THE TRAINING EFFECTS OF HYPERCAPNIA AND HYPOXIA INDUCED BY TUBE BREATHING

by

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The Training Effects of Hypercapnia and Hypoxia Induced by Tube Breathing

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ABSTRACT

The main purpose of this study was to determine if the imposition of increased respiratory dead space during exercise could improve training results in athletes.

Ten males were randomly assigned to control or experimental groups and then exercised for 8 weeks on cycle ergometers. Frequency of training was 3 times per week, at an intensity of 90% max. heart rate, using a 3:3 minute work:rest protocol (five repetitions per session). During the last six weeks of the training schedule the experimental group exercised while breathing through tubing which increased the subject's respiratory dead space. End-tidal gases were monitored biweekly in both groups during training. Anaerobic treadmill run performance and $\dot{V}_{O_2}$ max. on the cycle ergometer were assessed biweekly.

The experimental group had significantly lower ($P<.05$) end-tidal O_2 (103.8 ± 2.7 vs. 117 ± 2.0 Torr, week 6) and higher CO_2 tensions (43.8 ± 1.5 vs. 30.2 ± 1.5 Torr, week 6) than the control group during the tube rebreathing period. During exercise with increased dead space from tube breathing, P_{CO_2} levels were higher in arterialized capillary blood samples taken immediately after exercise than in the control group (47.5 ± 0.5 vs. 33 ± 2.7 Torr, week 6). Both groups significantly improved anaerobic treadmill endurance at 8 mph, 20% grade and endurance during $\dot{V}_{O_2}$ max. tests on a cycle ergometer, but differences between the groups were insignificant in these

variables. Significant decreases were noted in the ventilatory equivalent for CO_2 during the $\dot{V}_{O_2}$ max tests in the experimental group (22.66 $\pm$ 0.53 vs. 21.12 $\pm$ 0.88, pre and post values, respectively). The experimental group also had significantly higher ventilatory threshold changes than the control group after training. The change in work time to pre and post ventilatory threshold in the experimental group was 98 $\pm$ 25 seconds and 26 $\pm$ 8 seconds in the control group. These times corresponded to pre and post work rates at ventilatory threshold of 1400 $\pm$ 100 and 1700 $\pm$ 200 kp·m·min.$^{-1}$ in the experimental group, and pre and post values in the control group of 1200 $\pm$ 100 and 1300 $\pm$ 100 kp·m·min.$^{-1}$, respectively.

It is concluded that a beneficial training effect occurred in the experimental group as a result of tube breathing while exercising. The exact nature of this adaptation is unclear, but ventilatory data implicate improved ventilatory efficiency as one effect. The change in ventilatory threshold may implicate improved buffering capacity in the experimental group.

DEDICATION

This thesis is dedicated to my wife Betty, for her encouragement, patience, and gentle prodding.

ACKNOWLEDGMENTS

The author would like to acknowledge the effort and patience of the members of the supervisory committee, Dr. Eric Banister and Dr. John Wilkinson, with sincere thanks.

Thanks for technical assistance must also be extended to Pat Good for computer graphics, to Derrick Hamilton for skilled blood letting, and to Rob Maskell for begetting the 'cart'.

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I. Introduction

Dill and co-workers (1932) made an early attempt to improve athletic performance by increasing the buffer capacity of the body. They demonstrated that a subject who ingested sodium bicarbonate prior to performance ran longer. The authors felt that an initial alkaline state increased one's capacity for neutralizing lactic acid. Subsequent studies have both reaffirmed (Rummler and Bruemmer, 1966; Jones et al., 1977) and refuted (Asmussen et al., 1948; Margaria et al., 1971) the importance of such increased buffering capacity for enhancing exercise performance.

Clinical studies of acute (Brackett et al., 1965) and chronic hypercapnia (Van Ypersele et al., 1966) have indicated that plasma bicarbonate concentration increases curvilinearly during both acute and chronic hypercapnia. Schaefer, Nichols, and Carey (1964) observed acid-base balance and blood electrolyte change in submariners throughout 42 days of exposure to 1.5% CO_2. Red cell bicarbonate increased from 13.8 mmoles$\cdot l^{-1}$ to 15.4 mmoles$\cdot l^{-1}$. and remained elevated for up to four weeks after exposure.

Particularly relevant to the investigation proposed in this study are the recent studies of Graham et al.,(1980) which suggested that hypercapnic exercise results in lower blood lactate levels and enhanced fat metabolism during the exercise. Other investigators have noted increases in myoglobin and

citrate synthase concentrations in the skeletal muscle of rats exercised in a hypercapnic environment. These changes were noted to be similar to those observed after several weeks of eucapneic and normoxic training. (Gimenez and Florentz, 1979)

Schaefer et al., (1963) noted that submariners exposed to low levels of carbon dioxide for long periods exhibit a respiratory acclimatization to CO_2, involving an increase in tidal volume and a decrease in respiratory rate. These adaptations are also characteristic of the ventilation pattern shown by endurance athletes.(Martin et al., 1979)

By its effects on energy metabolism, ventilatory response, and pH defense mechanisms, hypercapnia may be regarded as an additional stress if imposed during exercise and seemed worthy of investigation, in a training study, for its its effectiveness as a training stimulant.

II. Review of Literature

Increased External Dead Space and Respiration

Tube breathing experiments at rest:(Fenner et al., 1968, Goode et al., 1969) and during exercise: (Jones et al., 1971, Ward and Whipp, 1980) have been used to determine basic ventilatory responses to increasing dead space. An incidental observation occurring during these studies was that rebreathing also induced hypercapnia and mild hypoxia.

Fenner et al., as early as 1968 studied enhancement of the ventilatory response to carbon dioxide by tube rebreathing. In ten healthy subjects ventilation ($\dot{V}_E$) and alveolar carbon dioxide partial pressure ($P_{A_{CO2}}$) were measured at rest during two ten minute periods. Rebreathing through a plastic tube 14 mm in diameter and 1400 ml in volume resulted in increases in $P_{A_{CO2}}$ of 7-8 mm Hg and 15 $l \cdot min^{-1}$. in $\dot{V}_E$(approximate figures at tenth minute of observation). Goode et al., (1969) studied tube breathing under similar conditions and found that breathing CO_2-free gas through an external dead space of 1.4 liters was associated with a small increase of end-tidal P_{CO_2}, a slightly larger fall of end-tidal P_{O_2}, and an increase in ventilation.

Jones et al., (1971) used a mixing chamber of variable volume to increase the respiratory dead space in four normal subjects. Subjects exercised with 700 and 1400 ml of added dead

space at two or three work rates. Their observations showed that: the addition of dead space had no consistent effect on CO_2 output, or oxygen uptake ($\dot{V}_{O_2}$), $\dot{V}_E$ increased progressively with increasing dead space, (due mainly to an increase in tidal volume) and at any given work rate end-tidal CO_2 and arterial P_{CO_2} both increased as the dead space was enlarged. However, this study used relatively low work rates.

More recently it has been shown that subjects who performed cycle ergometer exercise on six different occasions with different external dead spaces (0.1-1.0 liters), at work rates which increased every five minutes by 15-20 watts, demonstrated an upward shift of the ventilation-CO_2 production ($\dot{V}_E/\dot{V}_{CO_2}$) ratio and an elevated $P_{A_{CO2}}$, independent of $\dot{V}_{CO_2}$.(Ward and Whipp, 1980) It was concluded by the latter authors that increasing the external dead space did not impair an individual's respiratory capacity to regulate $P_{A_{CO2}}$ during exercise. $P_{A_{CO2}}$ regulation was merely shifted to a higher level. These observations suggest that tube breathing during exercise may cause the equilibrium $P_{A_{CO2}}$ concentration to be also reset higher, adding hypercapnia to the exertional stress.

Body Carbon Dioxide Capacity

The CO_2 storage capacity of the body resides mainly in bone. This tissue accounts for some 110 of the approximately 130 liters of CO_2 stored in the body. (Bursaux and Poyart, 1974) The latter authors considered bone to be a carbon dioxide sink

dramatically influencing dynamic exchange of whole body carbon dioxide stores and playing a significant role in maintenance of a normal acid-base balance. Rats ventilated for one hour on 4-6% CO_2 exhibited an increase in bone carbon dioxide compared with control animals. The slope of a proposed linear relationship existing between bone carbon dioxide content and mixed venous blood P_{CO_2} was 1.27 mM. $CO_2 \cdot kg^{-1}$ bone$\cdot$Torr^{-1}, demonstrating the existence of a bone carbon dioxide change during acute hypercapnic acidosis. (These investigators used direct methods to determine their findings. i.e. rat femurs and tibia were removed and placed in a sodium hydroxide solution, allowing direct carbon dioxide measurement by titration. All other studies reported here use indirect methods to determine carbon dioxide storage.)

Farhi and Rahn (1955) ventilated anesthetized dogs at a constant alveolar CO_2 tension until a steady state was reached.(40-50 min.) They then increased alveolar CO_2 tension by increasing the pressure in the respirometer and continued until another steady state respiratory $P_{A_{CO2}}$ was observed. The slope of the whole body CO_2 dissociation curve was calculated by dividing the total CO_2 storage change by the difference between the initial alveolar tension and the final alveolar tension. This yielded an average CO_2 capacity of 1.5 cc$\cdot kg^{-1}$ body wt.$\cdot$ mm^{-1} P_{CO_2}. The authors noted the magnitude of bone storage capacity for CO_2 and the fact that one could not expect bone to reach a new equilibrium for CO_2 content during such acute

exercise experiments. The results of this and subsequent calculations produced an "acute experimental CO_2 dissociation curve" applicable to exposures of less than one hour for tissues. Matthews and co-workers (1968) found that labelled CO_2 inspired by resting human subjects equilibrated rapidly with only 5 to 8 liters of body CO_2. This represents a volume greater than that of the blood volume but considerably less than that of the whole body CO_2 content. The proportion of the whole body CO_2 pool measured in the experiments probably represents only the part active in short term regulation of body CO_2 stores. This pool would probably be that involved during acute exercise.

Clode (1966) attempted to measure CO_2 balance during exercise by assuming that CO_2 production is the sum of that produced from aerobic metabolism, from that chemically displaced from buffer stores, and that evolved from body stores. Clode et al., (1967) estimated the immediate CO_2 storage capacity of the body during exercise by measuring changes in mixed venous P_{CO_2} (used as a measure of tissue P_{CO_2}), and compared it with the retention of carbon dioxide during rebreathing. The carbon dioxide storage capacity of the body estimated by rebreathing was calculated empirically from the equation:

$$\text{CO2 storage capacity} = \frac{\dot{V}CO2 \text{ in preceding control period}}{\text{rate of rise in PvCO2} \times \text{weight}} \qquad \text{Eq.1}$$

The authors concluded that an acceptable value to use for body CO_2 storage capacity in interpreting the exchange of CO_2 stores during exercise was 1 $ml \cdot mm^{-1}$ Hg $\cdot kg^{-1}$.

A more recent study by Jones and Jurkowski (1979) also addressed the problem of determining the body carbon dioxide storage capacity during exercise. They used a hyperventilation technique rather than rebreathing to estimate CO_2 storage. A criticism leveled at former rebreathing studies was that rebreathing took place during a very limited time period (1.5 min.) and probably reflected changes only in the most accessible CO_2 stores. The latter study employed a 30 minute equilibration period and two different work rates (30 and 60% $\dot{V}_{O_2}$ max.). At the lower power output a CO2 storage capacity of 1.83 $ml \cdot kg^{-1} \cdot Torr^{-1}$ was noted and a mean value of 1.19 $ml\ kg^{-1}\ Torr^{-1}$ at the higher work rate. One notable conclusion was that CO_2 storage capacity seemed inversely related to mixed venous P_{CO_2} during exercise and decreased progressively with increasing intensity of physical effort.

Chermiack and co-workers (1974) attempted to explain why the immediate CO_2 storage capacity of the body seemed rather low. They proposed factors which might limit CO_2 storage capacity in certain tissues of the body including: finite rates of CO_2 diffusion within organs, slow chemical processes (e.g. hydration in absence of carbonic anhydrase, which is absent in the large pool of muscle tissue) and uneven distribution of blood flow relative to CO_2 storage capacity. The same authors observed, interestingly, that the whole blood CO_2 dissociation gradient might be able to be chronically regulated, enabling preservation of a constant body pH in the event that ventilatory

compensation alone proved inadequate. (Cherniack et al., 1974) These authors cite unevenness in the distribution of perfusion of different organs as the most important factor enabling the increase in storage capacity with time. Studies of body CO_2 storage capacity in exercising humans have been limited to the few mentioned in this section. Observations on positive or negative changes in CO_2 storage capacity induced by training under hypercapnic conditions are even sparser.

Exercise and Hypercapnia

Luft, Finkelstein and Elliott (1974) investigated reports of astronauts experiencing premature physical exhaustion during extra-vehicular activity, which might have been due to their rebreathing a carbon dioxide contaminated atmosphere. The effects of breathing 2% carbon dioxide on physical performance was studied. Results indicated that breathing this concentration of carbon dioxide caused a 12% decrease in maximum oxygen uptake in exercising subjects. Although ventilation was increased considerably in the hypercapnic group at low and medium work rates, the disparity with control values decreased at higher work rates and CO_2 output was considerably lower. Blood lactate concentrations may be low during hypercapnia either because a low pH inhibits glycolysis (Trevidi and Danforth, 1966; Relman, 1972) or because lactate efflux from muscle is altered by low pH. (Harken, 1976; Benade and Heisler, 1978) This study was of

an acute nature only and did not attempt to draw conclusions regarding long term exposure to CO_2.

The ventilation and tidal volume of well trained young subjects increased over control values during exercise at work rates of 90 and 140 watts in a hypercapnic environment consisting of 4% CO_2 (Rizzo et al., 1976) Carbon dioxide production and respiratory exchange ratio decreased, and the arterial partial pressure of carbon dioxide increased. Oxygen consumption at these 2 submaximum work rates (40 and 70% of $\dot{V}_{O_2}$ max., respectively) was the same breathing either normal air or 4% CO_2, although maximum levels of work were not attempted in hypercapnia. Again, the study was of an acute nature.

Results from investigations of Menn and co-workers (1970) on the effects of 0, 8, 15, 21, and 30 mm Hg inspired CO_2 tension on the response of subjects to cycle ergometry, are at variance with studies of Luft et al.(1974)(see above) Menn et al.(1970) found no change in $\dot{V}_{O_2}$ arising from breathing an increasing $P_{A_{CO2}}$ in exercising subjects, indicating that the metabolic cost of work was not influenced by acute exposure to hypercapnia. However, there was an increased ventilation at submaximal work rates and a decreased carbon dioxide production in the subjects. An altered alveolar-inspired air gradient for CO_2 was cited by the authors as the reason for a failure of trainees to reach an adequate ventilation.

Jones and co-workers (1977) noted the general effect of acute alkalosis and acidosis on the cardiorespiratory and

metabolic responses to exercise in untrained subjects. Exercise endurance was increased in those investigated after ingestion of sodium bicarbonate and was decreased after ingestion of ammonium chloride. Oxygen consumption, carbon dioxide production, and the respiratory exchange ratio did not differ significantly between conditions during exercise in the subjects. A developing acidosis, in both conditions, was accompanied by decreased plasma lactate and inhibition of lipolysis and it was concluded that these effects were mediated directly by the metabolic action of the ingested chemicals rather than by oxygen transport inadequacy. While hypercapnia was not directly produced in the above study, the similarity in results between it and hypercapneic induced changes in respiratory gas exchange suggest that it is a pH change induced by hypercapnia that exerts the common effect.

Gimenez and Florentz (1979) studied the effects of hypercapnia on glycolytic metabolism, enzyme activity and myoglobin levels of electrically stimulated skeletal muscle of rats, during concomitant exposure to 10% CO_2 for one hour. At rest both phosphohexose isomerase and three-phosphoglycerate kinase activity were decreased while citrate synthase activity was increased during exercise while CO_2 breathing. This latter phenomenon, in addition to a concomitant decrease in plasma lactate, indicated that hypercapnia inhibited glycolysis, and might augment tissue oxidative metabolism. A distinguishing feature of the study was the increase of heart and soleus muscle

myoglobin produced at rest by electric stimulation of muscle. The proposal that acute hypercapnia induced changes in muscle metabolism during work, similar to those acruing from several weeks of exercise training under normal conditions, is an attractive one.

Graham and co-workers (1980) studied metabolic responses to progressive, exhaustive work during hypercapnia and normal air breathing in young men. The work time, peak oxygen consumption, carbon dioxide production and attained heart rate were the same in both control and experimental (4% CO_2) conditions for each subject. However, ventilation was significantly greater and blood lactate significantly lower during hypercapnic work. The authors suggested that a reduction in lactate concentration during hypercapnia might be due to glycolytic inhibition and enhanced fat metabolism.

A later study by the same investigators (1980) sought to determine the influence of steady state work under hypercapnic conditions ranging from 0 to 6% CO_2, on fat metabolism, carbon dioxide storage, endurance and perceived exertion in young men. Changes in lactate concentration and the respiratory exchange ratio (R) both had a significant inverse relationship with arterial CO_2 partial pressure during work at 67.7% of $\dot{V}_{O_2}$ max., suggesting once again that suppression of glycolysis and enhanced fat metabolism had occurred, although the authors conceded that enhanced CO_2 storage might also account for the decrease in R. A second series of experiments was reported by

the same authors on young men working at 64.9% of $\dot{V}_{O_2}$ max. with an inspired CO_2 fraction of 4% until cessation of exercise at the point of exhaustion. The mean lactate concentration had decreased 31.4% (from 3.14 mmoles$\cdot l^{-1}$ while breathing 0% CO_2 to 2.15 mmoles$\cdot l^{-1}$ breathing 4% CO_2). Concomitantly, the R value decreased from .90 to .85. The mean endurance times of the subjects were 71.7 in normoxia and 78.8 minutes in the hypercapnic conditions. It was concluded by the authors that the decreased R value reflected a true increase in fat metabolism since CO_2 storage would have had to increase from 3-40 fold to account for the variously observed lower values in R.(Graham et al., 1980)

Conspicuous by their absence, are studies of the chronic effects of CO_2 exposure on work performance. This study will attempt to provide such data, although the exposure might better be described as repeated, acute exposures to carbon dioxide induced by tube rebreathing.

Hypercapnia and Ventilation

Schaefer and co-workers (1963) observed that submariners exposed to low levels of CO_2 (1.5%) for prolonged periods (42 days) demonstrated respiratory acclimatization, accompanying a continuous increase in tidal volume throughout the period (although the respiratory rate declined after an initial transient increase). These changes in respiratory pattern were associated with an increase in physiological and anatomical dead

space. A significant increase in both the arterial-alveolar CO_2 and alveolar-arterial P_{O_2} gradients suggested an increased alveolar dead space during hypercapnia. The ventilatory response to 5% CO_2 was markedly reduced at the end of each CO_2 exposure period.

Schaefer (1958) had also previously noted that some subjects showed a significantly lower respiratory rate and a larger tidal volume, as well as a higher alveolar CO_2 level breathing normal air. Additional recent work by Florio, Morrison and Butt (1978) has indicated that divers also show a reduced ventilatory response to CO_2.

Byrne-Quinn and co-workers (1971) observed that the normal low altitude native athlete has marked attenuation of both hypoxic and hypercapnic ventilatory drive at rest. This suggests they have a diminished peripheral chemoreceptor function. A study by Martin et al., (1979) demonstrating a lower ventilatory response to hypercapnia in endurance athletes, despite a 3 Torr higher average end-tidal P_{CO_2}, supports such a proposal.

Martin and co-workers (1979) concluded that the contribution of low exercise ventilation to an outstanding athlete's endurance performance is equivocal. Some illumination of the problem may result from observations of the link between an athlete's breathing pattern during exertion as acclimatization to hypercapnia in training proceeds. Schaefer (1963) attempted to account for the functional significance of an increased alveolar dead space occurring with acclimatization

to CO_2. The work of a previous investigation (Severinghaus and Stupfel, 1957) indicated that alveolar dead space increased disproportionately in dogs breathing with high tidal volumes, a pattern also observed in both athletes and the submariners. Ross and Farhi (1960) found that breathing alveolar dead space gas limited the range of gas compositions able to be attained in the lungs. This may be advantageous in situations where large inspired CO_2 concentrations are experienced in inspired ventilation. Schaefer (1963) indicated that a large alveolar dead space produced and maintained a higher arterial CO_2 tension and a correspondingly large buffer capacity (bicarbonate) in the blood. If CO_2 is inhaled under these conditions, mechanical buffering of the CO_2 in the lungs (the increase in alveolar dead space) is added to the chemical buffering capacity of the blood. This effectively reduces the developement of peak CO_2 tensions in arterial and mixed venous blood, thereby limiting ventilatory response to CO_2.

The common experience of athletes, submariners, and divers is to be exposed to elevated CO_2 tensions for prolonged periods, so it should not be surprising that they show similar adaptations in their respiratory response to CO_2.

Tube Breathing Induced Hypoxia and Exercise

Goode et al., (1969) observed that tube breathing (1.4 liters volume) at rest was associated with a fall of end tidal P_{O_2} levels. These authors also compared the hypercapnia produced by tube breathing to that caused by inhalation of CO_2 mixtures. When a given $P_{A_{CO2}}$ was produced by both of these methods and compared, tube breathing was found to be different in its effect on $P_{A_{CO2}}$ (The hypoxic effect of tube rebreathing resulted in a $P_{A_{CO2}}$ of 92 mm Hg. vs. 127 mm Hg. while inspiring CO_2/air mixtures). Goode's data may be used to determine the equivalent altitude simulated by tube breathing of this volume, if values for pressure are substituted into the equation:

$$\log \frac{760}{P} = \frac{h}{221.15\ (273 + t)} \qquad \text{Eq.2}$$

relating altitude to barometric pressure.(Pugh, 1957) (Where P=barometric pressure in mm Hg, h =height in feet, and t=temperature in degrees Centigrade.) Solving equation 2 for height with P equal to 664 mm Hg. (the barometric pressure appropriate to the tube P_{O_2} and a temperature of 20 degrees Centigrade), tube breathing at rest may be calculated to be equivalent to breathing at an altitude of 3800 feet. Data from preliminary studies with tube volumes used in this experiment showed that $P_{A_{CO2}}$ levels dropped to 82 mm Hg in two subjects breathing through 1.4 liters of added dead space, while exercising at 900 kp·m·min^{-1}. From equation 2 this would represent the equivalent of breathing ambient air at a height of

5911 feet.

Intermittent exposure to such relatively mild levels of hypoxia would not be expected to result in dramatic changes in hematocrit, blood bicarbonate levels and other hematological indicators, but may be regarded as being a significant stress on the aerobic and anaerobic capacities of individuals training at a strenuous level. (Woo, 1972)

In summary, carbon dioxide exposure has been shown to have interesting acute effects on aspects of metabolism, body storage capacity, ventilation and work performance. The effects of repeated exposure on these variables is not very well known. Previous investigators have shown that it is possible to elevate CO_2 levels moderately by tube rebreathing. This study will attempt to determine if training benefits will result from repeated, acute episodes of hypercapnia and hypoxia experienced while exercising.

III. Objectives

The purpose of the study was to investigate the effectiveness of a physical training regime combined with the stresses of hypercapnia and hypoxia. Hypercapnia and hypoxia were uniquely induced by a method of tube rebreathing. The relation of the elements of hypercapnic- hypoxic training such as dead space volume, work rate, degree of developed hypercapnia and hypoxia to changes in CO_2 storage, CO_2 ventilatory response, and work capacity were examined.

Specifically, the objectives of the study were:

1) to evaluate the effectiveness of hypercapnia/hypoxia as a training stimulus, as evidenced from the growth in aerobic and anaerobic power.

2) to monitor the effects of hypercapnic/hypoxic training on the ability of the body to store carbon dioxide and to buffer carbonic acid. These may be evidenced by changes in blood gases and pH measurements of the blood.

3) to examine the effects of hypercapnic/hypoxic training on an individual's ventilatory response to carbon dioxide

IV. Methods

Experimental Design

Ten subjects were recruited from an athletic population aged 20-30 yr. and were assigned to one of two groups. A control group (N=5) participated in a conventional training program for a period of eight weeks. The experimental group (N=5) trained for two weeks in a similar manner, but for the last 6 weeks trained while rebreathing through a determined length of tubing. An eleven week study in all was undertaken by all the subjects according to the following schedule:

week	activity
1-2	Familiarization with procedures, Pretesting: (1) Performance of a $\dot{V}O_2$ max. test (2) Performance of a CO_2 ventilatory response test (3) Performance of a CO_2 storage capacity test and calibration of tube length needed to produce a designated hypoxic and hypercapnic training stimulus
3-4	Period of isocapnic/normoxic training Biweekly monitoring of blood gases and pH while training and performance of a biweekly criterion test of performance ability.
5-10	Period of training using tube breathing to produce added training stress in a designated training group (controls carry on as before) monitoring as above

11 Posttesting:
Performance of a:
(1)$\dot{V}O_2$ max. test
(2)ventilatory response test
(3)CO_2 storage capacity test

The control group followed a similar schedule except for the ommission of tube breathing while training. Arterialized blood gas analysis using the method of Siggaard-Andersen et al., (1960) was performed during one training session every two weeks, to monitor the effects of tube breathing on the partial pressure of arterial P_{CO_2} during actual training sessions. The two phases of training (with and without tube breathing) followed a weekly schedule in which a minimum number of three training periods per week and the performance of one criterion test every 2 weeks, was demanded from the subject. A typical weekly schedule was:

day:	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.	Sun.
activity:	test	train	rest	train	rest	train	rest

The training protocol session itself was based on the work of Astrand et al., (1960) who found that 3 minute intense work intervals with 3 minute rest intervals elicited the highest oxygen uptake and blood lactate concentrations compared with work intervals of shorter duration or continuous exercise. This suggests that the work schedule used in this study was appropriate for developing both aerobic and anaerobic fitness. Banister and Woo (1978) found that both aerobic and anaerobic power increased using a similar training protocol. The training

intensity used by these investigators was at a work rate of 1800 $kg \cdot m \cdot min^{-1}$. Such a high work rate would probably be appropriate only for a very athletic population however, and a work rate sufficient to elicit 90% of the maximum heart rate was used to train the subjects of this study. A training session consisted of bouts of 3 minutes of work followed by 3 minutes of rest until completion of 5 bouts or exhaustion occurred.

Calibration of Tube Rebreathing

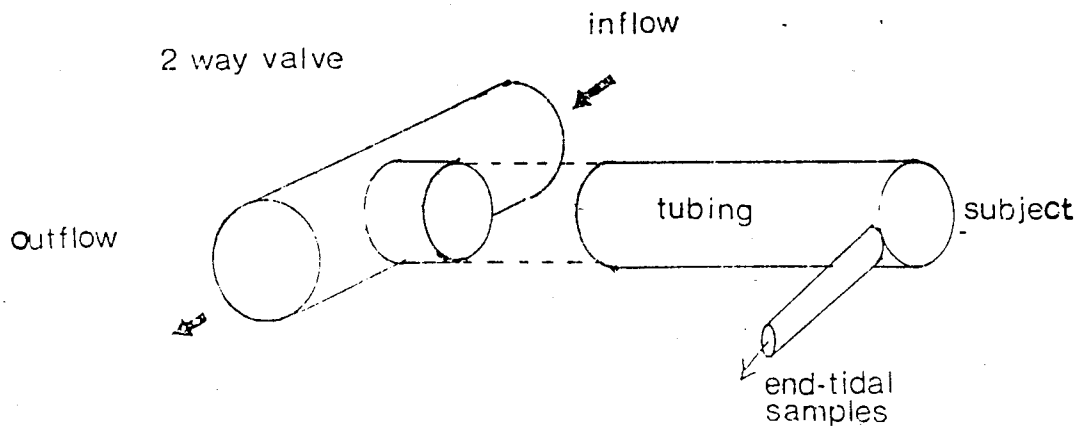
The level of hypercapnia/hypoxia was standardized for each subject. Ward and Whipp (1980) found $P_{A_{CO2}}$ to be independent of work rate during ergometer tests when respiratory dead space was increased. $P_{A_{CO2}}$ increased in direct proportion to external dead space over the entire aerobic $\dot{V}_{CO_2}$ range. A typical finding in the Ward and Whipp study was an increase in $P_{A_{CO2}}$ from 33.2 Torr in the in the absence of external dead space, to 41.1 Torr following the addition of 1.0 liter to the external dead space volume, during moderate exercise.

In the present study hypercapnic training was induced by the introduction of appropriate lengths of 1.5 inch in diameter tubing in a subject's breathing circuit. The extent of the hypercapnic/hypoxic stress produced by different tube lengths fitted in this manner during exercise was determined by calibrating tube length against $P_{ET_{O2}}$ and $P_{ET_{CO2}}$ during work at several standard power outputs. Fig.1 shows diagramatically the ventilatory arrangement used. This a modification of that

employed previously by Fenner *et al.* (1968)

Figure 1: The ventilatory arrangement for tube rebreathing that was used by the experimental group while training. End-tidal sampling of repesentative training sessions in both groups enabled the effects of the different regimes to be followed throughout the study.

Figure 1


inflow
2 way valve
outflow
tubing
subject
end-tidal
samples

Criterion Tests

Maximum Oxygen Uptake Test

A test of a subject's response to the training being undertaken was made biweekly on members of both control and experimental groups. Each subject completed a mixed step/ramp test to exhaustion on an electrically braked cycle ergometer.(Quinton model 845) A pedal rate of 90 revolutions per minute (Banister and Jackson, 1967) and a ramp slope of 100 kpm.min^{-1} per 30 seconds was maintained throughout the test until a subject was exhausted, as evidenced by his inability to maintain the work rate. A 2 minute period of unloaded pedalling preceded the onset of the ramp, beginning at 900 kpm.min^{-1}. $\dot{V}_{O_2}$ and heart rate were monitored during the test. (Fig.2)

An important advantage of the incremental work test is that it is more likely that the ventilatory threshold will be observed as work rate is progressively increased. (Wasserman and Whipp, 1975)

Measurement of Oxygen Uptake

Throughout subjects breathed through a low resistance, two-way breathing valve that directed the expirate through respiratory gas flow and composition analyzers.(Fig.2)

Ventilatory volume was obtained by integrating the flow rate obtained from a pneumotachograph over a ten second period and conditioning the signal with a Hewlett Packard 17403 Carrier Preamplifier. Mixed expired gas was analyzed for oxygen and carbon dioxide content with an S-3A Applied Electrochemical Oxygen Analyser and an Applied Electrochemistry CD-3A Carbon Dioxide Analyzer.

Outputs from the gas analyzers, electrocardiograph and carrier preamplifier were sampled at ten second intervals by a Hewlett Packard 3497A Data Acquisition Unit, controlled by a desktop computer (Hewlett Packard 85). Software written specifically for the metabolic analyzer controlled the sampling rate of the HP 3479A and computed ten second values for oxygen uptake, carbon dioxide production, ventilation, and respiratory exchange ratio. Minute values were computed by averaging six ten second samples for that particular minute. Gas volumes were standardized for barometric pressure and temperature.(STPD)

Analyzers were calibrated prior to each test with gases which had been precisely analyzed in a Scholander micro-apparatus. The pneumotachograph was calibrated with a one liter volume syringe.

The nominal sensitivity of the pressure transducer in the pneumotach was $\pm$ 0.5 mA. output for $\pm$ 20 mm H2O differential input pressure. From the transducer current proportional to the differential pressure was applied to an amplifier which converted current to voltage. The sensitivity setting on the

pneumotach used was 2.5 $l \cdot sec^{-1} \cdot volt^{-1}$ and full scale flow rate was 10 $l \cdot sec^{-1}$. The pneumotach is linearized to $\pm$ 2.0% of the reading from 0 to 100% of full scale flow and $\pm$ 4% of the reading from 0 to 130% of full scale flow.

By means of a digital voltmeter, the outputs of the flow transducer and integrator were zeroed before each on line calibration of the system.

Prior to the beginning of the study the computerized system's ventilatory measurement was tested against that of a 600 liter Collins Compensated Gasometer. Briefly, the description of this procedure was that measurement of ventilation by the computer was compared to that determined by observing the vertical movement of the gasometer. Compressed air pushed a 6 liter pump at flows of between 60 and 110 liters $\cdot$ min^{-1} and the flow was directed through the pneumotach and then into the gasometer. The two flow measurements had a correlation of 0.9997 with each other. (no intercept)

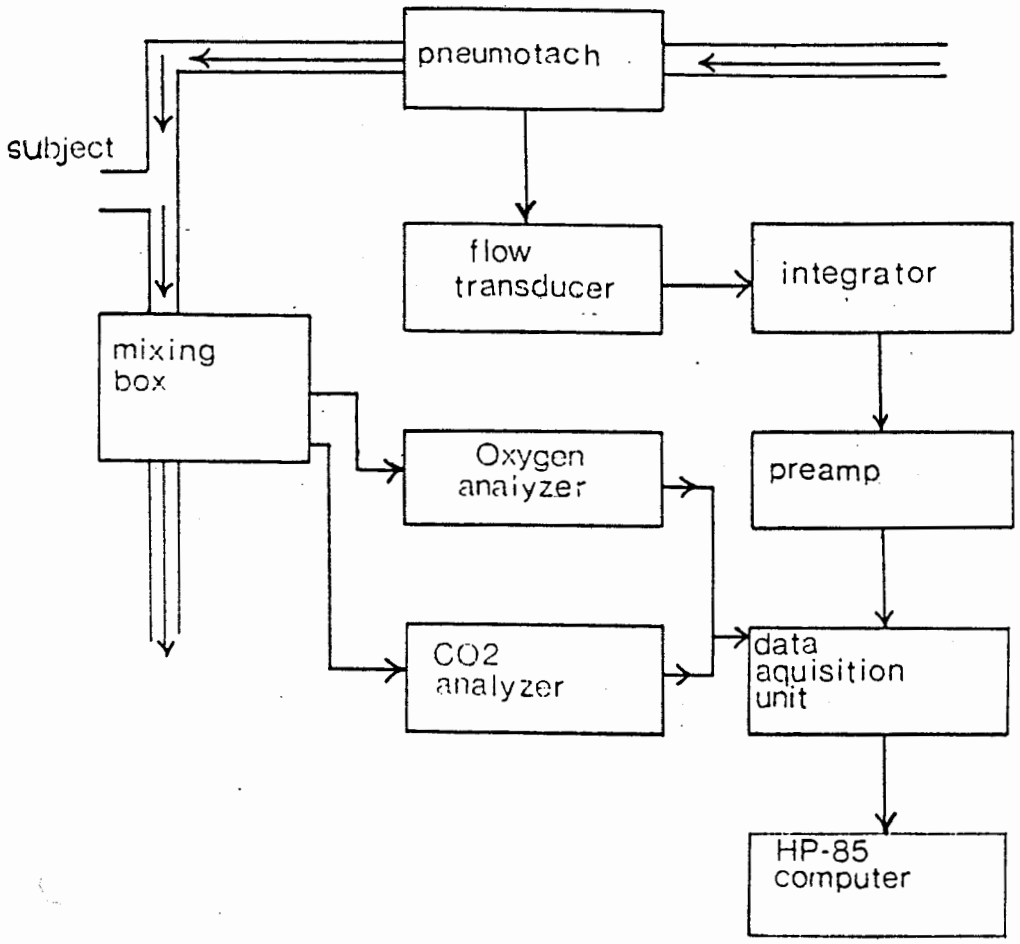
During the study 1 minute bag samples of expired gas were taken during random $\dot{V}_{O_2}$ max. tests. These measurements had a correlation of 0.8677 with each other. (the regression equation was found to be:

computer $\dot{V}_{O_2}$ = .341 + .891 (bag $\dot{V}_{O_2}$)

(R square = .732, standard error of estimate = 0.219)

Figure 2. The experimental arrangement used for measuring oxygen consumption during criterion tests of performance is shown here.

Figure 2


pneumotach
subject
flow
transducer
integrator
mixing
box
Oxygen
analyzer
preamp
CO2
analyzer
data
aquisition
unit
HP-85
computer

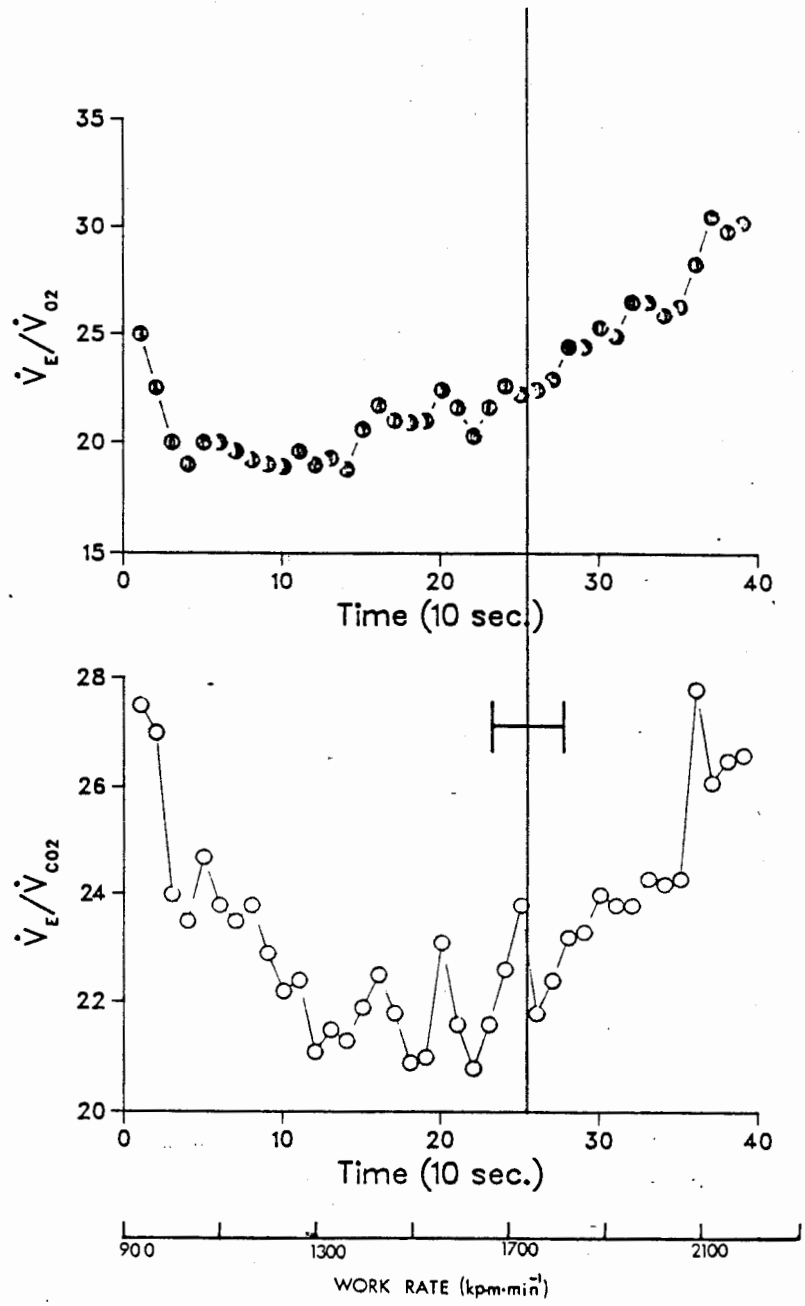
Anaerobic Run

In addition to the indirect assessment of anaerobic power derived from the partitioning of the recovery oxygen uptake curve, (see below) a treadmill test of anaerobic power measured from an all-out run to exhaustion at 20% grade and 8 miles per hour was used. (Cunningham and Faulkner, 1969)

Determination of Ventilatory Threshold

A noninvasive method determined the ventilatory threshold from analysis of the respiratory gas exchange pattern through the exercise test. Five experienced exercise physiologists, not directly involved with the study, analyzed respiratory gas data for each subject. They were provided with a written instructions (Simon et al., 1983) describing determination of the ventilatory threshold from a criterion time point given by the beginning of a consistent increase in $\dot{V}_E/\dot{V}_{O_2}$, without a marked increase in the ratio $\dot{V}_E/\dot{V}_{CO_2}$. (See Appendix.) The judges were provided with relevant graphs of $\dot{V}_E/\dot{V}_{O_2}$ vs. time and $\dot{V}_E/\dot{V}_{CO_2}$ vs. time and were asked to identify the time at which the given criteria applied, as shown in figure 3. (This time could then be converted to a corresponding work rate.) In order to minimize bias in judgements, the judges knew no details of subject identity, seriality of data or other judges' ratings.

Figure 3: Determination of the ventilatory threshold in one subject is shown in this figure. $\dot{V}_E/\dot{V}_{CO_2}$ data points are indicated by the open circles. $\dot{V}_E/\dot{V}_{O_2}$ data points are indicated by the filled circles. The vertical line indicates the average of the five judgements of the ventilatory threshold. This line is bracketed by the standard error of that value. The abscissa on the lower figure is given in time and work rate.


35
30
25
20
15
$\dot{V}_E/\dot{V}_{O2}$
0
10
20
30
40
Time (10 sec.)
28
26
24
22
20
$\dot{V}_E/\dot{V}_{CO2}$
0
10
20
30
40
Time (10 sec.)
900
1300
1700
2100
WORK RATE (kpm·min^{-1})

Kinetics of Recovery Oxygen Uptake

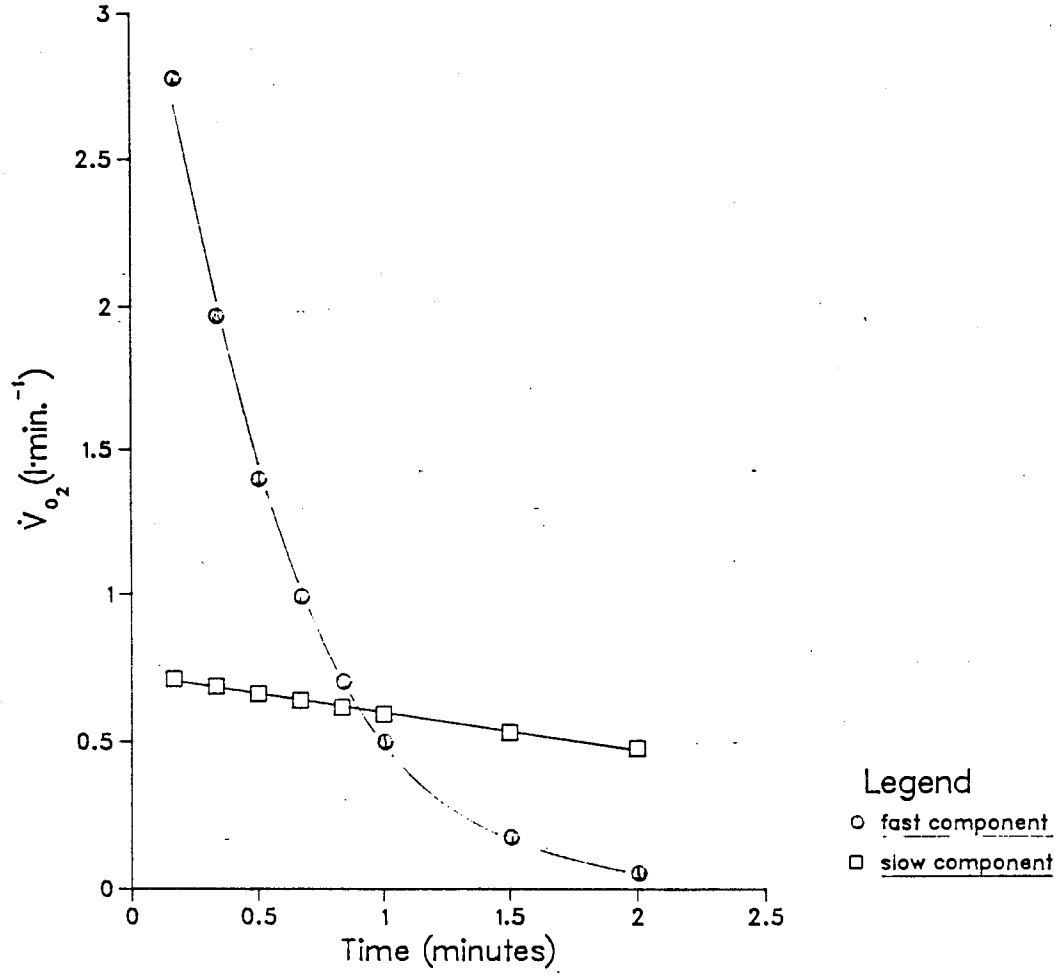
As oxygen uptake accelerates to meet the demand of the energy output during work in humans, an oxygen debt develops in an amount depending upon the kinetic response of an individual's oxygen transport capacity and the size of the work rate demand. Roberts (1977) used a graphical method proposed by Solomon (1960) to solve the two compartment problem of ascribing the oxygen debt at the end of exercise to alactacid and lactacid portions. Although Margaria (1963) has argued that oxygen debt repayment may be adequately described by a single exponential decay curve, most investigators have described it in terms of the sum of two exponential decay curves of the form:

$$\dot{V}_{O_2} = C + P_1 e^{-P2\ t} + P_3 e^{-P4\ t} \qquad \text{Eq.3}$$

(Katch et al., 1972, Katch, 1973) where C is standardized baseline oxygen uptake at t=0, P1 represents the alactacid component of the oxygen debt, P3 represents the lactacid debt, and P2 and P4 are rate constants of exponential decay of these latter two processes. The recovery oxygen uptake curve was analyzed by non-linear regression analysis using a computer package. (BMDP3R) Assumption of a standardized elevated baseline oxygen uptake (resting oxygen uptake plus 10%) has been proposed by previous authors in estimations of this kind (Thomas et al., 1965; Wright, 1972) and reduces the time of observation required after exercise necessary to describe the recovery oxygen kinetics accurately. C + P1 + P3 represents the oxygen uptake at

the beginning of the recovery process and the exponential terms represent different aspects (fast and slow components) of the oxygen uptake recovery process. The values of the rate constants P2 and P4 have values of approximately 30 seconds and ten minutes, respectively.(Katch, 1973) Integration of the recovery oxygen uptake curve and subtraction of component C allowed quantification of the oxygen debt and the alactacid and lactacid components in units of liters of oxygen. The integration was achieved using a fortran program provided by NAG (Numerical Algorithms Group, subroutine D01BDF), which had been developed by Patterson (1968). An attempt was made to account for the common area occupied by both components of the recovery curve. The approximation was made that 50% of that area was contributed by each component. This information was to be used to monitor any changes in the contributions of energy sources used to perform the criterion test during the phases of training. A figure follows showing a typical recovery curve from real data and a curve fitted with an equation provided by nonlinear regression.(figure 4)

Figure 4: Fast and slow components of the recovery curve. These components were derived by nonlinear regression of the actual recovery oxygen consumption data recorded following a $\dot{V}_{O_2}$ max. test. Classically, the fast component has been associated with the alactacid debt and the slow component with the lactacid debt (see discussion).


3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
$\dot{V}_{O_2}$ (l·min.$^{-1}$)
Time (minutes)
Legend
fast component
slow component

Ventilatory Response to CO_2

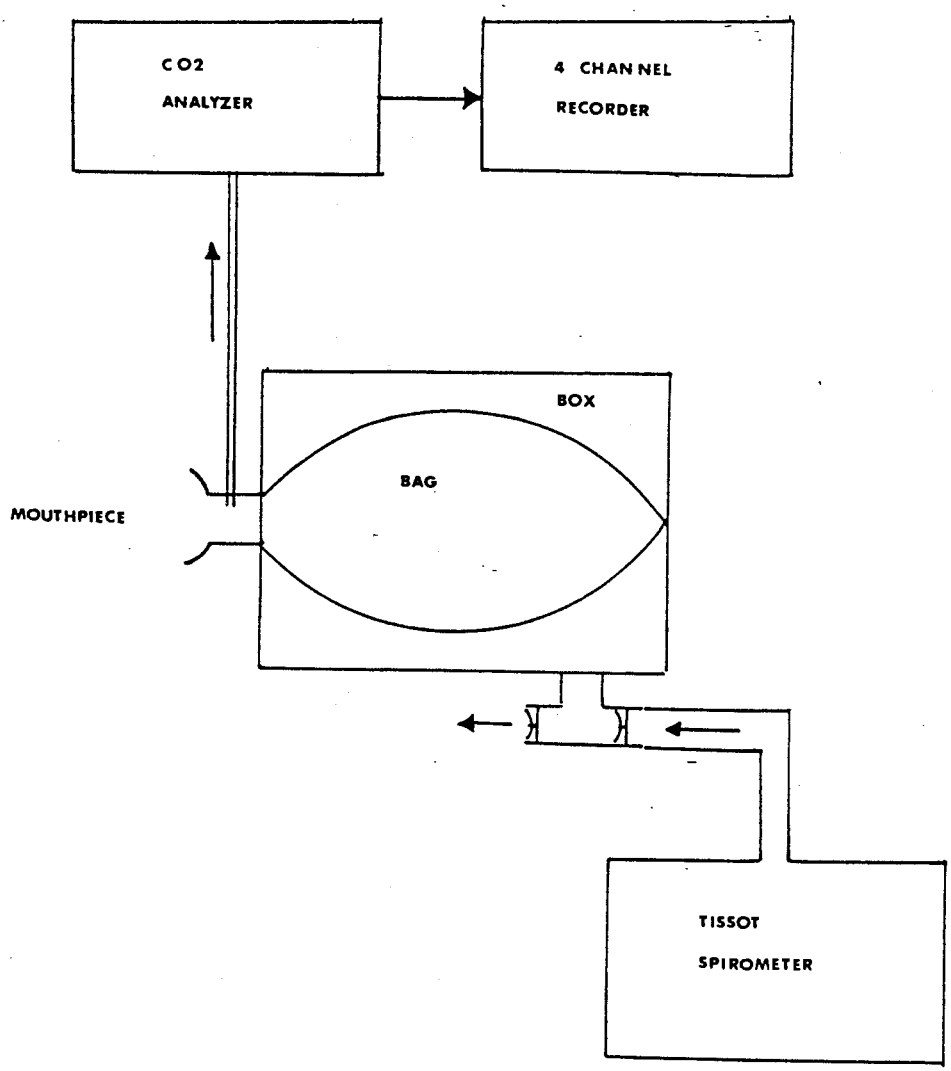
CO_2 ventilatory response was determined from subjects rebreathing a mixture of 10% carbon dioxide, balance oxygen, so that progressive hypercapnia occurred. End-tidal P_{O_2} ($P_{ET_{O2}}$) remained above 200 mm Hg throughout in order to eliminate hypoxic stimulation to ventilation. The equation relating $\dot{V}_E$ and $P_{A_{CO2}}$:

$$\dot{V}_E = S\ (P_{A_{CO2}} - B) \qquad \text{Eq.4}$$

(Cormack et al., 1957) allowed the constants B, the extrapolated intercept on the $P_{A_{CO2}}$ axis when $\dot{V}_E = 0$, and S, the slope of the line expressed as a change in ventilation per unit change in $P_{A_{CO2}}$, to be calculated. (Miyamura et al.,, 1976) The experimental arrangement for the measurement of the ventilatory response to rebreathing CO_2 is schematically shown in in Figure 5. Ventilation was recorded by the 'bag in box' system. Exhalations into the bag compressed air in the box and forced air out of the box, and into the atmosphere, via a two-way valve. During the subsequent inhalation, the air in the box became subatmospheric and withdrew air from the Collins gasometer via the two-way valve. A rotating drum recorded the downward movement of the gasometer. End-tidal measurements of CO_2 were made by the CD-3A Applied Electrochemistry CO_2 analyzer and recorded on an HP 7404A 4 channel recorder. Determination of the ventilatory response to CO_2 was made at a standardizized

work rate, after a period at the same work rate breathing normally.

Figure 5: The experimental arrangement used for measuring the ventilatory response to carbon dioxide rebreathing. Continuous end-tidal CO_2 sampling was recorded and ventilation was determined by a 'bag in box' method during rebreathing.


CO2
ANALYZER
4 CHANNEL
RECORDER
BOX
BAG
MOUTHPIECE
TISSOT
SPIROMETER

CO_2 Storage Capacity Test

Body carbon dioxide storage capacity was assessed by the method of Jones and Jurkowski (1979). Subjects exercised for five minutes at 60% of their maximal oxygen uptake to produce a steady state $\dot{V}_{O_2}$, $\dot{V}_{O_2}$, and $\dot{V}_E$. During the last minute of this period, measurements of end-tidal P_{CO_2}, and mixed venous P_{CO_2}, (obtained by rebreathing, Jones et al., 1967) were taken. After a one minute interval following rebreathing, to eliminate rebreathed CO_2, ventilation was voluntarily increased for several minutes. At the end of this period of hyperventilation a final measurement of mixed venous P_{CO_2} was made.

Jones and Jurkowski (1979), Cain (1970) and Khambatta and Sullivan (1974) have observed that during the rebreathing procedure respiratory alkalosis may result in an increased $\dot{V}_{O_2}$. To allow for the associated increase in metabolic CO_2 production Jones and Jurkowski assumed that the RQ equalled the R value obtained in the steady state control conditions, thus CO_2 output during hyperventilation was calculated from the area under a $\dot{V}_{CO_2}$/time curve.

Net CO_2 evolved was then calculated from the equation:

$$\text{net } CO_2 = \dot{V}_{CO_2} - (\dot{V}_{O_2} \text{ X steadystate R}) \qquad \text{Eq.5}$$

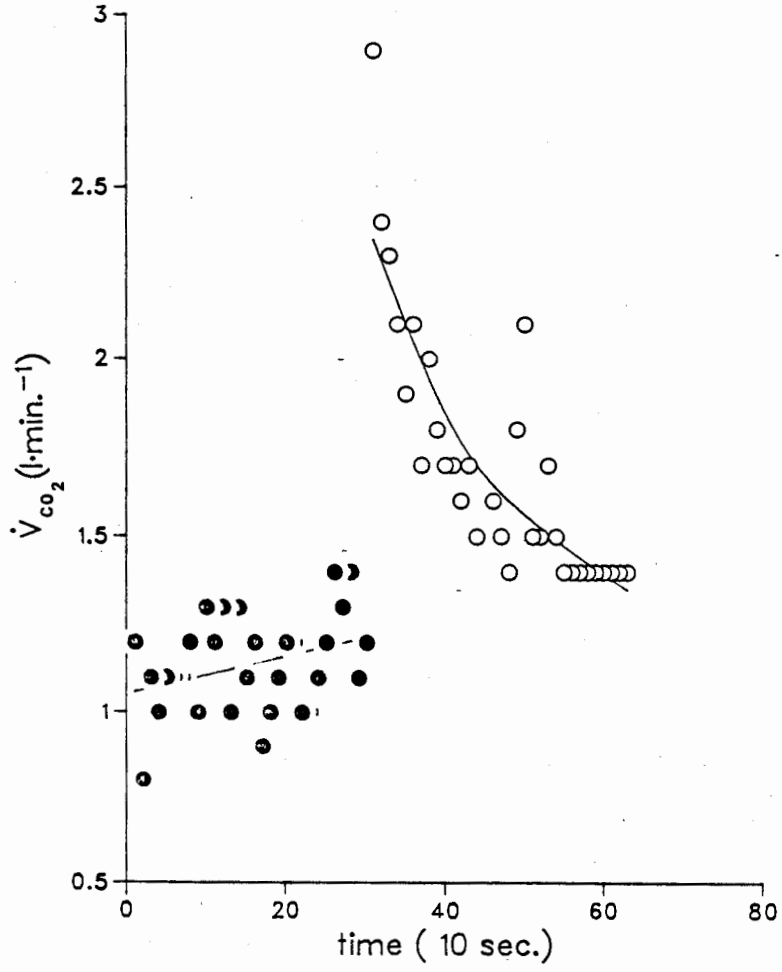
CO_2 storage capacity in ml CO_2 kg^{-1} $Torr^{-1}$ was obtained by dividing the total CO_2 washed out by the product of the change

in mixed venous P_{CO_2} and by body weight. Thus:

$$CO2 \text{ storage capacity} = \frac{\text{net } CO2}{\text{change in PvCO2 x weight}} \qquad \text{Eq.6}$$

Figure 6 shows a typical CO_2 washout curve from the hyperventilation procedure.

Figure 6: A typical washout curve resulting from hyperventilation Solid circles indicate $\dot{V}_{CO_2}$ during a control exercise period. Open circles indicate $\dot{V}_{CO_2}$ during the hyperventilation procedure. Lines represent linear and non-linear regressions, respectively. during the CO_2 storage test.


3
2.5
2
1.5
1
0.5
$\dot{V}_{CO_2}$ (l·min.$^{-1}$)
0
20
40
60
80
time (10 sec.)

Blood Measurements

Blood pH and P_{CO_2} were determined by the method of Siggaard-Andersen, Engel, Jorgensen and Astrup (1960) during representative training sessions throughout the period of the experiment. Arterialized capillary blood was collected from the lobe of the ear or the pulp of the finger. Free flowing cutaneous blood originates from the arterioles and therefore corresponds to arterial blood in composition. (Siggaard-Andersen, 1966) Vascular dilation was produced before making the puncture by application of a heated pad. After first swabbing with alcohol, a puncture approximately 5 mm deep was made by means of a lancet. Blood was collected in a heparinized glass capillary tube which was then provided with a small pin (facilitates mixing with magnet), blocked with wax at both ends, and placed in ice. The pH was measured directly by means of a capillary glass electrode.(Radiometer, BMS2 Mk 2 blood micro system). The pH electrode was calibrated before each set of measurements with buffer solutions of pH 7.383 and 6.841. Immediately before each test calibration was checked from the 7.383 buffer. P_{CO_2} was calculated by interpolation on the pH, log P_{CO_2} equilibration curve.(i.e. the Siggaard-Andersen Curve Nomogram) Arterialized blood was equilibrated with a gas of known low (5.63%) and high (8.68%) CO_2. After each equilibration the pH of the blood was measured using the pH electrode.

Quantification of Training

Training was monitored and quantified as previously described by Calvert et al., (1976). A theoretical training impulse calculated for each individual's training session was made from the product of the total duration and intensity of the cycling bouts. The average of the immediate recovery heart rate from each bout of cycling gave an approximate measure of the relative intensity of the training session, when expressed as a fraction of the individual's maximum heart rate.

A positive weighting factor varying with the degree of fractional heart rate elevation corrected the training impulse for potential inaccuracies stemming from overcompensating long duration activity carried out at a relatively low fractional heart rate elevation, compared with short duration, high heart rate activity. The weighting factor varied according to the classical rise in blood lactate associated with various intensities of work, expressed as a percentage of maximum heart rate elevation. It was based on blood lactate-work rate relationships determined in the recent literature. (Green et al., (1983). The weighting factor was of the form:

$$k = 0.86e^{1.67x}$$

where k is the weighting factor, e is the base of the natural logarithm, and x is the fractional heart rate elevation. (Banister and Hamilton, 1984)

In this way a quantitative measure of training undertaken by each subject in the program could be estimated and related to each person's training response. It was assumed that the training impulse generated both a cumulative increase in fatigue and fitness, which grew during the period of training. Criterion performances measured at any time during the period were able to be deduced from this model as the simple difference between accumulated fitness and fatigue. The pattern of the difference could then be compared to the pattern of actual performance measured biweekly, as described above in 'criterion performance tests'.

Statistical Treatment

The effectiveness of training with increased dead space was assessed by comparing the following variables measured at the beginning and at the end of the experimental period in both the experimental and control groups:

1. change in aerobic power (as measured by $\dot{V}_{O_2}$ during the criterion test). The serial data was analyzed with a repeated measures analysis of covariance (BMDP2V). The first test served as the covariate to minimize the effect of any initial differences.

2. change in anaerobic power (as measured by change in lactacid oxygen debt, time of an anaerobic run, and ventilatory threshold). Recovery curve equation parameters and curve areas were assessed pre and post training with an ANCOVA, with the

initial values serving as the covariates. The change in ventilatory threshold was assessed by calculating gain scores (i.e. post-test time was subtracted from the post-test score for each subject). Mean gain scores were calculated for each group and a t-test was used to compare the two groups, using BMDP3D. The anaerobic run times were subjected to an analysis of covariance with the initial run serving as the covariate, using BMDP2V.

3. levels of arterialized P_{CO_2}, pH, $P_{ET_{CO2}}$, $P_{ET_{O2}}$ during biweekly training sessions in both control and experimental groups. Mean differences were compared with a repeated measures ANOVA (BMDP2V) and where differences were found to be significant, post-hoc testing using the Newman-Keuls test located them.

4. mean change in respiratory response to CO_2 (as evidenced by the values of the constant terms (S and B) in the equation relating ventilation to $P_{A_{CO2}}$:

$$\dot{V}_E = S\ (P_{A_{CO2}} - B)$$

and by the ventilation to carbon dioxide production relationship obtained during maximal testing. The latter was subjected to an analysis of covariance (BMDP1V), which controlled for any initial differences in the groups.

5. mean change in carbon dioxide capacity

The comparisons were made on the basis of an analysis of covariance on pre and post-test values which controlled for any initial differences (BMDP1V).

6. Patterns of improvement in criterion performances were used to evaluate the rebreathing contribution to the training impulse. The level of significance was set at $P < .05$.

V. Results

Calibration of Tube Volume

During the initial two weeks of training, on several isolated occasions subjects of both the experimental group and control group were used to calibrate the combination of tube length and work rate producing various levels of $P_{ET_{CO2}}$ and $P_{ET_{O2}}$ (N=41). The regression equation relating $P_{ET_{CO2}}$ to work rate and tube volume was :

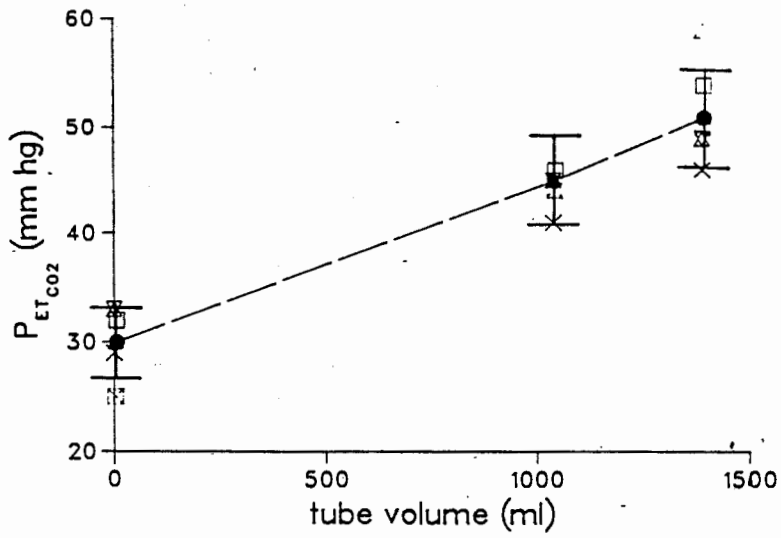
$$P_{ET_{CO2}} = 46 - 0.0088\ W + 0.0089\ V$$

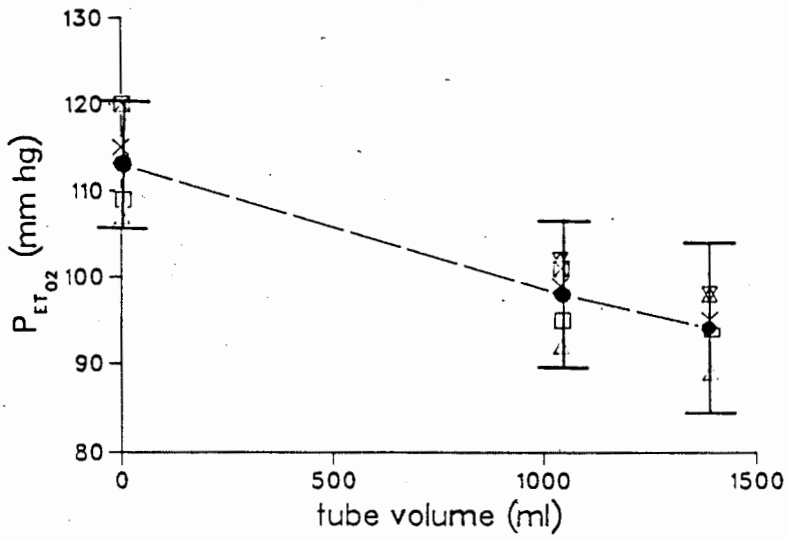
where $P_{ET_{CO2}}$ is measured in mm Hg., W is work rate in kg m min^{-1}, and V is volume in ml. (multiple R = .8332, multiple R-square = .6943, standard error of estimate = 3.7) The equation relating $P_{ET_{O2}}$ to work rate and and tube volume was found to be:

$$P_{ET_{O2}} = 96 + 0.0102\ W - .0088\ V$$

where $P_{ET_{O2}}$ is measured in mm Hg., W and V as above. (multiple R = .7693, multiple R-square = .5918, standard error of estimate = 4.7) (See figure 7 for plots of end-tidal gases vs. tube volume.)

Figure 7: Mean and individual end-tidal gas tensions of carbon dioxide and oxygen are plotted against tube volume, respectively. Mean values are bracketed by $\pm$ SEM and are connected.

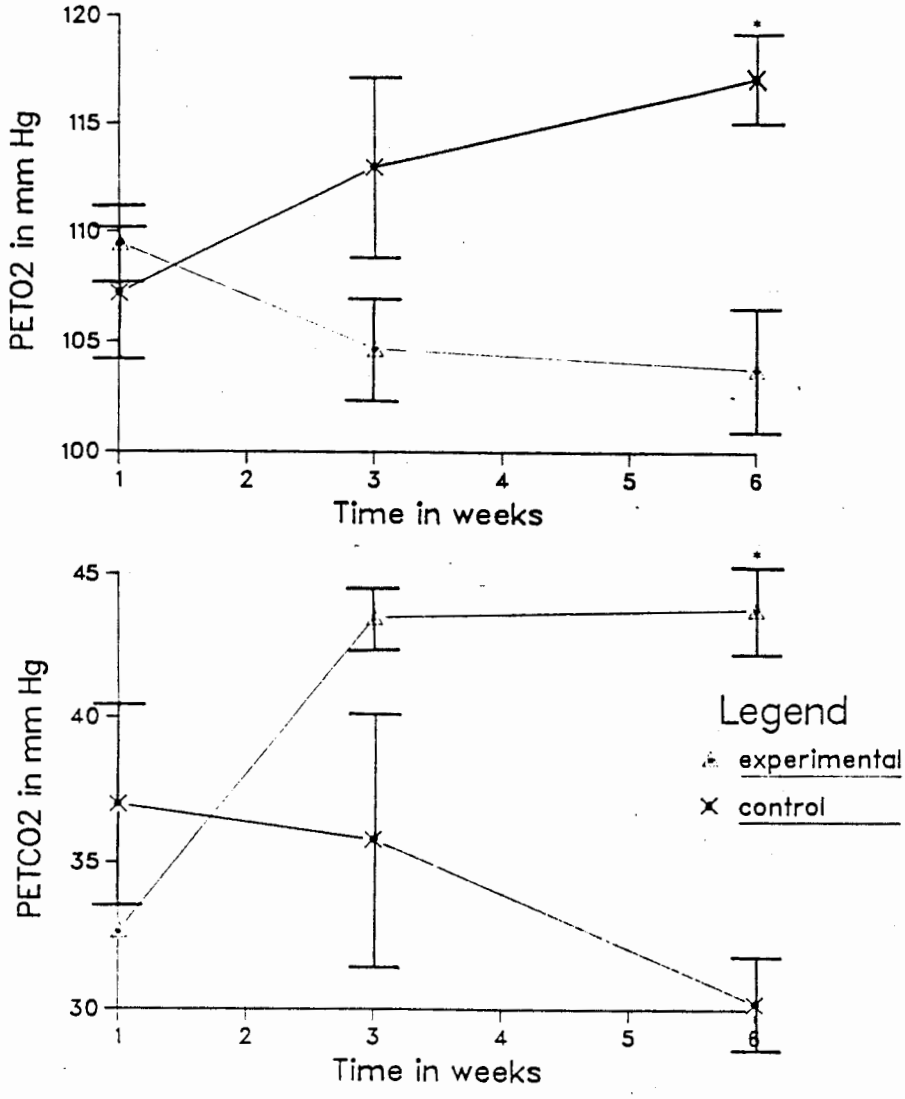

60
50
40
30
20
$P_{ET_{CO2}}$ (mm hg)
0
500
1000
1500
tube volume (ml)


130
120
110
100
90
80
$P_{ET_{O2}}$ (mm hg)
0
500
1000
1500
tube volume (ml)

Serial End-Tidal Gas Monitoring During Training

Mean end-tidal carbon dioxide tensions were 32.6 ± 1.2, 43.5 ± 1.1, and 43.8 ± 1.5 mm Hg, in the first, third, and sixth week respectively in the experimental group(Figure 8). In contrast, the corresponding tensions in the control group were 37 ± 3.4, 35.8 ± 4.4, and 30.2 ± 1.5 mm Hg, sampled similarly during the same period. Mean end-tidal oxygen tensions in the experimental group were 109 ± 1.8, 104.7 ± 2.2, and 103.8 ± 2.7 mm Hg and mean control end-tidal oxygen tensions were 107.2 ± 2.9, 113 ± 4.1, and 117 ± 2.0 mm Hg, during the period at the interval time designated above (Figure 8). A significant difference was noted between the two groups in both end-tidal carbon dioxide tension and oxygen tension when analyzed by a repeated measures ANOVA. Post-hoc tests performed on the means using Newman-Keul's test showed significant differences between the control and experimental groups in weeks 6 only.

Figure 8: Serial endtidal gas measurements of oxygen and carbon dioxide were measured during repesentative workouts in both control and experimental groups during the training period. Mean values are bracketed by $\pm$ SEM and are connected by a solid line.


120
115
110
105
100
PETO2 in mm Hg
1
2
3
4
5
6
Time in weeks
45
40
35
30
PETCO2 in mm Hg
1
2
3
4
5
6
Time in weeks
Legend
experimental
control

Serial Blood Gas Data

Mean arterialized capillary P_{CO_2} levels followed the end-tidal measurements quite closely. In weeks 1, 3, and 6 they were 42 $\pm$ 1.3, 43.3 $\pm$ 3.9, and 47.5 $\pm$ 1.1 in the experimental group. At corresponding times the control group mean values were 37.4 $\pm$ 4.4, 39 $\pm$ 1.6, and 33 $\pm$ 2.7 mm Hg. Mean values were subjected to a repeated measures ANOVA and found significantly different. Follow-up with post-hoc testing using a Newman-Keuls test revealed that a significant difference between the control and experimental groups existed in week 6 only.

Mean arterialized capillary pH values were determined at the same time as the P_{CO_2} values. In weeks 1, 3, and 6 they were 7.12 $\pm$ .02, 7.15 $\pm$ .02, and 7.19 $\pm$ .03 in the experimental group. Corresponding values in the control group were found to be 7.18 $\pm$ .01, 7.20 $\pm$ .02, and 7.21 $\pm$ .05. A repeated measures ANOVA found no significant differences between the control and experimental groups.

Enumeration of Training

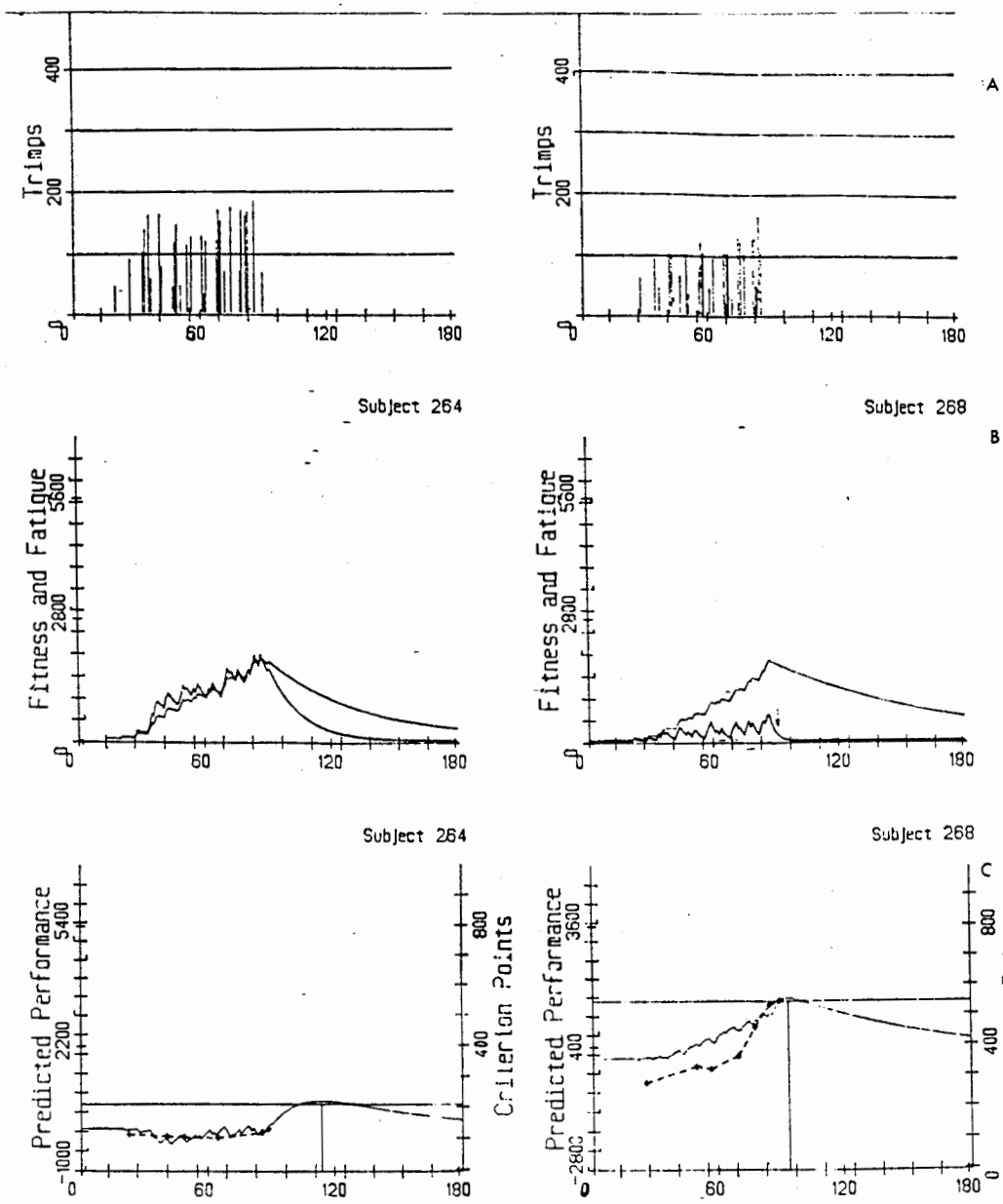
Figure 9 shows best and worst case examples of the result of modeling training against actual performances for 2 subjects of the experimental group. Actual performances are shown on a points scale allocating 1000 pts. for a performance 10% longer than the lab record for the treadmill run test at 20% grade, 8 mph. A least squares, best fit, modeled curve (bottom panel) of

predicted performance against actual performance determined both hypothetical constructs of the model, fitness and fatigue, shown in the middle panel.

It can be seen that for the same training subject 268 showed much more sensitivity to the imposed training than subject 264. The accumulated trimp score for subject 268 was 2395, while 264 accumulated 3100.

Cumulative trimp scores of the control and experimental groups were summed at the end of the study. Group means were 2628 $\pm$ 319 in the experimental group and 2290 $\pm$ 745 in the control group, and were found not to be significantly different.

Figure 9: A comparison is made of subjects 264 and 268.
A indicates the training impulses that were accumulated due to the product of work, heart rate and an intensity factor.
B indicates the growth of fatigue (thick line) and fitness (thin line) that occurred due to training.
C indicates the predicted performances of the subjects (continuous line) versus the actual performances.(dashed lines)


A
Trimps
400
200
0
60
120
180
Subject 264
Subject 268
B
Fitness and Fatigue
5600
2800
Subject 264
Subject 268
C
Predicted Performance
5400
2200
-1000
3600
400
-2800
Criterion Points
800
400
0

Maximum Oxygen Uptake

Pre and post maximum oxygen uptake ($\dot{V}_{O_2}$ max.) values were analyzed by ANCOVA to minimize the effect of any initial differences in the control and experimental group. Post-testing indicated that $\dot{V}_{O_2}$ max. declined significantly in the experimental group (4.6 $\pm$ .15 - 3.9 $\pm$ .15 l min.$^{-1}$) whereas in the control group $\dot{V}_{O_2}$ max. remained relatively unchanged. (3.8 $\pm$ .25 - 3.7 $\pm$ .2 l min.$^{-1}$) (See figure 10) The change in the power-time index was found not be significantly different in the two groups when analyzed by a repeated measures ANCOVA. (See figure 11)

Figure 10: Serial maximum oxygen uptake levels that were determined by maximal tests on the cycle ergometer are shown for both experimental and control groups. Mean values are indicated by solid circles, are bracketed by $\pm$ SEM, and are connected by solid lines.

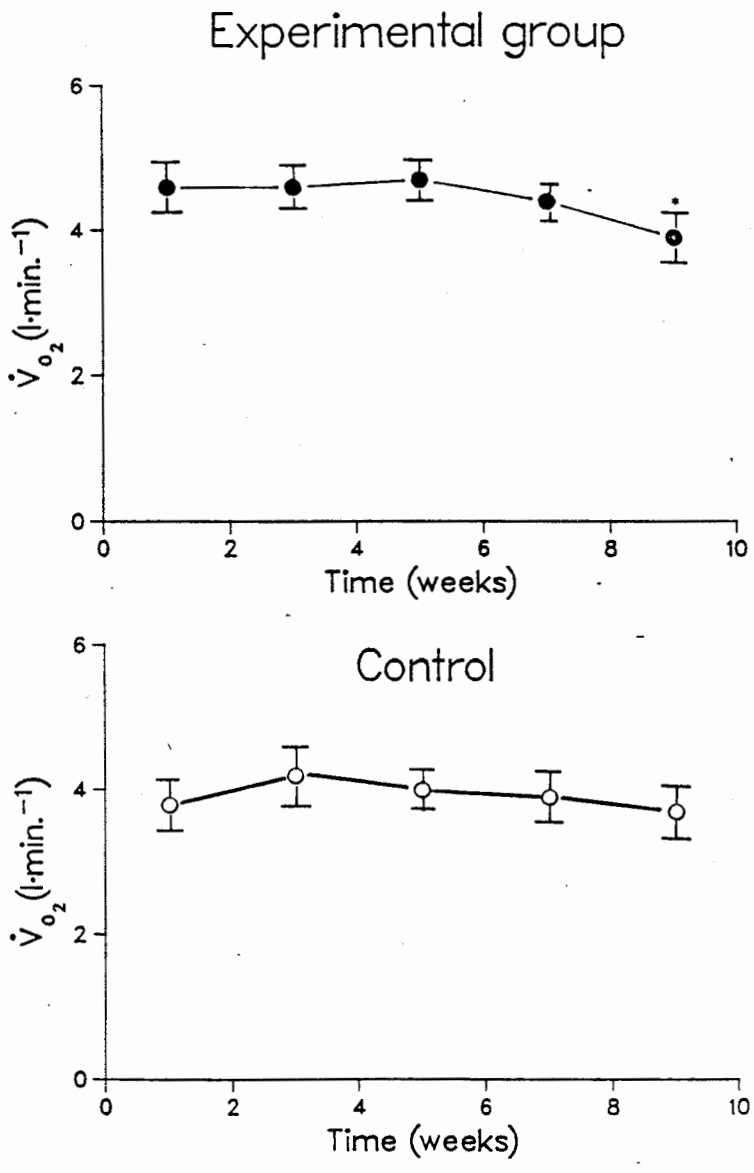
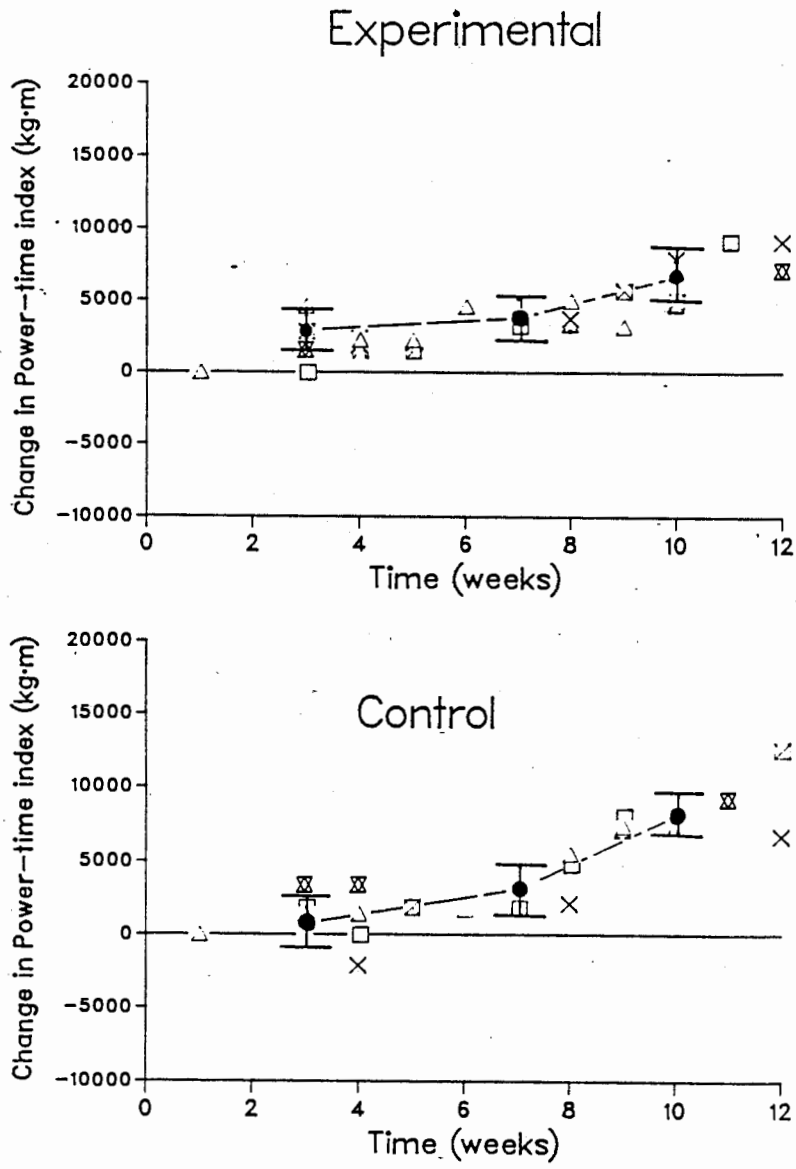

Experimental group
$\dot{V}_{O_2}$ (l·min.$^{-1}$)
0
2
4
6
0
2
4
6
8
10
Time (weeks)
Control
$\dot{V}_{O_2}$ (l·min.$^{-1}$)
0
2
4
6
0
2
4
6
8
10
Time (weeks)

Figure 11: Serial change in power-time indices that resulted from the testing are shown. The data are derived from the product of the work rates and the time at each work rate, and give an indication of the total amount of work done during each maximal test. The power-time index of test #1 provided the arbitrary zero point for each subject. Each subsequent test then deviated from this value, and the change was plotted. Mean values are indicated by solid circles, are bracketed by $\pm$ SEM, and are connected by a solid line.


Experimental
Change in Power–time index (kg·m)
20000
15000
10000
5000
0
−5000
−10000
0
2
4
6
8
10
12
Time (weeks)
Control
Change in Power–time index (kg·m)
20000
15000
10000
5000
0
−5000
−10000
0
2
4
6
8
10
12
Time (weeks)

The respiratory exhange ratio (RER) and maximum ventilation during the maximal tests were noted in both groups pre and post training, and tested with an ANCOVA. (see table 1)

TABLE 1 - MAXIMAL TEST DATA

Group		RER	$\dot{V}_E$
Experimental	pre	1.02 ± .02	133 ± 8
	post	1.14 ± .04	125 ± 5
Control	pre	1.10 ± .03	117 ± 7
	post	1.26 ± .02*	116 ± 3

The changes of ventilation and were not significantly different between groups. The change in RER was greater in the control group, when the initial values were taken into account.

Ventilatory Thresholds

Five independent sets of judgements made of the ventilatory threshold for each pre and post $\dot{V}_{O_2}$ max. test were correlated against each other. These results are shown in Table below.

TABLE 2 - CORRELATION MATRIX FOR OBSERVERS

	obs #1	obs #2	obs #3	obs #4	obs #5
obs #1	1.0000				
obs #2	0.9142	1.0000			
obs #3	0.6682	0.6575	1.0000		
obs #4	0.8361	0.8867	0.6683	1.0000	
obs #5	0.8527	0.8482	0.7969	0.8732	1.0000

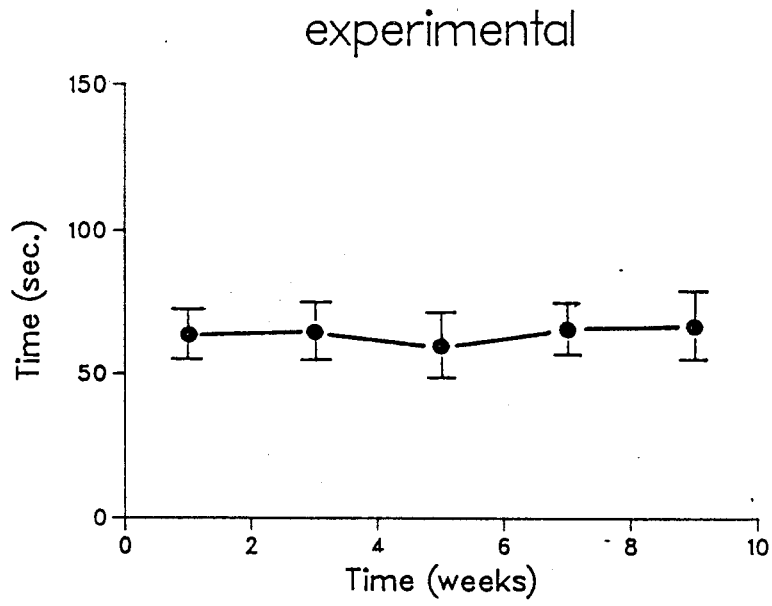
The means of the 5 independent analysts' observations of each subject's pre training ventilatory threshold was subtracted from the post training ventilatory threshold to determine a gains

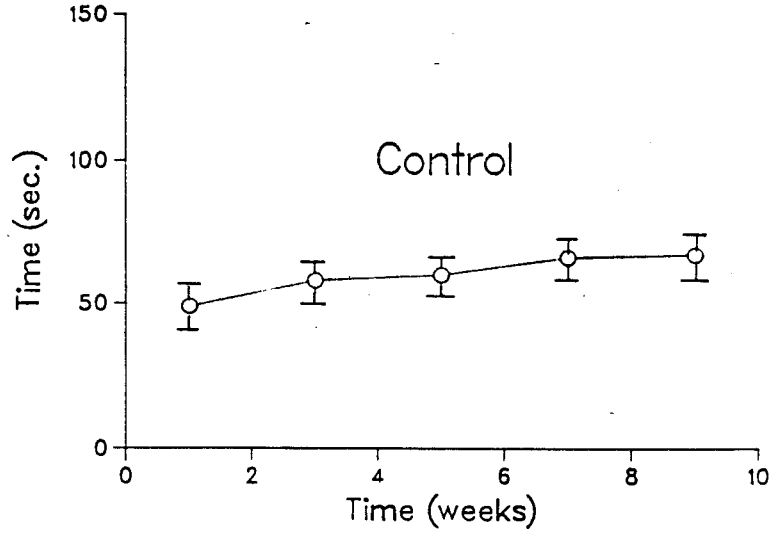
score. Mean gain scores for each group were compared with a t-test using BMDP3D. The control group increased their ventilatory threshold from 116 ± 17 seconds at the beginning of training to 141 ± 23 seconds (gain score = 25 ± 8) at the end of the study, whereas the experimental group improved from 166 ± 13 to 264 ± 32 seconds (gain score = 98 ± 25). The differences between group mean gain scores were significant at the .05 level. All correlations between the observers' judgements were significant at the .01 level. However, observer #3 differed considerably from the others.

Anaerobic Run Time

The run time to exhaustion on the treadmill increased from 49.4 ± 4.8 to 66.6 ± 4.3 seconds in the control group during the course of the study and the experimental group increased on the same test from 59.5 ± 7.3 to 74.3 ± 10.9 seconds. Experimental and control anaerobic run times analyzed by an ANCOVA showed no significant group differences. (See figure 12) Pre and post mean values indicated an overall improvement in total run time to exhaustion on the treadmill in both groups, but both groups improved their run times by a similar amount.

Figure 12: Anaerobic run performances of the experimental and control groups are shown during the course of the study. Mean run times are indicated by solid circles, are bracketed by $\pm$ SEM, and are connected by solid lines.


experimental
150
100
50
0
Time (sec.)
0
2
4
6
8
10
Time (weeks)


150
100
50
0
Time (sec.)
Control
0
2
4
6
8
10
Time (weeks)

Carbon Dioxide Storage Capacity

Control group mean CO_2 storage capacity changed from 2.6 $\pm$ 0.5 to 2.7 $\pm$ 0.6 $ml \cdot kg^{-1} \cdot min.^{-1}$ between the beginning and end of the training period. Corresponding values in the experimental group were 2.1 $\pm$ 0.5 and 2.2 $\pm$ 0.2 $ml \cdot kg^{-1} \cdot mm^{-1}$ Hg. An analysis of covariance was carried out on the data to control for any initial differences between the groups. No significant differences were found.

Analysis of Recovery Curve

The parameters P_1, P_2, P_3, and P_4 of the recovery curve were fitted to the recovery curve $\dot{V}_{O_2}$ data from equation 3.(see above) P_1, P_2, P_3, and P_4 values were not significantly different in the two groups post-training, when the initial values were taken into account.

TABLE 3 - RECOVERY CURVE KINETICS

(parameters of the equation:

$$\dot{V}_{O_2} = C + P1e^{-P2t} + P3^{-P4t})$$

group	parameter	pre	post
control	P_1	3.07 $\pm$ .28	2.51 $\pm$ .23
	P_2	-1.21 $\pm$ .30	-0.86 $\pm$ .09
	P_3	0.59 $\pm$ .11	0.40 $\pm$ .10
	P_4	-0.11 $\pm$ .04	-0.07 $\pm$ .01
experimental	P_1	3.45 $\pm$ .29	2.62 $\pm$ .20
	P_2	-0.86 $\pm$ .08	-0.83 $\pm$ .05
	P_3	0.74 $\pm$ .20	0.67 $\pm$ .08
	P_4	-0.26 $\pm$ .15	-0.08 $\pm$ .02

(P_1 and P_3 have units of l/min., P_2 and P_4 have the units of time.)

Component Areas of the Recovery Curves

Component areas of the recovery $\dot{V}_{O_2}$ curves attributable to lactic and alactacid mechanisms were evaluated. Total debt, lactacid and alactacid values were not found to be significantly different, either within (pre vs. post) or between (experimental vs. control) groups. ($p > .05$, from ANCOVA)

TABLE 4 - RECOVERY CURVE COMPONENT AREAS (liters)

group	area	pre	post
control	total	10.89 ± 3.61	8.23 ± 1.56
	alactacid	3.20 ± 0.61	3.11 ± 0.20
	lactacid	6.36 ± 3.55	5.44 ± 1.23
experimental	total	11.06 ± 1.56	10.78 ± 1.60
	alactacid	4.07 ± 0.25	2.92 ± 0.31
	lactacid	5.64 ± 1.42	6.40 ± 0.64

Ventilation/Carbon dioxide output

Measurements were made of the ventilatory response to CO_2 production during maximal oxygen uptake tests in both control and experimental groups. The regression of ventilation on carbon dioxide production for each group was plotted from data of the maximum oxygen uptake test. Analysis of covariance of these results showed a significant effect of the different training experienced by the tube breathers. The effect of the tube breathing exercise regimen was to decrease the slope of the ventilatory response to CO_2.

TABLE 5 - VENTILATORY EQUIVALENT ($\dot{V}E/\dot{V}CO2$)
(ventilation vs. CO2 production during maximal tests)

group	pre	post
control	21.44 ± 0.75	22.64 ± 0.37*
experimental	22.66 ± 0.53	21.12 ± 0.89*

Ventilatory response to rebreathing CO_2

At the end of the training period, a determination was made of control and experimental group respiratory responses to rebreathing carbon dioxide while exercising at 700 kp.m·min.$^{-1}$ during cycle ergometry. In this manner, the intercept (B) and the slope (S) of equation 4 were determined. The S value of the control group was 0.935 ± 0.063 l·min.$^{-1}$ mm Hg. with an intercept of -1.3 mm Hg. S and B values in the experimental group were 1.276 ± 0.138 l·min^{-1}. mm^{-1} Hg and -17 mm Hg. Slopes and intercepts of the two groups were significantly different.($P<.04$) Pre training values of S and B in the groups were unavailable due to technical problems.

VI. Discussion

Acute Effects of Tube Breathing During Exercise

Calibration of Tube Volumes

Tube breathing in exercising subjects produces both a hypercapnic and hypoxic stress. As has been previously demonstrated, (Jones et al., 1971; Ward and Whip, 1980) the introduction of increased amounts of ventilatory dead space in the respiratory circuit of an exercising subject results in resetting the steady state level of alveolar carbon dioxide concentration. In the present studies a similar increase in end-tidal carbon dioxide tension was observed in experimental subjects between the onset and end of a cycling period when they exercised while rebreathing through tubes of varying length ($P < .05$). Multiple regression of $P_{ET_{CO2}}$ on work rate and tube volume indicated an expected direct relationship between $P_{ET_{CO2}}$ and tube volume, but an inverse relationship with workrate. Jones et al. (1971) found that $P_{ET_{CO2}}$ increased with added dead space, but also found that $P_{ET_{CO2}}$ increased with work rate. This discrepancy between the Jone's group and the present study might be explained by the fact that the present study used much higher work rates that required a respiratory compensation

for lactic acidosis. pH values observed in the study support this.(see results) In the present study, end-tidal oxygen was inversely related to tube volume and directly related to work rate. These relationships were all significant ($P < .05$). The multiple regression equation was:

$P_{ET_{CO2}} = 46 - 0.0088\ W + 0.0089\ V$, where W is work rate in kpm·min^{-1} and V is volume in ml.

Serial Monitoring of Tube Rebreathing

During the first week of training when the experimental group was rebreathing through an added respiratory circuit volume of 1042 ml, end tidal P_{CO_2} increased significantly during each monitored training session(37.0 $\pm$ 3.4 Torr in experimental group with 1042 ml added dead space vs. 32.6 $\pm$ 1.2 Torr in controls not rebreathing). This increase is similar to that reported by Ward and Whipp (1980) who reported an increase of $P_{A_{CO2}}$ of 33.2 $\pm$ 0.9 to 41.1 $\pm$ 0.8 Torr in one subject rebreathing through an an equivalent 1.0 liter length of tubing during moderate exercise. Arterialized capillary P_{CO_2} measured by the Astrup method also increased significantly from 37 $\pm$ 2 (not rebreathing) to 42 $\pm$ 1 Torr (rebreathing through 1042 ml dead space) in subjects exercising at the same work rate ($P < .05$). These values compare well with those reported by Jones *et al.*, (1971) who measured CO_2 tensions in arterial blood directly by catheterization and reported a change from 36.5 Torr (no deadspace) to 39.3 Torr (900 ml added dead space) in a subject

exercising at the same work rate.

Tube breathing also produced a relative hypoxia during exercise. During submaximal tube breathing exercise, $P_{A_{CO2}}$ was 14 $\pm$ 2.0 mm Hg lower, compared with normoxic controls, during the sixth week of training. (a decrease in inspired oxygen concentration comparable to that caused by a decrease in the ambient pressure to 669 mm Hg from 760 mm Hg under control conditions). For an ambient temperature of 20 degrees Celsius, (laboratory conditions) this corresponds to an equivalent altitude of 3600 ft. (equation 2) Similar values have been reported for equipment designed expressly to develope hypoxic stress from rebreathing (Berryhill and Williams, 1984) and illustrates the difficulty of producing low oxygen tensions from rebreathing circuits. This is a modest hypoxic challenge. Lower end-tidal values of $P_{A_{CO2}}$ were obtained at lower work rates during preliminary studies. At a higher intensity of exercise however the additional hyperpnea of exercise compensated somewhat by increasing alveolar ventilation. Unfortunately, the only other laboratory reports of exercise using dead space (Ward and Whipp, 1980 and Jones *et al.*, 1971) do not report endtidal oxygen pressures. Goode *et al.*, (1969) reported a change in endtidal O_2 from 127 to 90 Torr from the onset of rebreathing to steady state respiration in a subject at rest breathing through a 1400 ml tube.

Enumeration of Training

Training was monitored and modeled against serial performances measured during the course of the study. The fit of performances predicted from the training undertaken and actually recorded was able to be accomplished quite well. The input for the model was derived from the duration of exercise and the relative individual strain of the activity, as it was reflected in exercise heart rates. This method takes into direct consideration the hypercapnic stress imposed on the experimental subjects in the study. Any particular beneficial biological modification in ventilatory tissue modulated by the direct effect of high CO_2 on the tissue would of course not be accounted for, but such an effect is unlikely. What these data show (see RESULTS) is that total training intensity in each individual could be modeled against this individual real peformance. However, the individual response to the training differs radically as shown for subjects 268 and 264, respectively, who show quite different responses to identical training stress. On the one hand, subject 268 is very responsive to the level of training presented, while on the other hand subject 264 appears to resist any adaptation to training as evidenced by improvement in anaerobic run time, in spite of a seemingly similar program, which in fact did not translate into the same trimp score. Thus, one could deduce that the hypercapnic stress in subject 264 was insufficient and should have been increased appropriately. This is a common problem of

training studies where no enumeration of individual training stimuli in members of a group is made. If then individual results are averaged to determine group statistics large variability may result.

Exercise Testing

Davis and co-workers (1982) concluded that valid assessment of aerobic function (maximal oxygen consumption), $\dot{V}_{O_2}$ at the anaerobic threshold, the time constant for $\dot{V}_{O_2}$ kinetics, and work efficiency during exercise tests is possible with ramp slopes for work rate between 20 and 50 watts/min. Hughson and Green (1982) found that peak $\dot{V}_{O_2}$ and the gas exchange anaerobic threshold were similar for fast (65.4 watts/min.) and slow (8.2 watts/min.) ramp tests, but concluded that the $\dot{V}_{O_2}$ at which blood lactate increased 0.5 mM above rest was lower than the gas exchange anaerobic threshold for the slow ramp test. Hughson and Green (1982) found that very high rates of incremental work led to greater pH changes and increased CO2 arterial partial pressures in contrast to the decline in $P_{A_{CO2}}$ normally associated with exhaustive exercise. However, these confounding results are perhaps only evident at very high rates of increase and may not apply to this study. The ramp test used to test the subjects in this study had a slope of 200 kpm/min./min., corresponding to 32.7 watts/min.

The hypercapnia produced by tube breathing (mean endtidal CO_2 partial pressures, 43.5 $\pm$ 1.1 vs. 35.8 $\pm$ 4.4 mm Hg in the

experimental and control groups respectively, developed by the third week of training) was expected to produce a greater training stress on the buffer capacity of the experimental group, compared to the controls. However, the nonsignificant change in pH reported during this same time may indicate that the degree of hypercapnia-induced acidosis was insignificant compared to the metabolic acidosis. In fact, using the Henderson-Hasselbalch equation, this degree of hypercapnia would only be expected to produce a difference of .08 pH units in the groups. This small degree of respiratory acidosis was probably negligible compared to the metabolic acidosis caused by the high intensity training. Use of lower intensity training may have resulted in a greater experimental effect.

A possible contaminant of these results could be due to changes in hematocrit. The major protein buffer in the blood is hemoglobin because of its high concentration.(Selkurt, 1971) However, it is unlikely that a change in hematocrit would occur in such a short program.

Although the experimental group did indeed run longer on the treadmill than the controls, the degree of their improvement from the beginning was no greater than the control group (mean increases of 59.5 $\pm$ 16 to 74.3 $\pm$ 21.9 and 49.4 $\pm$ 10.6 to 66.6 $\pm$ 9.6 seconds, respectively). If the changes in buffer capacity were solely muscular, the Wingate test might have been preferable to use to demonstrate these changes. An important variable influencing these tests, and not measured in this

study, is the intracellular buffering capacity of muscle. Parkhouse and McKenzie (1984) have reported considerable variation between trained and untrained subjects in the average non-bicarbonate buffer values for skeletal muscle determined by homogenate titration.

The change in group means time to exhaustion during the maximal oxygen uptake test on the cycle ergometer by the end of training was also not significantly different between the groups (124 $\pm$ 12 and 146 $\pm$ 10 seconds respectively in experimental and control groups), although both groups also improved significantly compared to the initial value at the onset of training. Maximum oxygen uptake in the control group did not change significantly during the period but a decrease occurred in the experimental group.

The lack of statistical significance in these performance data may indicate that the training program was not carried on long enough to show significant changes in the groups. The lack of significance in the arterialized capillary P_{CO_2} values until the sixth week may indicate this. An alternative explanation is that hypercapnia (or the levels of hypercapnia used here) is ineffective as a training stimulant.

Ventilatory Threshold

The results of this study indicated that the experimental group increased their ventilatory threshold significantly more than the control group did. (The change in ventilatory threshold for the control group was 26 ± 8 seconds and 98 ± 25 seconds in the experimental group. The means were significantly different. ($P<.05$)) Davis and co-workers (1979) have also reported significant changes in the ventilatory threshold resulting from a nine week cycling program.

The correlation matrix between the analysts of the ventilatory threshold data revealed that a significant positive agreement existed between observers. Subjectively the observers felt that the method of subjective estimate of the ventilatory threshold using graphical information was possible in most cases, but in one or two subjects was quite difficult. This confirms Jones and Ehrsam's (1979) observation that it may be difficult to identify the ventilatory threshold in some subjects because of a variable pattern of ventilation or because the relationship of $\dot{V}_E$ to $\dot{V}_{O_2}$ curve is without an obvious point of inflection.

Interpretation of the 'anaerobic threshold' is a matter of some dispute in the literature. Gaesser and Brooks (1984) criticize the traditionally accepted relationship between blood lactate levels and a given work intensity: that blood lactate does not accumulate appreciably until a workrate is reached that

demands a significant anaerobic contribution to energy production during exercise. The authors propose that blood lactate levels result from the balance between production and removal of the acidic product and that blood lactate is poorly correlated to muscle lactate concentration. Protagonists of the concept of a lactate threshold (Karlsson and Jacobs, 1982) consider that there is abundant evidence for the existence of a physiological threshold reflecting a shift in muscle metabolism which leads to increased lactate production inspite of sufficient oxygen available to the organism at the cellular level. The physiological consequences of such an increase are reported to be an increased intracellular lactate accumulation, reduced intracellular pH, disturbed cellular integrity, and carbon dioxide and potassium release. Karlsson and Jacobs (1982) presented evidence that the OBLA (onset of blood lactic acid) concept integrates the effects of peripheral metabolic potential, cardiac output, and oxygen delivery capacity. According to Davis et al., (1982) the use of the dual ventilatory equivalents for oxygen and carbon dioxide respectively, (increase of $\dot{V}_E/\dot{V}_{O_2}$ without increase of $\dot{V}_E/\dot{V}_{CO_2}$) is specific for determining the onset of lactic acidosis and is superior to arbitrary use of an absolute concentration of lactic acid. In this study, the latter has been termed a ventilatory threshold as previously suggested by Jones and Ehrsam (1982).

Whatever its true physiological meaning, there seems to be enough evidence to justify use of the concept to judge occurence of a desirable training effect i.e. when the ventilatory anaerobic threshold (VAT) is able to be postponed. Jones (1984) proposed that dyspnea is probably the most prominent of the varied sensations preventing athletes, untrained individuals and patients with cardiopulmonary disorders from exercising longer or harder, since high ventilatory rates are associated with increased perception of effort. It is reasonable to hypothesize that if the VAT is postponed, then dyspnea would also be postponed. High ventilatory rates immediately precede fatigue and the cessation of work. High ventilatory rates may rob the working musculature of oxygen and contribute lactate to an already acidic blood. A higher VAT would postpone these undesirable effects.

Besides these effects, tube breathing may have more direct benefits. Martin et al., (1984) found that seated isocapnic reproduction of peak exercise ventilation resulted in oxygen consumption increases that paralleled the increases of ventilation in their subjects. They also showed that during severe exercise the respiratory muscles produce enough lactate to increase blood lactate concentrations significantly. Their results implied that ventilatory muscle training may be a useful adjunct to standard endurance exercise training and suggested that ventilatory muscle fatigue may have a significant influence on exercise tolerance. Tube breathing undoubtedly is a form of

ventilatory muscle training. If the ventilatory pattern persisted in non-tube breathing situations, greater tidal volumes would theoretically produce lower dead space ventilation and result in lower exercise ventilation rates. However, lower rates of breathing may only indicate greater work efficiency together with increased intracellular buffering (Hultman and Sahlin, 1980)

Partitioning the Oxygen Debt

This study found no significant differences in the areas under the recovery curve of $\dot{V}_{O_2}$ max. in tests pre and post training in either the control or the experimental groups which might indicate a change in the relative contribution of the various energy sources to maximum effort.

The validity of partitioning oxygen debt into component areas has been exhaustively reviewed by Gaesser and Brooks (1984). These authors, while acknowledging the fast and slow component of the oxygen recovery curve, criticize the idea of according specific oxygen recovery volumes (resulting from the integration of the recovery curve) to alactacid and lactacid mechanisms. Knuttgen and Saltin (1972) however, found a close relationship between reduction in ATP and CP concentrations and both total oxygen deficit and the fast component of the oxygen debt. A rectilinear relationship was observed between high energy phosphate and the fast component with a correlation of 0.94. Harris and co-workers (1976) also emphasized that the

kinetics of phosporylcreatine synthesis during recovery were very similar to those of oxygen debt repayment. Although Gaesser and Brooks (1984) conceded that 55-70% of the lactate produced in severe work is oxidized post exercise, they denied a causal link between the latter and oxygen uptake during work. It is possible that the relationship between the two is obscured by the 30-45% of lactate produced during exercise which is not oxidized but which may be used as a carbon skeleton for amino acids, TCA cycle intermediates or glycogen synthesis.

Results of the mathematical determination of the area under the oxygen uptake recovery curve allocated to lactacid debt seem to indicate a nonsignificant training change. The experimental group showed change in this lactacid area from 5.6 $\pm$ 1.42 to 6.4 $\pm$ 0.64 liters while the control group changed from 6.54 $\pm$ 2.90 to 5.58 $\pm$ 0.96 liters. However, the large variability of these data prevented any statistically significant differences being shown between groups, pre and post training. Some of this variability may be due to the aforementioned change in lactate metabolism.

It may be better to refer to the fast component as the phosphorylcreatine debt and the second component as the aphosphorylcreatine debt. This would be a more accurate method of describing the simple time course of the oxygen debt without attempting to explain or account for the pattern of blood lactate disappearance or of biochemical energy production.(Katch,1973)

Ventilatory Adaptations

Ventilatory Equivalent for CO_2

The degree of adaptation to hypercapnia produced in the present study might be expected to be modest considering the relatively low total time spent training under the combined hypercapnic and hypoxic stress each day. This was confirmed by the assessment of the training impulse. However, a ventilatory change was noted in the experimental group which was not evident in the control group, shown by a decreased $\dot{V}_E/\dot{V}_{CO_2}$ during serial maximal exercise tests. (21.44 $\pm$ 0.75 vs. 22.64 $\pm$ 0.37 in controls pre and post; 22.66 $\pm$ 0.53 vs. 21.12 $\pm$ 0.88 in the experimental group pre and post) This is similar to the change observed by Schaefer in submariners subjected to long periods of very low concentrations of CO_2.(Schaefer *et al.*,1964)

It is possible that the subjects in the experimental group may have developed a change from a shallow to a deeper respiratory pattern during exercise training that carried over into maximum effort. A similar change was observed previously by Schaefer (1963) in submariners. Theoretically such a change from a shallow to a deeper breathing pattern would be more efficient in exercise since a deeper breath would enable a subject to maintain a given alveolar ventilation with less dead space ventilation. (Youmans and Sieben, 1973)

Hiegenhauser, Oldridge, and Jones (1983) noted competitive swimmers and synchronized swimmers demonstrated significantly lower values of the $\dot{V}_E/\dot{V}_{CO_2}$ ratio than recreational swimmers. The former group, of course, would have been regularly subjected to periods of moderate hypoxia and hypercapnia of a similar nature to that which was imposed on the experimental group in this study. The same phenomenon of a low $\dot{V}_E/\dot{V}_{CO_2}$ ratio has been demonstrated by the Ama diver of Japan who performs repeated, breath-hold dives.(Masuda et al., 1982)

A furthur aspect of ventilation possibly improved by tube breathing is ventilatory endurance. Martin and Chen (1982) found ventilatory endurance in athletes was double that of untrained siblings. They concluded that a lack of familial clustering in this trait suggests that hereditary and shared environmental conditions may be relatively unimportant influences on this parameter compared with the effect of training. Ventilation is normally not considered a limiting factor to endurance during exercise. However, ventilatory work often becomes a significant energetic cost. According to Roussos and Macklem (1982), a ventilation of 120 liters·min.$^{-1}$ will require a respiratory muscle oxygen consumption of approximately 400 ml·min.$^{-1}$. Mognoni et al., (1982) observed a 140-180% increase in respiratory work at 3500 m altitude at a given submaximum work rate compared with sea level work in three subjects. At the point of $\dot{V}_{O_2}$ max. also, respiratory work was 30% higher at 5800 m, despite reduced airway resistance experienced by the subjects

due to the less dense air. The increased resistance and required depth of breathing demanded of a subject with tube breathing may be of benefit in preparing an athlete for the added respiratory effort encountered during exercise at altitude.

Rebreathing Ventilatory Response to CO_2

Ventilatory response to rebreathing CO_2 was determined at the end of the study and the slopes and intercepts of the equation:

$\dot{V}_E = S(P_{A_{CO2}} - B)$

were found to be .9 $\pm$ .06 and 1.3 $\pm$ .14 $l \cdot min.^{-1} \cdot mm^{-1}$ Hg. in the control and experimental groups respectively and the B values were -1 and -18 mm Hg. These values were significantly different. ($P<.04$) Assmussen and Neilson (1957) found that the slope of the ventilatory response to CO_2 was not significantly different at rest and during exercise, but the curve was shifted to the left during exercise. Their data from 3 subjects exercising at a variety of intensities indicated that S ranged from 2.9 to 4.5. Examination of their data on one subject exercising at a similar $\dot{V}_{O_2}$ to that demanded of the subjects in this study indicated that B was approximately -20 mm Hg. The much higher S value reported by these authors is probably accounted for by the use of different methodological techniques (elevation of $P_{A_{CO2}}$ by inspiration of high CO_2 gas mixtures compared with rebreathing, as in this study). Clark and Godfrey (1969) used a rebreathing technique and found S and B values of

2.60 ± .21 $l \cdot min.^{-1} \cdot mm^{-1}$ Hg and 42.4 ± 1.8 mm Hg, respectively. However, the work rate used in that study was only 200 $kg \cdot m \cdot min.^{-1}$. The authors reported that one subject exercising at 600 $kg \cdot m \cdot min.^{-1}$ showed a pronounced fall in S and B became less than zero. Miyamura *et al.* (1976) also used a rebreathing technique to study the ventilatory responses of athletes and untrained subjects. These authors reported a common slope of .62 $l \cdot min.^{-1} \cdot mm^{-1}$ Hg in both rest and during exercise at a work rate of 360 $kg.m \cdot min.^{-1}$ They did not report B values, but examination of their graphical data indicates the occurrence of negative B values during the exercise rebreathing test. Heigenhauser *et al.* (1983) found that resting ventilatory responses of synchronized and competitive swimmers to rebreathing were not significantly related to the ventilatory equivalent for CO_2 obtained during treadmill walking or arm cranking. Menitove *et al.* (1984) also found no correlation between CO_2 rebreathing at rest and the ventilatory response CO_2 production during exercise in healthy untrained male subjects and in patients with obesity hypoventilation syndrome. They suggested that the CO_2 rebreathing response does not measure only relevant parameters of ventilatory control during exercise. Other factors, such as the rate of change of CO_2 during the respiratory cycle, or the flux of CO_2 delivered to the lung, may be more relevant. The present study found no relationship between exercise rebreathing ventilatory response and the exercise ventilatory equivalent.

Carbon Dioxide Storage Capacity

Jones and Jurkowski (1979) reported that 90% of the carbon dioxide is washed out from the labile accessible body carbon stores in as little as four minutes during exercise. Hence, a 5 minute hyperventilatory period used during this study was considered a reasonable time period for establishing washout. (Previous studies used much longer periods of assessment in determining CO_2 storage, but these studies involved the study of slower responding body stores.) Values of CO_2 storage reported in the present study are slightly higher than those reported by Jones and Jurkowki: 2.38 $\pm$ .21 (all groups combined) compared with 1.83 $\pm$ .55 $ml \cdot kg^{-1} \cdot torr^{-1}$ in Jones' group, but were lower than those reported by Lillehei and Balke (1955). Adaptation to carbon dioxide by means of increased storage capacity evidently only results from chronic exposure to CO_2. The period of hypercapnic exposure experienced by the experimental subjects of this study seemed not sufficient to induce a change in their storage capacity.

Possible Metabolic Changes

Graham et al., (1982) have noted the effects of hypercapnia on the metabolic response to steady state exercise. They found that R decreased in proportion to P_{CO_2} elevation. This suggested that carbohydrate metabolism may have been inhibited and lipid

metabolism enhanced by hypercapnia. Hypercapnic induced changes in metabolism may be due to the decreased pH that accompanys an increase in carbon dioxide production or inspiration. Jacey and Schaefer (1972) exposed guinea pigs to 15% CO_2 for periods up to one week and noted that decreases in phoshphofructokinase activity strikingly paralleled decrease in blood pH. The important effects of acidosis on metabolism may have been overlooked in previous studies. Adams and Welch (1980) hypothesized that higher intracellular pH ,due to slowing of glycolysis rather than an elevated partial pressure of oxygen, was responsible for "the hyperoxic effect" of increased time to exhaustion at 90% $\dot{V}_{O_2}$ max. when subjects inspired 60% oxygen. Another possible solution to the mechanism of this effect is that hyperoxic conditions may cause the oxidation of hydrolytic enzymes such as lactic dehydrogenase, by the formation of a disulfide form of the enzyme (Haugaard, 1968). Graham and Wilson (1983) compared the effects of hypercapnia and hypoxia on metabolism during longer periods of exercise than investigated in their previous study. These authors again found lower blood lactate levels during hypercapnia and lower R values. They conceded that lower R values could be either due to increased fat metabolism or to increased CO_2 storage capacity, but rejected the latter when it was calculated that storage would have to range from 4.5 to 5.6 $ml \cdot kg^{-1} \cdot mm^{-1}$ Hg (four times that reported by Jones and Jurkowski (1977).) in order to account for their observations.

There seems to be both a detrimental effect on carbohydrate metabolism or enhanced fat metabolism during exercise in hypercapnia. Perhaps there is a role for hypercapnia in the training of endurance athletes (marathon runners?) who need to manipulate these particular metabolic systems in precisely this manner in order to run well. The short duration of the testing procedures used in the present study did not assess the energy systems that might have benefited from this aspect of hypercapnic training.

A study by Gimenez and Florentz (1979) is intriguing in its assertion that acute hypercapnia led to changes in rat muscle similar to those seen only after weeks of exercise training. (increased myoglobin and citrate synthetase levels) However, their work does not seem to have any parallel in the literature and the results may be due in part to the particular aspects of their use of electrical stimulation and a perfused hind limb preparation. Exercise performance results in the present study did not indicate any such dramatic changes in the experimental group, except for one individual in the experimental group who showed remarkable improvement in the anaerobic treadmill run.

Hypoxic/hypercapnic exercise stresses the acid/base balance of the body and would seem to be of value for athletes who develop a large base deficit in anaerobic exercise. Osnes and Hermansen (1972) have reported blood pH values as low as 6.8 and plasma bicarbonate values of 2.6 mEq/l. (vs. normal resting value of 24 mEq./l.) resulting from intense, intermittent

exercise in athletes. If it were possible to improve the buffering capacity of the body to prevent the early onset of such acute levels of acidosis, an increase in working capacity could be expected.

Recently there has been renewed interest in the manipulation of the acid/base balance of exercising subjects. Kowalchuk,Heigenhauser and Jones (1983) fed calcium carbonate (control), sodium bicarbonate (basic) and ammonium chloride (acidic) to groups of control and experimental subjects who then performed progressively more intense exercise to exhaustion. The lowest mean power output attained by a group was under the acidic conditions. Costill and co-workers (1983) conducted a similar study with sodium bicarbonate and sodium chloride (control) ingestion prior to bouts of cycling exercise. Subjects ingesting alkali cycled 42% longer than controls. Rupp and co-workers (1983) used a double blind study with sodium bicarbonate and lactose capsules and again used exhaustive cycle ergometer exercise to assess the results. They also concluded that bicarbonate ingestion increased time to exhaustion, but made little or no differences in muscle pH between groups. This suggested that increased muscle pH was not the reason performance was improved. The blood pH values at the end of the training sessions in the present study were not significantly different in both the control and experimental groups. ($P > .05$) Arterialized capillary P_{CO_2} in the experimental group however was significantly higher than control group values in the sixth

week of the rebreathing training period. ($P < .05$) This seems to indicate that by the end of the study the experimental group was experiencing both respiratory and metabolic acidosis during the training while the control group only was only experiencing a metabolic acidotic stress.

Apansenko et al., (1978) reported that test subjects chronically exposed to low CO_2 concentrations exhibited an increased alkaline reserve of the blood and increased 2 min. step test performance.(indicative of improved anaerobic performance) In this study there was no evidence of increased alkaline reserve of the blood which is probably attributable to the brief duration of each hypercapnic exposure.

Studies of Chronic Airflow Obstruction

The use of added dead space has been valuable in studying patients with chronic airflow obstruction (CAO). Brown et al. (1984) found that the imposition of modest dead space volumes in these subjects resulted in reduced exercise tolerance with decreased arterial pH, P_{O_2}, and increased P_{CO_2}.

Conclusions

Participants in this study completed a training program with added hypercapnic and hypoxic stress uniquely induced by tube rebreathing. The study established a linear relationship between endtidal P_{CO_2} and P_{O_2} tensions and the combined effect of rebreathing tube volume and work rate. Both a control group,

exercising normally, and an experimental group, in whom training included rebreathing through a tube during every exercise period, improved a similar amount in terms of their anerobic run performance and their endurance time to exhaustion during $\dot{V}_{O_2}$ max. testing. No significant changes were evident in CO_2 storage capacity during the study. Significant differences between the control and experimental group were noted in observed ventilatory threshold and exercise ventilatory equivalent for CO_2 during $\dot{V}_{O_2}$ max. testing as a result of training while rebreathing respired gases through a tube.

VII. Appendix 1

Technique for Determining Ventilatory Threshold

The method of determining the ventilatory threshold used in this study is shown by a paper by Simon and co-workers (1983). The non-invasive ventilatory threshold was estimated through the analysis of ventilatory transients. A marked consistent increase in the ventilatory equivalent for oxygen, without a marked increase in the ventilatory equivalent for carbon dioxide, was used as the criterion for the threshold in this study. Judges were given a copy of Simon *et al.*'s paper which contained these instructions and accompanying figures illustrating the technique.

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