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Influence of pedal cadence on the respiratory compensation point and its relation to critical power

R.M. Broxterman[a,b,*], C.J. Ade[d], T. Barker[c], T.J. Barstow[a]

[a] Department of Kinesiology, Kansas State University, Manhattan, KS, USA
[b] Department of Anatomy and Physiology, Kansas State University, Manhattan, KS, USA
[c] Orthopedic Specialty Hospital, Murray, UT, USA
[d] Department of Health and Exercise Science, University of Oklahoma, Norman, OK, USA

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ABSTRACT

It is not known if the respiratory compensation point (RCP) is a distinct work rate (Watts (W)) or metabolic rate ($\dot{V}_{O_2}$) and if the RCP is mechanistically related to critical power (CP). To examine these relationships, 10 collegiate men athletes performed cycling incremental and constant-power tests at 60 and 100 rpm to determine RCP and CP. RCP work rate was significantly ($p \leq 0.05$) lower for 100 than 60 rpm (197 ± 24 W vs. 222 ± 24 W), while RCP $\dot{V}_{O_2}$ was not significantly different (3.00 ± 0.33 l min^{-1} vs. 3.12 ± 0.41 l min^{-1}). CP at 60 rpm (214 ± 51 W; $\dot{V}_{O_2}$: 3.01 ± 0.69 l min^{-1}) and 100 rpm (196 ± 46 W; $\dot{V}_{O_2}$: 2.95 ± 0.54 l min^{-1}) were not significantly different from RCP. However, RCP and CP were not significantly correlated. These findings demonstrate that RCP represents a distinct metabolic rate, which can be achieved at different power outputs, but that RCP and CP are not equivalent parameters and should not, therefore, be used synonymously.

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1. Introduction

An incremental exercise protocol allows for the determination of the gas exchange threshold (GET) and respiratory compensation point (RCP) in healthy and patient populations (Beaver et al., 1986; Bergstrom et al., 2013; Dekerle et al., 2003; Green et al., 2003; Oshima et al., 1997; Tanehata et al., 1999; Tokmakova et al., 2007; Whipp and Ward, 2009; Whipp et al., 1986). The GET is a noninvasive estimate of the lactate threshold and is the point at which CO_2 production ($\dot{V}_{CO_2}$) increases disproportionately to oxygen uptake ($\dot{V}_{O_2}$) along with an increase in minute ventilation ($\dot{V}_E$) relative to $\dot{V}_{O_2}$, while $\dot{V}_E/\dot{V}_{CO_2}$ remains constant (Beaver et al., 1986; Whipp et al., 1986). RCP is distinguished by an increase in $\dot{V}_E/\dot{V}_{CO_2}$ and a concomitant decrease in both arterial P_{CO2} (Pa_{CO2}) and the end-tidal P_{CO2} (PET_{CO2}) (Rausch et al., 1991; Whipp, 1994; Whipp et al., 1989), reflecting frank hyperventilation. Critical power (CP) is another important parameter for assessing activity tolerance, as CP is the highest rate of O_2 utilization matched by O_2 delivery (Broxterman et al., 2014b; Dekerle et al., 2012; Monod and Scherrer, 1965; Moritani et al., 1981; Vanhatalo et al., 2010) and as such, distinguishes the highest intensity for which a physiological steady-state may be achieved (Broxterman et al., 2013; Jones et al., 2008; Poole et al., 1988; Vanhatalo et al., 2010).

The GET and CP are distinct metabolic rates (i.e., $\dot{V}_{O_2}$) that are independent of the external work rate. Barker et al. (2006) utilized cycling pedal cadences of 60 and 100 rpm to alter the work rates associated with the GET and CP and demonstrated that the work rates associated with the GET and CP were lower for 100 rpm than 60 rpm. Importantly, the $\dot{V}_{O_2}$ associated with each parameter were not altered by the change in pedal cadence. Thus, the metabolic rate associated with each parameter appears to be robust and a more appropriate way to quantify the GET and CP. It currently is not known if RCP is similar in this regard and is itself a distinct metabolic rate that is independent of work rate. The results of Scheuermann and Kowalchuk (1998) suggest that this is the case, as the work rate associated with RCP was altered by the incremental protocol ramp rate and the $\dot{V}_{O_2}$ associated with RCP appeared to remain constant. Importantly, however, in that study the RCP was not able to be determined in five of the seven subjects during the fast ramp protocol. The authors therefore estimated the fast ramp

* Corresponding author at: Department of Kinesiology, Kansas State University, Manhattan, KS 66506, USA. Tel.: +1 785 532 5114; fax: +1 785 532 6486.
E-mail address: rbrox@ksu.edu (R.M. Broxterman).

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RCP using the $\dot{V}_{O_2}$ associated with RCP during the slow ramp. Thus, the $\dot{V}_{O_2}$ values for RCP between the two protocols were "forced" to be equivalent, and therefore it is unclear if the $\dot{V}_{O_2}$ associated with RCP is indeed robust.

It has previously been postulated that RCP and CP are equivalent and that RCP demarcates the intensity above which a physiological steady-state may not be achieved (Bergstrom et al., 2013; Pessoa Filho et al., 2012). RCP and CP have often been reported to occur at similar intensities (Bergstrom et al., 2013; Broxterman et al., 2014a; Dekerle et al., 2003). However, as Cross and Sabapathy (2012) pointed out, the work rate associated with RCP is dependent upon the exercise protocol and therefore identifying RCP as a discrete work rate is not appropriate. Highlighting these issues, Broxterman et al. (2014a) demonstrated that the similar work rates associated with RCP and CP appear to be a spurious affect, as there is an appreciable degree of variability between the two parameters. This variability between RCP and CP is not to be unexpected, as RCP is a ventilatory response resulting from the influence of multiple stimuli on ventilation (Forster et al., 2012; Whipp, 1981) and CP is the highest rate of O_2 utilization matched by O_2 delivery within the active skeletal muscle (Broxterman et al., 2014b; Dekerle et al., 2012; Vanhatalo et al., 2010), with no mechanistic link yet established between the two parameters. To date, no intervention has been utilized to manipulate RCP and CP in order to assess a mechanistic link between the two parameters.

Therefore, the aim of the present study was to utilize 60 and 100 rpm cycling pedal cadences to assess the work rates and metabolic rates associated with RCP and the relationship between RCP and CP. We hypothesized that (1) the work rate associated with RCP would be significantly lower for 100 rpm than 60 rpm, while the metabolic rate associated with RCP would not significantly differ across pedal cadences, and (2) CP and RCP would occur at similar work rates and metabolic rates on average, but CP and RCP would not be significantly correlated. Division I collegiate level cross-country and 100 m runners were utilized for this study due to the expected contrasting muscle fiber types between these two athlete groups enabling the hypotheses to be tested over a wide range of $\dot{V}_{O_{2peak}}$, CP, and RCP values.

2. Methods

2.1. Experimental overview

The data from 10 healthy men who completed the study of Barker et al. (2006) were retrospectively analyzed. At the time of the original study, the subjects were currently competing or had recently competed at the Division I collegiate level in either cross-country ($n = 5$) or 100 m ($n = 5$) running events. Each subject provided written and verbal consent prior to data collection. All experimental procedures were approved by the Institutional Review Board of Kansas State University and conformed to the standards set forth by the Declaration of Helsinki.

Subjects reported to the Human Exercise Physiology Laboratory at Kansas State University on 11 separate occasions. Initially, each subject performed two randomly ordered incremental ramp tests to volitional exhaustion on a cycle ergometer (Lode Corival model 844, Corival Lode BV, Groningen, Netherlands) at 60 rpm and 100 rpm on separate occasions to determine $\dot{V}_{O_{2peak}}$, peak work rate (W_{peak}) in Watts (W), GET, and RCP for each pedal cadence. Subjects then performed constant-power exercise to exhaustion at four different work rates for each pedal cadence (8 in total) to determine the power-duration relationship specific for 60 and 100 rpm. Finally, the subjects completed an 8-min ride at the determined CP for both 60 and 100 rpm for $\dot{V}_{O_2}$ kinetic analysis (reported in Barker et al., 2006).

Table 1
Mean incremental ramp data.

	60 rpm	100 rpm
GET ($l\,min^{-1}$)	2.01 ± 0.39	2.06 ± 0.46
W_{peak} (W)	325 ± 29	322 ± 31
$\dot{V}_{O_{2peak}}$ ($l\,min^{-1}$)	3.78 ± 0.45	3.73 ± 0.53

Data presented as mean ± SD.

2.2. Determination of GET, RCP, and $\dot{V}_{O_{2peak}}$

Each incremental ramp protocol consisted of 4 min of unloaded cycling, followed by a ramp increment of 20–30 W min^{-1} (the same ramp rate was used for both 60 and 100 rpm protocols per subject). Breath-by-breath metabolic and ventilatory data were continuously measured (Cardio2, Medical Graphics Corp., MN, USA) throughout each protocol. The metabolic system was calibrated prior to each use according to the manufacturer's instructions. The breath-by-breath data were converted into 10 s time binned mean values. For each protocol, $\dot{V}_{O_{2peak}}$ and W_{peak} were defined as the highest 10 s value achieved during exercise. The GET was determined as the point at which $\dot{V}_{CO_2}$ increased disproportionately to $\dot{V}_{O_2}$, and $\dot{V}_E/\dot{V}_{O_2}$ increased, while $\dot{V}_E/\dot{V}_{CO_2}$ remained constant (Beaver et al., 1986; Whipp et al., 1986). The RCP was determined as the point at which $\dot{V}_E/\dot{V}_{CO_2}$ increased (Beaver et al., 1986) and PET_{CO2} began to decrease (Whipp et al., 1989). The GET and RCP was determined by two blinded investigators. The work rates for the GET and RCP were determined from the $\dot{V}_{O_2}$ vs. work rate relationship from the incremental ramp test, which compensated for each subject's determined mean response time.

2.2.1. Determination of the power–duration relationship

CP was determined by fitting the power output vs. time-to-exhaustion data to the two-parameter hyperbolic model: $t = W'/(P - \mathrm{CP})$, where t is time-to-exhaustion in s, P is the power output in W, CP is the critical power in W, and W' is the curvature constant in Joules (J). In Barker et al. (2006) the CP − $\dot{V}_{O_2}$ was determined as the predominant $\dot{V}_{O_2}$ response with appreciable influence of any $\dot{V}_{O_2}$ slow component. The RCP in the current study was determined from the incremental ramp protocol and as a result the data contained the expression of the $\dot{V}_{O_2}$ slow component. In order to appropriately relate the $\dot{V}_{O_2}$ associated with RCP and CP in the current study, the total amplitude of the $\dot{V}_{O_2}$ response (A_{tot} in Barker et al. (2006)) was utilized to determine the $\dot{V}_{O_2}$ at CP so as to incorporate the $\dot{V}_{O_2}$ slow component.

2.3. Statistical analysis

Comparisons among the RCP and CP parameters across and within the 60 and 100 rpm protocols were made using two-way ANOVAs with repeated measures. Tukey's post hoc analyses were performed when main effects were detected. The level of agreement between RCP and CS was assessed with linear regression analyses. Statistical significance was set a priori at $p \leq 0.05$ and the results are presented as mean ± SD.

3. Results

The mean age, height, and body weight of the subjects were 21 ± 2 years, 180.0 ± 6.0 cm, and 76.0 ± 10.6 kg, respectively. There were no significant differences for $\dot{V}_{O_{2peak}}$, W_{peak}, or the $\dot{V}_{O_2}$ at the GET between 60 and 100 rpm. The data from the incremental ramp tests are presented in Table 1. The work rates associated with both RCP and CP were significantly lower for 100 rpm than 60 rpm (Table 2). Within each pedal cadence condition, the work

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