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Cardiovascular Responses of Exercises Performed Within the Extreme Exercise Domain

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Summary

Stroke volume (SV), heart rate (HR) and arterio-venous O_2 difference (a–vO_{2diff}) responses to heavy and severe-intensity exercise have been well documented; however, there is a lack of information on the SV, HR and a–vO_{2diff} responses of work rates within extreme exercise domain. The aim of this study was, therefore, to focus on central and peripheral components of $\dot{V}O_2$ responses to exercises performed within the heavy, severe and extreme exercise domain. Eight well-trained male cyclists participated in this study. Maximal O_2 consumption ($\dot{V}O_{2max}$) and corresponding work rate (P@$\dot{V}O_{2max}$) were determined by multisession constant work rate exercises. Cardiovascular responses to exercises were evaluated by nitrous-oxide rebreathing method with work rates from 40 % to 160 % of P@$\dot{V}O_{2max}$, $\dot{V}O_{2max}$ corresponded to 324±39.4 W; however, maximal SV responses occurred at 205±54.3 W ($p<0.01$). Maximal cardiac output (Q), HR, and a–vO_{2diff} responses were revealed by the P@$\dot{V}O_{2max}$. $\dot{V}O_2$ response to exercise significantly decreased from severe-intense exercises to the first work rate of extreme exercise domain due to significant decreases in Q, SV, and HR responses ($p<0.05$), except a–vO_{2diff} ($p>0.05$). Moreover, non-significant decreases in Q, SV, and a–vO_{2diff} were evaluated as response to increase in work rate belonging to extreme work rates ($p>0.05$), except the HR ($p<0.05$). Work rates within the lower district of the extreme exercise domain have an important potential to improve peripheral component of $\dot{V}O_2$, while the P@$\dot{V}O_{2max}$ seems the most appropriate intensity for aerobic endurance development as it maximizes the central component of $\dot{V}O_{2max}$.

Key words

Arterio-venous O_2 difference • Cardiac output • Heart rate • Sports performance • Stroke volume

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Introduction

Exercise domains are classified as moderate, heavy, severe, and extreme [1,2]. The lactate threshold is accepted as the upper boundary of moderate exercise domain, while the maximal lactate steady-state is the upper boundary of heavy exercise domain [3,4]. The upper boundary of severe exercise domain is accepted as the highest intensity given the $\dot{V}O_{2max}$ (I_{HIGH}) [5-10]. If the I_{HIGH} is exceeded, within the extreme exercise domain, VO_2 response to exercise does not attain $\dot{V}O_{2max}$ [9]. Aerobic power is one of the most important indicators of aerobic performance. Exercise VO_2 is related to the increase in stroke volume (SV), heart rate (HR) and arterio-venous O_2 difference (a–vO_{2diff}). SV and HR, which produce the cardiac output (Q), are the central component of VO_2, while a–vO_{2diff} forms the peripheral component. The Q and SV rather than HR or a–vO_{2diff} are the key factors of the aerobic power [11] because maximal SV (SV_{max}) responses of non-elite athlete

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groups occur within the heavy exercise domain, but not within the severe exercise domain [12]. Conversely, maximal HR and a–vO_{2diff} have typically occurred within the severe exercise domain [13].

Extreme-intensity work rates have been used for aerobic adaptations, especially over the last two decades. It has been shown that very high intense, low volume training strategies have been used for a rapid improvement aerobic adaptation by increasing oxidative muscle capacity, carbohydrate/lipid metabolism and metabolic control during exercise [14-16]. Consequently, exercise modalities including supramaximal intensities referring to work rates greater than severe intensity exercises, e.g. 25-s×12 repetitions with 1:4 workout/resting ratio at ~120-140 % of power output corresponding to the maximal O_2 utilize (P@$\dot{V}O_{2max}$) given the $\dot{V}O_{2max}$, have become popular in terms of aerobic endurance development [17-19]. Currently, even sprint intervals, e.g. 30-s×6 bouts of exercise with 1:8 workout/resting ratio at 160 % of P@$\dot{V}O_{2max}$, have been used to improve both aerobic and anaerobic endurance [20]. However, although SV, HR and a–vO_{2diff} responses in heavy and severe intensity exercises have been well documented [21-23], there is a lack of information on SV, HR and a–vO_{2diff} responses of extreme exercises, i.e. 120 %, 140 %, and 160 % of P@$\dot{V}O_{2max}$, which have been typically used for endurance development [24]. The aim of this study was, therefore, to focus on central and peripheral components of VO_2 responses to exercises performed especially within the lower district of extreme exercise domain.

Methods

Participants

The study was approved by the University's Research Ethics Committee (Celal Bayar University Ethics Committee, Chairman: Prof. Ercument Olmez; Protocol no: 20478486-84; Date: 02.2015) and conducted based on the principles of the Declaration of Helsinki, except prior registration of the study in a database. Eight well-trained male cyclists participated in this study (age: 22±2.2 years; body height: 178±5.55 cm; body mass: 71.9±8.24 kg). Cyclists were informed about the benefits and risks of the investigation just before signing an institutionally approved informed consent document to participate in the study. They had been training for ~7 years, and their training sessions corresponded to ~18 $h\cdot wk^{-1}$. The study was conducted after the competition season to minimize training effects or periodization and completed within four weeks. Additionally, the time of the day allocated for testing was standardized to minimize any effect of circadian variance for each volunteer. They were requested not to take part in any exhausting exercise during the study. None of the participants suffered from any injuries or had a known systemic disease, and they were not under the influence of any medication.

Experimental design

Following familiarization session (Stage 1 in Fig. 1), cyclists' first and second ventilatory threshold (VT_1 and VT_2) were evaluated by a submaximal step incremental test. $\dot{V}O_{2max}$ was determined by maximal step incremental test and constant work rate trail (Stage 2 in Fig. 1). Multisession constant work rate exercises were applied to determine cyclists' individual I_{HIGH} levels (Stage 3 in Fig. 1). Then, work rates ranged from 40 to 100 % of P@$\dot{V}O_{2max}$ were analysed to reveal exercise intensity associated with SV_{max} (Stage 4 in Fig. 1). Moreover, further two transition constant work rate exercises (i.e. 120-140-160 % of P@$\dot{V}O_{2max}$) were conducted to determine cyclists' $\dot{V}O_2$, Q, SV, and a–vO_{2diff} responses to exercises performed within the lower district of extreme exercise (Stage 5 in Fig. 1) (Fig. 1). The Q, SV, HR, and a–vO_{2diff} values belonging to exercises were then analysed to test hypotheses. Each individual visited the laboratory for 16-18 days.

Procedures

Cardiac performance measurements and respiratory gas analyses

Q, SV, and a–vO_{2diff} were conducted cardiac measurement system (Innocor Inno-500, Odense, Denmark). using a valid and reliable non-invasive inert gas rebreathing method (N_2O_{RB}) [25,26]. For this method N_2O (blood soluble gas) and SF_6 (blood insoluble gas) gasses used and their approximate inspired concentrations were 0.5 % and 0.1 %, respectively. Rebreathing bag volume and bolus volume (volume of gas mixture, consisting of N_2O, SF_6 and O_2) were regulated automatically by device. The rebreathing maneuver was performed typically using 5-7 breaths. The Innocor system calculates Q from the last two or three breaths of the maneuver [26,27]. SV responses belonging to each measurement was calculated by dividing Q by the HR. The Q data could not be recorded continuously during the tests, since N_2O_{RB} method needs approximately 2-3-min for washout of N_2O between repeated measurements for the same individual.

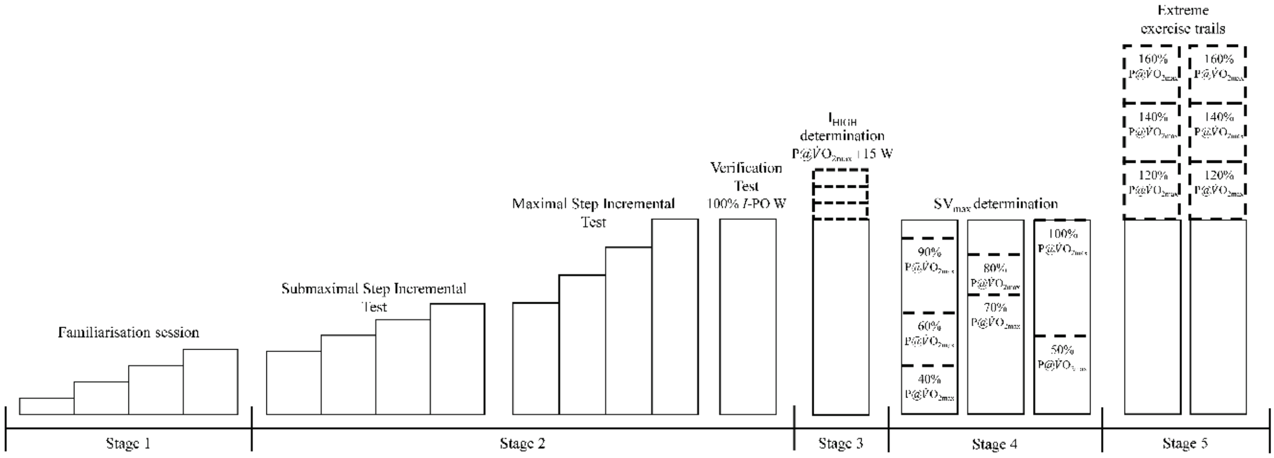

Fig. 1. Flow chart of experimental study design. *I*-PO: Power output given the highest 30-s mean value of $\dot{V}O_2$ obtained from the incremental step test; I_{HIGH}: Highest constant intensity giving the $\dot{V}O_{2max}$; P@$\dot{V}O_{2max}$: Power output corresponding to the $\dot{V}O_{2max}$; SV_{max}: Maximal stroke volume.

Soluble gas concentration was therefore checked just before and after each measurement. If the N_2O increased at the end of the test due to the recirculation, the measurement was recalculated with selected last two breaths after mixing. This calculation from two last breaths helps to avoid recirculation in N_2O_{RB} measurements during supramaximal exercises [26,27]. At the beginning of the subsequent measurements, end-tidal gas values were checked. If N_2O and SF_6 were above 0.002 % and 0.001 % respectively, the subsequent test was delayed due to insufficient recirculation time and/or missing washout of the lungs between two measurements. Breath-by-breath gas exchanges were measured using the same system. Due to technical limitations, $\dot{V}O_2$ and $\dot{V}CO_2$ exchange was not recorded during the N_2O_{RB}. Arteriovenous oxygen difference was calculated from Q and $\dot{V}O_2$ using the Fick Principle [28]. In addition to Polar heart rate monitoring system, HR responses were recorded via the pulse-oximeter equipment of the Innocor system and heart rate monitoring system (Polar RS400, Polar Electro Oy, Kempele, Finland). Device calibrations were undertaken according to the manufacturer's instructions.

Familiarization session and pilot studies

Familiarization sessions were performed to adapt the participants to electromagnetically braked cycle ergometer (Lode Excalibur Sport, Groningen, Netherlands), cardiac measurement system, heart rate monitoring system and climatic chamber, which allows fixed special standard laboratory conditions (20 °C temperature, 20.8 % O_2, <500 ppm CO_2, 50-60 % relative humidity). For this purpose, incremental exercise consisted of four stages for each 5 min with ~6 W initial loading and ~30 W increments, terminated within 50 % of maximal HR reserve predicted by Karvonen's HR reserve formula, were conducted.

Step incremental test and constant work rate verification phase to elicit $\dot{V}O_2max$

Submaximal step incremental test consisted of four 5 min stages with ~25-30 W increments. The test initiated the work rates corresponding to 50-60 % of maximal HR and terminated ~85 % of maximal HR reserve predicted by Karvonen's HR reserve formula. If ventilatory threshold was not seen within the submaximal step incremental test, procedure would continue with ~25-30-W increments. After 30 min passive recovery, maximal step incremental tests were initiated with 4 min of cycling without resistance. Then, work-loads were increased by 30 W for each 2-min steps. Cyclists were allowed to reach a cadence between 90±10 rpm and were instructed to maintain this cadence until task failure. The test was terminated when the pedal rate fell below 80 rpm for more than 10 s despite the strong verbal encouragement. The validation of tests was checked by a plateau with an increase in $\dot{V}O_2<2.1$ $ml \cdot min^{-1} \cdot kg^{-1}$, greater than 90 % of age-predicted maximum HR (maximal HR=220-age), 1.1 or above respiratory exchange ratio and rate of perceived exertion of 19-20 in Borg's 15-point scale [29]. The VT_1 and VT_2 were found by the first and second breakpoints of V_E/VO_2 (minute ventilation/oxygen consumption) vs. W [30,31].

In order to determine verified $\dot{V}O_{2max}$, constant work rate test was conducted on the limit of tolerance. The test was initiated at the power output given the highest 30-s mean value of $\dot{V}O_2$ obtained from the incremental step test. Test validation criteria of verification phases were accepted as the same with incremental tests. Cyclists were encouraged verbally throughout the tests. The highest 30-s averages of $\dot{V}O_2$ values were recorded as the cyclists' $\dot{V}O_{2max}$, and corresponding power outputs were accepted as the P@$\dot{V}O_{2max}$.

Determination of the highest work rate to elicit $\dot{V}O_2$ max

Individual work rates corresponding to the I_{HIGH} were analysed by multisession constant work rate exercises to determine the lower district of extreme exercises. In those exercises, $\dot{V}O_2$ responses to exercise greater than 95 % of $\dot{V}O_{2max}$ were analysed [32-34]. The I_{HIGH} bound of a well-trained cyclist was accepted as the highest work rate that provides a $\dot{V}O_2$ value, which is still greater than 95 % of $\dot{V}O_{2max}$ [8,34]. In order to obtain the I_{HIGH}, the first test was performed at P@$\dot{V}O_{2max}$+15 W, and constant work rate tests were continued by +15 W intervals on different days.

Determination of maximal stroke volume responses by constant work rate exercises

Tests were conducted by constant work rate exercises performed from 40 % to 100 % of P@$\dot{V}O_{2max}$. The exercises competed on three different days; *i)* 40-60 % and 90 % of P@$\dot{V}O_{2max}$, *ii)* 70 % and 80 % of P@$\dot{V}O_{2max}$, *iii)* 50 % and 100 % of P@$\dot{V}O_{2max}$, respectively, using 15 min rests. Work rates from 40 % to 70-80 % of P@$\dot{V}O_{2max}$ were maintained for 10 min; in the meantime, three N_2O_{RB} were completed between 4:30-5:00, 7:00-7:30 and 9:30-10:00 min. Besides, 70-80 % to 100 % of P@$\dot{V}O_{2max}$ were sustained for 5-7 min, and N_2O_{RB} were accomplished between 2:30-3:00, 4:30-5:00 and 6:30-7:00 min, if the test was prolonged [12]. Individual SV_{max} (ml) and corresponding work rate (P@SV_{max}), $\dot{V}O_2$, Q, HR, and a–vO_{2diff} values were recorded.

Determination of cardiac output, stroke volume and arterio-venous O_2 difference responses of extreme exercises

Extreme exercise trails were conducted by three different constant work rates with two transitions (i.e. 120 %, 140 %, and 160 % of P@$\dot{V}O_{2max}$). Firstly, for each cyclist, time to task failures and $\dot{V}O_2$ responses of extreme exercise trails were determined without rebreathing applications on separate days. Then, these extreme exercise trails were repeated on different days in order to obtain Q, SV, and a–vO_{2diff} responses. Therefore, the N_2O_{RB} applications could be applied just before cyclists' exhaustion of each extreme exercise trail. The highest $\dot{V}O_2$, Q, SV, HR, and a–vO_{2diff} values of each extreme exercise were recorded, individually.

Statistical analysis

Results were evaluated using SPSS 21.0 (SPSS Inc., Chicago, USA). The Shapiro-Wilk test was applied to determine whether data were normally distributed or not. Differences between variables were assessed by repeated-measures ANOVA. Tukey's honestly significant difference *post hoc* test was used to perform pairwise comparisons. In order to avoid the loss of statistical power, confidence interval adjustment was not performed for multiple pairwise comparisons. Effect size (ES) was analysed on the basis of mean and standard deviation. Cohen's effect sizes were categorized as trivial (0-0.2), small effect (0.2-0.5), medium effect (0.5-0.8), and a large effect (>0.8) [35]. Results with a $p<0.05$ were considered statistically significant.

Results

Mean P@$\dot{V}O_{2max}$ corresponded to 324±39.4 W; however, mean P@SV_{max} responses of cyclists occurred at 205±54.3 W with the gap of ~119 W ($p<0.001$). Indeed, individual P@SV_{max} values of six cyclists corresponded an exercise intensity below the VT_2 and above the VT_1, referring to heavy exercise domain, while only two of cyclists' P@SV_{max} values occurred at the first work rates of severe exercise domain (i.e. above the VT_2) referring to significantly lower work rates than the P@$\dot{V}O_{2max}$. Data belonging to work rates (P@SV_{max}, P@$\dot{V}O_{2max}$, 120 %, 140 % and 160 % of P@$\dot{V}O_{2max}$) corresponding to $\dot{V}O_{2max}$, Q, SV, HR, and a–vO_{2diff} are presented in Table 1.

Work rates of 120 %, 140 %, and 160 % of P@$\dot{V}O_{2max}$ corresponded to 389±47.4, 454±55.1, and 519±63.2 W, respectively. Group mean of the I_{HIGH} was 358±48.9 W (i.e. ~111 % of P@$\dot{V}O_{2max}$). Time to task failures of 120 %, 140 %, and 160 % of P@$\dot{V}O_{2max}$ corresponded to 164±34.2, 109±25.9, and 74.5±15.1 s, respectively. The highest HR and a–vO_{2diff} responses were revealed by the P@$\dot{V}O_{2max}$ where the $\dot{V}O_{2max}$ was obtained. Peak oxygen uptake at 120 %, 140 %, and

160 % of P@$\dot{V}O_{2max}$ exercises were significantly lower than the $\dot{V}O_{2max}$ due to decreases in Q (Table 2), SV (Table 3) and HR (Table 4) responses. Additionally, significant a–vO_{2diff} decrements occurred only at 160 % of P@$\dot{V}O_{2max}$ compared to the P@$\dot{V}O_{2max}$ (Table 5). Additionally, a–vO_{2diff} responses tended to decrease at 140 % of P@$\dot{V}O_{2max}$ compared to the P@$\dot{V}O_{2max}$. (p=0.076, *d*=0.73) (Table 2). Moreover, non-significant Q, SV, and a–vO_{2diff} decrements were evaluated within increasing work rates belonging to extreme exercise intensities (i.e. 120 %, 140 %, and 160 % of P@$\dot{V}O_{2max}$); however, the $\dot{V}O_2$ and HR decrements were significant at 120 % to 160 % of P@$\dot{V}O_{2max}$ ($p<0.05$).

Table 1. The highest $\dot{V}O_2$, Q, SV, HR and a–vO_{2diff} responses obtained from exercises performed at P@SV_{max}, P@$\dot{V}O_{2max}$, 120 % of P@$\dot{V}O_{2max}$, 140 % of P@$\dot{V}O_{2max}$ and 160 % of P@$\dot{V}O_{2max}$.

Variables	**$\dot{V}O_2$ (ml·min^{-1}·kg^{-1})**	**Q (l·min^{-1})**	**SV (ml)**	**HR (beats·min^{-1})**	**a–vO_{2diff} (ml)**
P@SV_{max}	43±8.59	21.9±2.32	152±12.6	144.4±13.9	14.3±3.36
P@$\dot{V}O_{2max}$	62.7±6.31	25.8±2.53	143±13.5	190±7.08	17.3±0.5
120 % of P@$\dot{V}O_{2max}$	57.8±5.77	24.8±2.74	138±12.5	184±9.45	16.7±1.48
140 % of P@$\dot{V}O_{2max}$	56.5±7.44	24.4±3.61	137±16.6	183±10.7	16.6±1.37
160 % of P@$\dot{V}O_{2max}$	54.5±6.55	24.2±3.41	136±14.3	181±11.8	16.1±0.72

P@SV_{max}: Power output corresponding to maximal SV responses; P@$\dot{V}O_{2max}$: Power output corresponding to the $\dot{V}O_{2max}$; $\dot{V}O_2$: O_2 utilize; Q: Cardiac output; SV: Stroke volume; HR: Heart rate; a–vO_{2diff}: Arterio-venous O_2 difference.

Table 2. Results of p and Cohen's d values of Q responses, obtained from exercises performed at P@SV_{max}, P@$\dot{V}O_{2max}$, 120 % of P@$\dot{V}O_{2max}$, 140 % of P@$\dot{V}O_{2max}$ and 160 % of P@$\dot{V}O_{2max}$.

Variables	**P@$\dot{V}O_{2max}$**	**120 % of P@$\dot{V}O_{2max}$**	**140 % of P@$\dot{V}O_{2max}$**	**160 % of P@$\dot{V}O_{2max}$**
P@SV_{max}	**p=0.005** **_d_=1.42**	**p=0.028** **_d_=0.98**	p=0.105 *d*=0.66	p=0.076 *d*=0.73
P@$\dot{V}O_{2max}$	-	**p=0.043** **_d_=0.87**	**p=0.035** **_d_=0.92**	**p=0.022** **_d_=1.03**
120 % of P@$\dot{V}O_{2max}$	-	-	p=0.225 *d*=0.44	p=0.112 *d*=0.64
140 % of P@$\dot{V}O_{2max}$	-	-	-	p=0.707 *d*=0.14

Q: Cardiac output; P@SV_{max}: Power output corresponding to maximal stroke volume; P@$\dot{V}O_{2max}$: Power output corresponding to the $\dot{V}O_{2max}$.

Table 3. Results of p and Cohen's d values of SV responses, obtained from exercises performed at P@SV_{max}, P@$\dot{V}O_{2max}$, 120 % of P@$\dot{V}O_{2max}$, 140 % of P@$\dot{V}O_{2max}$ and 160 % of P@$\dot{V}O_{2max}$.

Variables	**P@$\dot{V}O_{2max}$**	**120 % of P@$\dot{V}O_{2max}$**	**140 % of P@$\dot{V}O_{2max}$**	**160 % of P@$\dot{V}O_{2max}$**
P@SV_{max}	**p=0.01** **_d_=0.95**	**p=0.002** **_d_=1.73**	**p=0.009** **_d_=1.28**	**p=0.001** **_d_=1.89**
P@$\dot{V}O_{2max}$	-	**p=0.046** **_d_=0.86**	**p=0.041** **_d_=0.88**	**p=0.014** **_d_=1.15**
120 % of P@$\dot{V}O_{2max}$	-	-	p=0.632 *d*=0.18	p=0.609 *d*=0.19
140 % of P@$\dot{V}O_{2max}$	-	-	-	p=0.942 *d*=0.03

SV: Stroke volume; P@SV_{max}: Power output corresponding to maximal stroke volume; P@$\dot{V}O_{2max}$: Power output corresponding to the $\dot{V}O_{2max}$.

Table 4. Results of p and Cohen's d values of HR responses, obtained from exercises performed at $P@SV_{max}$, $P@\dot{V}O_{2max}$, 120 % of $P@\dot{V}O_{2max}$, 140 % of $P@\dot{V}O_{2max}$ and 160 % of $P@\dot{V}O_{2max}$.

Variables	$P@\dot{V}O_{2max}$	120 % of $P@\dot{V}O_{2max}$	140 % of $P@\dot{V}O_{2max}$	160 % of $P@\dot{V}O_{2max}$
$P@SV_{max}$	**p=0.001** **d=3.06**	**p=0.001** **d=2.21**	**p=0.001** **d=2.08**	**p=0.001** **d=1.81**
$P@\dot{V}O_{2max}$	-	**p=0.006** **d=1.38**	**p=0.013** **d=1.16**	**p=0.003** **d=1.53**
120 % of $P@\dot{V}O_{2max}$	-	-	p=0.390 *d*=0.32	**p=0.024** **d=1.02**
140 % of $P@\dot{V}O_{2max}$	-	-	-	p=0.072 *d*=0.75

HR: Heart rate; $P@SV_{max}$: Power output corresponding to maximal stroke volume; $P@\dot{V}O_{2max}$: Power output corresponding to the $\dot{V}O_{2max}$.

Table 5. Results of p and Cohen's d values of $a-vO_{2diff}$ responses, obtained from exercises performed at $P@SV_{max}$, $P@\dot{V}O_{2max}$, 120 % of $P@\dot{V}O_{2max}$, 140 % of $P@\dot{V}O_{2max}$ and 160 % of $P@\dot{V}O_{2max}$.

Variables	$P@\dot{V}O_{2max}$	120 % of $P@\dot{V}O_{2max}$	140 % of $P@\dot{V}O_{2max}$	160 % of $P@\dot{V}O_{2max}$
$P@SV_{max}$	p=0.28 *d*=0.98	**p=0.046** **d=0.86**	**p=0.038** **d=0.91**	p=0.11 *d*=0.65
$P@\dot{V}O_{2max}$	-	p=0.215 *d*=0.48	p=0.076 *d*=0.73	**p=0.001** **d=2.9**
120 % of $P@\dot{V}O_{2max}$	-	-	p=0.899 *d*=0.05	p=0.244 *d*=0.46
140 % of $P@\dot{V}O_{2max}$	-	-	-	p=0.133 *d*=0.14

$a-vO_{2diff}$: Arteriovenous O_2 difference; $P@SV_{max}$: Power output corresponding to maximal stroke volume; $P@\dot{V}O_{2max}$: Power output corresponding to the $\dot{V}O_{2max}$.

Discussion

It is known that very high intense and low volume training strategies have been used for a rapid improvement in aerobic performance [14-16]. Indeed, those adaptations can be induced by high-intensity exercises or sprints performed within the extreme exercise domain due to increasing rate of blood flow within the resting periods between succeeding workouts and increasing rate of aerobic contribution during recovery period [36,37]. However, there is a lack of information on Q, SV, HR, and $a–vO_{2diff}$ response of extreme exercises, which have been typically used for aerobic endurance development. Whereas, if there is an important SV response during high intensity exercises, central adaptations (i.e. Q and SV), besides peripheral adaptations (i.e. $a–vO_{2diff}$), may be ensured by high-intense exercises. Therefore, this study aimed to analyze central and peripheral components of $\dot{V}O_2$ responses to exercises performed within the lower district of extreme exercise domain. The main results showed that there were expected $\dot{V}O_2$ decrements at extreme exercises compared to the exercise corresponding to the $P@\dot{V}O_{2max}$ due to significant decrease in Q, SV and HR responses of well-trained cyclists. However, $a–vO_{2diff}$ responses were not different at extreme work rates (i.e. 120 % and 140 % of $P@\dot{V}O_{2max}$) than that of the $P@\dot{V}O_{2max}$. Consequently, none of the components of $\dot{V}O_2$ come out predominant within varying extreme exercise intensities. Due to the increase in anaerobic contribution and shortening exercise duration, SV, HR, Q and $a–vO_{2diff}$ response to exercises decreased together with the small differences during extreme exercises (i.e. 120 %, 140 %, and 160 % of $P@\dot{V}O_{2max}$) compared to the $P@\dot{V}O_{2max}$ exercises.

Individual SV responses to exercise indicate that the SV pattern during maximal incremental or constant work rate protocols is greatly dependent on exercise intensity and duration. According to Lepretre *et al.* [38],

$\dot{V}O_{2max}$ is reached lower SV responses in heavy-intense constant exercises than severe intensity exhaustive exercises. Indeed, it was reported that a 6-min ramp incremental test that resulted in a significantly greater SV decrement that leads an important cardiac output decrease than a 12-min progressive exercise [39]. Conversely, Colakoglu *et al.* [40] showed that SV_{max} responses of well-trained but non-elite athletes correspond to heavy-intense exercises, and if the number of steps or stage durations during incremental test increases or extents, cardiac performance significantly decreases based on cardiac fatigue. In fact, according to authors, short bouts of verification phases terminated by athletes' exhaustion has been an important method to reveal a real $\dot{V}O_{2max}$. Indeed, the highest $\dot{V}O_2$ means were reached by verification bouts when compared to step incremental exercises in this study (i.e. 62.7±6.31 ml·kg·min^{-1} vs. 61.3±5.21 ml·kg·min^{-1}; $p<0.05$, respectively).

It is known that SV responses to 4-8 min of constant work rate exercises reached maximal within 2-3 min and then decreased prior to fatigue, suggesting a central limitation (e.g. myocardial) to maximal aerobic power [41]. Indeed, there were greater SV responses at the first measurement rather than second N_2O_{RB} maneuver during severe exercises, and SV_{max} response of each cyclist was attained within 2:30-3:00-min of exercise durations. However, due to technical limitation of the rebreathing system, N_2O_{RB} measurements could be applied only once during extreme exercises based on insufficient exercise durations. Moreover, due to shortening exercise duration at supramaximal constant work rates, rebreathing maneuver could not be applied at greater work rates than the 160 % of P@$\dot{V}O_{2max}$ (i.e. 180 % and 200 % of P@$\dot{V}O_{2max}$). Indeed, N_2O_{RB} measurements would be applied just before cyclists' exhaustion rather than throughout workout sessions, and gas exchange parameters would not be measured during this time interval. Therefore, more accurate analyses for the supramaximal exercises can be made by measuring these parameters with direct methods (e.g. thermos-dilution methods). Additionally, only a limited number of well-trained cyclists could be recruited for this study. Thus, the results may not have general validity for the general population. Therefore, future studies may be focus on high-intensity training for female athletes or other disciplines.

Conclusions

Q, SV, and HR responses were significantly lower in extreme exercises compared to the P@$\dot{V}O_{2max}$. Therefore, it can be said that severe exercise intensities (i.e. P@$\dot{V}O_{2max}$) have more potential to improve aerobic power. However, none of the $\dot{V}O_2$ components (i.e. Q, SV, HR, and a–vO_{2diff}) come out predominant within varying extreme exercise intensities of well-trained cyclists. Moreover, a–vO_{2diff} responses were not different between P@$\dot{V}O_{2max}$ and the exercises performed at 120 % and 140 % of P@$\dot{V}O_{2max}$. Additionally, there was no dramatic decrease in any of the SV, HR, Q or a–vO_{2diff} responses during exercises performed at 120 %, 140 % and 160 % of P@$\dot{V}O_{2max}$. Only the decrement in HR response between 120 % and 160 % of P@$\dot{V}O_{2max}$ was significant; however, the decreasing rate was negligible (3 beats per minute). It may be said that work rates within the lower district of extreme exercise domain (i.e. 120 % of P@$\dot{V}O_{2max}$) have an important potential to develop aerobic endurance by improving the peripheral components of the $\dot{V}O_2$.

Conflict of Interest

There is no conflict of interest.

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