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Evaluation of the relationship between venous function and post exercise oxygen consumption recovery kinetics

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EVALUATION OF THE RELATIONSHIP BETWEEN VENOUS FUNCTION AND
POST EXERCISE OXYGEN CONSUMPTION RECOVERY KINETICS

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ABSTRACT

Excess post-exercise oxygen consumption (EPOC) has been attributed to metabolic, hemodynamic, neuroendocrine, and pulmonary factors. In one particular study, Barclay (*J Appl Physiol* 1986;61(3):1084-90) suggested that a lower rate of fatigue and hyperperfusion following a bout of exercise was due to a mechanism other than increased oxygen and substrate delivery. Interestingly, few studies have examined the influence of venous function on EPOC. The purpose of this study was to examine the relationship between measures of vascular function and EPOC. Measures of vascular function and VO_2 recovery kinetics were examined in 20 individuals [age=22 ± 2.41 yrs]. Nondominant forearm arterial inflow, venous capacitance and venous outflow were evaluated at rest and after 5 minutes of upper arm occlusion, using strain gauge plethysmography. VO_2 recovery kinetics was assessed using gas exchange analysis following a six-minute constant work rate protocol at 60 percent of VO_{2peak}, on a cycle ergometer. The average VO_{2peak} was 33.48 ± 8.22 ml/kg/min (Range: 18.7 to 46.1 ml/kg/min). Recovery half-time ($T_{1/2}VO_2$) and Tao were 17.01 ± 3.51 seconds and 54.45 ± 11.28 seconds, respectively. Resting inflow was 2.77 ± 1.51 ml/100ml/min, reactive hyperemic blood flow was 17.72 ± 3.65 ml/100ml/min, venous capacitance was 2.86 ± 0.72 percent, and venous outflow was 34.19 ± 10.03 ml/100ml/min. Bivariate correlations revealed significant associations between $T_{1/2}VO_2$ and the reactive hyperemic response (r=-0.48, p=0.03) and $T_{1/2}VO_2$ and venous outflow post-occlusion (r=-0.50, p=0.02). In conclusion, these findings suggest an important role of both the arterial and venous circulation on EPOC.

CHAPTER 1 – INTRODUCTION

Recent evidence clearly shows that heart-rate recovery immediately after exercise is a significant predictor of mortality (1-3). Consequently, there has been a re-emergence of studies that are focusing on recovery kinetics from exercise. Although the precise factors involved in recovery from exercise are not entirely understood, a vast amount of research has been conducted to investigate the contributors to the recovery period. In terms of heart-rate recovery, it appears that the autonomic nervous system is a major contributor to the magnitude of change in heart rate following exercise.

Oxygen consumption (VO_2) recovery kinetics has also been identified as a possible prognostic marker in several clinical populations (4, 5, 6). VO_2 recovery kinetics following a bout of exercise has been defined as the excess post exercise oxygen consumption (EPOC) (12). A.V. Hill (7-9) was the first to report on the post exercise phase, which was later termed "O_2 debt" (10). Hill attributed this period to the need to repay the metabolic requirement attained at the onset of exercise (7-9), which was termed "O_2 deficit" (10). Based on early investigations, the O_2 debt was hypothesized to result from the reconversion of lactate to glycogen during the recovery period (11). Subsequent investigations however, suggest that these explanations might be too simplistic to accurately describe this phenomenon (12).

Following the early studies by A.V. Hill, several additional factors have been found to contribute to the observed phenomenon of EPOC. These factors, summarized in Figure 1.1, include resynthesis of phosphocreatine in the muscle, lactate removal, restoration of muscle and blood oxygen stores, elevated body temperature, post-exercise elevation of heart rate and breathing, and elevated hormones (13).
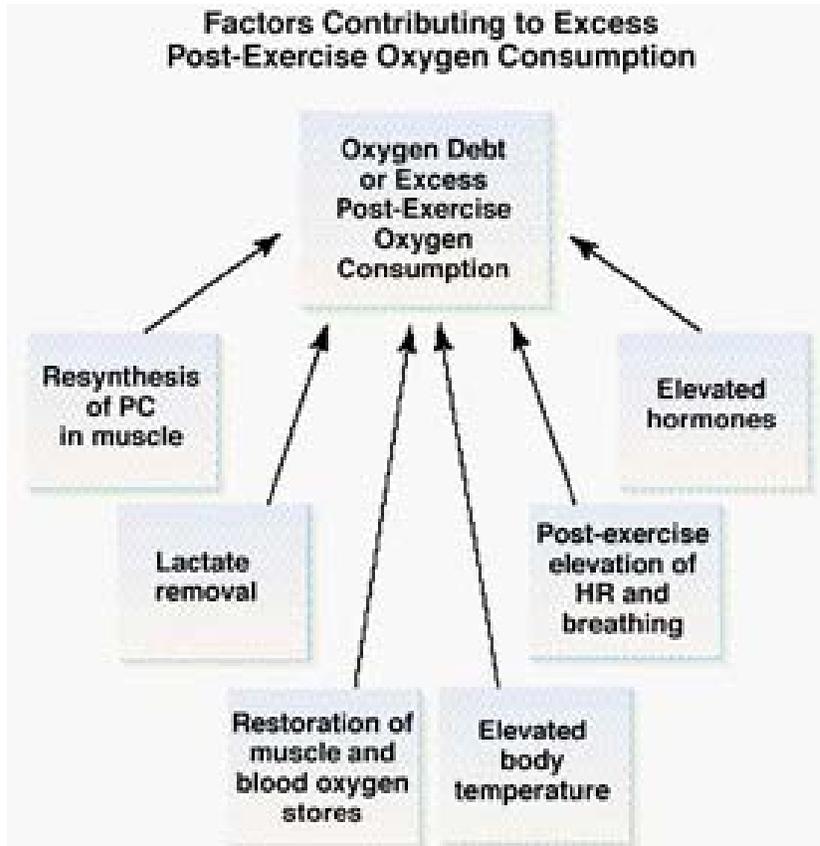
Figure 1.1. Factors That Contribute to EPOC.

VO_2 recovery kinetics is generally slower in individuals who are less fit (14), older (15), or those who have heart failure (16). In general, younger, fitter, and disease free individuals have significantly faster VO_2 recovery kinetics as compared to older, more unfit, or sicker cohorts (16-22). The apparent differences between fitter, healthier, and/or younger persons have been attributed to more efficient metabolic waste removal and replenishing systems (20, 22, 23).

For instance, Belardinelli et al. (20) suggested that a slower rate of recovery could reflect a slower rate of phosphocreatine resynthesis. Therefore, the early repayment of the O_2 debt is more likely to reflect rate of recovery of phosphocreatine and venous blood

oxygenation (20). Also, indirect control of mitochondrial respiration may be affected by a variety of factors, such as catecholemine levels, thyroxin, glucocorticoids, and the accumulation of other metabolic byproducts (12). These studies suggest that prolonged VO_2 recovery kinetics following a bout of exercise may have a large metabolic origin.

Interestingly, Barclay (23) reported that muscle fatigue characteristics were greatly affected by high flow versus low flow conditions, which were thought to be independent of oxygen and nutrient delivery. Given the improved fatigue characteristics with these high flow conditions, Barclay concluded that the effects were not due to an improved delivery of oxygen and substrate delivery, but were more than likely the result of enhanced removal of metabolic waste products (23). Furthermore, in a study by Van Beekvelt et al. (24), following a bout of heavy exercise, forearm blood flow was inadequate to meet the demands of metabolism and waste removal, which was indicated by a marked and prolonged post exercise hyperemia. This points toward an important vascular component in the recovery kinetics following exercise.

Study Purpose

Given the apparent interest in both metabolic waste removal and vascular function in VO_2 recovery kinetics, it is somewhat interesting that there are no apparent studies that have investigated the role of the venous system on EPOC. Therefore, the purpose of this study was to examine the possible relationship between measures of vascular function and VO_2 recovery kinetics. It is thought that such information may provide a greater understanding of the contributors to post exercise recovery. Furthermore, a link between the venous system and exercise recovery may ultimately provide a better understanding into the symptoms of chronic fatigue.

Hypothesis

Based on the results of previous investigations, we believe that individuals with higher values VO_2 will have faster recovery half-times, defined as $T_{1/2}VO_2$, following a single bout of exercise (17, 30). Moreover, based on previous work from this and other laboratories (25, 28), we believe that individuals with greater levels of VO_2 will also demonstrate better overall vascular function. Finally, we believe that measures of venous function will be inversely related to VO_2 recovery kinetics.

CHAPTER 2 – METHODOLOGY

Participants

Individuals between the ages of 18 and 26 were recruited for participation in this study. The participants were recruited primarily from laboratory classes within the Kinesiology department at Louisiana State University. Individuals with any unstable manifestations of cardiovascular, metabolic, orthopedic, or neurological disease, as well as any individuals taking medications (e.g., digitalis), which could affect the results of this study, were excluded from participation. Informed consent was obtained from each individual before participating in the study.

Procedures and Design

The study was an observational study involving three distinct visits. The first visit involved assessment of vascular function. This was accomplished using venous occlusion plethysmography (Hokanson EC-5R plethysmography system, Bellevue, WA) (25). The second visit involved an incremental maximal exercise test using a standard cycle ergometer (Monark). Breath-by-breath respiratory gas analyses (Sensormedics software, Yorba Linda, CA) were used to obtain measures of oxygen consumption, carbon dioxide production and pulmonary ventilation before, during and after exercise (26). The main purpose of this visit was to determine the individuals VO_{2peak}, which was used to determine the workload requirement for the final visit. The third and final visit of the study involved a constant workload exercise test for a period of 6 minutes, using the same cycle ergometer used for visit 2, performed at an intensity of 60% of the subjects VO_{2peak}. Throughout the exercise tests, heart rate, blood pressure and perceived exertion

were monitored using a polar heart rate monitor (Woodbury, NY), a sphygmomanometer, and a rating of perceived exertion scale (RPE Borg's 20-point scale), respectively (27).

In addition, the time period between visit 1 and visit 3 was no longer than two weeks, which was used to minimize any possible affects of training or detraining in the participant during the investigation. Furthermore, a recovery period of at least 48 hours was placed between visit 2 and visit 3 to make sure that the participant had adequately recovered from the incremental exercise test. The various measures obtained during each of the visits are presented in Tables 2.1 and 2.2.

Table 2.1. Vascular Function Assessments

Table 2.1. Visit 1	
Familiarization	1. Consent form 2. Height and weight measurements 3. Forearm circumference

Vascular Assessments	1. Resting Blood Flow
	    a. Resting forearm blood flow
	    b. Venous capacitance
	    c. Venous outflow
	2. Post-Occlusion
	    a. Reactive hyperemic blood flow
	    b. Venous capacitance post-occlusion
	    c. Venous outflow post-occlusion

Table 2.2. Exercise Protocols

Table 2.2. Visit 2 and Visit 3			
	Exercise Mode	**Description**	**Dependent Measures**
Symptom Limited Graded Exercise Test	Cycle Ergometer	Speed - 60 rpm Stages – 2 minutes Load - 30 W increments / stage	VO$_2$peak HRpeak Peak Workload
Submaximal Steady State Exercise Test	Cycle Ergometer	Speed - 60 rpm Duration – 6 minutes Intensity – 60% of VO$_2$peak	VO$_2$ HR Workload Recovery half times

Visit 1:

Forearm Circumference and Vascular Function Assessment

Following informed consent and a brief explanation of the procedures, a series of physical measurements were conducted. Forearm circumference was measured using a weighted measuring tape 10 cm distal to the midpoint between the lateral epicondyle and olecranon processes of the non-dominant arm. Following forearm measurement, indices of vascular function were obtained in the non-dominant forearm using a non-invasive technique by way of mercury-in-Silastic strain gauge plethysmography (25). Prior to the experiment, blood pressure cuffs were positioned around the participants' upper arm and wrist, and a mercury-in-Silastic strain gauge was placed around the forearm. Blood pressure was taken periodically throughout the protocol in the individuals' dominant arm.

Resting forearm vascular function measures were obtained following 10 minutes of rest in the supine position. Immediately before the resting measurements, hand circulation was occluded for one minute by inflating the wrist cuff to 240 mmHg. Forearm blood flow was then examined using an upper arm venous occlusion pressure of 7 mmHg below diastolic blood pressure. The venous occlusion pressure was held for a subsequent five-minute period, after which resting venous capacitance was measured. At

the end of the five-minute period, the upper arm cuff was rapidly deflated during which time the resting venous outflow was obtained (25).

The second part of the vascular function assessment involved total blood flow occlusion in the non-dominant arm for five minutes. This involved the inflation of the upper arm cuff to a pressure of 240 mmHg. Following four minutes of occlusion, the wrist cuff was inflated to 240 mmHg. After the fifth-minute of occlusion, the upper cuff was deflated to a pressure of diastolic blood pressure minus 7 mmHg, this allowed for the measurement of reactive hyperemic blood flow. Post-occlusion venous capacitance was also measured after holding the venous pressure for an additional five-minute period. Finally, the upper arm cuff was completely deflated allowing for the measurement of post-occlusion venous outflow (25). Blood pressure, heart rate, and electrocardiogram measurements were monitored prior to and during the procedure. The estimated contact time between the participant and the researcher for this visit was approximately one-hour, and was conducted in the morning, following at least 12 hours of restriction from food, alcohol, and nicotine consumption.

Visit 2:

Incremental Exercise Test (Maximal)

A cycle ergometer test was used to determine the individuals cardiorespiratory exercise capacity. Following a baseline or resting period of five minutes, the participant began pedaling at a speed of 60 revolutions per minute (rpm) with a resistance of 0 watts. Every two minutes the resistance was increased by 30 watts until the subject requested to stop, could not maintain a speed of 60 rpm, or exhibited signs or symptoms which required the termination of the test. During the exercise test, heart rate, blood pressure,

and ratings of perceived exertion were obtained at the end of each minute using a standard sphygmomanometer, Polar (Woodbury, NY) heart rate monitor, and Borg's perceived exertion scale (RPE, Borg's 20-point scale) (27), respectively. Following the test, heart rate, and blood pressure were monitored for 10 minutes. The estimated contact time between the participant and the researcher was 45 to 60 minutes for this visit.

Visit 3:

Constant Work Rate Exercise Test (Submaximal)

This visit consisted of a single constant work rate exercise test on a cycle ergometer. The workload used for the test was 60% of the subjects VO_{2peak} determined from the maximal test, which was administered in visit 2. The VO_{2peak} was determined from a 30-second average at the end of the maximal test. Prior to the constant work rate test, baseline measures were obtained for five minutes. After this period, the subject began pedaling at the pre-calculated submaximal intensity for six-minutes. After the six-minute exercise protocol, which was modeled after Belardinelli et al. (18), the participant was monitored for a 10-minute recovery period.

Throughout the test, breath-by-breath respiratory gases and volumes were measured. In addition, heart rate (Polar, Woodbury, NY), and ratings of perceived exertion were obtained at the end of each minute throughout the test using a standard sphygmomanometer and Borg's perceived exertion scale (20-point, RPE) (27), respectively. Following the test, heart rate, and blood pressure were monitored for the 10-minute recovery period. The estimated contact time between the participant and the researcher for this visit was approximately 45 minutes.

Data Analysis

Indices of vascular function were reported in terms of resting forearm blood flow, reactive hyperemic blood flow, venous capacitance, venous capacitance post-occlusion, venous outflow, and venous outflow post-occlusion. Measurements of VO_2 recovery kinetics were assessed as half-time of oxygen consumption ($T_{1/2}VO_2$) and Tao.

Arterial Indices

Resting forearm blood flow was recorded at a paper speed of 5 mm/sec and values were derived from the slope drawn at a best-fit tangent using the first three pulses. Calculations were made as a function of 60 seconds divided by the horizontal distance (mm) needed for the slope to rise vertically from baseline to the top of the recording paper and multiplied by the full chart range. Reactive hyperemic blood flow was recorded at a paper speed of 25 cm/sec. Analyses were performed using a slope drawn at a best-fit tangent to the curves of the first two pulses of the flow curve post cuff release. The blood flows were then calculated from 60 seconds multiplied by the paper speed (25 cm/sec) divided by the horizontal distance (mm) needed for the volume slope to increase by 20 mm vertically (25).

Venous Indices

Venous capacitance was measured as the vertical distance measured (mm) representing the increase in forearm-volume graph after the designated period for venous filling. Analysis of venous outflow was derived from a tangent line that represents the vertical drop in volume-graph from the excursion line and drawn at 0.5 seconds and 2 seconds after the release of pressure from the upper arm cuff (25).

Oxygen Consumption Recovery Kinetics

The time course for the decrease in VO_2 following cessation of exercise was characterized by determining the time required to return 50 percent of the way from the VO_2 value obtained during the sixth-minute of exercise to the pre-exercise baseline value (17). Tao is also a measurement of the return to baseline values of VO_2, which is represented by the time it takes for VO_2 at the cessation of exercise to return to the resting value. The pre-exercise value for VO_2 was obtained during the 5-minute resting period.

Statistical Analysis

Values are reported as mean + SD. Pearson product moment correlations were used to assess the relationships of $T_{1/2}VO_2$ with VO_{2peak}, reactive hyperemic blood flow and venous outflow post-occlusion using the SPSS system. Also, participants were placed into groups on the basis of their VO_{2peak} to allow for a comparison of differences between individuals with higher and lower values of VO_2. The alpha level for this study was set a priori at $p < 0.05$.

CHAPTER 3 – RESULTS

Participant Characteristics

      Twenty adults (8 Men and 12 Women) between the ages of 18 and 26 years old participated in this study. Baseline characteristics for age, height, weight, systolic blood pressure (SBP_{rest}) and diastolic blood pressure at rest (DBP_{rest}), resting heart rate (RHR), and peak oxygen consumption (VO_{2peak}) are expressed in Table 3.1.

Table 3.1. Participant Characteristics.

	N	Minimum	Maximum	Mean	SD
Age (yrs.)	20	18.00	26.00	22.00	2.41
Height (cm)	20	157.00	185.00	170.12	9.08
Weight (kg)	20	52.00	118.00	69.98	16.52
SBP_{rest} (mmHg)	20	99.00	139.00	116.55	12.36
DBP_{rest} (mmHg)	20	57.00	89.00	69.60	8.80
RHR (bpm)	20	61.00	103.00	82.85	12.93
VO_{2peak} (ml/kg/min)	20	18.70	46.10	33.48	8.22

Vascular Function Assessments

      Indices of vascular function are shown in Table 3.2. The average for the resting forearm blood flow of the participants was 2.77 ± 1.51 ml/100ml/min and increased to 17.72 ± 3.65 ml/kg/min following upper arm occlusion (p=0.03). Venous capacitance at rest was 2.86 ± 0.72 and dropped significantly to 1.75 ± 0.87 ml/100ml/min following upper arm occlusion. Measurements of venous outflow were similar before and after upper arm occlusion.

Table 3.2. Indices of Vascular Function.

	N	Minimum	Maximum	Mean	SD
Resting forearm blood flow (ml/100ml/min)	20	1.36	7.50	2.77	1.51
Reactive hyperemic blood flow (ml/100ml/min)	20	12.63	23.63	17.72	3.65
Venous capacitance (%)	20	1.10	4.05	2.86	0.72
Venous capacitance post-occlusion (%)	20	0.70	3.35	1.75	0.87
Venous outflow (ml/100ml/min)	20	16.75	50.00	34.19	10.03
Venous outflow post-occlusion (ml/100ml/min)	20	16.21	56.60	36.25	11.32

Oxygen Consumption Kinetics

Values for VO_{2peak}, $T_{1/2}VO_2$, and Tao are expressed in Table 3.3 and figure 3.2. The VO_{2peak} of the participants in this study ranged from 18.7 to 46.1 ml/kg/min. The average submaximal VO_2 used during the six-minute continuous workload test was 20.29 ml/kg/min and the average workload was 95 W. The average $T_{1/2}VO_2$ for the participants was 17.01 sec and Tao was 54.45 sec.

Table 3.3. VO$_2$ Kinetics.

	N	Minimum	Maximum	Mean	SD
VO_{2peak} (ml/kg/min)	20	18.70	46.10	33.48	8.22
VO_{2sub} (ml/kg/min)	20	12.50	30.77	20.29	5.36
$T_{1/2}VO_2$ (sec)	20	7.36	23.32	17.01	3.51
Tao (sec)	20	24.00	76.00	54.45	11.28

Pearson Product Moment Correlations

Analyses of the associations between vascular function and VO_2 recovery kinetics are expressed in Table 3.4. These data show that there is a significant relationship between measures of venous outflow and exercise capacity (r=0.459, p=0.04) and the half-time of recovery (Venous outflow: r=-0.500, p=0.02; and Venous outflow post-occlusion: r=-0.484,

p=0.03). In addition, there was also a significant relationship between reactive hyperemic

blood flow and recovery half-time (r=-0.476, p=0.03), but not for reactive hyperemic blood

flow and VO$_{2peak}$. Furthermore, when we do partial correlations controlling for height, we

see similar associations for measures of vascular function and VO$_2$ recovery kinetics.

Figures 3.1, 3.2, and 3.3 represent the relationships between the half-time of recovery with

VO$_{2peak}$, reactive hyperemic blood flow, and venous outflow, respectively.

Table 3.4. Pearson Product Moment Correlations.

	Resting forearm blood flow	Reactive hyperemic blood flow	Venous outflow	Venous outflow post-occlusion	VO$_2$peak	Recovery 1/2 Time	Tao	Venous capacitance	Venous capacitance post-occlusion
Resting forearm blood flow (ml/100ml/min)	1.000								
Reactive hyperemic blood flow (ml/100ml/min)	.488*	1.000							
Venous outflow (ml/100ml/min)	.414	.680**	1.000						
Venous outflow post-occlusion (ml/100ml/min)	.229	.649**	.871**	1.000					
VO$_2$peak (ml/kg/min)	.519*	.212	.437	.459*	1.000				
Recovery 1/2 Time (sec)	-.323	-.476*	-.484*	-.500*	-.454*	1.000			
Tao (sec)	-.257	-.419	-.457*	-.437	-.446	.949**	1.000		
Venous capacitance (%)	.297	.682**	.782**	.654**	.178	-.320	-.278	1.000	
Venous capacitance post-occlusion (%)	.047	.573**	.504*	.570**	.023	-.349	-.304	.707**	1.000

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).
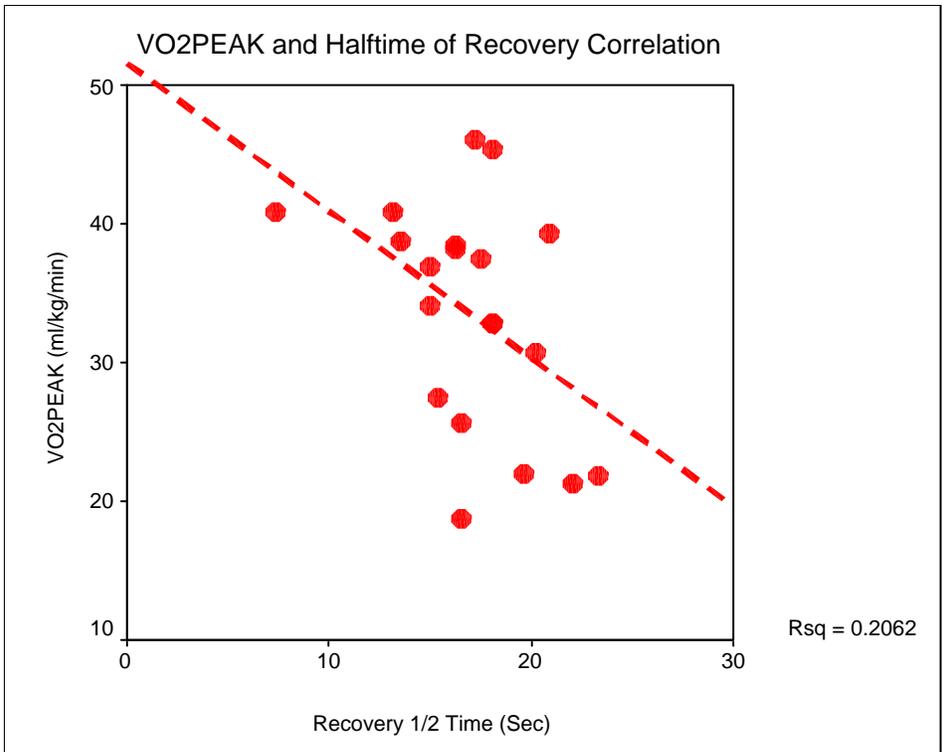
Figure 3.1. Relationship Between VO$_{2peak}$ and Half-time of Recovery.
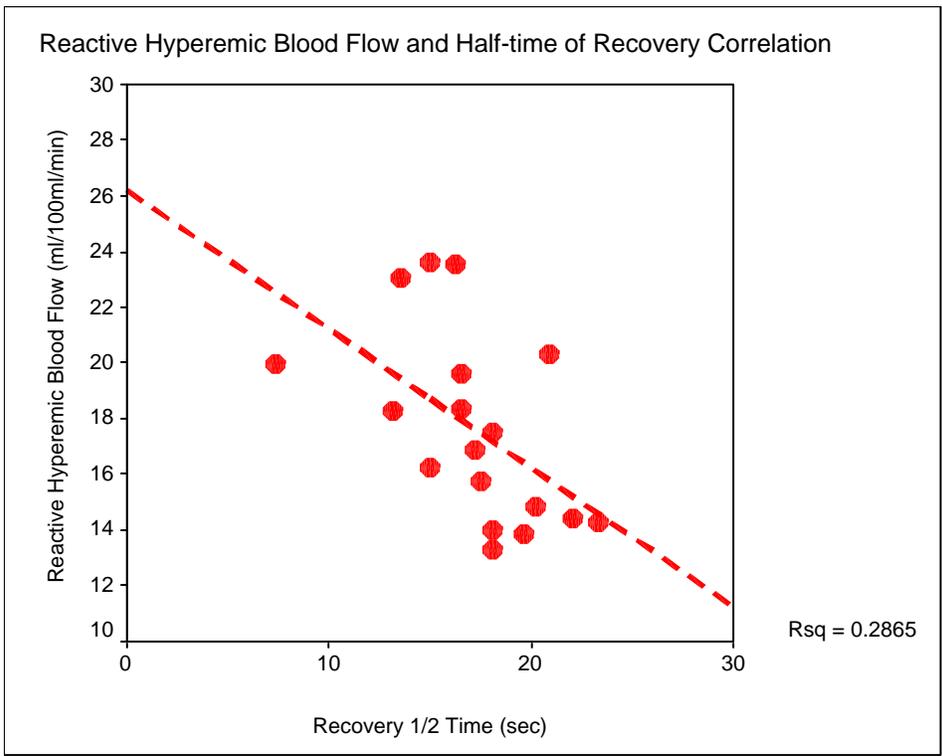
Figure 3.2. Relationship Between Reactive Hyperemic Blood Flow and Half-time of Recovery.
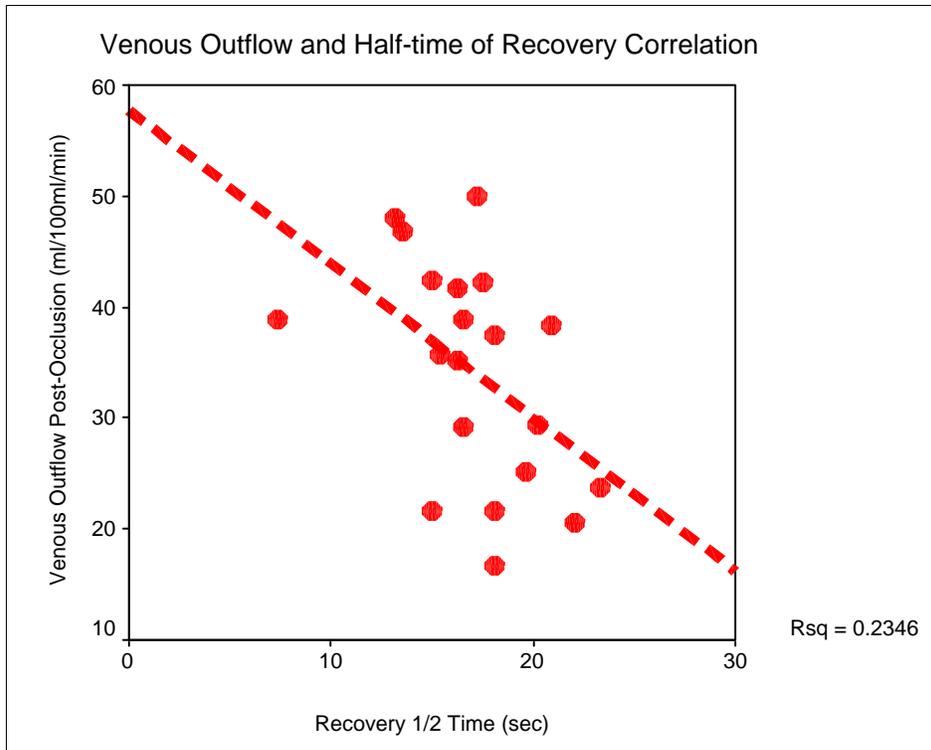
Figure 3.3. Relationship Between Venous Outflow Post-Occlusion and the Half-time of Recovery.

Differences Between Groups of High and Low VO_{2peak}

Further analyses amongst the participants allowed for the examination of the influence of fitness on recovery kinetics and vascular measures. The participants were separated in tertiles on the basis of their VO_{2peak} (Highest Fitness: VO_{2peak} >40 ml/kg/min; Lowest Fitness: VO_{2peak}<35 ml/kg/min). Subsequently, the highest and lowest tertiles were compared for differences. The results are shown in Table 3.5. The data show a significant difference between the $T_{1/2}VO_2$ of a group with higher compared to lower VO_{2peak} (High: 15.34 sec, Low: 19.11 sec; $p<0.01$). Moreover, significant differences for venous outflow and reactive hyperemic blood flow were also reported, between high and low VO_2 groups (High: 39.46 and 19.43 ml/100ml/min, Low: 28.96 and 15.4 ml/100ml/min; $p<0.05$).

Table 3.5. Differences Between Groups of High and Low VO_{2peak}

	Fitness	N	Mean	Std. Deviation
VO_{2peak} (ml/kg/min)	High	8	40.98*	3.08
	Low	7	23.96	4.15
$T_{1/2}VO_2$ (Sec)	High	8	15.34†	4.05
	Low	7	19.11	3.04
Tao (Sec)	High	8	49.50†	13.15
	Low	7	60.00	10.71
Venous Capacitance (%)	High	8	2.98	0.94
	Low	7	2.65	0.39
Venous Outflow (ml/100ml/min)	High	8	39.46*	10.55
	Low	7	28.96	6.55
Reactive Hyperemic Blood Flow (ml/100ml/min)	High	8	19.43*	3.38
	Low	7	15.40	2.44

* $P < 0.05$; † $P < 0.01$

CHAPTER 4 – DISCUSSION

The purpose of this study was to examine the relationship between measures of vascular function and post exercise recovery. Specifically, this study aimed at correlating measures of venous outflow with VO_2 recovery kinetics following a short constant work rate bout of exercise. The unique finding of this study is that measures of venous function are indeed associated with VO_2 recovery kinetics following a bout of exercise (r=-0.500, p=0.02). In addition, this study confirms previous findings that reactive hyperemic blood flow is also associated with VO_2 recovery kinetics. Finally, this study also indicates that individuals with higher VO_{2peak} appear to have greater venous function and faster VO_2 recovery kinetics.

Previous research has acknowledged the contribution of several factors to the magnitude of EPOC (11, 12, 13). However, the role of the venous system on VO_2 recovery kinetics has not been fully examined, despite evidence of the importance of metabolic waste removal from the exercising tissue beds. The importance of waste removal was previously suggested by Barclay (23), who observed a lower rate of fatigue in skeletal muscle that received high flow versus conditions of low flow, which was independent of oxygen content. The altered fatigue characteristics were thought to be due to a mechanism other than increased oxygen and substrate delivery. In fact, it was also suggested that the high flow condition through the tissue beds contributed to greater removal of metabolites, such as carbon dioxide, which contributed to a lower rate of fatigue (23). Thus, it would appear as though waste removal is an important factor in EPOC. In addition, the venous system, which is designed to remove waste products, could certainly affect these kinetics.

How Our Data Compare to Others

In terms of the vascular measures observed in this study, the data appears to follow the results of several studies from this and other laboratories (22, 25, 28). The reactive hyperemic blood flow values observed in this study also appear to be similar to those seen in groups from lower fitness categories (28, 29). Perhaps this reflects the overall fitness level of this group that on the basis of the VO_{2peak}, is considerably below the average for this age group. For example, it has been reported that VO_{2max} values for sedentary, young individuals is 45.0 ml/kg/min for males and 38.0 ml/kg/min for females (13), which are both higher than the average VO_{2peak} for the participants of this study.

The measures for venous function also appear to be similar to previous studies from this and other laboratories. For example, Alomari et al. (29) reported venous capacitances of 3.8 and 4.0 for lower and higher cardiovascular fitness groups of similar age. Moreover, the venous outflow measures for the lower fit participants (Venous outflow: 40.7±7.9) in Alomari's study are quite similar to those observed in the present study (Venous outflow: 35.2±10.03) (29). Wecht et al. (28) also reported similar mean total venous outflow 39.0±19.0 for a sedentary group of individuals (28), which are also similar in comparison to the participants of this study. Thus the vascular measures observed appear to reflect the fitness status of these individuals, as it is generally accepted that individuals of lower fitness levels demonstrate poorer vascular function. Finally, the venous measures in the individuals with a higher VO_2 range (40> ml/kg/min) compared to those in the lowest tertile of VO_2 (35<ml/kg/min) were significantly different. Thus providing a measure of construct validity.

Interestingly, consistent with previous work from this laboratory (22, 25, 29), we report a drop in venous capacitance following 5 minutes of arm occlusion. The mechanism for this drop is not entirely clear. However, it is thought to reflect the opening of deep tissue capillary beds that were unopened in the resting state. The opening of these deep tissue beds may not contribute to the expansion of the forearm circumference, but may in fact cause a slight drop in forearm expansion as fluid settles in these areas.

The values for the VO_2 recovery kinetics in this study are difficult to compare to the existing literature secondary to a lack of consensus on protocols used and analyses performed. However, the direction of the data is quite similar to several other investigators, especially as it relates to the ability to differentiate between higher and lower fitness groups. Several studies have examined the VO_2 recovery kinetics in populations similar to the participants used. For example, Hagberg et al. (17) and Billat et al. (30) examined the effects of endurance training on recovery kinetics. The average maximal oxygen consumption (VO_{2max}) of the two study groups were 41.46 and 56.0 ml/kg/min, respectively, which were both higher than the mean VO_{2peak} of the participants in this study (17, 30). Both Hagberg et al. (17) and Billat et al. (30) examined the VO_2 recovery kinetics following high intensity submaximal exercise that was much higher than those used in this study. Consequently, the half-times (26.5+2.1 and 29.0+8.0, respectively) observed in these studies were considerably longer than those observed in the present study. The longer recovery times in those studies more than likely reflects the higher intensities used. Furthermore, Hagberg et al. (17) reported that

exercise training resulted in significantly faster recovery kinetics (Pre: 29.0 ± 2.7, Post: 26.5 ± 2.1; $p<0.05$).

Considerably more studies have addressed the post exercise VO_2 recovery kinetics in clinical populations. For example, Belardinelli et al. (20) studied recovery kinetics in 10 patients with stable chronic heart failure (CHF) and 8 healthy individuals following a similar cycle ergometer protocol as was utilized in this study. Their findings indicate that the half-time of recovery was inversely related to the VO_{2peak} of the participants (Average VO_{2peak}: Controls: 22.58, CHF: 13.95 ml/kg/min, $p<0.001$; Average Time Constants: Control: 48.0, CHF: 66.8 sec, $p<0.05$) (20). Moreover, these findings are similar to the findings in this study, which demonstrate a relationship between exercise tolerance and recovery half-time.

Cohen-Solal et al. (16) also reported an inverse relationship between VO_2 recovery kinetics in patients with heart failure. Moreover, the recovery times were strongly associated with the severity of the disease, with slower recoveries in patients with the greatest dysfunction. In addition, Cohen-Solal (16) also noted that VO_2 recovery time was negatively correlated with VO_{2peak} ($r=0.65$) and was reproducible ($r=0.96$).

Influence of Vascular Function on Recovery Kinetics

The influence of the vasculature on VO_2 recovery has been well documented in terms of the delivery of oxygen and substrates to active tissue (23, 24, 59). Consistent with those findings, this study reports a direct association between reactive hyperemic blood flow and the half-time of recovery. Interestingly, this study suggests that the arterial system may account for as much as 29 percent of the recovery phase ($r^2=0.29$). In addition, those with the greatest reactive hyperemic blood flow response appear to have

the fastest VO_2 recovery kinetics. This implies that the recovery of VO_2 is in part determined by the delivery of blood, and more importantly oxygen and substrate to the recovering tissue. In fact, resynthesis of PCr and other metabolic substrates is highly dependent on an adequate blood supply.

It is interesting to note that individuals who are trained tend to have greater aerobic capacity, which is in part defined by reactive hyperemic blood flow. The mechanisms involved in greater vascular function following endurance training are not completely understood, but are thought to include alterations in neural, local, structural and metabolic components (22, 25, 31). However, the effects of exercise training on venous function have received much less attention. This is surprising considering the evidence of the venous systems role in facilitating a transient vasodilation, which results in an elevated arterial inflow (32, 33). Most previous studies have attributed training-induced improvements in venous function to the greater blood volume, which is associated with an increased VO_2 (34, 35). Other studies have reported increased cross-sectional area (36), and density (37) of the venular structure in response to endurance training (25). Moreover, Wecht et al. (28) suggested that improved venous function in endurance-trained individuals was due to improved overall venous hemodynamics.

Previous findings from our laboratory also reported an association between forearm arterial and venous function indices (r=0.43, p=0.014) (29). In this particular study, our data suggest that venous function may account for as much as 23 percent of the recovery period (r^2=0.23), which is quite significant. Moreover, compelling evidence has recently emerged which supports the role of the venous system as more than a "passive volume reservoir." For instance, Tschakovsky and Hughson (32) reported a greater arterial

inflow with increased venous emptying following arm elevation. The local venoarteriolar sympathetic reflex was linked to these findings by the authors (32). Therefore, the relationship between arterial and venous function suggests that vasoreactivity may be influenced by venous hemodynamics (28), which confirms the role of venous function in cardiovascular control, muscle perfusion, and exercise tolerance (29, 32). In addition, the location of the venous system in relation to the arterial circulation may be instrumental in producing a feedback mechanism, which influences arterial "reacitivities" (29).

Clinical Relevance

The clinical relevance of this study is not entirely clear at this point. Although, it can be suggested that one of the reasons that the magnitude of EPOC varies amongst groups of clinical and healthy populations, as well as active and sedentary groups, may lie in the level of deterioration in venous function. For example, previous studies have related diminished venous function to respiratory-cardiovascular hemodynamics, plasma norepinephrine, and severity of disease in CHF patients (16, 21, 22). Furthermore, venous compliance, which is the measure of responsiveness of the venous vascular system, was found to be significantly greater in able-bodied individuals compared to SCI patients (28). As previously reported, a rapid venous emptying rate can stimulate a transient vasodilatory response, which is mediated by the venoarteriolar reflex (32). Consequently, reductions in the distensibility of the venous system may result in a withdrawal of this reflex vasoconstriction and the subsequent elevation in blood flow (32).

Moreover, in the study by Wecht et al. (28), a lower venous capacitance was observed in a sedentary group when compared to an active group. This finding suggests

that an individuals level of physical fitness, contributes to the magnitude of the venous distensibility by enhancing the vasodilatory response of the vasculature (28). In addition, similar values for venous emptying rate (passive phase) and differences in the total venous outflow between the active and sedentary groups suggest the active phase of venous emptying is responsible for the differences between groups (28). As a result, these findings acknowledge the role of regular endurance training on improving indices of venous function such as active venous constriction, venous smooth muscle tone, central and peripheral venous pressures and venous return (28).

Furthermore, previous studies from this laboratory have been successful in demonstrating a relationship between venous function and exercise tolerance. For example, Welsch et al. (22) suggested that the factors that contribute to exercise impairment in the CHF population might extend to the venous system. Therefore, future studies should attempt to see if a change in recovery kinetics might somehow be related to a change in venous function.

Limitations

This study poses several limitations that may have influenced the outcomes that were obtained. One such limitation involves the number of subjects that participated in the study. A greater number of participants would have increased the power of the study and may have also affected the reported results. Also, the population itself was a limitation. By examining a population consisting of apparently healthy individuals, the role of vascular function may not have been completely appreciated.

This leads to another limitation to the study, which lies in the design. A true experimental design, which would have compared these findings with those of elderly, or

diseased populations, would have been more effective at controlling threats to the study's internal validity. Furthermore, providing a training intervention and a control group may have lead to a greater understanding of the contributions of vascular function to oxygen recovery kinetics, as well as demonstrating the importance of exercise training to various populations.

Finally, the methods of this study may also be considered a limitation to the study. These factors include instrumentation error, specifically the calibration of the cycle ergometer, as well as the human error involved in the measurement of vascular function by way of the plethysmography system. In addition, the intensity of the submaximal test, which was set at 60 percent of the participants' predetermined VO_2 peak, may not have effectively demonstrated the magnitude of recovery from steady-state exercise. Also, the submaximal intensity setting had to be continuously controlled throughout the exercise protocol. Due to the breath-by-breath analysis, the intensity of the bicycle ergometer had to be adjusted during the test to keep the participant in the 60 percent of VO_2 range.

Future studies may benefit from addressing these limitations. Addressing the issues of participant non-compliance and familiarization of the instruments involved in data collection prior to testing will aide in the success of the study as well as, improve the internal validity. Also, now that a relationship between vascular function and recovery kinetics has been established, a true experimental design will also improve on the studies limitations.

Conclusion

In conclusion, this study has provided insight into the relationship between vascular function and VO_2 recovery kinetics. Therefore, the role of the venous system on

VO$_2$ recovery kinetics must also be considered in the future. The findings demonstrate the necessity for further research into the importance of improving vascular function. Specifically, the relationship between vascular function and recovery kinetics, which was reported in this study, suggests an important role of the vasculature in the recovery period.

Although we are not able to completely understand the role of the venous system in recovery kinetics, the contributions of this experiment have allowed us to look beyond the current explanations for recovery VO$_2$. Therefore, it becomes important to continue the examination of the recovery process following a bout of exercise and its relationship with vascular function, as well as how this relationship is affected by a change in vascular function.

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APPENDIX: REVIEW OF LITERATURE

Faster recovery times following exercise in apparently healthy individuals as opposed to CHF patients has been well documented (16, 20, 21). The symptoms that characterize patients with CHF include abnormal gas exchange, reduced peak VO_2, a reduced slope of the increase in VO_2 with time, and a prolonged recovery VO_2, which worsens as the severity of the condition increases (16, 18, 20, 21). In one particular study, Belardinelli et al. (20) reported that recovery VO_2 and muscle oxygenation mean response times were longer in CHF patients than in apparently healthy, age matched control subjects [CHF: 66.8 ± 23 sec, Control: 48.0 ± 16 sec; $p < 0.05$]. In another study, Hagberg et al. (17) demonstrated that adaptations to endurance training result in a smaller O_2 debt, and a subsequent faster recovery time following training at both the same absolute and relative work rates following exercise at an intensity of 70% VO_{2max} [Before Training: 35.5 ± 1.4; After Training (Absolute): 26.7 ± 0.9, (Relative): 29.5 ± 1.2; $p < 0.01$]. The numerous adaptations that occur as a result of aerobic training appear to have a significant impact on decreasing the magnitude of EPOC following a bout of exercise. As a result, many factors have been suggested to play a role in the occurrence of this phenomenon. Therefore, an examination of the factors that contribute to EPOC may provide future prognostic benefits to both clinical and athletic populations.

Spinal chord injury (SCI) populations have also reported prolonged recovery times following a single bout of exercise. The kinetics of oxygen consumption, carbon dioxide production, and pulmonary ventilation during exercise and in recovery, are some of the longest ever reported for a patient population (38). Prolonged recovery kinetics for phosphocreatine (PCr) and Pi (inorganic phosphate) resynthesis have also been reported

in SCI patients following exercise (38). One of the main causes for this occurrence is that individuals suffering from SCI undergo a rapid atrophy in the muscles of the affected limbs, as well as a concurrent reduction in resting limb blood flow (38). The inability for this population to achieve normal increases in heart rate was also suggested as a potential limitation on the individuals' ability to sustain aerobic metabolism during transitions to and from submaximal exercise (38). The average time constant of an SCI patient following exercise has been shown to be very comparable to congestive heart failure populations (SCI: 102 sec, Congestive Heart Failure: 104 sec, Cyanotic congenital heart disease: 91 sec; respectively) (38). However, the recovery times become much faster following a period of exercise training (38). These findings suggest that adaptations, which occur as a result of exercise training, can elicit a significant impact on VO_2 recovery kinetics.

Deconditioning, which can occur throughout a range of clinical and athletic populations also result in prolonged VO_2 recovery kinetics (39). Following seven days of bed-rest-induced deconditioning, a group of apparently healthy individuals demonstrated a significant change in oxygen kinetics in terms of reduced $VO_{2max,}$ increased O_2 deficit, and increased recovery VO_2 (39). In contrast to the negative affects of deconditioning, aerobic training has been shown to enhance VO_2 kinetics following exercise. For example, in cross-sectional studies it has been shown that trained individuals have a faster post-exercise VO_2 recovery when performing exercise at either the same absolute or relative work rates (14, 17). Following a nine-week training program, Hagberg and colleagues (17) found that half-times for VO_2 ($T_{1/2}VO_2$), carbon dioxide production, pulmonary ventilation, and heart rate at the same absolute work rate were significantly

different than before training. The benefits that were attained as a result of the endurance training, allowed the individual to adjust to and recover from submaximal exercise at a faster rate, resulting in smaller O_2 debt (17). In a similar study, an acceleration of the off-transient phase was also reported following training, and it was also reported that there was a decrease in the rate of blood lactate accumulation at 95% VO_2 (Pre: 11.9 mmol·l, Post: 12.1 mmol·l) (30).

Prognostic Value of Heart Rate Recovery Kinetics

The elevation of heart rate in response to a bout of exercise is the result of a combination of parasympathetic withdrawal and the activation of the sympathetic nervous system (40). Furthermore, the fall in heart rate following the exercise bout is a function of parasympathetic reactivation (41). Based on the association between increased vagal activation and a reduced risk of death (42), heart rate recovery following a bout of exercise was suggested to be an important prognostic marker of mortality (1). In a study by Cole et al. (1), 2428 patients underwent symptom-limited exercise testing and single-photon-emission computerized tomography with thallium scintigraphy over a six-year period for diagnostic purposes (1). Univariate analyses revealed a low value for the recovery of heart rate following a bout of exercise was strongly predictive of death (relative risk, 4.0; 95 percent confidence interval, 3.0 to 5.2; $p<0.001$) (1). As a result, delayed decrease in heart rate during the first minute of recovery from graded exercise (12 beats per minute or less), was suggestive of an increased risk of overall mortality, despite the absence of myocardial perfusion defects and changes in heart rate during exercise (1).

The contribution of the autonomic nervous system to cardiodeceleration (heart rate recovery) after exercise is not completely understood. However, slower changes in the stimuli to metaboreceptors and baroreceptors accompanying clearance of metabolites and delayed elimination of body heat and catecholemines are also suggested to be contributing factors to heart rate recovery following a bout of exercise (43). As a result of elevated levels of catecholemines and metabolic byproducts, sympathetic activity must continue. Therefore, the effects of metabolism and vascular function play a role in the delay to parasympathetic reactivation following the bout of exercise.

Neurohumoral Influence on Vascular Function

Evidence has also been presented which suggests that there may be a neurohumoral influence on venous function in CHF patients (22). For example, a relationship between plasma norepinephrine levels and severity of CHF has been established (56). Furthermore, it has been suggested that a depression in baroreflex control of heart rate in CHF patients, is responsible for the increase in sympathetic tone to the peripheral circulation and to the heart, which contributes to the delay in heart rate recovery (56). Moreover, elevated levels of circulatory endothelin (57) and angiotensin II (58), contribute to increased sympathoexcitation in CHF patients, which suggests a possible neurohumoral influence on venous function.

Metabolic Factors That Affect EPOC

The effect of metabolic factors on EPOC has recently received a great amount of attention. Initial investigations on the EPOC phenomenon by Hill and colleagues attributed the rise in the VO_2 following exercise to energy requirements, resulted from the reconversion of lactate to glycogen (7-9). However, further investigations observed that

the majority of the O_2 debt was repaid by the time that peak lactate concentration had appeared (10). Alpert and Root (44) confirmed these findings by reporting that infused lactate did not elicit an O_2 debt, which provided a direct conflict to the classical O_2 debt theory. The development of alactacid and lactacid components of O_2 debt by Margaria et al. (10) provided a resolution to the threat against the early concept. The alactacid phase, or the fast phase of recovery, was shown to not be associated with a decrease in lactate, but represent the resynthesis of energy stores (12, 30). The slow phase, or lactacid phase, was originally considered to be a mirror image of glycogen resynthesis of lactate (10). However, it was later shown that lactate is constantly entering and leaving the blood after exercise, so oxidation was shown to be the ultimate fate of lactate (30, 45).

During the initial part of recovery, at least a portion of the O_2 that is consumed is used to restore PCr levels in the blood and tissues, as well as in muscle (12, 13, 20, 46). The restoration process of PCr concentration has been shown to occur over the first two to three minutes of the recovery period (48). According to Gaesser and Brooks (12), the fast component and much of the slow component of post-exercise VO_2, are representative of the alterations in PCr concentration as a result of the exercise period. This biphasic time course of PCr resynthesis was shown to appear very similar to the recovery of VO_2 to resting values (48). Furthermore, since the rate of adenosine triphosphate (ATP) resynthesis from aerobic metabolism is expected the match the rate of O_2 consumption, a prolonged recovery rate may suggest a slow rate of PCr resynthesis, resaturation of venous blood, and the O_2 cost of gluconeogenesis (20). In a study that investigated the recovery times of CHF patients, nuclear magnetic resonance spectroscopy revealed that the ratio of Pi and PCr, demonstrated a linear correlation with $T_{1/2}VO_2$ (r=0.70, p<0.01)

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(21). However, according to a review by Gaesser and Brooks (12), the magnitude of EPOC due to resynthesis of PCr during recovery following maximal exercise, accounts for only 10 percent of the total EPOC volume, which leads to the suggestion of multiple factors being responsible for EPOC. For example, early research also suggested that increases in heart rate and ventilation following exercise required a greater O_2 consumption, which could not be completely entirely accounted for by the resynthesis of depleted energy stores (12).

Another important factor that has been shown to contribute to EPOC is increased body temperature, which occurs during the exercise period. The impact of elevated temperature on post-exercise VO_2 is strongly related to its effect on mitochondrial energetics (12). The elevation in temperature increases nonconservative respiration as well as decrease phosphorylative coupling efficiency in the mitochondria of rat skeletal muscle and liver (12). As a consequence of this occurrence, increased oxygen consumption is required order to resynthesize adenosine triphosphate (ATP) (12). Similar to the resynthesis of PCr, the decline in whole-body VO_2 and the return to baseline tissue temperature following exercise exhibits a very close association (12). For example, Hagberg et al. suggested that 60-70 percent of the slow component of recovery VO_2 may be due to the Q_{10} effect of temperature on metabolism, when the intensity of the exercise ranges from 50-85 percent of VO_2max (49, 50). In addition, it was suggested that the extent to which temperature contributes to the magnitude of EPOC, probably is related to the effects of elevated temperature on mitochondrial energetics (12).

Catecholemine levels have also shown to contribute to the magnitude of EPOC. Catecholemines play an indirect role on increasing mitochondrial respiration by

stimulating energy-requiring processes within the cell (12). The rise in norepinephrine concentration during exercise has been shown to increase the permeability of the cell membrane, which allows for an increase in sodium (Na^+)-potassium (K^+) pump activity (12). This action responds by facilitating an increase in ATP production and, therefore, O_2 consumption (12). In a study by Gladden et al. (51), infusion of norepinephrine into canine skeletal muscle resulted in an increased recovery VO_2 by 40 percent, demonstrating a profound influence of catecholemines on recovery kinetics. Therefore, increased levels of catecholemines have a negative affect of VO_2 recovery kinetics.

Moreover, this finding appears to support previous reports of a decrease in the recovery VO_2 in dogs following administration of propranolol, which is a beta-adrenergic blocking agent (53). The action of propranolol to block the effects of catecholemines may contribute to the increased recovery VO_2 (52). The explanations for prolonged recovery time are suggested to be a direct effect of norepinephrine on the metabolic rate during recovery, or alternatively, the increased net recovery VO_2 during the infusion of norepinephrine, which is due to a limitation in O_2 transport during the preceding contractions (51). Therefore, the role of catecholemines and hormone levels must also be seriously considered as factors that contribute to the volume of EPOC.

The effect of mitochondrial respiration may also be affected by the concentration of Ca^{++} ions. Mitochondria sequester Ca^{++}, resulting in increased oxygen consumption, despite no increases in ATP production (12). An increased rate of O_2 consumption is also required as a result of the negative affect of increased Ca^{++} concentration, which results in a poor linkage between O_2 and phosphorylation (12). Also, the Ca^{++} uptake of cardiac and skeletal muscle during exercise may impact the overall energetics of mitochondrial

respiration following the exercise period (34). As a result, Ca^{++} concentration can also be a factor in the magnitude of EPOC.

Skeletal muscle abnormalities have also been suggested as a possible factor for prolonged VO_2 recovery kinetics. For example, Wilson and colleagues (54) suggested that factors related to intrinsic abnormalities in skeletal muscle might play a role in a prolonged recovery time in CHF patients. Their basis for this hypothesis stemmed from the finding that approximately 25 percent of the patients with CHF in their study that suffered from exertional fatigue, demonstrated a normal leg blood flow (54). As a result of this finding, it was hypothesized that skeletal muscle abnormalities, which have been found by several investigators in almost all patients with CHF, could be the major explanation for exercise intolerance in the absence of skeletal muscle underperfusion (54).

In response to Wilson and colleagues findings, Belardinelli and colleagues (20) argued that if intrinsic muscle dysfunction prevented the resynthesis of PCr at a normal rate, as opposed to a blood flow limitation, then the venous oxygen content should be higher than the normal range. According to Belardinelli and colleagues (20), this response did not occur and the role of the muscle itself in preventing the resynthesis of phosphocreatine was contradicted. Furthermore, the level of severity of circulatory dysfunction, responded with a slower recovery of VO_2 as well as muscle oxygenation as previously reported (20). These findings coincide with the observations of Cohen-Solal et al. (16), which reported that a redistribution of blood flow to nonexercising muscle groups, secondary to adrenergic-mediated vasoconstriction or to a decreased blood flow that reduces carbon dioxide elimination and prolongs muscle oxidative metabolism (20).

Therefore, a correlation between the kinetics of both muscle oxygenation and VO_2 in recovery and peak VO_2 suggests that a reduced peripheral oxygen supply is probably the major determinant of exercise intolerance in patients with circulatory problems (16, 20). Despite the mention of skeletal muscle dysfunction causing prolonged recovery kinetics, there is much stronger indication that circulatory dysfunction is much more profound in instances of delayed recovery time.

Role of the Vasculature on EPOC

Despite the influence of previously mentioned factors, investigation into the role of vascular function on the volume of EPOC has been somewhat limited. Since circulatory function has been shown to play a key role in determining the speed of recovery kinetics, the role of venous and arterial function should also be considered. In a study done by Welsch et al. (22), the relationship between exercise capacity and vascular function was examined in CHF and apparently healthy populations. Results of this study indicated a strong correlation between maximal walking distance (Controls: 562+/-136 m; CHF: 178+/-65m, P=0.0001) and forearm vascular function (forearm arterial inflow: CHF 15.3+/-6; Controls 22+/-6.7; forearm venous capacitance: CHF 1.4+/-0.5; Controls 2.0+/-0.4; forearm venous outflow: CHF 24.5+/-9.4; Controls 33+/-10 ml/100ml tissue/min; and forearm vascular resistance: CHF 7.8+/-3; Controls 4.6+/-1.4 U) (17). These data also confirm earlier studies, which recognize the significance of vascular function on exercise tolerance in patients with CHF (16, 20, 21), as well as suggest the importance of venous function as a major contributor to exercise performance (22). Based on the results of this research, a relationship between exercise performance and vascular function has been clearly established.

The role of the vascular system in determining physical fitness has been well documented (11). Increases in local blood flow appear to be significantly affected by increases in vascular conductance (VC) and by the pressure gradient from arteries to veins across the vascular bed (55). Venous emptying, which commonly occurs following limb elevation or muscle contraction, is thought to increase localized blood flow via an increase in the pressure change within the vessel (32). The mechanical effect of this pressure change upon blood flow forms the muscle pump hypothesis, which predicts that local blood flow can be elevated by the mechanical emptying of the veins, following muscle contractions (55). Therefore, an increase in regional blood flow can have a beneficial effect on sustaining physical activity. However, the muscle pump hypothesis neglects to fully consider the potential vasodilatory effect in response to enhanced venous emptying (32). As a result, the importance of the venous system in recovery from exercise is not completely understood.

Previous research has successfully demonstrated that venous filling, which has been shown to occur when a limb is moved into the dependent position, mediates a reflex vasoconstriction in both subcutaneous, and muscle tissue (32). The vasoconstriction that occurs as a result stimulates the reduction in venous volume. A local sympathetic axon reflex, which is referred to as the venoarteriolar reflex, has been shown to mediate this vasoconstriction (32). The potential existence of a vasodilatory response as a result of reductions in venous volume, may be important in maintaining or increasing blood flow under certain conditions where venous volume is reduced, such as during limb elevation (33).

Moreover, Tschakovsky and Hughson tested the hypothesis that a reduction in venous volume would facilitate a vasodilatory response, which would lead to an increase in regional blood flow (32). According to the results of a timed arm elevation test, a rapid reduction in venous volume and pressure occurred as a result of the arm being elevated above the heart for a period of two minutes (32). Also, within approximately five seconds of arm elevation, a transient (86%) increase in blood flow began, and subsequently peaked at eight seconds, which indicate the vasodilatory effect (32). Another significant finding to this study showed that following a brief (4-seconds) arm elevation; arterial inflow was increased by 343 percent (32). Based on the results of the experiment, it was concluded that venous emptying stimulated the vasodilatory response following the arm elevation, which resulted in a substantial hyperemic response.

<u>VITA</u>

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