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Re-Evaluation of Old Findings on Stroke Volume Responses to Exercise and Recovery by Nitrous-Oxide Rebreathing

by
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It is important to verify the old findings of Cumming (1972) and Goldberg and Shephard (1980) who showed that stroke volume (SV) may be higher during recovery rather than during exercise, in order to organize the number of intervals throughout training sessions. The purpose of this study was to re-evaluate individual SV responses to various upright cycling exercises using the nitrous-oxide rebreathing method. Nine moderate to well-trained male athletes volunteered to take part in the study (maximal O_2 uptake (VO_{2max}): 60.2 ± 7 mL·min^{-1}·kg^{-1}). Workloads ranging from 40-100% of VO_{2max} were applied to determine individual peak SV (SV_{peak}) response. Results showed that SV responses were higher during exercise compared to recovery in all exercise loads from 40-100% of VO_{2max}. Mean SV responses to individual SV_{peak} loads were also higher during exercise compared to recovery (122.9 ± 2.5 versus 105.3 ± 5.93 mL). The highest SV responses to 10 min exercises of 40-70% of VO_{2max} were obtained in the 5th or 7.5th min of each stage ($p \leq 0.05$). Meanwhile, during 5 min exercises between 80-100% of VO_{2max}, peak SV responses were observed in the 3rd min of loading ($p \leq 0.05$). In conclusion, individual SV_{peak} levels encountered over wide exercise intensity ranges showed that SV_{peak} development may also be correlated to exercise intensity corresponding to individual SV_{peak} loads.

Key words: *Inert-gas, Interval, Training, VO_{2max}.*

Introduction

Maximal O_2 uptake (VO_{2max}) is one of the most important criteria of the functional limit of the cardiovascular system. It has been shown that improvement in stroke volume (SV) is the main factor to enhance VO_{2max} capacity (Vella and Robergs, 2005). The magnitude of diastolic filling time plays a critical role in SV, based upon exercise; an increase in blood volume circulated to the heart causes a physiological adaptation in heart tissue (Blomqvist and Saltin, 1983). Consequently, it is very important to be exposed to higher SV loads to improve VO_{2max} capacity. Therefore, evaluating peak responses in SV (SV_{peak}) may be essential for VO_{2max} development.

Only a number of studies revealed that supine and upright cycling exercises yielded a greater SV response during recovery, instead of during the loading period (Cumming, 1972; Goldberg and Shephard, 1980; Takahashi et al., 2000). Therefore, training modalities should be focused on introducing a higher number of rest periods. Takahashi et al. (2000) evaluated SV responses during both upright and supine cycling exercises by using an impedance cardiograph. They found that resultant mean SV values in the recovery period were 10% greater compared to the values obtained during exercise only in the supine position. Similarly, Cumming (1972) found greater SV responses during recovery compared to the exercise period using an invasive technique known as thermo-dilution. However, most of exercise modalities that are performed in upright positions require higher VO_{2max}. Since the studies carried out by Cumming (1972) and Takahashi et al. (2000) were performed at a supine cycling position, those results are not applicable for

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upright exercises. On the other hand, there is only one study that showed a greater SV response during recovery rather than the exercise in the upright position; however, Goldberg and Shephard (1980) utilized a non-invasive carbon-dioxide rebreathing method. The carbon-dioxide rebreathing method, compared to acetylene washout, was shown to be unreliable when used during exercise (Rosenthal and Bush, 1997). It appears that evaluating SV responses during exercise and recovery by newer non-invasive techniques, such as acetylene or nitrous-oxide rebreathing (N_2O_{RB}), can be highly reliable (Fontana et al., 2009). Therefore, reanalyzing SV responses to exercise and recovery in upright positions seems to be necessary to confirm the data reported by previous studies. If peak SV is achieved during a recovery period instead of a loading phase, then the number of recovery periods is likely to be the most important element of training sessions aiming at SV improvement. Thus, the purpose of this study was to evaluate individual SV responses to various upright cycling exercises in order to form a basis for our prospective hypotheses on short interval training modalities.

Material and Methods

Participants

The study was designed according to the rules and principals of the Declaration of Helsinki and was approved by the Ege University ethics committee. Written informed consent was obtained after explanation of the nature and risks of the experiment. Nine moderate to well-trained male athletes who competed in cycling and athletics events at regional level volunteered to take part in the study (age: 23.6 ± 4.1 years; body mass: 75.8 ± 4.7 kg; body height: 181 ± 6.7 cm; body fat: 13.6 ± 1.6%; VO_{2max} : 60.2 ± 7 mL·min^{-1}·kg^{-1}). At the time of the study, participants were involved in 5 ± 1 training sessions per week. Their average athletic experience was 7.5 ± 2.6 years. Procedures were performed using standard conditions of 20-21°C temperature and 50-55% relative humidity in a climatic chamber equipped with the possibility to control the temperature and relative humidity, as well as having an integrated heat recovery system by fresh air supplementation. Participants consumed approximately 300 mL of water 1 h before the experiment and were requested not to take part in any exhaustive exercise during the course of the study. None of the participants suffered from any injuries or took any medications.

Procedures

A computer-controlled electromagnetically braked Lode Excalibur cycle ergometer was used for this study (Excalibur Sport, Lode B.V., Lode Medical Technology, Groningen, Netherlands).

Cardiac Output (Qc) was determined using a valid and reliable (Fontana et al., 2009) non-invasive inert-gas re-breathing (N_2O_{RB}) method (Innocor Inno-0500, Innovision A/S, Odense, Denmark). SV was then calculated by dividing Qc by the heart rate (HR). Qc data was not recorded continuously during the tests just like in other rebreathing techniques. Since the N_2O_{RB} method needs sufficient time for washout of inert gasses (N_2O and SF_6) between repeated measurements for the same individual, time delay of approximately 5 min at rest and 2-3 min during high to moderate intensity exercise for subsequent measurements was necessary. After the test, soluble gas concentration (N_2O) was checked. If N_2O increased at the end of the test due to recirculation, the measurement was cancelled. At the beginning of the subsequent measurement, the end-tidal value of soluble and insoluble gas concentrations was checked. If N_2O and SF_6 levels were not below 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. The HR, breath-by-breath VO_2 and VCO_2 were measured using the same system. Device calibrations were undertaken according to the manufacturer's instructions.

The submaximal graded exercise test consisted of four 5 min stages with increments of ~25-30 watts. Initial and final loads of the submaximal test were set using workloads corresponding to 50-60% and 70-85% of the HR_{max} reserve predicted by the Karvonen's HR reserve formula. In case the ventilatory threshold was not reached within the submaximal test, the procedure continued with increments of ~25-30 watts. The data to estimate the initial load of maximal graded exercise tests (GXTs) was planned to be completed within 8-12 min (da Silva et al., 2012; Myers et al., 1991). Maximal GXTs were then performed to determine VO_{2peak} of the participants. The initial load was adjusted to a workload representing ~70-85% of the HR_{max} predicted by the Karvonen's HR reserve formula. Stage duration was set at one 4 min and three 2 min phases, followed by 1 min phases until volitional exhaustion. Stages were continued until volitional exhaustion occurred. Then, traditional GXT termination criteria were assessed as follows: a) a plateau in VO_2 defined as the O_2 requirement change less than 150 $mL·min^{-1}$, b) HR responses within 10% of the age-predicted maximum (220-age) $beats·min^{-1}$, c) respiratory exchange ratio (RER) of 1.10 or above (Midgley and Carroll, 2009). In addition, the rate of perceived exhaustion (RPE) was also checked using the Borg's 15-point scale (Midgley et al., 2007). In case the total test duration was not between 8-12 min, the test was repeated another day to obtain standardization for determining VO_{2peak} (Buchfuhrer et al., 1983). Participants received verbal encouragement, especially after the first 4 min stage, in order to produce a maximal effort. VO_{2peak} was determined as the highest 30 s average VO_2 during the test. Constant-load exhaustion tests were planned to verify the results of GXTs. A constant bout of exercise, with a workload equivalent to serve as the highest 30 s average VO_2 derived from GXT, was performed to the limit of tolerance with verbal encouragement throughout the test. Test termination criteria of the verification phase were accepted as the same with GXTs.

Constant loading SV tests were conducted to determine individual SV_{peak} levels of participants by using the N_2O_{RB} method. Workloads in the range of 40-70% of VO_{2max} were performed over a period of 10 min, and N_2O_{RB} was applied at the 5th, 7.5th and 10th min, while workloads in the range of 80-100% of VO_{2max} were used during 5 min, and N_2O_{RB} was conducted in the 3rd and 5th min, if the test was continued. At the 2nd min of recovery, N_2O_{RB} was repeated to observe SV changes from exercise to recovery after each exercise load from 40-100% of VO_{2max}.

Statistical analysis

Results were evaluated using SPSS 20.0 (SPSS Inc., Chicago, USA) statistical software. Descriptive results were reported as mean values and standard deviations (±SD). The normality of data was evaluated by the Shapiro-Wilk test. After ANOVA, LSD as post-hoc was used to analyze mean differences between SV responses according to various exercise intensities. Pearson analysis was used to evaluate correlation between SV_{peak} and VO_{2max}. Results with $p \le 0.05$ were considered statistically significant.

Results

Results showed that peak SV responses during exercise were higher than after the recovery period in all loads from 40-100% of VO_{2max} ($p \le 0.05$) (Figures 1 and 2). Three participants had SV_{peak} responses at a workload of 40% of VO_{2max}, while three had SV_{peak} responses at 60%, two at 80% and one at 90% of VO_{2max}. The highest SV responses to 10 min exercises between 40-70% of VO_{2max} were obtained in the 5th or 7.5th min of each stage ($p \le 0.05$). Meanwhile, in 5 min exercises between 80-100% of VO_{2max}, top SV responses were observed in the 3rd min of loading ($p \le 0.05$). Moreover, there was no significant decrease in SV response from the end of exercise to recovery measurement for only 50% of VO_{2max} (121.1 ± 17.1 versus 113 ± 13.8; $p > 0.05$), while decreases in SV were significant for 40% (117.6 ± 17.5 versus 101 ± 20.6 mL), 60% (119.4 ± 16.1 versus 120.9 ± 21.3 mL), 70% (119.1 ± 11 versus 95.6 ± 15.3 mL), 80% (117.9 ± 13.5 versus 115.7 ± 19.5 mL), 90% (119.3 ± 12.4 versus 110.1 ± 15.6 mL) and 100% (116.9 ± 13.5 versus 108.7 ± 10.8 mL) of VO_{2max} ($p \le 0.05$). Mean peak SV responses in all exercise loads from 40-100% of VO_{2max} were also higher during exercise than recovery (122.9 ± 2.5 versus 105.3 ± 5.93 mL). In addition, SV_{peak} levels were highly correlated with $\dot{V}O_{2max}$ (r = 0.82).

Discussion

This is the first study to evaluate SV responses from exercise to recovery in a wide range of workloads from 40 to 100% of VO_{2max}. If our assumption i.e. SV responses are greater during recovery than during the loading period of exercise, had been confirmed in this study, then we would have also assumed that a high number of rest periods in interval training may yield higher SV responses throughout exercise. Instead, greater SV responses were observed in loading phases and dramatically decreased during recovery periods ($p \le 0.05$). Interestingly, SV did not significantly decrease from the end of exercise to recovery for only 50% of VO_{2max} ($p > 0.05$).

It has been speculated that peak SV

responses appear during recovery after exercise. Although there are a few currently available experimental studies focused on SV responses during various exercises and succeeding recovery periods (Burr et al., 2015; Stanley and Buchheit, 2014), only three studies found significantly greater SV responses during recovery periods than during exercise (Cumming, 1972; Goldberg and Shephard, 1980; Takahashi et al., 2000). However, two of these studies were on exercise in the supine position, and they did not refer to upright exercises. Only Goldberg and Shephard (1980) reported greater SV responses during recovery rather than during exercise in the upright position. Moreover, Buchheit and Laursen (2013) speculated that SV reached a peak level during the recovery periods of high intensity intervals in well-trained cyclists based on an unpublished data obtained by impedance cardiography (Buchheit and Laursen, 2013). Therefore, we decided to re-analyze SV responses to exercise and recovery in the upright position by well-trained athletes.

Recent reports have highlighted that interval training at various intensities and repetition numbers may yield higher SV responses compared to continuous loading during training sessions (Daussin et al., 2007; Helgerud et al., 2007).

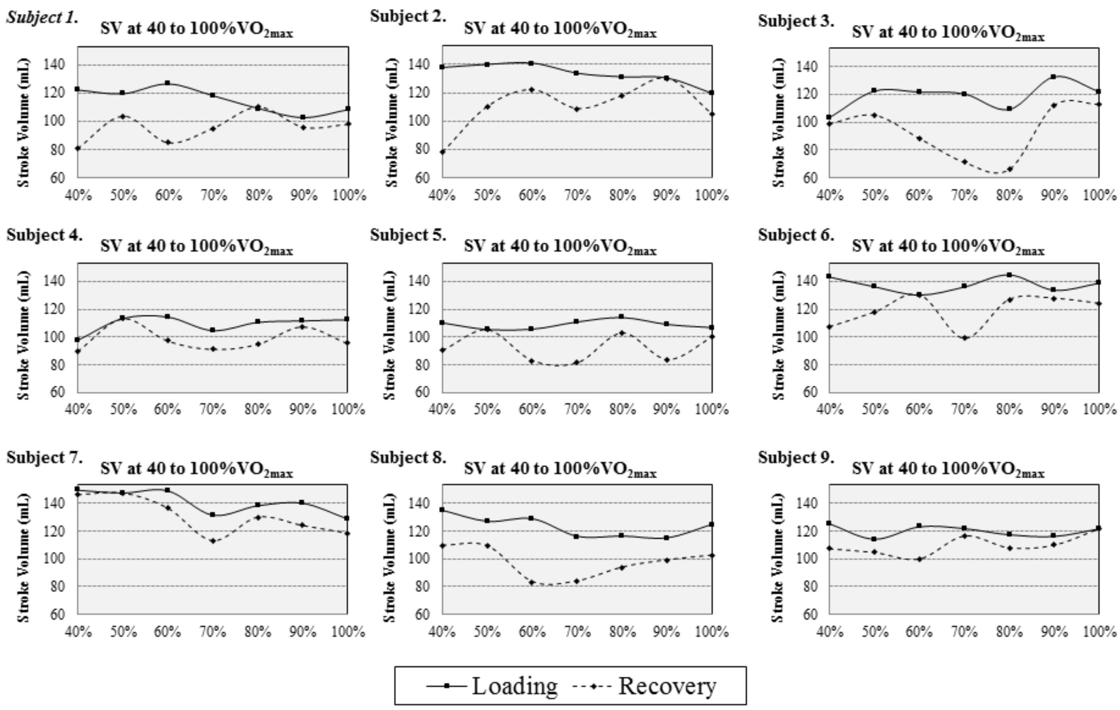

Figure 1

Individual SV responses of the nine participants observed from the loads of 40-100% VO_{2max} during loading and recovery sessions

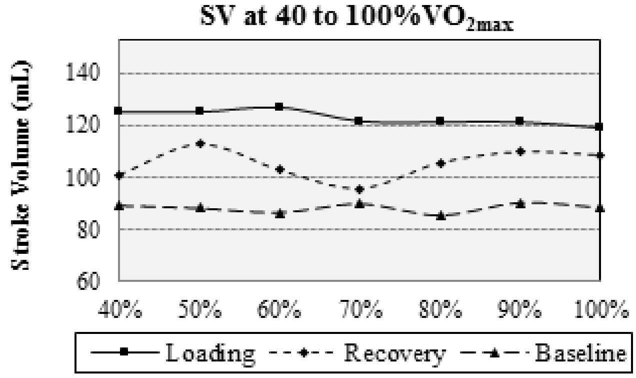

Figure 2

Mean SV responses of loading and recovery sessions observed from the loads of 40-100% $\dot{V}O_{2max}$

Main training modalities focused on VO_{2max} development are short and long intervals corresponding to 90-105% of VO_{2max}. Moreover, interval training models, including high intensity interval training (~120% of VO_{2max}) and sprint interval training (~150-160% of VO_{2max}), resulted in greater velocities than 105% of VO_{2max}, with 1:4 to 1:10 loading-to-rest ratios possibly inducing high SV development while causing sufficient peripheral adaptations in skeletal muscles (Burgomaster et al., 2005; Daussin et al., 2007). Comparison of the data obtained from the aforementioned studies with our data shows that SV responses to exercise are higher than during recovery; therefore, it can be considered that SV development obtained by maximal and supra-maximal exercises is related to exercise duration or intensity more than recovery. Studies on VO_2 kinetics have shown that the increase in oxygen uptake during the first 20 s of exercise results solely from the pulmonary blood flow (Jones et al., 2003) which stems from increased cardiac output. On the other hand, the second phase of O_2 kinetics is related to an increased oxygen demand of active muscles (Grassi, 2000) which reach a steady state in two to three minutes during submaximal exercises. Thus, short intervals seem to be more effective in the central component of VO_{2max} than long intervals and continuous exercises. These findings indicate that higher SV improvement after interval training instead of continuous exercises may be related to an increased number of recovery periods, while longer ones may have a higher potential to improve muscle oxygenation (Colakoglu et al., 2015).

Although short and long intervals focused on VO_{2max} development usually correspond to loads of VO_{2max}, SV_{peak} responses do not always equal VO_{2max}. It has been shown that SV_{peak} levels of moderately trained athletes are usually in the range of 40-80% of VO_{2max} (Vella and Robergs, 2005). It has been recently reported that before peripheral exhaustion, the brain limits myocardial functions to prevent heart damage (Noakes et al., 2001; St Clair Gibson et al., 2001). Since this limitation is regulated by a SV decrement (Gonzalez-Alonso and Calbet, 2003; Noakes, 1998; Noakes and Gibson, 2004), the decrease may adversely affect the training capacity of athletes. Indeed, it was shown that most participants had peak SV responses between 40-60% of VO_{2max}

(n=6) rather than higher exercise loads (n=3). Therefore, in addition to exercise duration, exercise intensity corresponding to individual SV_{peak} also seems to be related to VO_{2max} development. Indeed, the SV_{peak} distribution throughout the examined exercise loads indicated a high correlation between SV_{peak} (mL) and VO_{2max} (VO_2 mL•min^{-1}). It seems that the greater the SV_{peak}, the higher the level of VO_{2max}. Unfortunately, it is not possible to measure real-time and continuous Qc data by the N_2O_{RB} method. The shortest interval between repeated measurements should be 2-3 minutes, since Innocor needs approximately 2-3 minutes for washout of inert gasses (N_2O and SF_6) for the same individual. For this reason, Qc data was not continuously analysed throughout loading and recovery phases.

Conclusion

This is the first study to evaluate SV responses from exercise to recovery in a wide range of workloads between 40 and 100% of VO_{2max}. Peak SV responses corresponding to 40-70% of VO_{2max} were obtained in the 5th and 7.5th min of exercise, while in the 3rd min these values reached 80-100% of VO_{2max}. During recovery periods, SV responses declined. In conclusion, SV does not reach peak value during recovery compared to exercise at submaximal and maximal intensities in moderately trained athletes. Beside exercise duration, exercise intensity yielding individual SV_{peak} response seems to be related to aerobic power development. On the other hand, SV_{peak} levels were highly correlated with $\dot{V}O_{2max}$.

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