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VENTILATORY MUSCLE FATIGUE IN
PROLONGED EXERCISE

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Master of Science
Degree
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ABSTRACT

Maximal Voluntary Ventilation (MVV) measured in time segments ranging from 12 seconds to 1 minute has been utilized in some studies to determine if ventilation is a limiting factor in exercise performance in normal subjects, athletes, and in those with respiratory diseases. Some investigators have claimed that it is inappropriate to use the short-term MVV to analyze ventilatory muscle endurance and propose, instead, the measurement of the maximal sustainable ventilatory capacity (MSVC) in studies of this nature. The MSVC is a test that measures the maximum ventilation that can be sustained for 15 minutes. The purpose of this study was to determine if changes in the MSVC and endurance time of the ventilatory muscles was affected by prolonged exercise.

Ten healthy, non-smoking men and women volunteered for the study. The highest rate of ventilation that could be maintained for approximately 15 minutes was determined on one day utilizing a ventilatory apparatus that regulated the rate of air flow through the system, provided saturated air, and allowed partial rebreathing of CO_2 . On a day when no exercise was performed, subjects hyperventilated at the designated rate for as long as

possible. The following day, the subjects ran for 30 minutes, and eventually to fatigue, at a pace that required an oxygen consumption of 70-80% of their $\text{VO}_{2\text{max}}$. The subjects then attempted to repeat the MSVC rate and time that was achieved the day prior to the run.

One-tailed paired t-tests on the MSVC and MSVC time showed significant differences in the pre-exercise and post-exercise values ($p < .05$). The peak exercise ventilation represented $72.6 \pm 12.8\%$ of the pre-exercise MSVC and $50.5 \pm 8.86\%$ of the pre-exercise MVV measured for 15 seconds.

The results of this study suggest that ventilatory muscle fatigue can occur in healthy adults of average fitness who participate in prolonged exercise. Possible mechanisms for fatigue include decreased ventilatory muscle efficiency, decreased blood flow to the respiratory muscles, increased O_2 cost of breathing, decreased rate of lactate removal, and/or increased rate of lactate accumulation.

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CHAPTER I

INTRODUCTION

The role of ventilation in exercise performance has been a topic of discussion since 1968 when Tenney and Reese completed a detailed study of muscle endurance and suggested that the endurance of the ventilatory muscles might be important in determining exercise performance. Their study initiated research that has produced conflicting results and created controversy over the importance of ventilation in exercise compared to possible contributions from other physiological systems such as the cardiovascular system. Two general schools of thought emerged from the research. One view is that ventilation limits exercise in the elite athlete (Dempsey, 1986) and in those with respiratory diseases (Grassino et al, 1979; Stubbing et al, 1980), but not in normal subjects (Dempsey et al, 1982; Dempsey, 1986; Martin and May, 1987). The other holds that ventilation limits exercise in normal subjects as well as in elite or impaired subjects through lactate accumulation, increased oxygen cost of breathing, reduced oxygen supply to the ventilatory muscles, or ventilatory muscle fatigue (Bellemare et al, 1983; Ouellet et al, 1969; Riley, 1960; Roussos and Macklem, 1977; Shephard, 1987; Tzelepis et al, 1988).

Some support for the theory that ventilation limits exercise performance through ventilatory muscle fatigue has come from studies that examined the effect of exercise on the pre-exercise measurement of maximum voluntary ventilation (MVV). The MVV is usually measured over a period of 12 to 15 seconds and is considered the most direct method of assessing maximal breathing capacity (MBC) (Carter et al, 1987; Gandevia and Hugh-Jones, 1957; Gray et al, 1950). Studies utilizing a MVV taken over a period of 12 seconds up to one minute have demonstrated that the post-exercise MVV values were less after exercise than before exercise, leading the investigators to conclude that ventilatory muscle fatigue must have occurred (Bender and Martin, 1985; Loke et al, 1982; Martin et al, 1984; Shephard, 1967). It has been argued, however, that a MVV measurement taken over a period of a few seconds is not a valid measurement of ventilatory muscle endurance that requires high levels of ventilation over many minutes (Freedman, 1970; Martin, 1987; Martin and Stager, 1981).

Ventilatory muscle endurance is the capacity to sustain high levels of ventilation for long periods of time (Freedman, 1970; Shephard, 1967; Tenney and Reese, 1968; Zocche et al, 1960). Leith and Bradley (1976) found

that an exponential relationship between the rate of ventilation and endurance time develops into an asymptote at 15 minutes when the ventilatory volume is approximately 65% of a MVV measured over 15 seconds (MVV_{15}). This led them to define ventilatory muscle endurance as the maximum ventilation that can be sustained for 15 minutes, or the maximum sustainable ventilatory capacity (MSVC). Freedman (1970) chose to use a 4-minute MVV to assess the ventilatory demands of long-term exercise because (1) four minutes is long enough to surpass the time for which anaerobic metabolism can fuel the respiratory muscles, (2) four minutes falls within the time required to achieve steady-state exercise, and (3) a reduction in MVV was noticed between two and ten minutes.

Belman and Sieck (1982) suggest that the measurement of ventilatory endurance is the MSVC. The relationship between the MSVC and exercise ventilation has not yet been determined, nor has evidence been provided that shows the MSVC to be impaired as a result of prolonged exercise in the same manner that the short-term MVV has been shown to be affected.

Purpose of the Study

The purpose of this study was to compare the pre-exercise MSVC and MSVC endurance times to the post-

exercise MSVC and MSVC endurance times and determine if a difference in these measures exists. A comparison was also made to investigate the relationship between the maximum exercise ventilation and the pre-exercise MSVC. It was hypothesized that there would be a significant difference between pre-exercise and post-exercise values.

Need for the Study

In some recent studies investigators have interpreted changes in pre-exercise MVV and post-exercise MVV values as evidence that ventilatory muscle fatigue is a limiting factor in exercise performance in normal, healthy individuals as well as in athletes (Bender and Martin, 1985; Loke et al, 1982; Martin et al, 1984). Although the MVV may be measured easily with a spirometer in a few minutes, it is not considered an appropriate measure of ventilatory muscle endurance (Bye et al, 1983; Martin, 1987; Martin and Stager, 1981). If the same differences can be observed with pre-exercise and post-exercise MSVC measurements, which are considered more direct measures of ventilatory muscle endurance (Belman and Sieck, 1982; Leith and Bradley, 1976) and MSVC endurance times, there will be much stronger support for the theory that ventilatory muscle fatigue may limit performance.

CHAPTER II

REVIEW OF THE LITERATURE

There has been considerable debate over whether or not ventilation is a limiting factor in exercise performance. There is a general consensus among physiologists that some elite athletes and those with respiratory diseases such as chronic obstructive pulmonary disease (COPD) and cystic fibrosis are limited by ventilation in exercise (Berglund, 1979; Dempsey, 1986; Killian and Campbell, 1983; Silverman et al, 1988). There is marked disagreement, however, over whether normal subjects are susceptible in the same manner.

The Ventilatory Response in Heavy Exercise

In moderately heavy steady-state exercise, an increase in ventilation occurs largely from an increase in tidal volume. At about 65% of the ventilatory capacity, tidal volume plateaus and further increases in ventilation are brought about by an increase in breathing frequency (Dempsey, 1986; Jones, 1984; Younes and Kivinen, 1984). When exercise becomes intense enough to cause an accumulation of carbon dioxide and lactate in blood and muscle most healthy individuals will hyperventilate; this acts to maintain arterial PO_2 in the face of metabolic

acidosis (Dempsey, 1986).

In high heat and humidity, prolonged exercise brings about an increase in breathing frequency, dead space ventilation, arterial carbon dioxide concentration ($P_a\text{CO}_2$), and minute ventilation (Hanson et al, 1982). The increase in dead space ventilation requires increased inspiratory muscle force development to maintain alveolar ventilation (Killian and Campbell, 1983), and this higher level of muscular tension tends to compress the intramuscular vessels and decrease blood flow and oxygen delivery to the respiratory muscles (Bellemare et al, 1983). It has been suggested that the imbalance between oxygen supply and demand creates respiratory muscle fatigue (Roussos and Macklem, 1977).

The ventilatory response to exercise may be altered by a change in altitude as well. At altitudes below 12,000 feet, $P_a\text{CO}_2$ remains at resting levels during high-intensity exercise although the ventilatory demands on the pulmonary system to maintain these levels is great (Dempsey et al, 1977). At altitudes above 14,000 feet, however, arterial hypoxemia occurs despite the hyperventilatory attempt to maintain resting levels (Torre-Bueno et al, 1985).

Evidence Against the Theory of Ventilatory Limitations in Non-athletes

Dempsey (1986) and Gardner and others (1979) have stated that normal subjects are not limited by ventilation at sea level since they are able to hyperventilate sufficiently to sustain arterial PO_2 at a constant level even during heavy exercise. In trained subjects, however, the arterial concentration of oxygen (P_aO_2) is decreased due to the inability of some athletes to hyperventilate at a rate that matches their high cardiac output, pulmonary capillary blood volume, and decreased red blood cell transit time (Dempsey, 1986; Dempsey et al, 1982; Powers et al, 1984). As a result of these high ventilatory demands (which may exceed 200 L/min), the athlete may approach maximum flow or mechanical limitations or may suffer from ventilatory muscle fatigue (Dempsey et al, 1975 and 1982).

Dempsey rejects the theory that ventilatory muscle fatigue occurs in normal subjects since his study showed that there was no decrease in hyperventilation and no CO_2 retention with exercise duration. Some investigators believe that fatigue occurs in the peripheral muscles before the ventilatory muscles (Dempsey et al, 1982; Killian, 1985; Suzuki et al, 1988). The evidence against ventilatory fatigue has also been demonstrated by Shephard

(1967), whose subjects were able to perform 100% of their MVV after 15 minutes of work at 80% of VO_{2max} even after increasing their ventilation from 50 to 80% of the short-term MVV. Research has also shown that the maximum breathing capacity, usually measured by the 15-second MVV, often exceeds the exercise ventilation in normal subjects by approximately 70%, indicating a possible ventilatory reserve (Bye et al, 1983; Dempsey et al, 1982).

Evidence Supporting the Theory of Ventilatory Limitations in Non-athletes

Several investigators have produced evidence demonstrating the presence of ventilatory muscle fatigue or some other related limitation as a result of exercise.

Martin and Stager (1981) found that athletes have greater ventilatory endurance than controls. They have suggested that the difference in endurance makes normal subjects more prone to ventilatory muscle fatigue than athletes.

Leith and Bradley (1976) have shown that the ventilatory muscles are capable of increasing in both strength and endurance after specific training of those muscles. After five weeks of static inspiratory and expiratory maneuvers, 12 healthy subjects demonstrated a 55% increase in strength. An increase in endurance (19% improvement in the MSVC and 14% in MVV_{15}) was seen after

five weeks of ventilatory work to exhaustion at different target ventilations.

Studies have shown that the highly fatiguable fast-twitch glycolytic (FG) fibers of striated muscles may be converted to the more fatigue resistant fast-twitch oxidative glycolytic (FOG) type as a result of endurance training (Gollnick et al, 1973; Holloszy and Booth, 1976). The diaphragm is composed of approximately 55% slow-twitch oxidative (SO) fibers (Lieberman et al, 1973) and since the intercostal muscles have only half of the oxidative capacity of the diaphragm they tend to fatigue quicker (Keens et al, 1977a).

The ventilatory muscles can be trained for increases in strength and endurance and are subject to fatigue like other striated muscles, but ventilatory muscles are more like cardiac muscle in that a high utilization rate by the ventilatory muscles of the lactate produced during exercise is evident. The diaphragm has a much greater oxidative capacity and capillary density than other striated muscles with the same fiber type, and a high rate of lactate utilization has been noted during prolonged high-intensity stimulation (Rochester and Briscoe, 1979; Saltin and Gollnick, 1983). Moore and Gollnick (1982) noted a 90% reduction of the diaphragmatic glycogen

content in rats after prolonged treadmill running; Gorski et al (1978) showed a decrease of 50% in rats after an hour of swimming. In addition, Cobley et al (1981) demonstrated an increase in blood lactate from 0.6 to 2.7 mmol/L after maximum ventilation that maintained alveolar PCO_2 . This is considered a large amount of lactate for that volume of tissue and suggests that the ventilatory muscles are susceptible to fatigue.

Diminished energy supplies to the ventilatory muscles have also been known to cause fatigue. Aubier and others (1981) and Hussein and others (1985) have demonstrated that in septic and cardiogenic shock, diminished energy supplies can cause diaphragmatic fatigue without increasing the load or the work of breathing. In normal subjects, the cost of breathing in heavy exercise is thought to be so great that any extra oxygen brought into the body through increases in ventilation is used by the ventilatory muscles (Otis, 1954; Ouellet et al, 1969; Riley, 1960). Therefore, high levels of ventilation could deplete energy stores within the respiratory muscles and cause them to fatigue before other active muscles.

High levels of ventilation increase diaphragmatic blood flow exponentially as the work of breathing increases (Robertson et al, 1977). The augmented breathing frequency and heightened rate of contraction of

the diaphragm during high-intensity exercise produces an increased energy demand for the diaphragm and a much greater oxygen consumption (Buchler et al, 1985; Simkus et al, 1984). If the available oxygen supply is insufficient to meet the demands of the respiratory muscles and other active muscles, then one or both will be placed in oxygen debt and fatigue will occur (Bye et al, 1983).

Diaphragmatic fatigue can occur if the diaphragmatic pressure with each breath is more than 40% of the maximum transdiaphragmatic pressure ($P_{di_{max}}$) (Roussos and Macklem, 1977). The transdiaphragmatic pressure (P_{di}) is the difference between the gastric and esophageal pressures, and is used to measure the tension generated by the diaphragm. High pressures can create inspiratory muscle fatigue (Bellemare and Grassino, 1982). Fatigue of the inspiratory muscles will occur if the pleural pressure exceeds 50-70% of the maximum pressure (Roussos et al, 1979).

Nutrition may also play a role in the development of respiratory muscle fatigue. A four week restricted diet consisting of a 25-33% reduction in the food intake of hamsters resulted in decreases in both diaphragmatic muscle mass and contractile force (Kelsen et al, 1982). Alternatively, obese individuals typically exhibit

decreased chest wall compliance and inspiratory muscle weakness, and, when combined with the circulatory problems inherent in this population, CO_2 retention may develop. Obese individuals with this "hypoventilation syndrome" typically have inspiratory muscle strength equal to only 60-70% of normal, with less respiratory muscle efficiency and greater O_2 cost of breathing (Rochester and Enson, 1974).

There are three major mechanical forces that may restrict the increase in ventilation that is needed for maximal exercise. The elastic forces of the lungs and thorax can be limiting and the magnitude of the effect is dependent upon the pressure and volume capabilities of these two structures. Elastic limitations can occur when lung volume exceeds two-thirds of the vital capacity. Resistance is offered by air flow in the large airways and is due, in part, to the tendency of the trachea to narrow during inspiration. A third mechanical force that may impair increases in ventilation is inertance, i.e., the pressure required to overcome the acceleration of air flow (Jones, 1984).

Increased lung volumes provide another type of limitation that can decrease endurance by distorting the chest wall causing increased participation of other inspiratory muscles. Hyperinflation will decrease the use

of the diaphragm and increase use of the parasternal muscles. These changes decrease the diaphragmatic pressure and cause fatigue (DeCramer et al, 1987). An increase in lung volume above resting levels of 1.2 liters results in a 13-17% shortening of the diaphragm (Braun et al, 1982; Loring et al, 1985). At these shortened fiber lengths, there are fewer cross-bridge attachments available which results in the generation of less tension (Mashima, 1984).

There have been several studies that attempted to demonstrate the presence of respiratory muscle fatigue in normal subjects involved in exercise of a prolonged nature. Bender and Martin (1985) reported that, after a one hour treadmill run, eight non-runners could not reproduce their pre-exercise 1-minute MVV, indicating possible ventilatory muscle fatigue. No difference between pre-and post-exercise values was found in another group of subjects who ran for only 3-10 minutes. The results of the study lend support to the comment by Martin (1987) that changes in pre-exercise and post-exercise MVV_{15} may have been witnessed in a study conducted by Shephard (1967) had the 15-minute exercise session been extended for a longer period of time. A marathon run also resulted in a decrease of the pre-race MVV and Pdi,

demonstrating a loss of both strength and endurance of the respiratory muscles (Loke et al, 1982). Martin and others (1982) demonstrated that exercising the ventilatory muscles prior to a 60-minute run resulted in a decrease in maximal running performance as well as decreases in peak heart rate, ventilation, and oxygen consumption. There was no change in the 12 second MVV or in the forced expiratory volume in one second (FEV_1) from pre-exercise levels. The latter finding for FEV_1 suggests that increased bronchoconstriction occurring as a result of prior ventilatory work could not have been the cause of impaired running performance.

The parameter used most frequently to demonstrate fatigue of the respiratory muscles in many of the studies supporting the theory of ventilatory muscle fatigue in non-athletes has been the MVV. The MSVC has been suggested as the measure to be used to quantify endurance of the ventilatory muscles (Belman and Sieck, 1982; Leith and Bradley, 1976; Martin and May, 1987). There is some indication that the short-term MVV used in previous studies of ventilatory muscle fatigue may have been inappropriately used to assess long-term ventilation.

The Short-term MVV in Prolonged Work

The most direct measurement of maximal breathing capacity (MBC) is the MVV (Carter et al, 1987; Gray et al, 1950; Gandevia and Hugh-Jones, 1957), which is generally performed in time segments of 12 or 15 seconds (Carter et al, 1987). Its use as a measure to compare with prolonged exercise ventilation has been questioned because 100% of the ventilation achieved during the 15 and 20 second MVV can be maintained for only 1-1 1/2 minutes; the high ventilations that are encountered during exercise last for many minutes (Bender and Martin, 1985; Martin, 1987; Martin and Stager, 1981).

The short-term MVV cannot be maintained for long periods of time and the total volume of air is less after ventilating at high volumes for short periods of time than when ventilating at lower volumes for a longer period (Tenney and Reese, 1968). There is a rapid fall in MVV in the first 1 to 1 1/2 minutes with a more gradual fall thereafter (Freedman, 1970). Tenney and Reese (1968) maintain that 100% of the 15-second MVV cannot be sustained for periods longer than 40 seconds. The reasons for the inability to sustain the 15-second MVV for long periods, as explained by Freedman (1970), are (1) the respiratory muscles are not capable of maintaining the power output that 100% of the MVV requires for long

periods of time, (2) a change in the mechanical state of the thorax occurs which affects the level of oxygen supplied, and (3) the 15-second MVV is too unpleasant to be maintained for long periods. Approximately 55% of the MVV can be sustained indefinitely (Tenney and Reese, 1968) while 65% of the MVV can be sustained for 15 minutes (Leith and Bradley, 1976). Freedman (1970) chose to study the 4-minute MVV instead of the 15-second MVV because (1) four minutes is long enough to surpass the time for which anaerobic metabolism can fuel the respiratory muscles, (2) it falls within the time required to achieve steady-state exercise (Jones et al, 1967), and (3) a slower decrease in MVV was observed between two and ten minutes.

Freedman reported a maximal tolerable steady-state exercise ventilation that was 80% of the 4-minute MVV and 64% of the 15-second MVV, and a 4-minute MVV that averaged 72% of the 15-second MVV. Freedman noted that in four of his subjects the maximal exercise ventilation represented 91-101% of the 4-minute MVV. In the other four subjects the maximal ventilation was 55-74% of the 4-minute MVV. Freedman's subjects had been measured in whatever posture was most comfortable; some stood while others sat. The differences he found between subjects may have been due to the posture each assumed during the MVV measurement.

Townsend (1984) has demonstrated that FEV_1 and forced vital capacity (FVC) are significantly larger in the standing position than in the sitting position ($p < 0.001$); therefore differences in the posture assumed by the subjects in Freedman's study may account for the differences in the percent of the 4-minute MVV Freedman found within his groups.

Summary

The question of ventilatory limitations to exercise has been addressed many times in the last several years. Elite athletes and those with respiratory diseases are considered to be subject to ventilatory limitations in exercise, but controversy remains over whether or not normal subjects are similarly affected. Those opposed to the idea cite studies showing a possible ventilatory reserve (Bye et al, 1983; Dempsey et al, 1982) and maintenance of arterial PO_2 even during maximal exercise (Dempsey et al, 1982). Those in agreement with the idea cite studies which demonstrate possible ventilatory muscle fatigue resulting from high lung volumes, lactate accumulation, diaphragmatic pressure, high cost of breathing, or mechanical inhibitions (Cobley et al, 1981; Jones, 1984; Otis, 1954; Ouellet et al, 1969; Roussos and Macklem, 1977). Some studies that demonstrated

ventilatory muscle fatigue used a short-term MVV and compared it with long-term exercise ventilations. This procedure is not considered appropriate by some since the short-term MVV does not measure the endurance of the ventilatory muscles (Bender and Martin, 1985; Martin, 1987; Martin and Stager, 1981). For this reason and others, Freedman (1970) chose to use a 4-minute MVV and was able to record ventilations that were only 20% higher than the exercise ventilations, in contrast to the 15-second MVV which recorded ventilations 36% higher than the exercise ventilation. It would appear, from the results of this study, that the 4-minute MVV is a better measurement of prolonged exercise ventilation than the 15-second MVV which has been commonly, but perhaps errantly, used in other studies of long-term work. However, the subjects involved in the study were allowed to assume either a sitting or standing posture during pre-exercise MVV measurements, a methodological approach which may have affected the results. A study by Townsend (1984) has shown the standing posture to be more favorable in creating larger lung volumes than the sitting posture. The results might have been different had all the subjects in Freedman's study assumed the standing posture. Leith and Bradley (1976) have more precisely defined ventilatory muscle endurance as the maximum sustained ventilatory

capacity, or the MSVC. They have shown that approximately 65% of the 15-second MVV may be maintained for 15 minutes.

In the present study, an attempt was made to determine if exercise would produce any changes in the MSVC and/or ventilatory muscle endurance times from pre-exercise volumes/times. A decrement in MSVC endurance times from pre-exercise to post-exercise would be an indication that ventilatory muscle fatigue had occurred in normal healthy subjects. An attempt was also made to establish the relationship between peak exercise ventilation and the MSVC by expressing the exercise ventilation as a percentage of the MSVC.

CHAPTER III

METHODOLOGY

Subjects

Ten healthy, nonsmoking subjects volunteered for the study. Physical characteristics of the subjects may be found in Table 1.

Table 1. Subject Characteristics

	<u>Males (n=3)</u>			<u>Females (n=7)</u>		
	Mean	+/-	S.D.	Mean	+/-	S.D.
Height (inches)	71.00	21.50		64.80	1.76	
Weight (kilograms)	72.60	15.70		57.80	6.32	
Age	28.70	7.23		28.30	5.58	
Vital Capacity (L)	5.35	1.02		3.97	0.63	
VO _{2max} (ml/kg/min)	51.25	4.95		42.00	4.45	
MVV ₁₅ (L/min)	212.69	27.50		138.88	20.80	
MSVC (L/min)	153.71	41.50		96.22	16.00	

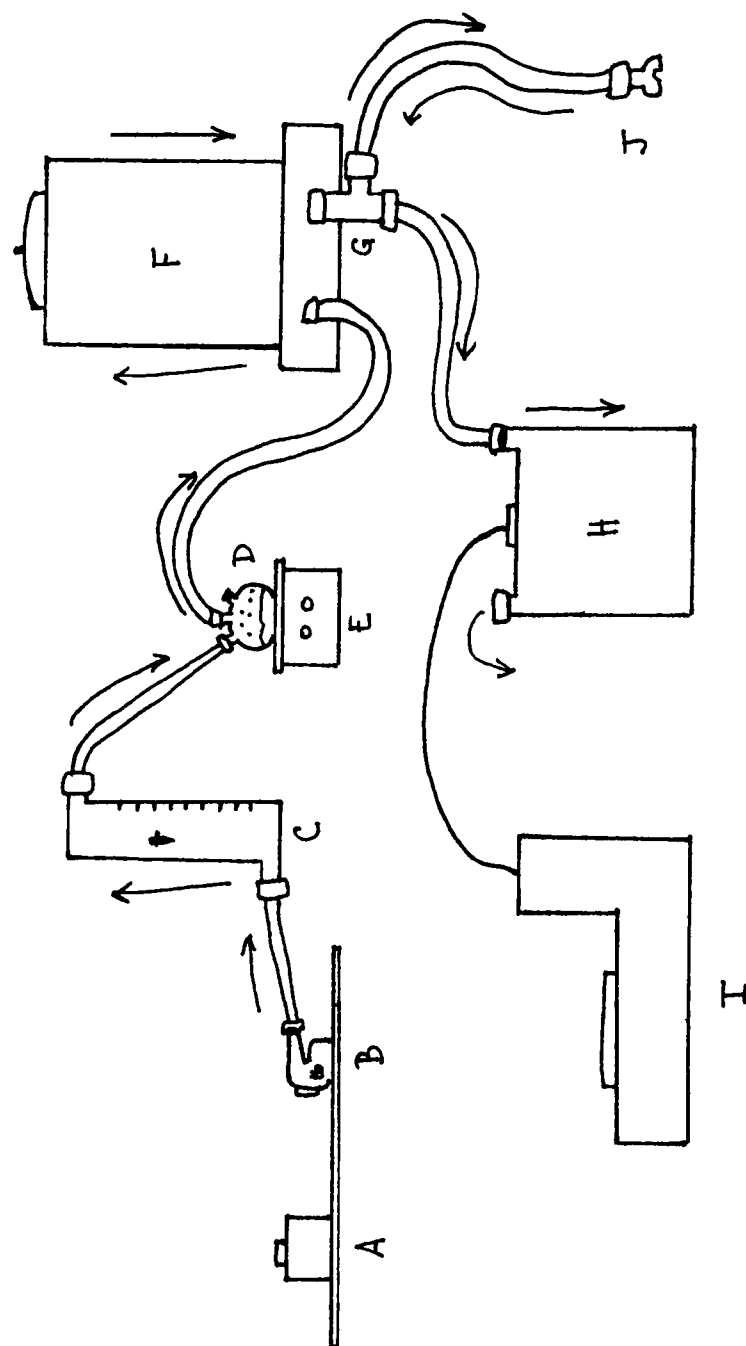
A questionnaire was distributed before any tests were completed to screen out those who had recent and/or chronic respiratory diseases, infections, and

cardiovascular disease (Appendix). Informed consent was obtained before any measures were taken. Participants were asked to refrain from using caffeine and nicotine, and to refrain from eating for at least three hours before pulmonary and treadmill testing. They were asked not to exercise before testing on each day.

Materials and Apparatus

A diagram of the apparatus used for all long-term ventilatory measurements is provided in Figure 1.

A 13.5 liter Collins spirometer was utilized for all pulmonary measurements. For long-term measurements, the inspiratory port of the spirometer was connected to the inspiratory side of a two-way valve (Daniels type). The expiratory side of the valve was connected to a Parkinson-Cowan dry gas meter equipped with a potentiometer. The potentiometer transmitted information concerning the amount of air passing through the dry gas meter and relayed that information to a Narco Biosystems Physiograph (DMP-48) which recorded expired ventilation. The open end of the Daniels valve was connected to dead space tubing (35 mm in diameter), the length of which varied according to the sensation of lightheadedness perceived by the subject during hyperventilation. The purpose of the dead space tubing was to prevent hypocapnia by permitting the



Legend: A = variable output generator, B = vacuum cleaner motor, C = flow meter, D = distilling flask, E = hotplate, F = 13.5 liter spirometer, G = Daniels valve, H = dry gas meter, I = physiograph, J = mouthpiece.

Figure 1. Diagram of ventilatory apparatus for hyperventilation tests. Arrows indicate direction of air flow.

subject to rebreathe CO_2 during the long-term ventilatory measurement.

The expiratory side of the spirometer was attached to tubing that led to the central neck of a 3-neck distilling flask heated by a Corning Hotplate. This central neck had a diameter of 34 mm at the top and 45 mm at the bottom. Another neck of the flask had a diameter of 24 mm at the top and 40 mm at the bottom and was connected by tubing to a flowmeter (Fischer and Porter type, model 10A3565S). The third neck of the flask had the same dimensions as the second neck and was stoppered. The distilling flask was heated in order to saturate the air the subject was breathing to keep airway drying to a minimum as suggested by O'Cain and others (1980). More tubing joined the flowmeter to a vacuum motor which, in turn, was connected to a variable output generator that controlled the rate of airflow through the system. The resistance of the circuit at 200 L/min was 1.9 cm/ H_2O .

The treadmill (Quinton) used for the exercise segment of the experiment was calibrated prior to testing of the first subject on each day. Inspired ventilation was measured via the Rayfield computer program, which was interfaced with an Electrochemistry S-3A oxygen analyzer and an Electrochemistry CD-3A carbon dioxide analyzer.

The analyzers were calibrated with gas checked by the Scholander technique.

Experimental Procedure

The subjects appeared in the lab on four separate occasions. On the first day the subjects signed a consent form, completed a brief health questionnaire, participated in pulmonary function tests involving FEV_1 and FVC measurements, and completed a VO_{2max} test. The second day entailed the performance of several MVV_{15} and MSVC tests. The subjects rested on the third day and returned on the fourth day to perform one MSVC test (pre-exercise MSVC). The final day consisted of several FEV_1 measurements followed by a prolonged run of at least 30 minutes duration at 70-80% VO_{2max} . At least one post-exercise FEV_1 was completed 5 minutes after the run, and was immediately followed by an MSVC at pre-exercise MSVC flow rates.

Day 1: Screening

A minimum of three lung volume measurements of FEV_1 and FVC were taken during the pulmonary screening, respiratory maneuvers continuing until two values within 5% of each other were obtained. All pulmonary measurements were obtained in the standing position with 30 seconds of rest between each measurement. Subjects

were equally instructed in the process of performing spirometric maneuvers in order to minimize a learning effect. Predicted volumes of FEV_1 and FVC for the male subjects were obtained from the nomograms of Boren and others (1966). Predicted FEV_1 volumes (Ferris et al, 1964) and FVC volumes (Needham et al, 1954) for females were calculated from formulas. A volunteer was not accepted as a subject if his/her FEV_1 or FVC was less than 80% of predicted. All lung volumes were corrected to BTPS.

Following the lung volume measurements the volunteer stretched for 10 minutes, then began a VO_{2max} test. The test consisted of a 3-minute warm-up at 3.5 mph. Heart rate and expired air were measured every minute. The speed was then raised to a predetermined speed of 6-9 mph and remained constant throughout the test. Grade was increased 1% every minute until the subject signaled to stop. All subjects at the end of the test reported a Borg Rating of Perceived Exertion of 19 or 20, had a respiratory exchange ratio of at least 1.0, and/or had an increase of less than 2.1 ml O_2 /kg/min with an increase in work rate, or had a drop in VO_2 with an increase in work rate. A volunteer was not accepted as a subject if the VO_{2max} was outside of the range of 35-50 ml/kg/min for

females or 45-60 ml/kg/min for males.

Day 2: Determining the MSVC

On this day the level of ventilation that could be sustained for 15 +/- 2 minutes was determined. At least three MVV_{15} were obtained, and 65% of the highest volume achieved became the starting point for the long-term ventilation tests. All long-term breathing exercises were performed in the standing position. The vacuum motor pumped air into the spirometer bell and the subject's inspirations drew air from the bell. The subject was asked to maintain the bell within a 2-liter range. The flow rate was raised 5% every 13-17 minutes until a rate was found that could not be maintained for 13 minutes. Alternatively, the rate was dropped 5% from initial levels if the pace could not be maintained for at least 13 minutes and the flowrate continued to drop by that amount until a pace was found that could be maintained for a minimum of 13 minutes. The moisture of the inspired air was adjusted according to subject preference and most preferred temperatures and saturation levels of 28 degrees celsius and 80%, respectively. The temperature and saturation of inspired air in the post-exercise MSVC test was consistent with the levels chosen in the pre-exercise MSVC test. All MSVC volumes were corrected to BTPS.

Day 3: Rest dayDay 4: Pre-exercise MSVC test

On the fourth day of the study, the subjects performed one MSVC at the final rate achieved on the second day. The subject hyperventilated for as long as possible and the time to fatigue, ventilatory volume per minute, and the reason for stopping were recorded.

Day 5: Post-exercise MSVC test

The final day consisted of obtaining at least three pre-exercise FEV_1 volumes followed by 10 minutes of stretching. The subject then walked on the treadmill for three minutes at 3.5 mph after which the speed was increased to elicit a pace that yielded approximately 70-80% of the VO_{2max} achieved on the first day. One-minute readouts on the computer allowed for adjustments to treadmill speed to maintain intensity. The run continued for 30 minutes, at which time the speed and grade were increased to the values reached on the final stage of the first day VO_{2max} . The subject continued to volitional fatigue and was allowed exactly five minutes to recover from the run before attempting a post-exercise FEV_1 . If the FEV_1 was not within 5% of the pre-exercise value, the subject waited a minute and tried again. This continued until a value reaching 95% of the pre-exercise value was

obtained. The subject began the long-term hyperventilatory effort within one minute of the last FEV_1 taken at a rate equal to that done the day before. The subject continued to hyperventilate for as long as possible and the time to fatigue, ventilatory volume per minute, and reason for stopping were recorded.

CHAPTER IV

RESULTS

Statistical analysis of the data utilizing one-tailed paired t-tests at the .05 level of significance revealed that the post-exercise MSVC time to exhaustion was significantly less than the pre-exercise time ($p < .05$) (Table 2).

Table 2. Pre-exercise and Post-exercise MSVC Endurance Times.

Subject	Pre-exercise MSVC Time (seconds)	Post-exercise MSVC Time (seconds)
A	1281	1500
B	1024	1500
C	1050	233
D	1500	143
E	1320	732
F	990	273
G	864	801
H	1500	705
I	960	1380
J	960	610
Mean	1144.9	787.7
+/- S.D.	234.8	515.9

These changes were accompanied by significant, though slight, decreases in the MSVC from pre-exercise to post-

exercise measurements ($p < .05$) (Table 3).

Table 3. Pre-exercise and Post-exercise MSVC, Breathing Frequency, and Tidal Volume Values.

Subject	Pre-exercise			Post-exercise		
	MSVC ^a	BF ^b	TV ^c	MSVC ^a	BF ^b	TV ^c
A	114.79	52.77	2.18	110.40	42.72	2.58
B	95.98	58.70	1.64	94.75	55.57	1.70
C	99.91	58.67	1.70	91.89	60.00	1.53
D	67.68	40.00	1.69	70.53	48.00	1.47
E	99.50	54.70	1.82	87.48	51.10	1.71
F	84.62	43.00	1.97	90.76	51.00	1.78
G	111.06	67.53	1.65	110.91	59.79	1.86
H	170.26	53.00	3.21	165.75	57.00	2.91
I	106.50	61.00	1.75	94.85	50.00	1.90
J	184.37	71.31	2.59	182.21	68.70	2.65
Mean	113.47	56.07	2.02	109.95	54.39	2.01
+/- S.D.	36.40	9.73	0.51	35.82	7.40	0.51

^aMSVC in L/min

^bBF in breaths/min

^cTV in L/min

Post-exercise FEV₁ values were not significantly different from those taken before exercise (Table 4), which would indicate that bronchoconstriction was probably not the reason for the observed differences in MSVC and ventilatory endurance time.

The pre-exercise MSVC represented, on the average,

69.9 $\pm$ 10.2% of the MVV_{15} . The peak ventilation achieved in the prolonged run averaged 72.6 $\pm$ 12.8% of the pre-exercise MSVC and 50.5 $\pm$ 8.86% of the MVV_{15} .

Table 4. Pre-exercise and Post-exercise FEV_1 Values.

Subject	Pre-exercise FEV_1 (L/min)	Post-exercise FEV_1 (L/min)
A	3.67	3.84
B	3.05	3.08
C	2.83	2.83
D	2.96	2.96
E	3.67	3.62
F	3.73	3.90
G	3.21	3.10
H	5.27	5.38
I	4.02	4.13
J	4.30	4.52
Mean	3.67	3.73
$\pm$ S.D.	0.74	0.81

CHAPTER V

DISCUSSION

The Effect of Prolonged Exercise on MSVC

Data analysis showed that approximately 69.9% of the MVV_{15} could be maintained for 15-20 minutes. This value is close to that obtained by Leith and Bradley (1976) who found that approximately 65% of the MVV_{15} could be maintained for 15 minutes. Zocche and others (1960) showed that their subjects could maintain 59% of their 12-second MVV for 15 minutes, while Freedman's (1970) subjects demonstrated the ability to maintain 72% of their MVV_{15} for four minutes. Approximately 80% of a 12-second MVV in another study was maintained for 11 minutes by eight athletes; the eight non-athletes could maintain their 12-second MVV for only three minutes (Martin and Stager, 1981).

Running at speeds that generated 70-80% of VO_{2max} for greater than 30 minutes in this study resulted in a significant decrease in MSVC from pre-exercise values. Loke et al (1982) observed that the marathon post-race MVV_{15} in four male runners was significantly less than their pre-race MVV_{15} 60 minutes after completion of the race. Shephard (1967) also witnessed a decrease in MVV_{15} in his subjects following 20 minutes of running ($190.9 \pm$ -

8.2 L/min pre-exercise versus 184.7 ± 12.6 L/min post-exercise), as did Bender and Martin (1985) with a 1-minute MVV performed by their subjects after a 60-minute run to exhaustion.

MSVC endurance time was also found to be impaired as a result of exercise in this study. With these results was the observation that reductions in the MSVC time in some subjects were coordinated with increases in BF and decreases in TV. An elevated speed of contraction of muscles increases the rate of energy consumption (Hill, 1964) and higher breathing frequencies increase the energy requirements of the diaphragm (Buchler et al, 1985). The adoption of a higher breathing frequency may have compromised the ability of subjects in this study to maintain high ventilations for the same length of time that could be achieved on the pre-exercise day because the energy demands of the diaphragm exceeded energy supply.

Shephard (1967) observed that when his 10 sedentary subjects ran for 20 minutes at $80\% \text{VO}_{2\text{max}}$ their MVV_{15} three minutes after exercise was approximately 100.8% of the pre-exercise value when breathing frequency was held at 50 breaths/minute. At 100 breaths/minute, the post-exercise MVV_{15} was 95.4% of the pre-exercise value. Many investigators have failed to consider the role of the

velocity of contraction in the expenditure of energy of the ventilatory muscles (Bellemare and Grassino, 1982).

On the average, the maximum exercise ventilation in this study represented $72.6 \pm 12.8\%$ of the pre-exercise MSVC and $50.5 \pm 8.86\%$ of the pre-exercise MVV_{15} . Bender and Martin (1985) reported that the exercise ventilation of their runners represented $42.8 \pm 4.8\%$ of the 1-minute MVV while that of the non-runners represented $53.0 \pm 4.5\%$ of the 1-minute MVV. Freedman (1970) found that the average exercise ventilation in all eight of his subjects was 64% of a MVV_{15} . In four of his subjects the exercise ventilation was 91-101% of a 4-minute MVV, but only 55-75% of a 4-minute MVV in the other four subjects. The differences between the eight subjects may have occurred because he gave his subjects the option of standing or sitting during ventilatory measurements. Ventilatory volumes will vary depending on the position assumed (Townsend, 1984).

Of the studies mentioned thus far in the discussion, only Bender and Martin (1985) and Martin and Stager (1981) saturated the air that was inspired by their subjects. With high ventilatory efforts such as that encountered during voluntary hyperventilation and exercise, the airways can become cooled enough to cause bronchoconstriction. The greater the ventilatory response

and the cooler the air temperature, the greater the bronchoconstriction (McFadden et al, 1982; O'Cain et al, 1980). Pre-exercise and post-exercise measures of FEV_1 may have detected whether or not bronchoconstriction occurred in these studies. In the present study, bronchoconstriction could be ruled out as a reason for decreased ventilatory muscle endurance times since a significant difference between pre-exercise and post-exercise FEV_1 values was not found.

Long-term Breathing

The maintenance of high ventilations for long periods of time is very uncomfortable for most individuals and is possibly the reason why there are few studies of MSVC with normal subjects. Nine out of the 10 subjects in the present study experienced headaches immediately following the highest ventilation achieved when the MSVC was determined on the second day, although only two of the 10 experienced the same following prolonged breathing on the pre-exercise day.

Most subjects experienced some degree of muscle soreness in the abdominal, neck, and/or upper chest regions 24-48 hours after the first day of prolonged breathing. Roussos et al (1979) noted similar occurrences with their subjects soon after ventilatory work.

Discomfort in the trapezius and sternomastoid, and in the ribcage areas were noted by subjects performing a 4-minute MVV in another study (Freedman, 1970). Two of the subjects in this study were forced to discontinue the post-exercise MSVC due to severe side stitches. In a previous study by Roussos and Macklem (1977) of ventilatory endurance, one of the subjects experienced abdominal pain similar to stitches. All three of their subjects had dull subcostal pain at the end of most ventilatory endurance tests. A possible cause for the stitches is that the respiratory muscles, particularly the diaphragm, when deprived of oxygen (Fox and Matthews, 1981), can result in fatigue from a decreased rate of energy supply to the muscle (Roussos and Macklem, 1977).

While the cause of the stitches is unknown, it may be that the subjects in this study adopted a pattern of breathing that decreased the efficiency of the respiratory muscles, reduced blood flow, and increased the work of breathing while decreasing the strength of inspiratory muscle force development (Roussos et al, 1979). Hyperinflation of the lungs can produce such a result by forcing the respiratory muscles to contract at shortened fiber lengths that compromise the length-tension relationship and thus decrease the amount of tension

generated (Luce and Culver, 1982; Roussos et al, 1979). Maintenance of the spirometer bell within the parameters given required a stronger concentration on inspiration than on expiration, and the observance was made that some subjects had a tendency to overinflate the lungs because of the failure to expire sufficiently before the next inspiration. When instructed to concentrate on exhaling, the subjects' comfort level and endurance times were dramatically increased.

The inability of these subjects to find the proper pattern of breathing that would maximize their endurance times might lead one to believe that individuals lacking running experience may tend to hyperinflate the lungs during exercise. One study has demonstrated the ability of experienced runners to synchronize gait and ventilation, while less experienced runners and fit non-runners failed to establish such precision and tended to alter breathing frequency and amplitude in an inconsistent manner despite steady limb motion (Bramble and Carrier, 1983). Peak ventilation has been shown to be increased through entrainment during other rhythmic activities such as cycling and rowing (Shephard, 1987).

Observation of the subjects during hyperventilation on the ventilatory apparatus revealed that all subjects were inclined to find a position that seemed to aid their

respirations when ventilation became difficult. Leaning forward slightly and resting the hands on the table in front of them, or, less frequently, on the hips were the tactics usually employed. Runners exhibit similar traits when exhaustion approaches by leaning forward slightly while running (Shephard, 1987) and resting the hands on the hips once the run is over. The subjects in this study also tended to breathe with the neck slightly extended when exhaustion approached. Haas and others (1982) found that subjects assuming a forward lean from the waist of approximately 11 degrees with the neck flexed and head extended 35 degrees forward from the spinal column increased their TV during 12-second MVV measurements, increased their ribcage stability, produced greater peak inspiratory and expiratory flow rates, and exhibited greater maximal inspiratory pressures than when assuming the upright posture normally observed in trained runners. Leaning forward and stabilizing the upper extremities and shoulder girdle may increase the efficiency of the inspiratory accessory muscles (Haas et al, 1982; Sharp et al, 1980).

Summary

The results of this study indicate that running at 70-80% of $\text{VO}_{2\text{max}}$ for at least 30 minutes and eventually to

exhaustion reduces the ability of the respiratory muscles to maintain high ventilations for prolonged periods of time in healthy individuals of average fitness. This may be due to the adoption of higher breathing frequencies and lower tidal volumes that place added energy demands on the diaphragm and accessory muscles of breathing. Muscle fatigue can occur when energy demand exceeds energy supply (Roussos and Macklem, 1977). Other possible reasons for fatigue exist and include depleted glycogen stores, a change in posture, and neuromuscular fatigue (Shephard, 1987).

The MSVC in this study was a better determinant of maximum exercise ventilation than the MVV and others have stated that it is a better measure of ventilatory muscle endurance than the MVV (Freedman, 1970; Martin and May, 1987).

Future studies examining the role of ventilation in the limitation of endurance exercise performance should include and focus on measurements of the MSVC, not the MVV. The present experiment should be replicated with the intention of measuring oxygen and carbon dioxide fractions of expired air as well as arterial PO_2 and PCO_2 to gain a better understanding of the roles and interactions between the respiratory and cardiovascular systems in the

performance of the MSVC. A longer period of adjustment to the ventilatory apparatus than was given to the subjects in this study should be allowed in order to minimize some of the learning effects of long-term hyperventilation.

A closer look at the relationship between the velocity of contraction of the ventilatory muscles, the effect of training these muscles at high breathing frequencies for short periods of time (interval training), and the result of such training on the MSVC and/or exercise ventilation may also be warranted.

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APPENDIX

INFORMED CONSENT FOR EXERCISE TESTING AND
PULMONARY FUNCTION TESTING AND MEASUREMENT

In order to determine my maximal aerobic capacity and my ventilatory capacity, I hereby consent, voluntarily, to a maximal exercise test on the treadmill and pulmonary function measurements on the spirometer. The pulmonary function measurements will be taken before and after a maximal running test on the treadmill. I understand that I may not be chosen as a subject in this study if the results of the initial pulmonary measurements show possible ventilatory obstructions. The run will begin at a low level and will be increased in stages lasting one minute. The test may be stopped at any time because of objective signs of fatigue. I understand that I may stop the treadmill test or the pulmonary function test at any time because of my feelings of fatigue, discomfort, or any other personal reason.

I understand that the risks of the testing procedure may include disorders of heart beats, an abnormal blood pressure response, or very rarely, a heart attack.

I understand that information from my tests may be used for research publications. I understand that my identity will not be revealed and that I may withdraw my consent at any time.

Signed

Witness

Date

Betty R. Lawton
308 HPER Bldg.
974-5111

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336 HPER Bldg.
974-1294

SCREENING FOR HEALTH-RELATED FITNESS PARTICIPATION

Instructions. Check yes or no by each of the following items:

 Yes No Presently have, or have had, cardiovascular disease (e.g., heart problems).

 Yes No Have pains or pressure in the left or midchest area, left neck, shoulder, or arm at rest or in response to exertion.

 Yes No Often feel faint or have spells of dizziness.

 Yes No Have had a cold, flu, or other upper respiratory tract infections in the last two weeks?

 Yes No Have a respiratory disease such as asthma or cystic fibrosis?

 Yes No Use a bronchodilator for any reason?

 Yes No Experience extreme breathlessness after mild exertion.

 Yes No Have high blood pressure.

 Yes No Am over 60 years of age and not accustomed to vigorous exercise.

 Yes No Have bone or joint problems that would interfere with exercise.

 Yes No Have two or more of the following:

- a. Family history of premature coronary artery disease.
- b. Obesity.
- c. Sedentary lifestyle.
- d. Type A behavior with stressful occupation and/or lifestyle.
- e. Diabetes.

 Yes No Have a medical condition not mentioned here which might need special attention in an exercise program.

If you've checked yes on one or more items, you need medical permission to participate in this study. If you've checked none of the items, you can participate in the experiment with minimum risk. If there is any question in your mind that exercise might cause any kind of problem, see your physician before engaging in the study.

* Adapted from, Exercise and your heart. U. S. Dept. of Health and Human Services, 1981 and Guidelines for graded exercise testing and exercise prescription. American College of Sports Medicine, 1980.

VITA

Betty Rhetta Lawton was born in Riverdale, Maryland on October 5, 1963. Most of her elementary school years were spent in and around Annapolis, Maryland. She moved to Montpelier, Vermont in 1976 and attended high school there, then went on to Johnson State College in Johnson, Vermont to obtain a Bachelor of Science degree in Allied Health.

In 1986, she accepted a graduate teaching assistantship at the University of Tennessee in Knoxville, then a consulting position with Martin Marietta Energy Systems, Inc. of Oak Ridge, Tennessee. She received a Master of Science degree in Physical Education (emphasis in exercise physiology) from the University of Tennessee-Knoxville in 1990.

The author is currently employed as the exercise physiologist for Indian Path Medical Center in Kingsport, Tennessee.