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ORIGINAL ARTICLE

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Effect of an acute period of resistance exercise on excess post-exercise oxygen consumption: implications for body mass management

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Abstract Studies have shown metabolism to remain elevated for hours following resistance exercise, but none have gone beyond 16 h, nor have they followed a whole body, high intensity exercise protocol. To examine the duration of excess post-exercise oxygen consumption (EPOC) following a period of heavy resistance exercise, seven healthy men [mean (SD) age 22 (3) years, height 177 (8) cm, mass 83 (10) kg, percentage body fat 10.4 (4.2)%] engaged in a 31 min period of resistance exercise, consisting of four circuits of bench press, power cleans, and squats. Each set was performed using the subject's own predetermined ten-repetition maximum and continued until failure. Oxygen consumption ($\dot{V}O_2$) measurements were obtained at consistent times (34 h pre-, 29 h pre-, 24 h pre-, 10 h pre-, 5 h pre-, immediately post-, 14 h post-, 19 h post-, 24 h post-, 38 h post-, 43 h post-, and 48 h post-exercise). Post-exercise $\dot{V}O_2$ measurements were compared to the baseline measurements made at the same time of day. The $\dot{V}O_2$ was significantly elevated ($P < 0.05$) above baseline values at immediately post, 14, 19, and 38 h post-exercise. Mean daily $\dot{V}O_2$ values for both post-exercise days were also significantly elevated above the mean value for the baseline day. These results suggest that EPOC duration following resistance exercise extends well beyond the previously reported duration of 16 h. The duration and magnitude of the EPOC observed in this study indicates the importance of future research to examine a possible role for high intensity resistance training in a weight management program for various populations.

Keywords Metabolic rate · Elevated post-exercise oxygen consumption · Energy expenditure

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Introduction

The purpose of the current research was to determine whether a period of resistance exercise would significantly elevate post-exercise $\dot{V}O_2$ during the 48 h following the exercise. Several physiological responses appear to contribute to this excess post-exercise oxygen consumption (EPOC). During steady-state, aerobic exercise, the body responds to increased energy demands by raising heart rate, stroke volume, and pulmonary ventilation. The subsequent rise in body temperature, as well as ionic disturbances and increased plasma catecholamine concentrations are believed to be linked to EPOC (American College of Sports Medicine, ACSM, 1998). In addition to the explanations proposed for steady-state exercise, the short bursts of energy characteristic of non-steady-state activities require anaerobic metabolic pathways. These pathways include the degradation of adenosine triphosphate (ATP) into adenosine diphosphate (ADP), the transfer of phosphate from phosphocreatine to ADP in order to recreate ATP, and the breakdown of glucose into pyruvic acid, which in the absence of oxygen becomes lactate. Following anaerobic exercise, the body requires oxygen for lactate disposal and rephosphorylation of creatine and ADP (ACSM 1998). Additionally, homeostatic imbalances of hormones (McMillan et al. 1993) or protein degradation and reparation also take place (Clarkson and Sayers 1999; Kuipers 1994). The EPOC is probably due to a combination of the aforementioned, but the significance of each factor is unknown.

Several studies have examined the EPOC of aerobic exercise with variable results. Many of the studies indicated that oxygen consumption ($\dot{V}O_2$) remained elevated for less than 60 min (Brehm and Gutin 1986; Kaminsky et al. 1987; Maresh et al. 1992; Sedlock et al. 1989; Short and Sedlock 1997) following cardiovascular exercise. Conversely, several other studies found EPOC to continue for 7.5–12 h (Bahr et al. 1987; Chad and Wenger 1988; Gore and Withers 1990; Laforgia et al. 1997; Maehlum et al. 1986). Although exercise intensity and duration are commonly implicated as causes for EPOC, they do not fully account for this discrepancy, because studies using similar intensities and durations have often produced contradictory results. Therefore, the entire range must be considered when comparing results of aerobic exercise to those of resistance exercise.

As with aerobic exercise, the duration of EPOC following resistance exercise varies in the literature. Some studies found EPOC to return to normal within 60 min (Elliot et al. 1992; Haltom et al. 1999; Melby et al. 1992) whereas others found $\dot{V}O_2$ to remain elevated for 14 h or more (Gillette et al. 1994; Melby et al. 1993; Osterburg and Melby 2000). However, in the case of resistance exercise, it appears that the intensity of the exercise is very influential in determining the duration of EPOC. The study that found EPOC to continue for several hours used a load that could be moved for a maximum of 8–12 repetitions, which is characteristic of a program designed for muscle hypertrophy (Stone et al. 1981). Other studies indicating a much more attenuated EPOC response used resistance exercise protocols emphasizing local muscle endurance (Elliot et al. 1992; Haltom et al. 1999; Melby et al. 1992) or muscle strength (Elliot et al. 1992). Therefore, it appears that the same damage and hormone mechanisms that lead to muscle hypertrophy may cause enough homeostatic disruption to maximize EPOC.

The magnitude and duration of EPOC have been identified as important components of a successful weight loss program. None of the previous investigations involving resistance exercise that found metabolism to be elevated for 14 h or more were able to determine at what point $\dot{V}O_2$ returned to baseline values. Therefore, the purpose of this study was to quantify the duration of EPOC following a very high intensity resistance exercise program designed for muscle hypertrophy.

Methods

Subject characteristics

Seven men volunteered to participate in the present study following in-class recruitment at the University of Wisconsin – La Crosse. All subjects had been weight training regularly (3–4 times a week) for a minimum of 6 months and denied using anabolic supplements prior to or during the study. They also were free from any known injuries or illness that could inhibit lifting performance or metabolism. Selected characteristics of the subjects are presented in Table 1. To ensure the safety of the subjects, all treatments involved in this study were examined and approved by the University of Wisconsin-La Crosse Institutional Review Board (IRB). In accordance with IRB guidelines, all subjects read and signed an informed consent form prior to participation.

Study design

The design of the study is summarised in Fig. 1. Data was collected over a 3 week period. Tests for 1 and 10 repetition maximum (RM) bench press, power cleans, and squats were conducted first, followed by a familiarization trial of the lifting protocol. To avoid any residual metabolic effects of the 1RM tests and the familiarization period, no further treatments were conducted during the subsequent 2 weeks. During the last 4 days of this 2 week respite and for the remainder of the study, subjects were required to refrain from any physical activity additional to the activities of daily living. Measurements of $\dot{V}O_2$ were then made three times daily, each preceded by a 4 h fast to prevent an interaction with the thermogenic effect of food. All measurements were also preceded by 30 min of supine rest, except the evening measurement of the 2nd day. In that instance, the resistance exercise protocol, consisting of four circuits of bench press, power cleans, and squats, was used in place of the habituation period. The $\dot{V}O_2$ measurements were taken at 34, 29, 24, 10, and 5 h pre-exercise, as well as immediately after and 14, 19, 24, 38, 43, and 48 h post-exercise.

1 RM Protocol

Maximal strength (1 RM) was assessed for the bench press, power cleans, and parallel squats. However, it is difficult to determine absolute strength in power movements, because technique tends to fail before the limit of muscle strength is attained. Due to this relative inaccuracy, weight selection was conducted using a 1 RM protocol similar to that outlined by McBride et al. (1999). First, a theoretical 1 RM was estimated for each subject as a function of body mass. Subjects then performed several warm-up sets based on 40% (8 repetitions), 60% (4 repetitions), 80% (2 repetitions), and 90% (1 repetition) of that theoretical 1 RM. Following execution of one repetition with that weight, the resistance was adjusted according to performance on this first lift. Increments and decrements of five or ten pounds were used at the discretion of the experimenter. After a 3 min rest, each subject performed a further single repetition trial with the new weight. This pattern continued until the subject was unable to complete a single repetition of the lift with good form. The subject's 1 RM was considered to be the weight used on the last successful trial.

10 RM Protocol

Following determination of the 1 RM, a theoretical 10 RM was approximated using 80%, 70%, and 75% of 1 RM for the bench press, power clean, and squat, respectively. Using these 10 RM estimations, the subjects familiarized themselves with the lifting protocol by performing four circuits of these exercises. Each lift was performed until failure, and 2 min rests were given between sets. Loads were adjusted after each set to maintain 10 repetitions on subsequent sets.

Table 1 Selected anthropometric data of the subjects ($n=7$)

Variable	Mean (SD)	Range
Age (years)	22 (3)	19–26
Height (cm)	177 (8)	167–193
Body mass (kg)	83 (10)	73–104
Body composition (% body fat)	10.4 (4.2)	7.0–19.3

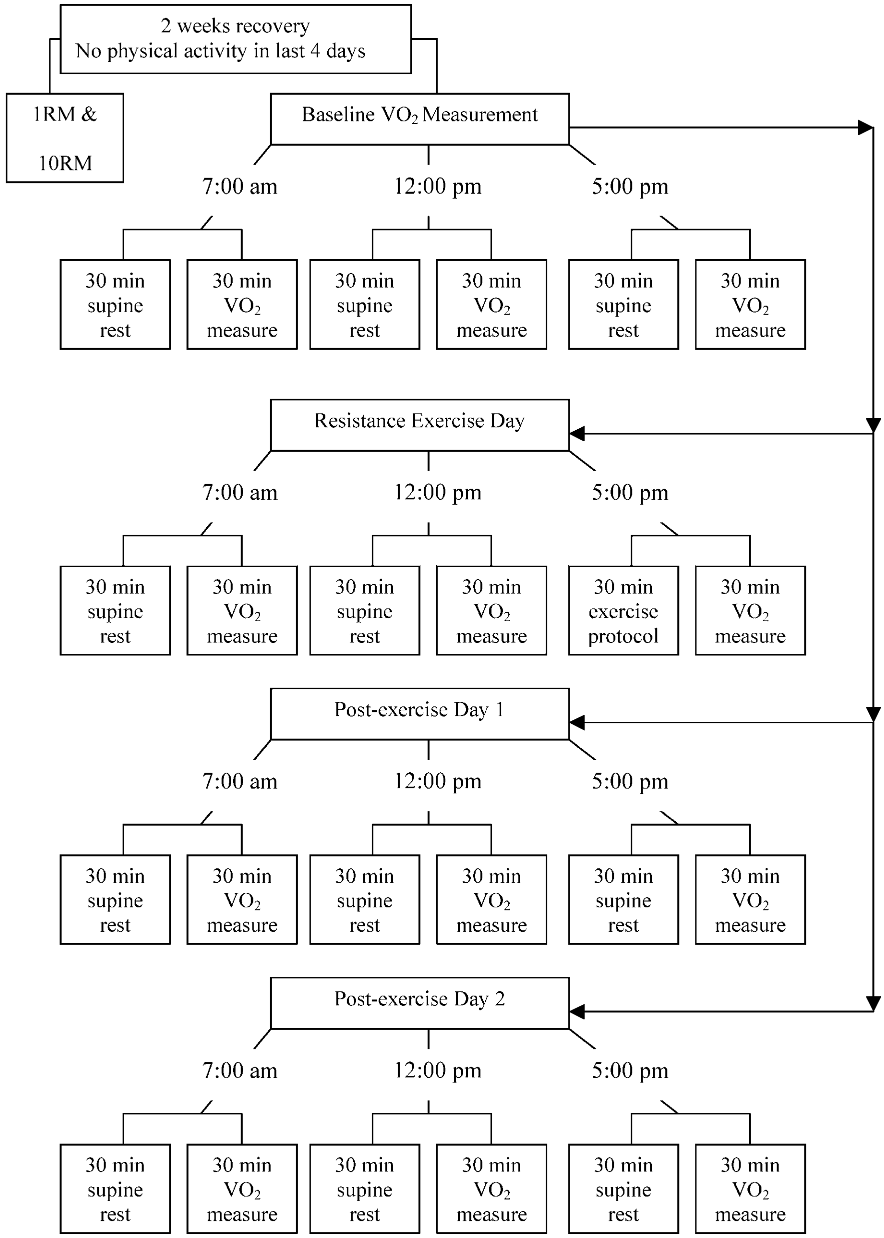

Fig. 1 Design of the study. $\dot{V}O_2$ Oxygen consumption, *RM* repetition maximum

$\dot{V}O_2$ Measurement

Baseline and post-exercise $\dot{V}O_2$ measurements were made in the University of Wisconsin-La Crosse Human Performance Laboratory using a Quinton metabolic cart (Quinton Instruments Co., Seattle, Wash.). Prior to each $\dot{V}O_2$ measurement, the cart was calibrated by entering ambient room temperature, barometric pressure, and relative humidity. Calibration also entailed injection of 1 l of a known gas mixture into the pneumotachometer. Prior to the tests, the subjects rested supine for 30 min. At the end of this period, the subjects were fitted with a facemask, that covered both the nose and mouth, to collect expired air and deliver it to the metabolic cart for analysis. Segal (1987) compared this facemask technique to the ventilated hood as a means of indirect calorimetry and found no significant differences. Throughout the 30 min of rest 1 min averages of $\dot{V}O_2$ were obtained. Each day, $\dot{V}O_2$ measurements were conducted at 5 h intervals (morning, midday, and evening), 14 h separating evening measurements from those of the following morning. This protocol was used for all baseline and post-exercise $\dot{V}O_2$ measurements, except for that immediately following the exercise protocol.

Resistance exercise protocol

On the 2nd day, in place of their evening rest period, the subjects gathered at the Mitchell Hall Strength Center (University of Wisconsin-La Crosse) to perform the weight lifting protocol. The session consisted of four sets on each of three lifts (bench press, power cleans, and parallel squats) in circuit formation. A 2 min rest was allowed between exercises. The resistance for each lift was set at the subject's predetermined 10 RM, and each set continued until the subject could not perform any more repetitions. Most subjects completed 8–12 repetitions before failure. In the case that a subject was unable to perform 10 repetitions, the resistance was lowered for subsequent sets. Similarly, if subjects performed more than 10 repetitions, the resistance was increased accordingly. Table 2 outlines the average intensity (percentage 1 RM) and number of

Table 2 Mean (SD) repetitions and intensity during the resistance exercise protocol. *% 1 RM* Percentage of one repetition maximum

Exercise	Trial	1	2	3	4
Bench press	Repetitions	10.8 (1.9)	9.0 (1.2)	8.0 (1.1)	9.2 (1.0)
	Intensity (% 1 RM)	73.6 (5.4)	73.8 (5.5)	72.6 (5.8)	70.4 (4.5)
Power cleans	Repetitions	12.2 (2.8)	8.8 (2.8)	8.4 (1.3)	9.6 (1.6)
	Intensity (% 1 RM)	74.6 (3.4)	78.7 (7.9)	73.1 (4.1)	73.0 (2.9)
Squats	Repetitions	10.8 (2.4)	8.0 (2.5)	8.8 (1.1)	10.0 (1.3)
	Intensity (% 1 RM)	77.7 (4.1)	77.4 (6.2)	76.5 (7.6)	75.6 (7.4)

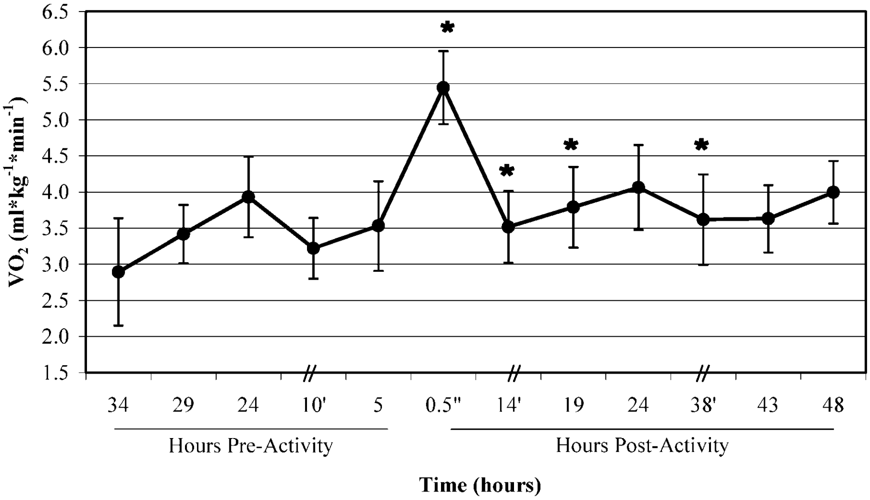

Fig. 2 Mean oxygen consumption ($\dot{V}O_2$) throughout the research protocol. *Significance ($P < 0.05$) over the baseline value for the corresponding time of day. *On the x-axis* the symbol ′ appearing after the hour denotes a 14 h overnight gap in measurement, and the symbol ″ denotes the beginning of post-exercise measurements

repetitions for each set during the workout. Throughout the weight lifting session, subjects were supervised to ensure a proper technique. This was done to minimize the risk of injury and to avoid cheating, such as arching the back or bouncing the bar. During this exercise session, subjects were allowed to consume water as desired between sets. Upon completion of the final set, the subjects were quickly returned to the Human Performance Laboratory to begin a post-exercise $\dot{V}O_2$ measurement. Due to subject transport and instrument preparation, approximately 5 min elapsed between the end of the last lift and the initiation of the 30 min metabolic measurement.

Statistical analysis

Prior to statistical analysis, outliers, identified as data with a Z-score greater than or equal to 3, were removed. Baseline and exercise $\dot{V}O_2$ and respiratory exchange ratio (R) data were then compared using a repeated measurements ANOVA (treatment×time) with specialized contrasts. Mean daily $\dot{V}O_2$ for pre- and post-exercise days were analysed using a single factor repeated measurements ANOVA, with a Scheffé F-test post-hoc comparison. Significance was set at $P < 0.05$.

Results

The comparison of pre- and post-exercise measurements at corresponding times of day revealed that significant ($P < 0.05$) differences existed between the morning baseline (34 h pre) and both mornings following the exercise (14 and 38 h post-exercise). The 19 h post-exercise measurement also differed significantly from the corresponding baseline time (29 h pre-). The only evening measurement that revealed a significant difference occurred immediately after the weight lifting session (Fig. 2). The R was found to be significantly lower than the baseline values immediately post-exercise ($R = 0.79$, 24 h pre $R = 0.89$) and 43 h post-exercise (43 h $R = 0.84$, 29 h pre $R = 0.90$).

The baseline measurements revealed a constant increase throughout the day. This was probably due to an accumulation of the effects of the activities of daily living, emotions, and circadian rhythms. During the morning baseline measurement, the subjects had been awake for only a short period, and therefore, they were all at a relatively low level of stimulation. However, as the day progressed, the subjects would all have experienced varying levels of physical and emotional stimulation. They were asked to keep this stimulation to a minimum, but a certain amount was unavoidable. As a result, there was likely to be more between subject variation as the day progressed, which made it more difficult to show significant differences. Therefore, the mean $\dot{V}O_2$ of each day was calculated by averaging the three measurements. Daily mean $\dot{V}O_2$ data are presented in Fig. 3. A comparison of these values revealed significant differences between the baseline and both post-exercise days ($P < 0.05$).

Discussion

The most noteworthy finding in this investigation was that $\dot{V}O_2$ following a strenuous period of heavy resistance exercise remains significantly elevated even at

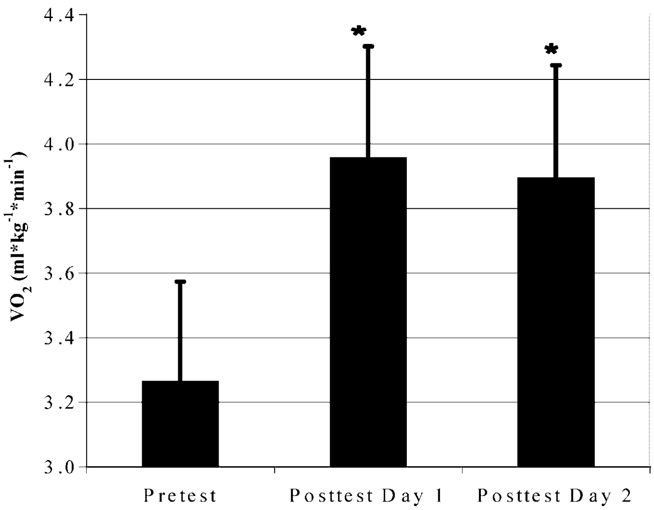

Fig. 3 Mean daily oxygen consumption ($\dot{V}O_2$). Both post-test days were significantly different ($P < 0.05$) than the baseline day. *Error bars* indicate standard deviation

39 h post-exercise. The mean $\dot{V}O_2$ for the 1st and 2nd days following the weight lifting session were also both significantly elevated above the mean of the baseline day. These findings parallel the results of Gillete et al. (1994), Melby et al. (1993), and Osterberg and Melby (2000) in which metabolism was found to be significantly elevated at 15, 14.5, and 16 h post-resistance exercise, respectively. It is important to note that these times are not when $\dot{V}O_2$ returned to baseline, but rather were at pre-determined times set by the investigators. Similarly, several other studies (Haltom et al. 1999; Burleson et al. 1998; Olds and Abernethy 1993) are not contradicted by the present findings. However, none of these studies continued data collection for more than 90 min following the resistance exercise, and therefore did not speak as to the duration of EPOC. Results from the present study are in disagreement with the Elliot et al. (1992), Haltom et al. (1999), and Olds and Abernethy (1993) studies, which found that $\dot{V}O_2$ had returned to baseline within 1 h. This may be due to variations in the intensity and duration of the different resistance exercise protocols.

The present results suggest that the energy required to recover from resistance training may be significant to a body mass management program. For the first 24 h period following exercise, the mean difference between baseline $\dot{V}O_2$ and that of post-exercise was 0.69 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$. Similarly, the second 24 h period following exercise showed a 0.63 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$ mean difference over baseline. This equates to 21.2% and 19.3% increases in metabolism for those 2 days, respectively. Assuming that an individual will burn 4.9 kcal·l $O_2^{-1}$and using the mean body mass of 83 kg, these mean differences equate to 404 kcal and 369 kcal increases per day, respectively, for these subjects. This equates to 773 kcal expended post-exercise, not including the amount of O_2 consumed between immediately post- and 14 h post-exercise (the high immediately post-exercise value would have overestimated $\dot{V}O_2$ over that time period). However, with the relatively few data collections throughout each day, we cannot be sure that the subjects' $\dot{V}O_2$ was consistently elevated. Therefore, these calculations are only estimations.

It is important to note that most resistance training studies that found $\dot{V}O_2$ remains for 14 or more hours, used a similar lifting protocol of eight to ten exercises for four or more sets, each set to failure with a load that could be lifted for 8–12 repetitions. Conversely, the studies that did not show a lasting EPOC were either using very low resistances such as the 50% of 1 RM (Elliot et al. 1992; Haltom et al. 1999) or very heavy loads that could only be moved for 3–6 repetitions (Elliot et al. 1992). Therefore, it appears that data from the current study supports our initial hypothesis that maximized post-exercise metabolic costs would occur as a result of resistance programs designed to enhance muscle hypertrophy.

Possible explanations for this may include the additional exercise duration required to perform 8–12 repetitions characteristic of muscle hypertrophy program designs relative to the 1–6 repetitions that characterize a strength training program (Stone et al. 1981). However, exercise duration alone cannot explain the entire increase in EPOC duration, because studies conducted on circuit weight training with up to 15 repetitions have not shown EPOC for longer than 60 min (Haltom et al. 1999). It appears that there is an optimal combination of intensity and duration in order to maximize EPOC with resistance exercise. From the current research, it appears that a 10 RM protocol, utilizing 2 min rest periods, may optimize post-exercise metabolism. Furthermore, this study has shown that an extended EPOC duration may be brought about by as few as four sets of three structural exercises. This indicates that it is unimportant whether several isolation exercises or fewer multi-joint structural exercises are used, as long as the major muscles groups are exhausted.

Of the studies examining EPOC and resistance exercise, none examined blood concentrations of catecholamines, lactate or anabolic hormones. However, elevated concentrations of these variables after a 10 RM, 2 min rest protocol have been reported in the literature (Hatta et al. 1989; McBride et al. 1998; 1999; McMillan et al. 1993; Sherwood 2001). The excess $\dot{V}O_2$ may mark the initiation of the muscle repair process or the body's attempts to eliminate homeostatic disruptions. Plasma hormone concentrations (e.g. growth hormone and norepinephrine) increase immediately post-exercise and may increase metabolism by stimulating protein synthesis and preventing programmed cell death (Sherwood 2001). Norepinephrine, specifically, promotes $\dot{V}O_2$ by stimulating the dilation of bronchioles and blood vessels; it is also functional in increasing heart rate (Sherwood 2001). Both growth hormone and norepinephrine had returned to baseline concentrations within 90 min (McBride et al. 1999). Blood lactate concentrations are also elevated during weight lifting (Burleson et al. 1998). Removal of lactate is carried out, in part, via aerobic metabolism in the skeletal muscle, kidneys and heart (Hatta et al. 1989). Following this immediate reaction to exercise a biphasic inflammatory response is elicited, in which the damaged muscle is first degraded by phagocytes and then repaired (Clarkson and Sayers 1999; Kuipers 1994; McBride et al. 1998). All of these factors could contribute to EPOC after intense resistance exercise, as performed in this investigation.

An alternate explanation for the prolonged EPOC may be a shift in substrate use. In the present study, R values immediately and 43 h post-exercise were significantly lower than the baseline values corresponding to the same time of day. As R values approach $R=1$, a greater percentage of carbohydrates is being used; lower R values indicate a greater utilization of fat. Therefore, the present R values may reflect a shift towards lipid metabolism due to glycogen depletion. An alternative interpretation of the R results is that blood concentrations of free fatty acids (FFA) are significantly elevated 20 h post-exercise (McMillan et al. 1993), fueling speculation that resistance training elicits a shift towards FFA metabolism. The excess oxygen required for fat oxidation in the Krebs cycle may explain the present findings. That study also showed that FFA levels varied greatly based on training level, with FFA levels much higher in untrained subjects. While subjects in the present study were recreational lifters and not untrained, they were not accustomed to the intensity of this protocol and therefore may have responded in a similar manner.

In conclusion, resistance exercise has been linked to a daily mean $\dot{V}O_2$ that remains elevated for at least 48 h following a lifting protocol providing for a significant cumulative energy expenditure. Intense resistance exercise needs to be further investigated as to its efficacy in weight management in comparison to current guidelines for prescription of aerobic exercise. In addition, the role of resistance exercise in terms of its use in a physician-directed weight management program, in addition to its current use for muscle strengthening, needs to be investigated.

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