $\dot{V}O_2max$ [15, 16], and the importance using a large muscle mass and maintaining motivation during testing is well documented. It is possible that the athletes recruited into this study favoured the cycle ergometer as a protocol to estimate $\dot{V}O_2max$, and experienced localised fatigue in both the treadmill and rowing protocols (potentially affecting motivation). However, this was unlikely to affect their efficiency as it has been shown that $\dot{V}O_2max$ and measures of efficiency do not correlate [17].

For each athlete, the 3 protocols used in this study were of similar duration, and all were between 10 and 15 min total duration. Recommendations regarding cardiopulmonary testing [18-20] suggest that the optimal duration is approximately 12 min, although both longer and shorter durations may also yield a reproducible $\dot{V}O_2max$ in athletes [21, 22]. The incremental tests used in this study may have limitations, and endurance athletes may prefer longer duration protocols. However, currently there remains a paucity of data concerning the role of test duration on the reproducibility of measures of efficiency, and this remains an area of potential future research. During protocols used to determine the blood lactate threshold in cyclists [3], it was shown that the ventilatory equivalent for $\dot{V}CO_2$ was minimal at or near the anaerobic threshold, but it remains unknown if the slopes of interest in the present study would be different if the starting point of the incremental test was at the anaerobic threshold (i.e. at a point when the lung appears to be most efficient).

The two linear models used to define cardiorespiratory system efficiency consistently yielded high correlation coefficients, clearly indicating the close association between $\dot{V}CO_2$ and $\dot{V}E$, and between $\log_{10}\dot{V}E$ and $\dot{V}O_2$. In the current study, the slope of each relation was determined using all data collected throughout the tests, up to $\dot{V}O_2max$. The OUES may become more reliable when calculated from data obtained from higher levels of exercise intensity [23] however the OUES differs little when calculated only from data up to 75% of a maximal test [7, 24]. Marginally higher $\dot{V}E$ vs. $\dot{V}CO_2$ slope values were reported in patients [3, 25] and athletes when all data up to $\dot{V}O_2max$ were included in the calculation.

The $\dot{V}E$ vs. $\dot{V}CO_2$ slope, when evaluated using data only up to the ventilatory threshold, is consistently linear. Alternatively, all data up to peak exercise capacity ($\dot{V}O_2max$) could be used which may include any exercise-induced hyperventilation. The suggested reason for not using data points beyond the ventilatory threshold is that there could be an acidosis-induced non-linearity in the $\dot{V}E$ vs. $\dot{V}CO_2$ slope such that ventilation may increase disproportionately with respect to arterial PCO_2 (which may not change). This would potentially record a higher slope, particularly if there was increased sensitivity to H^+, increased dead space – to – tidal volume ratio, and/or mismatching of ventilation and perfusion. It has been demonstrated that using all data (up to $\dot{V}O_2PEAK$) has potent prognostic capability in clinical cohorts [5, 26] and thus has been recommended for inclusion in clinical guidelines. However, for athletes, it remains questionable whether there is any benefit in excluding data for the $\dot{V}E$ vs. $\dot{V}CO_2$ slope above the ventilatory threshold as during both training and competition, endurance athletes may often exercise above their ventilatory threshold. Indeed, maintaining efficiency above the ventilatory threshold may be more important than efficiency below the ventilatory threshold. This requires further investigation and poses the interesting physiological question – "does the ventilatory response which accompanies high $\dot{V}CO_2$ at high exercise intensities, limit the exercise duration at these intensities?" Also, it remains unknown if ventilatory efficiency above threshold is responsive to training, or affected by ergogenic buffering agents (e.g. bicarbonate) – again, these are areas which require further investigation.

The data presented in this study also poses another interesting physiological question – "why should an oxygen uptake efficiency slope, which measures a system response to a metabolic disturbance, be different if the source of the disturbance is different?" This requires further investigation, but may have origins in motor unit recruitment and whole muscle selection during different exercise modalities. An avenue of further study would be to compare measures of efficiency during upper versus lower limb exercise protocols, and/or incremental protocols using one-legged versus two-legged cycling protocols. These further investigations may highlight the role of muscle mass in determining measures of human cardio-respiratory efficiency.

The OUES and the $\dot{V}E$ vs. $\dot{V}CO_2$ slope have different origins. The $\dot{V}E$ vs. $\dot{V}CO_2$ slope is an indicator of the efficiency of removal of CO_2 by the lung [27], whereas it has been suggested [7] that the OUES is an indicator of delivery, extraction, and O_2 use by the active tissue. A decline in pulmonary perfusion [28] and a mismatching of pulmonary ventilation to perfusion [29] contribute to a steeper $\dot{V}E$ vs. $\dot{V}CO_2$ slope. In contrast, it has been suggested that the OUES incorporates, in a single index, cardiovascular and peripheral factors that determine $\dot{V}O_2$ as well as pulmonary factors that influence the ventilatory response to exercise. Baba et al [7] suggested that the OUES was affected by both metabolic acidosis and by physiologic dead space, and was a variable that indicated the status of both systemic and pulmonary perfusion. It was further suggested that this accounted for the good correlation between the OUES and $\dot{V}O_2$max [7]. The distinction between the two slopes is that OUES is only affected by abnormalities that increase ventilation during exercise by a greater proportion than at rest, or in other words, increases in $\dot{V}E$ by a constant proportion, either at rest or during exercise, will not directly affect the OUES.

Endurance athletes usually have a high $\dot{V}O_2$max and typically have the ability to exercise at a high proportion of their $\dot{V}O_2$max. However, system efficiency may have little or no relevance at $\dot{V}O_2$max as the duration an athlete can perform exercise at $\dot{V}O_2$max is very short. This may suggest that although measures of system efficiency are adequate in quantifying the cardio-respiratory response to exercise in clinical populations and healthy untrained subjects, they may have little efficacy in quantifying the performance of physiological systems in endurance trained athletes.

The cardiopulmonary exercise test is now routinely used to measure both ventilatory efficiency and the oxygen uptake efficiency slope in cardiac patients [5, 9], and both have shown to be responsive to appropriate exercise regimens that are used in cardiac rehabilitation. Co-morbidities which limit lower limb exercise due to pain on exertion (for example, intermittent claudication) will preclude certain clinical populations from the tests used in the current study. Therefore, there is a need to quantify measures of cardiorespiratory efficiency using both the ventilatory efficiency and the OUES using alternative exercise protocols, for example arm ergometery.

In conclusion, this study uniquely reports that in endurance athletes, measures of ventilatory efficiency are not dependent on the type of ergometer used. However, the OUES and $\dot{V}O_2$max may be higher when measured during an exercise test on a cycle ergometer compared to either a rowing ergometer or treadmill protocol of similar duration. Some avenues of further research are suggested, including investigating the potential role of active muscle mass in determining the ventilatory responses to exercise, and the potential need for efficiency at higher exercise intensities.

Declaration of interest

The authors report no conflicts of interest.

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Authors' contribution
A – Study Design
B – Data Collection
C – Statistical Analysis
D – Data Interpretation
E – Manuscript Preparation
F – Literature Search
G – Funds Collection