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Physiological considerations in underwater exercise.

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PHYSIOLOGICAL CONSIDERATIONS IN UNDERWATER EXERCISE

BY

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A thesis submitted to the Faculty of Graduate Studies
in partial fulfillment of the requirements for the degree of
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Robin L. Battley

ABSTRACT

Five male subjects performed a continuous block lifting task for 15 minute intervals at four different levels - on the surface under laboratory conditions, and submerged in freshwater at 6 feet, 15 feet and 30 feet beneath the surface using standard SCUBA equipment. Heart rate was monitored each minute of every trial and expired gas samples were collected at rest, at 7 minute intervals during the work task and post recovery at each depth. Positive linear relationships were observed between heart rates, $\dot{V}O2$, $\dot{V}E$ STPD, O2 pulse and CO2 tensions as depth increased ($P < 0.05$). An inverse relationship was observed between O2 tensions and calculated work efficiency as the working depth increased ($P < 0.05$). These results are thought to be the combined influences of individual baroreceptic responses and the increased mechanical work of breathing in a hyperbaric environment. The significantly elevated physiological stress experienced at increasing depths by the subjects in this study leads the investigator to suggest that the use of open circuit SCUBA systems for so-called light underwater work be re-examined to ensure the safety of working divers.

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INTRODUCTION

The inception of self-contained underwater breathing apparatus (SCUBA) in 1942, has enabled a significant increase in man's ability to explore the underwater world (Hancock et al., 1982). However, many factors, both physiological and psychological, are involved in determining an individual's response to work in the varying environmental conditions encountered in SCUBA diving.

The scope of this thesis has been limited to some of the physiological variables affecting oxygen consumption and work efficiency while working underwater utilizing the single hose two-stage demand regulator common to sport diving and light commercial diving. It is understood that the psychological effects of functioning underwater at various depths, in limited visibility and at extreme temperatures also produce significant differences in human performance (Graver, 1980; Hancock et al., 1982; Mears et al., 1980) however, this was beyond the range of the current investigation.

Statement of the Problem

The purpose of this investigation was to determine whether or not the increasing pressure associated with increasing depth in a freshwater environment would have a significantly detrimental effect on a diver's ability to perform work underwater.

Subproblems

It was necessary to determine whether or not any significant differences existed in the following physiological parameters among the three experimental depths;

a) observed heart rates,

b) oxygen uptake,

c) calculated work efficiency.

Definitions

Advanced Open Water Diver: a certified sport diver who has successfully completed additional training in limited visibility diving, underwater searching, light salvage and deep diving to approximately 100 feet with a minimum of 10 logged dives.

Ambient Pressure: refers to the surrounding force exerted on a submerged object, usually expressed in pounds per square inch (psi), which increases 0.432 psi with every foot of descent in freshwater.

Anoxia: refers to the absence of oxygen.

Apnea: refers to the cessation of breathing for brief intervals of time.

Decompression Sickness: refers to the formation of bubbles in the bloodstream and/or the tissues of the body as a result of inadequate elimination of gas by pulmonary perfusion to parallel the rate of reduction of external pressure when the tissues are supersaturated with gas (usually nitrogen). Symptoms occurring depend upon the location of the bubbles, i.e. joints, muscles, bones or nerves.

Diver: refers to an individual who is underwater and fully exposed to the increased ambient pressure of depth and who is staying down longer than the individual's breath-holding time and must therefore be provided with an air supply.

Dyspnea: refers to difficulty in breathing.

Heart Rate: refers to the frequency of heart muscle contraction in beats/minute (b/min) to be used as an indicator of physiological stress on each subject.

Hyperbaric Chamber: refers to a vessel capable of being pressurized to simulate water depth. It may also be referred to as a recompression or compression chamber. It is a double-lock chamber having two compartments which may be pressurized independently enabling medical personnel and tenders to enter and exit the chamber to render aid to the patient without subjecting him to changes in pressure.

Hypercapnia: refers to an undue amount of carbon dioxide in the blood causing overactivity in the respiratory centre.

Hypoxia: refers to a failure of the tissues to receive enough oxygen.

Nitrogen Narcosis: refers to a mental state caused by the raised partial pressure of nitrogen in compressed air. Although physiologically inert under normal conditions, nitrogen is able to induce signs and symptoms of narcosis or anesthesia at sufficiently raised pressures.

Oxygen Pulse: Refers to the ratio of oxygen uptake in litres/minute (l/min) to heart rate in b/min.

P.A.D.I.: refers to the Professional Association of Diving Instructors, an international certifying agency which instructs and studies fundamental and advanced sport diving techniques.

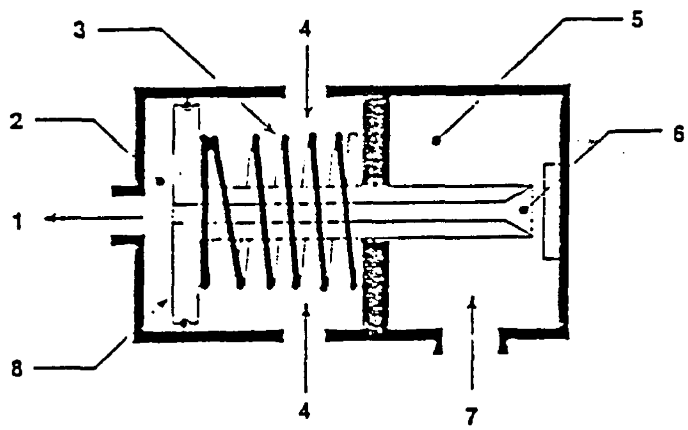
Two-stage Demand Regulator: refers to a single hose regulator designed to supply the diver with air at ambient pressure from a high pressure cylinder through two different stages of pressure reduction and provides breathable air at the mouthpiece upon inhalation by the diver. See Figure 1, p 5.

Visibility: refers to the horizontal distance underwater at which another diver or object can be clearly seen, and ranges from zero to over 200 feet depending upon lighting, bottom composition, turbidity and water movement.

Work Efficiency: refers to the mechanical competence of an individual to perform a task by determining work output accomplished at a given energy output, expressed as a percent.

Figure 1. Components of a Single Hose Two-Stage Demand Regulator.

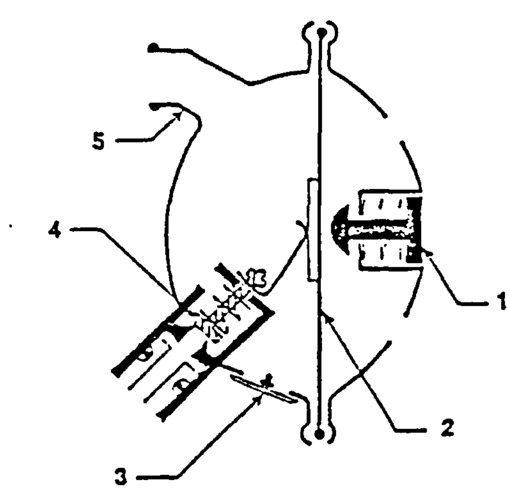
A. BALANCED PISTON FIRST STAGE



1. Air to Second Stage 2. Intermediate Chamber 3. Balance Spring 4. Ambient Water Pressure 5. high Pressure Air Chamber 6. Valve and Seat Assembly 7. High Pressure Air 8. Piston Assembly.

(Farley, 1981, p 61)

B. DOWNSTREAM SECOND STAGE VALVE



1. Purge Button
2. Diaphragm
3. Exhaust Valve
4. Second Stage Downstream Valve
5. Mouthpiece

(Farley, 1981, p 63)

Delimitations

The researcher has chosen to impose the following restrictions:

1. As a consequence of using a small sample size with expected variations in diving experience among the subjects, the results of this study cannot be generalized to the recreational or the commercial diving populations at large.

2. The depths of 6 feet, 15 feet and 30 feet were chosen for comparison with results obtained under surface laboratory conditions to provide maximum diver safety conditions.

Assumptions

The scope of this investigation necessitated one basic assumption:

1. The work rate at which each subject performed the work task was constant across all experimental conditions.

Limitations

The researcher acknowledged the following limitation and undertook measures to eliminate or minimize its effects:

1. All subjects were instructed regarding the procedures to be followed in this investigation and were provided with the opportunity to practice the work task on land and in the water before any data were collected to minimize learning effects.

Hypotheses

1. Ho: An increase in the ambient pressure at which a diver is working would produce no significant difference in the observed heart rates when compared to those heart rates obtained at shallow depths.

Ha: An increase in the ambient pressure, or depth, at which a diver is working would produce a significant decrease in the observed heart rates from those obtained at shallower depths as a result of re-directed blood flow from the periphery of the diver's body to decrease energy loss while submerged.

2. Ho: The observed oxygen uptake values were similar for all experimental conditions.

Ha: The observed oxygen uptake values increased significantly at depth as a result of the increased effort required to overcome the increased breathing resistance of compressed air through an open circuit SCUBA system as depth and ambient pressure increased.

3. Ho: Calculated values for work efficiency were similar for all experimental conditions.

Ha: The calculated values for work efficiency were inversely proportional to depth. For example, the amount of work performed decreased as depth and subsequent ambient pressure increased.

The null hypotheses will be rejected and the alternate hypotheses accepted if the variation among the sample proportions becomes larger than could be reasonably attributed to sampling error with $P < 0.05$.

Significance of the Study

As man's presence underwater continues to increase for industrial, explorational and recreational purposes, a greater understanding of the multiple variables affecting an individual's underwater work capacity is required to ensure the diver's safety (Mears et al., 1980; Osguthorpe et al., 1981) and the successful completion of assigned tasks. Unfortunately, as evident in the literature available, relatively little research has been reported concerning a diver's decreased operational capabilities in an underwater environment (Hancock et al., 1982). Also, the numerous studies conducted in dry recompression chambers have failed to account for the significant differences found between human performances in wet versus dry environments (Mears et al., 1980).

Therefore, by examining the effect, if any, on a diver's response to work at increasing ambient pressures in a natural underwater setting as monitored by heart rate, oxygen uptake, and calculated work efficiency, this study intends to provide useful information regarding impaired physiological responses to work underwater. In addition to increasing diver safety by suggesting physiological limits to human performance underwater, it may also enable more accurate administrative estimations of the time required to complete underwater work assignments. Further research will be required to expand the current study.

REVIEW OF LITERATURE

Since the development of the first completely automatic compressed air aqualung by Cousteau and Gagnon in 1942 (Cousteau, 1975), a continuing research effort has been aimed at extending man's capabilities in the underwater environment (D.C.I.E.M. Report, 1975). Only underwater, where pressure increases approximately one atmosphere with each 33 feet of descent (Miller, 1979), does man encounter a natural hyperbaric environment in which pressure is more than slightly above 760 mmHg (Lanphier, 1964 and 1974). Although man's exposure to high pressure remains relatively limited in both the magnitude and the duration (Lanphier, 1964), research has been aimed at increasing the diver's capabilities to deal with underwater hazards (D.C.I.E.M. Report, 1975).

The purpose of this Review of Literature is to examine some of the physiological limitations associated with prolonged underwater exercise and to provide an account of the research available in this relatively new area of study.

The Diving Environment

The direct effects of stress underwater are expressed in terms of the hydrostatic pressure exerted on a submerged object or organism, which increases linearly at the rate of 0.432 psi per foot of descent in freshwater (Miller, 1979). Even within the modest depths attained in sport diving, i.e. a maximal depth of 130 feet, the diver's body must accommodate up to a 500% increase in ambient pressure in the underwater environment. As Astrand (1977) mentions, the human body can tolerate the high pressures encountered underwater so long as the pressures are equalized inside and outside the body. Figure 2 illustrates the effects of depth increases on pressures and volumes.

The underwater environment is also associated with the 'diving reflex' (Lanphier, 1964). As a result of increased pressure on the carotid arteries upon submerging, diving animals exhibit a marked reduction and redistribution of circulation with accompanying bradycardia (Downing, 1979; Lanphier, 1964; Schaefer, 1965). This is commonly referred to as the diving reflex. The diving reflex may also be initiated with facial immersion (Lancet Editorial, 1981). It has been found that this diving reflex is present to some degree in all vertebrate species, including fish and man, but the development of this reflex may be subject to adaptive change (Lanphier, 1964). The precise regulatory control of the diving reflex is unknown at present.

Schaefer (1965) observed that the slowing of blood flow during diving further decreased the diffusion of nitrogen and oxygen gases into the tissues resulting in the subject's reduced metabolism while at pressures greater than one atmosphere absolute. Although pressure itself did not appear to be a direct factor in early studies (Lanphier, 1964; Schaefer, 1965), the rate of pressure change on the individual was thought to contribute to the diving reflex (Downing, 1979). The majority of studies, both past and present, have been conducted within dry recompression chambers. These chambers, as defined in Chapter 1, p 3, enable the precise control of the ambient breathing medium and

Figure 2. The Effect of Depth on Pressures and Volumes.

Depth in feet	Atmospheres, absolute	Total Pressure in lbs. per sq. in	Partial Pressures (in atmospheres) assuming N_2 = 80%	O_2 = 20%	GAS VOLUME
0	1	14.7	0.8	0.2	1
33	2	29.4	1.6	0.4	1/2
66	3	44.1	2.4	0.6	1/3
132	.5	73.5	4.0	1.0	1/5
165	6	88.2	4.8	1.2	1/6
297	10	147.0	8.0	2.0	1/10

(Lanphier, 1974, p 73)

pressure changes experienced by the subjects but they fail to account for the significant performance and psychological differences encountered in aqueous hyperbaric environments.

Nitrogen is the most commonly used inert diluent gas combined with controlled mixtures of oxygen for diving (Miller, 1979), and presents some unique problems to the SCUBA diver. Among its disadvantages is the fact that the partial pressure of nitrogen increases with the increased ambient pressures experienced at depth. This results in a distinct anesthetic effect known as nitrogen narcosis which can occur at depths greater than 75 feet, and is characterized by impaired judgement and diver disorientation (Lanphier, 1974; Miller, 1979; Strauss, 1982). Although nitrogen narcosis can be a limiting factor in a diver's capability to perform work underwater, the individual becomes somewhat conditioned to its effects with repeated exposures (Hancock et al., 1982; Miller, 1979).

Exercising Underwater

The conditions previously described regarding man's response to an underwater environment have not included exercise. As one might expect, the physiological responses to performing work underwater are governed by pressure-related restrictions briefly mentioned above which do not apply to comparable tasks done on land.

One of the most evident differences is the significantly higher energy cost of diving activities as compared to land activities which has been observed by several researchers including Baz (1979), Kooyman et al. (1982), Linaweaver (1981), and Mears et al. (1980). The diver requires energy to maintain thermal homeostasis while underwater, to warm the inspired air to body temperature, to overcome the mechanical difficulties of respiration in a hyperbaric environment, and to overcome the inertial properties of water to initiate movements. It should be noted that the mechanical difficulties of maintaining effective respiration by the diver, whether working or not, become greater as depth increases. In addition to increasing the density and resistance of the breathing medium as the diver descends, the intrathoracic to external pressure gradient increases. These factors couple to increase the energy demands of the diver to continue to ventilate effectively as he descends and/or works at depth (Bell, 1979; Kooyman, 1982; Schaefer, 1965). The results of a study conducted by Linaweaver (1981) showing the significantly elevated rates of oxygen consumption required for diving activities as compared to surface activities are provided in Table 1.

The activities studied by Linaweaver in 1981, as seen in Table 1, have all been represented in metres/minute (m/min) for comparison purposes. The increase in energy requirements for the in-water activities is evident between walking and slow swimming with the aid of fins. Although the ventilation values are similar at 24 litres/minute (l/min), the subject was able to move at four times the rate on land as compared to the in-water swimming. The comparison between increased activity rates from Table 1 provides important information. When the subject doubled his speed on land from a walk to a run, his ventilation requirements increased by a factor of 1.67. However, the subject doubling his

TABLE 1. OXYGEN CONSUMPTION OF SURFACE AND SKIN DIVING ACTIVITIES

Activity	Oxygen Consumption (litres/minute)	Ventilation (litres/minute)
Sitting	0.35	7
Standing	0.40	8
Walking (107.3 metres/minute)	1.20	24
Running (214.6 metres/minute)	2.00	40
Fin-Swimming (24.71 metres/minute)	1.20	24
Fin-Swimming (37.06 metres/minute)	2.50*	50
Fin-Swimming (46.33 metres/minute)	3.50*	70

*Very hard work.

(Linaweaver, 1981, p 29)

speed of fin-swimming from 24.7 m/min to 46.3 m/min increased his ventilation rate by almost three times. The significant differences between these values support the statement by Mears et al. (1980) that human performances are significantly impaired in wet versus dry environments.

Another result of Linaweaver's (1981) study was the observation that his subjects' tidal volumes averaged only 83% of their surface values. These results were in agreement with Rowell (1974), Baz (1979), Hesser et al. (1981), and Butler and Jones (1982) who all found decreased pulmonary functions, including tidal volume, vital capacity and functional residual capacity, during immersion in water. Astrand (1977) and Lanphier (1964) also reported a smaller residual volume/total lung capacity ratio in divers which they accounted for as an adaptive increase in a diver's respiratory work capacity to overcome the increased breathing resistance inherent in SCUBA with practice.

Depressed pulmonary ventilations observed at depths of 2 to 3 atmospheres by Linaweaver (1981) and Rowell (1974) in dry recompression chambers using human subjects were thought to be caused by increased gas density and hyperoxia effects. They also led to impeded carbon dioxide elimination while exercising which can be amplified by the diving conditions, i.e. the increase in pressure with increased depth (Lanphier, 1964; Linaweaver, 1981; Rowell, 1974; Schaefer, 1965). Hyperbaric studies of the 1960s, already cited, reported that with the increased work of breathing at depth, there is decreased maximal breathing capacity which contributes to the higher carbon dioxide tensions. Under some circumstances the higher carbon dioxide partial pressure can depress ventilations (Lanphier, 1964; Schaefer, 1965). Lanphier (1964) observed that the majority of his subjects who developed high carbon dioxide tensions during exercise at depth were also below average in their ventilatory response to carbon dioxide. Such an apparent adaptation to carbon dioxide could increase a diver's ability to remain underwater in voluntary apnea, but it also increases the likelihood of hypoxia, loss of consciousness and drowning. Lanphier (1964) also found that the increased carbon dioxide tolerance in experienced divers correlated to a decrease in mental acuity. If such a direct relationship exists, the proportionate decrease in mental acuity could prove dangerous if the diver's underwater task were of a complex and exacting nature.

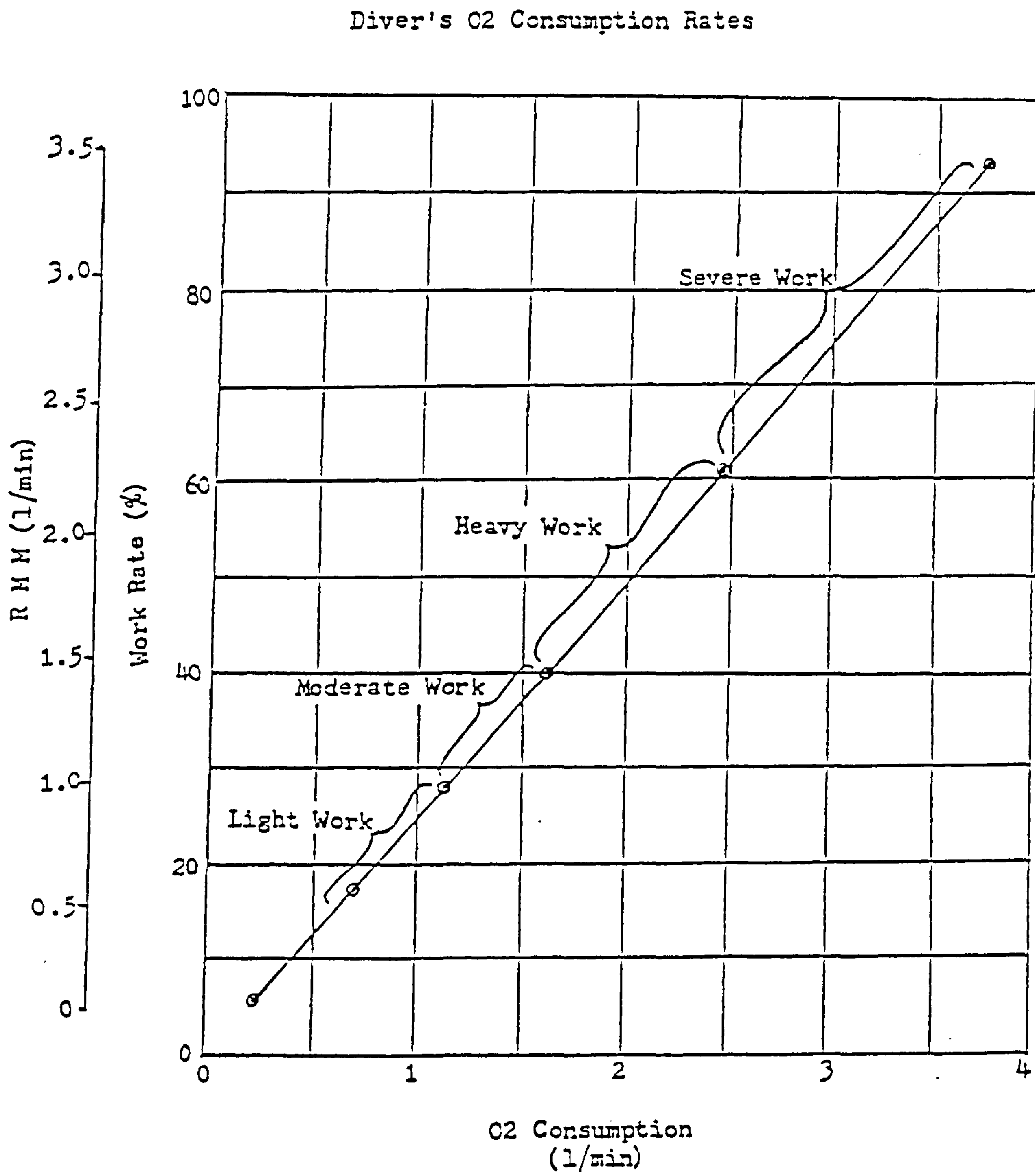
Butler et al. (1982) and Cormier et al. (1981) concur that the decreased carbon dioxide elimination, just mentioned, may be detrimental in a different manner. Both groups expressed concern that the increased carbon dioxide partial pressure would allow an increase in nitrogen concentration in the emptying alveoli which would continue to increase with time at depth and enhance the potential for decompression sickness.

Hesser and his colleagues (1981) observed that ventilation and expiratory flow are decreased by acute exposure to increased air pressure and gas density. In their study using 1, 3 and 6 atmospheres absolute in a dry recompression chamber as experimental conditions, the majority of subjects discontinued work at 6 atmospheres as a result of severe dyspnea. Work was discontinued at the shallower conditions due to muscle fatigue (Hesser et al., 1981). These results are in accordance with Linaweaver's (1981) study that the dyspnea experienced while working underwater was the combined result of a change in thoracic and diaphragm configurations. Specifically, this change involved an increased rigidity of the lung structures due to an increased intrathoracic to external pressure gradient and a consequent decrease in functional residual capacity (Hesser et al., 1981; Linaweaver, 1981). Simply stated, these results imply that the ability to ventilate decreases with depth. These results also imply that one of SCUBA diving's basic assumptions as mentioned by Astrand (1977), that the human body is capable of tolerating the increased ambient pressures encountered at depth since the internal and external pressure gradiets are equalized, is false.

If the ability to ventilate does decrease significantly with depth it would become possible for divers to unknowingly exceed their ventilatory capacity while working underwater. A diver's oxygen consumption has been shown to increase sharply with increases in exertion level or depth, or both (Miller, 1979). Figure 3 provides an illustration of a diver's oxygen consumption rate as a function of exertion level. Other factors which can influence the total air requirements of a diver include the anticipated bottom time, a normal ascent rate of 60 feet per minute, any required stage decompression time and the air consumption rate at depth (Graver, 1980; Miller, 1979).

The marked breathlessness caused by overexertion underwater has serious implications in that it is one of the most frequent causes of panic and subsequent death in diving (Graver, 1980; Lanphier, 1974; Miller, 1979). In addition to properly pacing underwater work to avoid overexertion, experience and experimental data have shown that the

Figure 3. Oxygen Consumption as a Function of Exertion Level.



(Miller, 1979, p 10-2)

diver can be trained to maintain an effective breathing pattern (Astrand, 1977; Lanphier, 1964; Miller, 1979; Schaefer, 1965). These authors concur that a reasonably constant respiration rate with a nearly complete inhalation and exhalation phase can help to compensate for the increased gas viscosity and decreased flow rate encountered at depth. This technique also aids in minimizing the rate of energy consumption while underwater which aids in increasing man's operational efficiency in the sea (Baz, 1979).

Other integrated components of the underwater environment which can affect diver performance include the size of the air supply, the type of breathing medium, depth of dive, time at depth, temperature of the water, water movement, visibility, the type of task to be performed, and the mental and physical fitness levels of the individual (Bell et al., 1979 and 1984; Lanphier, 1974; Miller, 1979).

SCUBA Equipment

Another area to be considered in determining an individual's respiratory requirements while working underwater is the equipment itself. Although not normally a consideration necessary for land activities, the proper function of SCUBA equipment is essential to the diver.

The rate at which air flows from the air supply to the diver depends upon whether the breathing apparatus is operating in a free-flow or demand mode (Farley, 1981; Miller, 1979). In SCUBA diving with a two-stage single hose demand regulator, the rate of flow must be sufficient to meet the diver's instantaneous peak flow requirements. The factors mentioned earlier regarding increased air consumption with depth and activity in addition to the direct increases in viscosity of the breathing gas with depth, are compounded by the increased resistance caused by the demand regulator itself.

The two-stage single hose demand regulator consists of a series of valves, hoses and other mechanical requirements of a lifesupport system which add to the dead space and the breathing resistance the diver must overcome (Farley, 1981). Consequently, the rate at which compressed air can be consumed by the diver is significantly less than his peak inhalation capacity (Miller, 1979). This requires that limits be placed on the work rate of the diver to avoid the complications of overexertion discussed previously. Well-designed and properly maintained equipment along with a reasonable personal fitness level (Bell, 1983) on the part of the diver will augment his ability to minimize the effects of existing resistance in the flow of the breathing gas. It becomes apparent at this point that careful and thorough planning are the keys to an efficient diving operation and are imperative for diver safety (Bell, 1979 and 1983).

Conclusion

Although the Review of Literature has been brief, it does illustrate that the interactional effects of breathing compressed air and exercising underwater remain unclear at the present time. These relationships require further empirical investigation (Hancock et al., 1982) to continue to isolate and quantify the confounding variables associated with underwater work. It is felt that such quantification will provide useful information which can be added to the current body of knowledge.

PROCEDURES

Selection of Subjects

The subject sample consisted of five (5) male SCUBA divers from southwestern Ontario who met the standards and certification requirements of the Professional Association of Diving Instructors (P.A.D.I.) for the Advanced Open Water diver rating. These standards are briefly described in Chapter 1, p 2.

All subjects were required to participate in diving skills training required for research diving which was provided by the investigator (P.A.D.I. Master Diver Trainer and Research Specialty Instructor #14726). Successful completion of the research diving techniques was mandatory before any data collection was carried out. In addition each subject completed the informed consent form as shown in Appendix A, pp 49-50, prior to the study.

Independent, Intervening and Dependent Variables

An overview of the following variables is required prior to examination of the Testing Protocol.

Independent Variables. The following variables remained constant across all experimental treatments to increase the validity of this study.

i) Depth - a surface control condition was compared with three experimental depths of 6 feet, 15 feet and 30 feet. All data collections, except the pilot studies to ensure equipment function, were conducted in a freshwater open water environment with no perceptible current.

ii) Standard Equipment - all subjects wore dry suits, 72 cubic foot SCUBA tanks, regulators equipped with submersible pressure gauges, buoyancy compensating devices, sufficient weights to achieve neutral buoyancy at the surface, masks, fins, and snorkels for all open water testing. In the swimming pool, with the exception of bathing suits being substituted for the dry suits, the standard equipment remained constant.

iii) Water Temperature - although the testing was conducted early in the diving season, i.e. April and May when water temperature may be assumed to remain relatively constant between surface and depth, the water temperature was recorded at each test site to accurately record any significant temperature fluctuations.

iv) Work Platform - a platform made to the specifications provided in Appendix M, p 67, was placed at the experimental depth on which the divers performed their work task to provide a standardized work site for all subjects at all depths. The use of a platform also maximized visibility and thereby facilitated data collection underwater at dive sites with silt and clay sediment bottom compositions.

v) Work Task - the work task performed by each subject required the lifting of a concrete building block measuring 20 cm x 25.5 cm x 30.5 cm and weighing 20.5 kilograms (kg), at a rate which required each subject to achieve 40% of maximal oxygen uptake ($\dot{V}O2$) on land. This task was practiced until each subject could maintain this work rate over a 15 minute interval on land. To maintain a constant work pace, an audio metronome was used on the surface. However, when underwater the subject maintained his individual work pace by following a visual metronome designed and built for this purpose. The visual metronome consisted of a flashing red light powered by 6 "C" batteries encased in a submersible plexiglass housing which was attached to the work platform in view of the diver. The rate of light flashes per minute could be adjusted on the surface prior to each trial.

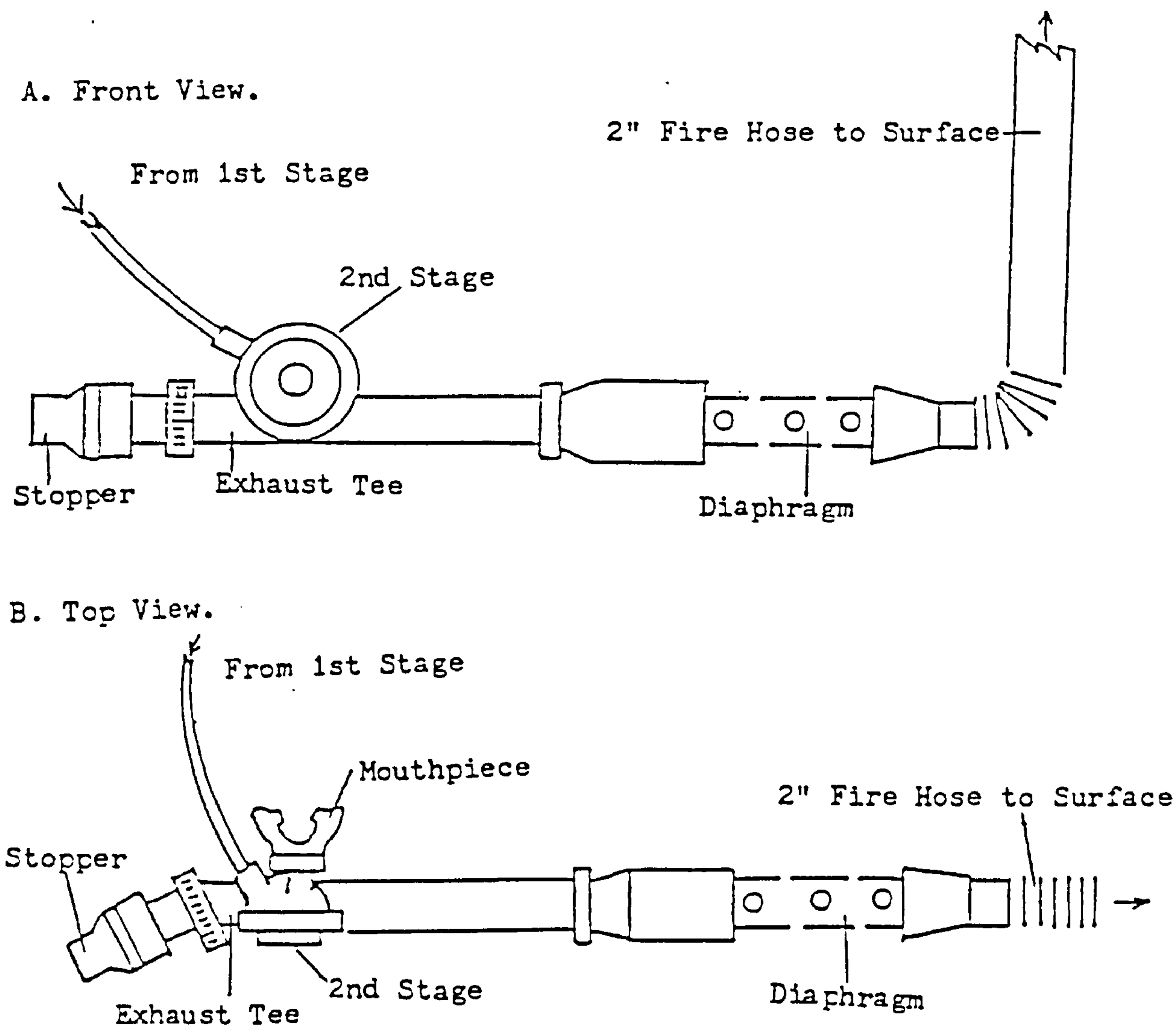
Intervening Variables. These variables consisted of those details which influenced the performance of the subjects and which were beyond the direct control of the investigator. Such factors included the motivation of the subjects, their level of fatigue from activity prior to the testing, their diving ability and their emotional state at the time of testing.

Dependent Variables. These variables were exposed to the treatment of the independent variables and included the following factors.

i) Heart Rate - was recorded for each subject by observing the digital readout of a Respironics Home heart rate monitor, Exersentry Model 3, from within a submersible plexiglass housing designed and built for this purpose. The heart rate values were then manually recorded on an underwater slate each minute the subject remained submerged.

ii) Oxygen Uptake - samples of the expired gas were collected from each subject at rest, at 5 minute intervals during the exercise sessions conducted on land and post recovery using the apparatus shown in Figure 4. This system was designed and built to collect the subjects' expired gases for later content analysis. Several criteria had to be met to achieve this objective - 1) the system had to be compatible with a

Figure 4. Expired Gas Collection System.



The expired air was directed through one side of the exhaust tee while the other side was stopped-up to prevent the escape of expired gases. The expired air then passed through a flexible diaphragm which was closed by ambient pressure during inhalation to prevent a free-flow mode.

This expired gas collection system was connected to a SCUBA tank worn by the diver during each trial and allowed the collection of 60 second gas samples on the surface.

standard single hose two-stage demand SCUBA regulator, 2) the system could not significantly alter the breathing mechanics of the subject at any test depth, 3) the system could not alter the buoyancy of the subject, and 4) the system had to be pressure-proof and gas-proof to prevent the influx of water and/or the escape of expired gases. This underwater expired gas collection system was repeatedly tested in the university swimming pool at depths of 5 feet and 15 feet to ensure its reliability as an accurate tool for assessing $\dot{V}O2$. In the water, expired gas samples were collected at rest, at 7 minute intervals during the work tasks, and post recovery. Fifty (50) cc samples were collected in glass syringes and later analyzed for oxygen and carbon dioxide content using a Lloyd Gallankamp gas analyzer (produced by A. Gallankamp and Company Limited in England) following on-site collection in Douglas air bags. On-site volumes were determined using a model 205 Potentiometer (Serial #45230-1, Computer Instruments Corporation, New York) equipped with a thermometer for later STPD calculations. See Figure 5, p 26 for the on-site equipment set-up.

iii) Work Efficiency - was calculated as the ratio of work output at a given energy input for each subject during each exercise session using the following equations;

$$\underset{\text{(kilocalories)}}{\text{Work Output}} = \frac{\text{Weight X Vertical Distance X Frequency}}{426.8} \quad (1)$$

$$\underset{\text{(kilocalories)}}{\text{Work Input}} = (\dot{V}O2 - \text{Resting } \dot{V}O2) \times 5 \quad (2)$$

$$\underset{\text{(per cent)}}{\text{Work Efficiency}} = \frac{\text{Work Output}}{\text{Work Input}} \text{ X } 200 \quad (3)$$

Figure 5. On-Site Data Collection.

A.

B.

A. Subject being connected to Exersentry Heart Rate monitor in submersible housing.

B. Subject entering water with expired gas collection system.

These equations (1 through 3) were taken from Fox and Matthews (1981) and make two assumptions. Namely that 1) 1 kilogram/metre/minute = 426.8 kilocalories; and 2) 1 litre of oxygen = 5 kilocalories.

Oxygen pulse (02 pulse) defined as the ratio of oxygen uptake in relation to heart rate was calculated using the following equation, also from Fox and Matthews (1981).

$$\text{Oxygen Pulse (millilitres/beat)} = \frac{\dot{V}O2\ \text{(Litres/minute)}\ X\ 1000}{\text{Heart Rate (beats/minute)}}$$

Testing Protocol

Each subject was required to participate in all the sessions described below.

i) The following anthropometric data were collected from each subject - sex, age in years, height in centimetres (cm), and weight in kilograms (kg). Each subject was then required to perform a discontinuous run on a motor-driven treadmill to determine their maximal oxygen uptake. An accommodation phase lasting five (5) minutes with speeds progressing from a walk (3 mph) to a run (7 mph) enabled each subject to familiarize himself with the running mechanics involved in treadmill testing. A discontinuous protocol with a 3 minute running phase followed by a 3 minute rest was used with the speed constant at 7 mph for every subject. Workload was increased by raising the treadmill gradient 2.5% with each running phase from a 0% gradient start. Subjects were instructed to run until exhaustion while heart rates were monitored each minute of the test and expired gas samples were collected the final 30 seconds of each running phase and near the point of exhaustion. The heart rate and oxygen uptake values obtained were then used to individually designate work rates for each subject which, on land, approximated 40% of maximal $\dot{V}O2$.

ii) On site, subjects equipped with the apparatus described earlier (see Figure 5, p 26) descended a safety line to the work platform previously anchored at one of the experimental depths, i.e. either at 6 feet, 15 feet or 30 feet. Subjects remained motionless on the platform until heart rates had stabilized. An initial expired gas sample (60 second sample) was collected and the work task begun.

Heart rates were subsequently recorded every minute of the 15 minute exercise session (block lifting task) and following the 5 minute recovery period. 60-second expired gas samples were collected at rest, every 7 minutes of the block lifting task and at the end of the recovery period. These expired gas samples were then analyzed as per the methodology provided on p 24.

During the recovery period, the subjects rated the task difficulty using a Borg scale, from 1 through 10, to provide a subjective opinion of task difficulty at each depth (Hancock et al., 1982). Post recovery, subjects were guided up the safety line to the surface and assisted in exiting the water.

iii) Several safety measures were incorporated into these procedures. In addition to the investigator, two P.A.D.I. Divemasters were always present to assist with data collection and serve as safety divers. Auxilliary air supplies were available to each subject while underwater and surface supervisory personnel trained in diver rescue were on-site. First aid kits and oxygen were also on-site in addition to a preset evacuation plan in the event of an accident. These measures reflect the standard diving procedures conducted for all advanced diving operations.

It is of interest to note that the weight of the concrete block was relatively unaffected by being submerged. There were no significant differences detected by a hydrostatic weigh scale when the block was weighed in air, at a 6-foot depth and at a 15-foot depth. The linear shape of the block displaced a comparatively small amount of water in relation to its density resulting in a negligible buoyant effect.

Statistical Analyses

The research design used for this study was a control and repeated measures group design in which the subjects acted as their own controls.

Since the subjects were already familiar with underwater work in the chosen environment using full SCUBA equpment, the possibility of a testing effect reducing the internal validity of the study was lessened. This research design aided in reducing the effect of between-individual differences by using the subjects as their own controls.

A repeated measures analysis of variance, SAS Stats Package, was used on the data obtained to indicate the existence of a significant relationship among heart rates, $\dot{V}O2$, work efficiency and/or subjective task difficulty values at the various depths. A post hoc pairwise t-test was subsequently used to identify the level at which the significant differences took place ($P < 0.05$).

RESULTS AND DISCUSSION

The results of pilot studies, a series of repeated measures administered to one subject, conducted in the university swimming pool which validated the reliability of the underwater expired gas collection system designed and built by the investigator for this study have been included in Appendices D - G, pp 53-58. As these results were consistent with the findings obtained during the open water testing sessions, a more thorough examination of the significant trends observed will be done in conjunction with all results.

Another pilot study (results shown in Appendix H, p 59) gave evidence that the rate of continuous work suggested for this study, 40% of maximal work capacity on land, does not result in elevated body core temperatures. Due to the gas-proof construction of the dry suits worn by the divers, any significant elevation in core temperatures which occurred during the block-lifting work task could not be dissipated and would confound the resulting $\dot{V}O2$ values. However, after running for 30 minutes at near 50% of maximal oxygen uptake, the core temperatures of two subjects did not increase significantly. Therefore core temperature was eliminated as a variable in the current study although its importance is recognized during longer periods of immersion.

The procedures outlined in Chapter 3, pp 27-29, were strictly adhered to in the interest of diver safety. All underwater tasks were completed as specified. None were aborted for any reason, thereby verifying that the protocol was within the subjects' experience and diving ability levels.

Water temperatures recorded throughout the open water testing sessions remained relatively constant between trials and across the three experimental depths. Recorded water temperatures at all dive sites ranged from 13°C to 14°C. As a result of this comparative consistency, water temperature was excluded as a contributing factor to the results obtained in this study.

The physical characteristics of the subjects are shown in Table 2 which follows on p 33.

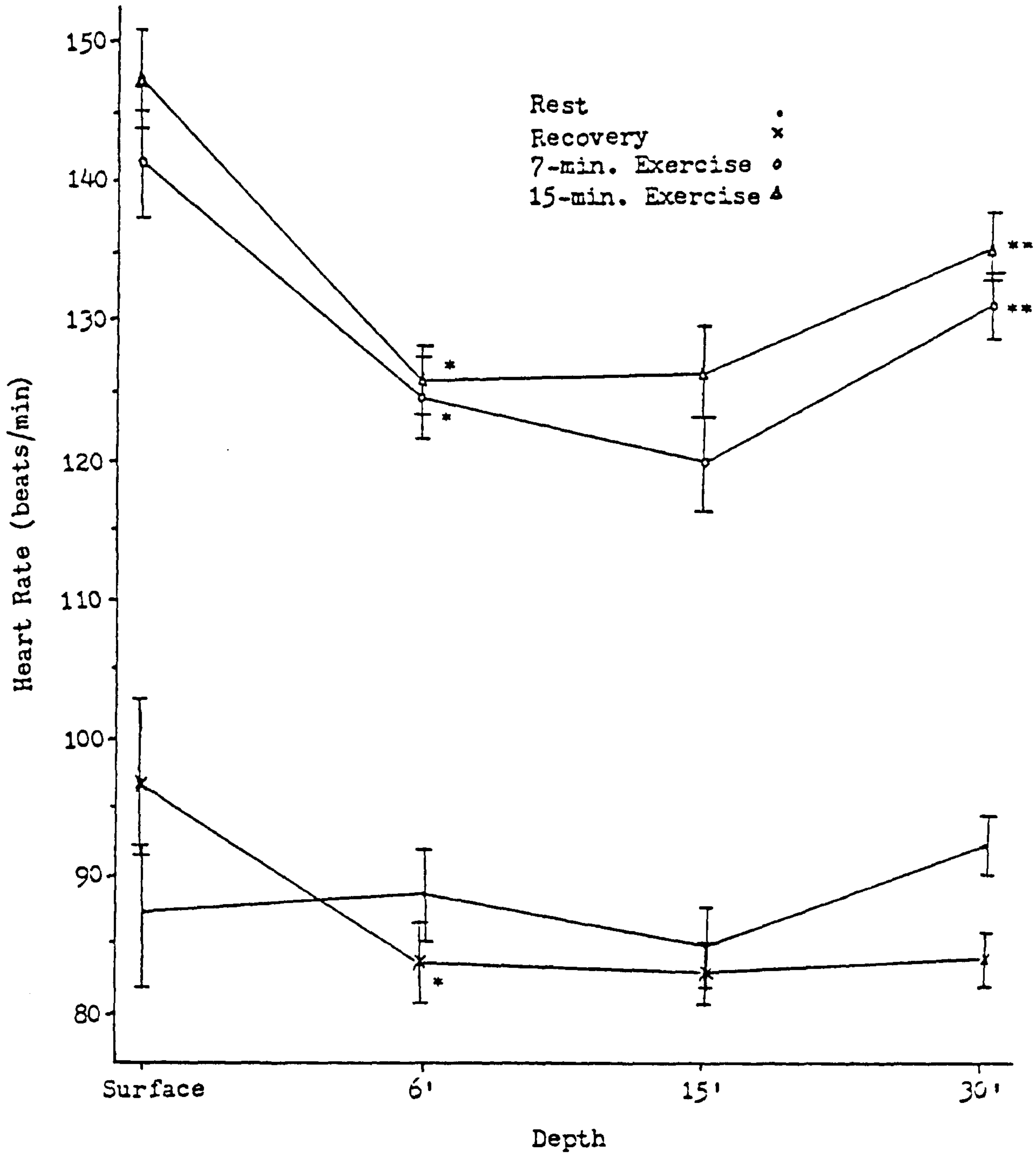
As shown in Figure 6, heart rates at rest showed no significant differences across the changes in experimental depth as compared to the surface tests performed in the laboratory. A slight increase in resting heart rates in evident as depth increases. This may be explained by the nature of the underwater breathing apparatus used in this study. Open circuit demand regulators supply air to the diver at the ambient pressure determined by the diaphragm of the regulator (see Figure 1.B, p 5). This pressure is usually not equal to the external ambient pressure at the level of the lung centroid, a baroreceptor in the lungs, and therefore imposes a hydrostatic imbalance upon the diver's respiratory system (Milne et al., 1979). This phenomenon coupled with the increased resistive loading of the breathing apparatus with increases in depth would result in higher heart rates to maintain resting metabolic levels in the diver even though no external workload was applied.

While performing the continuous work task, a significant difference ($P < 0.05$) was evident when the subjects worked in an underwater environment. The significant decrease in heart rates between the surface

TABLE 2. SUBJECT SAMPLE

Subject	Sex	Age	Height (cm)	Weight (kg)	Maximal $\dot{V}O2$ (l/min)	(ml/min/kg)
KG	M	25	154.0	77.05	4.60	59.18
JN	M	27	154.0	83.41	4.97	59.42
DB	M	32	154.0	65.69	3.43	52.40
GA	M	32	147.4	63.19	2.94	46.20
GE	M	33	155.1	76.84	4.14	54.83
Mean:		29.8	152.9	73.24	4.02	54.41
Std.Dev.		±3.18	±2.78	±7.56	±0.74	±4.84

Figure 6. Heart Rate Versus Depth.



* Indicates a significant decrease between the surface lab conditions and the 6-foot depth ($P < 0.05$).

** Indicates a significant increase between working at the 6-foot depth and the 30-foot depth ($P < 0.05$).

laboratory conditions and the 6-foot depth in open water is attributable to a number of factors. Initially, a portion of this decrease in heart rates may be the result of the diving reflex, also referred to as the carotid sinus reflex. The carotid sinus is a cartilaginous region located at the bifurcation of the carotid artery (Miller, 1979) and is influenced by changes in ambient pressure. As a baroreceptor, the carotid sinus is capable of inducing bradycardia with increases in ambient pressure. Another factor involved in the significant decreases in heart rates once the subjects were performing the task underwater is Archimedes' principle of buoyancy. As a result of displacing an amount of water equal to their bodies' volume, the divers were no longer required to overcome the effect of gravity on their upper bodies while performing the task underwater. Therefore, the subjects were working at a rate less than 40% of their maximal $\dot{V}O2$. By decreasing the workload necessary for the successful execution of the work task, cardiac output was effectively reduced.

A significant increase ($P < 0.05$) was evident between heart rates at the 6-foot depth and the 30-foot depth. A consistent rise in the subjects' heart rate once they are working underwater indicates that heart rate increases as depth increases while performing comparable tasks. This result is in conflict with the concept of the diving reflex. If the decrease in heart rates observed when the subjects began working underwater at the 6-foot level was mainly a result of the direct effects of pressure on physiological baroreceptors, then the heart rates would have been expected to continue to decrease as pressure and depth increased. The fact that heart rates increased significantly as depth increased at rest and while working indicates the presence of other factors. The hydrostatic imbalance previously discussed in relation to the increasing trend in heart rates at rest as depth increased becomes more pronounced with the addition of a workload. The divers were also required to overcome the increased density of the breathing medium and the increased resistance to flow of the compressed air as depth and ambient pressure increased. In order for the physiological demands of the increased work of breathing to be met under more restrictive conditions as depth increases, cardiac output and thereby heart rate must increase. These results suggest that heart rates would have continued to increase as depth increased to enable the diver to sustain the designated work task.

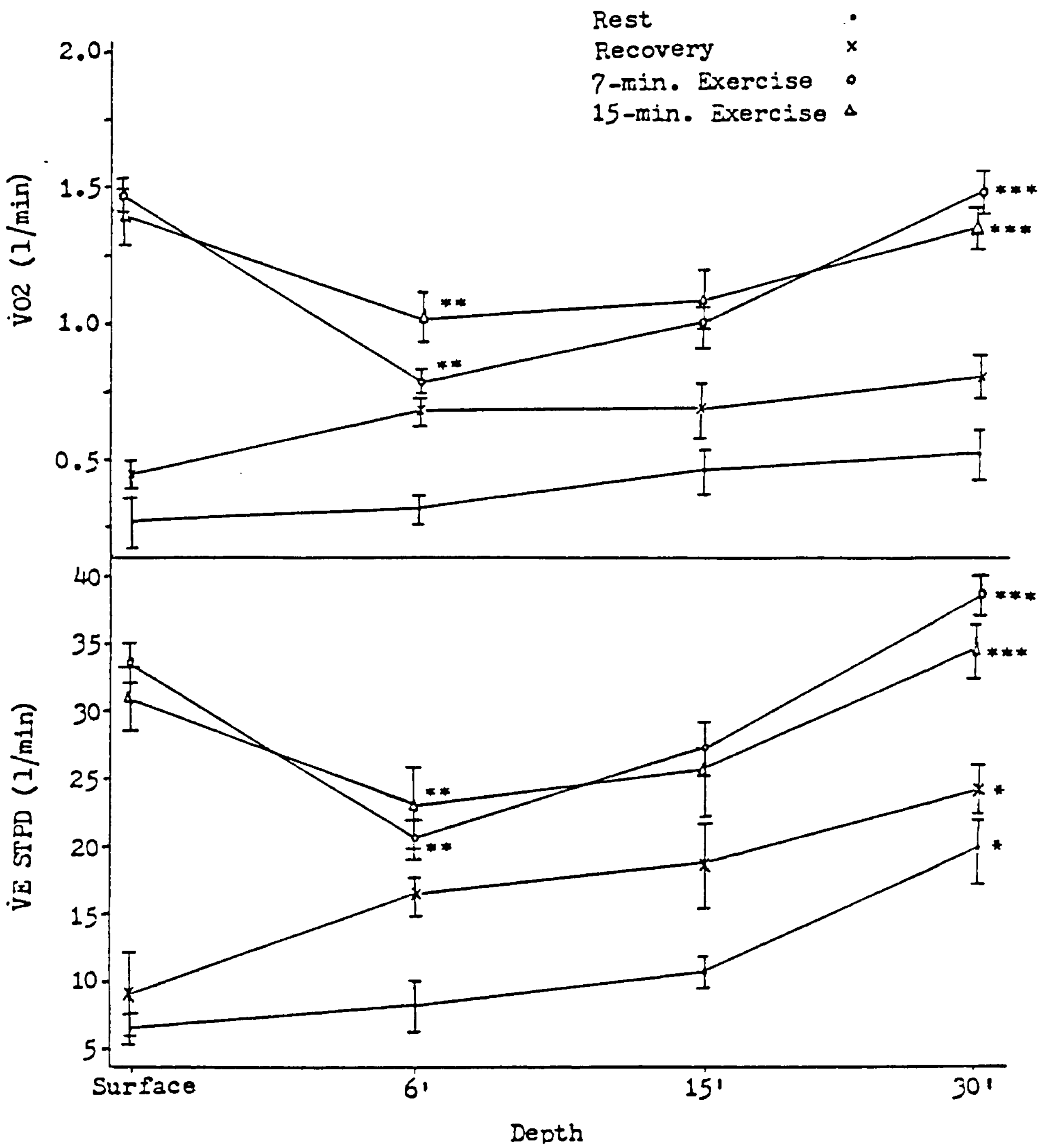
It is believed that the pressure gradient experienced throughout the underwater work sessions would also affect the release of the various chemical and neural controls within the Central Nervous System (CNS) in a manner different from standard one atmosphere surface working conditions. The extent of such CNS modifications is beyond the scope of the present study but deserving of further investigation.

The decrease in heart rates during the recovery phase following the work task when subjects were performing underwater indicates the influence of the carotid sinus reflex slowing down heart rates when ambient pressure is above normal on this baroreceptor. With the removal of the work stimulus, the work of breathing is reduced and the influence of the diving reflex is once again evident.

Figure 7 illustrates the relationships observed between oxygen uptake, $\dot{V}O2$, and expired volume, $\dot{V}E$ STPD, as depth increased. During both the rest and the recovery phase of each trial, a consistently greater respiratory demand exists for $\dot{V}O2$ and $\dot{V}E$ STPD denoting a significant increase ($P < 0.05$) in both values as depth increased. These results were consistent with the results observed during the pilot tests (see Appendices D - G, pp 53-58). It is thought that this subsequent increase in the subjects' end expiratory lung volume as depth increased was an attempt to equalize the hydrostatic imbalance which occurs upon submerging. As mentioned earlier, the hydrostatic imbalance between the lung centroid, a physiological baroreceptor, and the ambient pressure at the SCUBA regulator second stage diaphragm increases with increases in depth. The ability of a subject to reduce the resulting transthoracic pressure difference is limited through alterations in breathing pattern. However, the observance of increased $\dot{V}E$ STPD values and $\dot{V}O2$ values is consistent with procedures currently being taught to divers to maximize their breathing efficiency while underwater, i.e. a slow deep inhalation followed by a near maximal exhalation.

Both $\dot{V}O2$ and $\dot{V}E$ STPD values significantly decrease ($P < 0.05$) between the subjects' results observed in the surface laboratory setting and the first underwater setting at 6 feet. This decrease coincides with the significant decrease observed the divers' heart rates across the same situations. The decreased workload imposed upon the divers underwater, although performed at the same work rate, required less ventilatory effort as shown by the lower $\dot{V}O2$ and $\dot{V}E$ STPD values.

Figure 7. $\dot{V}O2$ and $\dot{V}E$ STPD Versus Depth.



* Indicates a significant increase between surface lab conditions and the 30-foot depth ($P < 0.05$).

** Indicates a significant decrease between the surface lab conditions and the 6-foot depth. ($P < 0.05$).

*** Indicates a significant increase between working at the 6-foot depth and the 30-foot depth ($P < 0.05$).

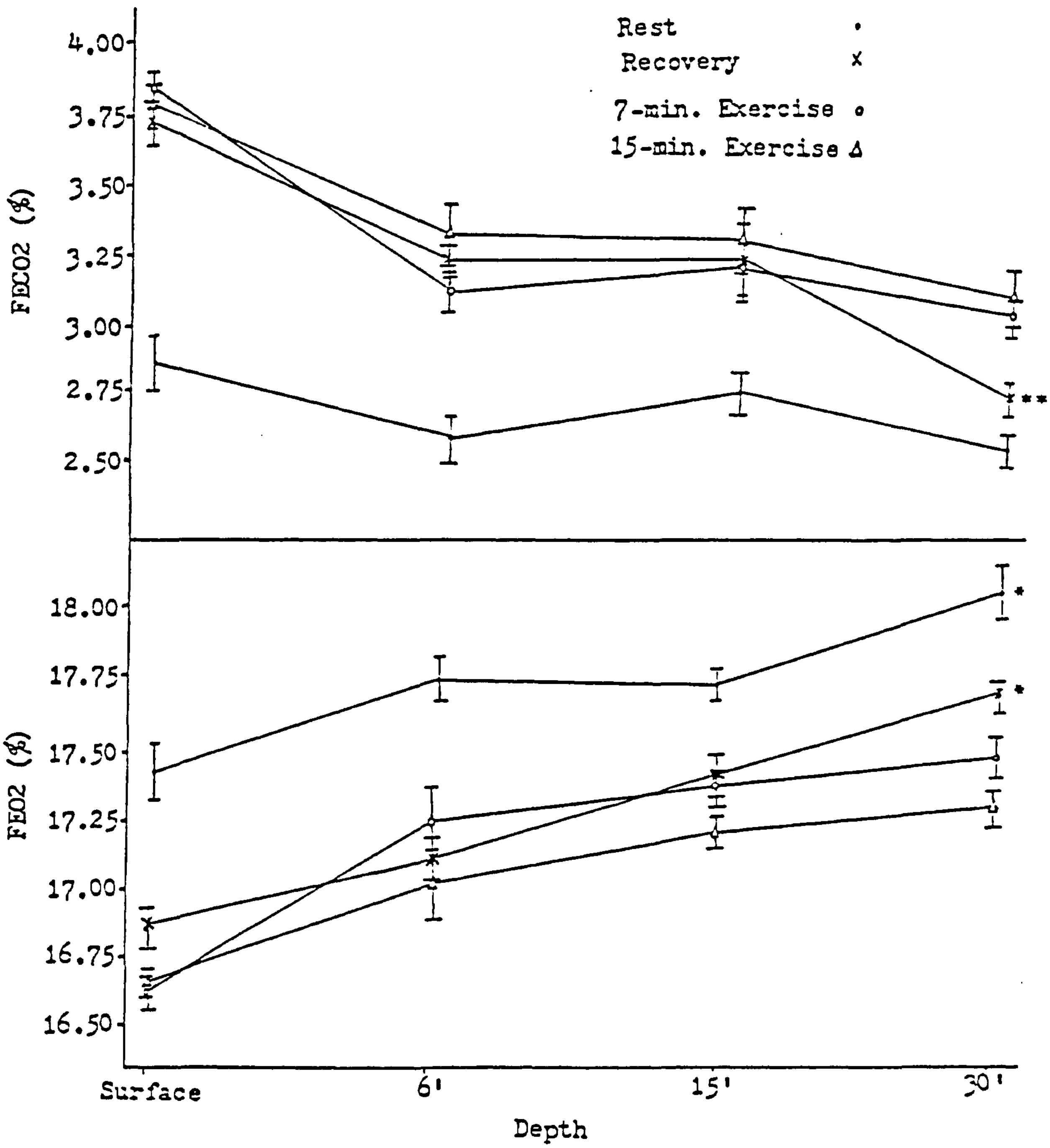
The influence of physiological baroreceptors is believed to be minimal at the 6-foot depth where the ambient pressure would only be an additional 2.60 psi above normal or surface values.

Once the work task has been transferred to the open water experimental settings, the hydrostatic imbalance in the chest cavity influences the subjects' respiratory patterns and changes in ventilatory flow become evident. As the depth increases to 30 feet, the influence of the physiological baroreceptors becomes significant as both $\dot{V}O2$ and $\dot{V}E$ STPD increase to match the increasing physiological demands of the work task and the increased work of breathing at almost twice normal ambient pressure.

Figure 8 emphasizes the limited effect of improving respiratory efficiency through alterations in breathing patterns while resting or working in an aqueous hyperbaric environment. A decrease was observed in the the percentage of oxygen utilized by the subjects' as depth increased. The fact that higher percentages of oxygen were found in the expired gas samples as depth increased indicates that less oxygen was capable of being absorbed across the transthoracic pressure gradient in the subjects underwater. The increasing respiratory volumes observed above as depth increased would be capable of compensating for the decreased 02 utilization capabilities of the subjects while working underwater but only to a limited extent.

Another observation from Figure 8 is the decreased percentage of carbon dioxide in expired gas samples as depth increased. It appears consistent that a pressure gradient impeding oxygen absorption by the

Figure 8. Expired Gas Concentrations Versus Depth.



* Indicates a significant increase between the surface lab conditions and the 30-foot depth ($P < 0.05$).

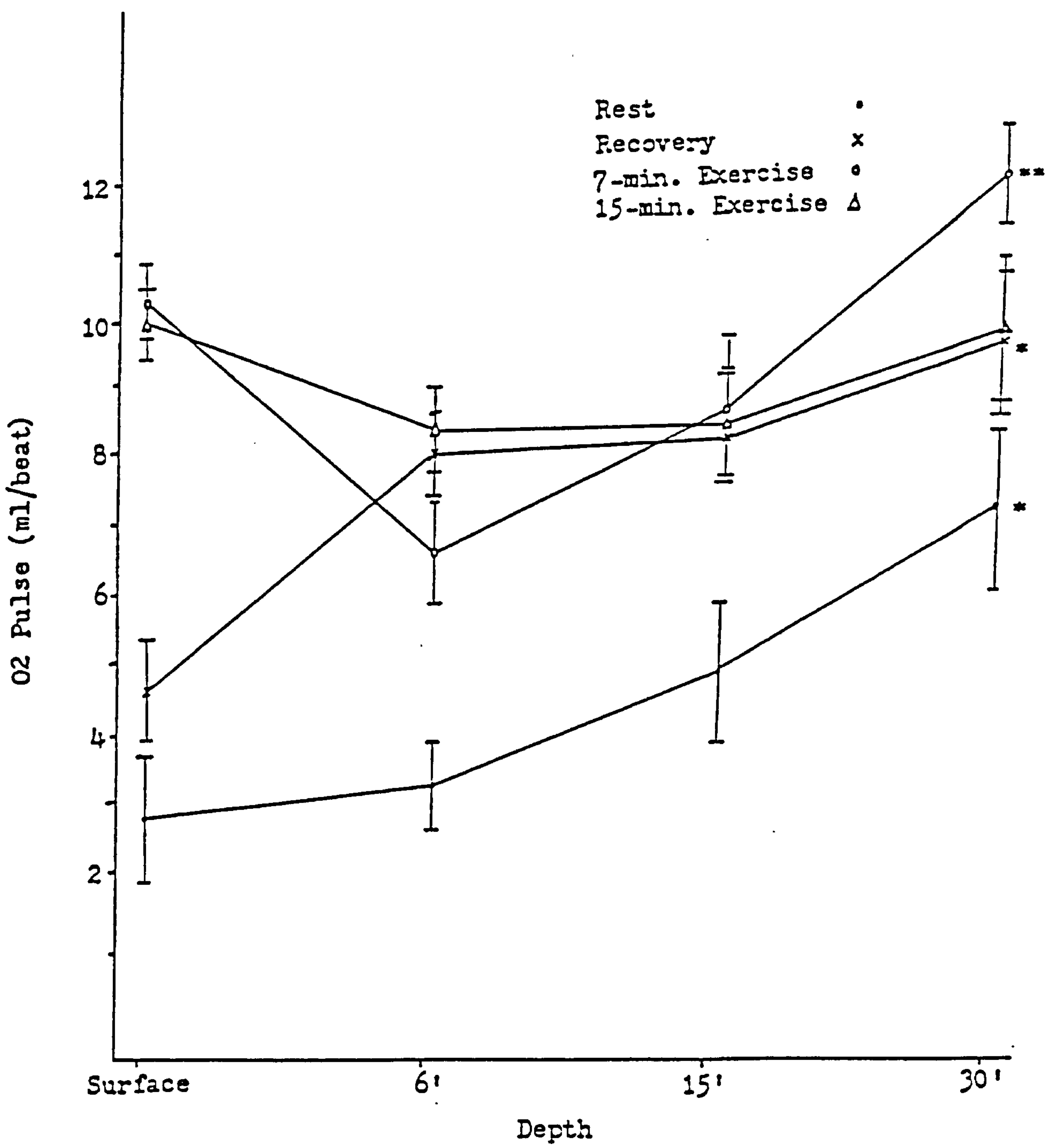
** Indicates a significant decrease between the surface lab conditions and the 30-foot depth ($P < 0.05$).

body would also hinder carbon dioxide elimination. As the humoral control of ventilation, an increased CO_2 level detected at the respiratory centre would increase the already accelerated rate of ventilation further impeding O_2 retention. This event is in accordance with the increased CO_2 retention and decreased mental activity observed in diving subjects by Lanpier (1964). Beyond a particular depth or workload, it is conceivable from these results that the working diver would experience memory lapses, respiratory fatigue, dyspnea, dizziness and potentially unconsiousness.

Figure 9 illustrates oxygen pulse in relation to increases in depth. Since oxygen pulse refers to the rate of oxygen uptake in litres/minute compared to heart rate in beats/minute, this figure serves as a summary of the aforementioned results. Again, an increase is observed in oxygen pulse once the subjects are performing the work task underwater at increasing depths. With increasing heart rates, the rate of oxygen uptake would be expected to increase until a plateau or maximal oxygen uptake situation occurs. It is the opinion of the investigator that the rate of $\dot{V}O_2$ would continue to increase with heart rate at increasing depths until the increasing hydrostatic imbalance at the lungs could no longer be overcome through altered breathing patterns and the work task would have to be discontinued for the safety of the diver.

The calculated work efficiency percentages in Table 3 reflect the same trends found in the results of the physiological parameters examinied in this study. That is, that the work task was performed more efficiently once the subject was submerged but the initial weightless advantage of

Figure 9. O2 Pulse Versus Depth.



* Indicates a significant increase between the surface lab conditions and the 30-foot depth ($P<0.05$).

** Indicates a significant increase between the 6-foot depth and the 30-foot depth ($P<0.05$).

TABLE 3. CALCULATED WORK EFFICIENCY (%)

	Surface	6'	15'	30'
7 minutes exercise	4.27	10.63	8.72	6.86*
	±0.48	±2.57	±1.69	±2.16
15 minutes exercise	4.61	7.57	9.52	7.86*
	±0.32	±2.19	±3.56	±2.16

* Mean and standard deviation values determined from 3 subjects. Other values determined from all 5 subjects. See Appendix L, p 68, for Work Output and Work Input calculations.

working in an aqueous environment was quickly lost as depth increased. The effect of increasing the hydrostatic imbalance at the lungs with increasing depth resulted in increases in the mechanical work of breathing, thereby decreasing work efficiency. This relationship has been apparent throughout this study. A study conducted by Milne and Morrison in 1979 cautions that merely changing the position of the diver relative to the breathing apparatus may cause the apparatus to exceed recommended standards for the extrinsic work of breathing. It is apparent that considerable more work is required in establishing the magnitude of the hydrostatic pressure gradient present in human subjects under working conditions while underwater.

Table 3 provides the results determined from all five subjects under three of the testing conditions, namely at the surface in the laboratory, at a depth of 6 feet and at a depth of 15 feet in open water. Two subjects were unable to perform the 30-foot open water testing due to personal time constraints.

As noted in Chapter 3, p 28, the subjects were requested to subjectively rank the task difficulty using a Borg 10-point scale with 10 representing the highest level of difficulty. This data is represented in Table 4. It was observed that the work task performed at the greatest depth, 30 feet, was ranked substantially less difficult that any of the other trials. The information previously discussed indicated that all the physiological indices of human performance examined in this study provided significantly elevated heart rates and respiratory responses coupled with decreased work efficiencies at the 30-foot depth when com-

TABLE 4. SUBJECTIVE RATINGS OF WORK TASKS.

Subject	Surface	6'	15'	30'
KB	4	7	6	*
GE	6	5	6	*
JN	4	6	4	3
DB	6	7	5	4
GA	6	6	6	4
Mean:	5.2	6.02	5.4	3.7
Std.Dev.:	±1.09	±0.84	±0.89	±0.58

* Subject did not participate in 30-foot testing condition.

pared to the shallower trials. Among divers, it is commonly considered that a 30-foot dive is a novice or beginner experience. However, a 30-foot dive combined with a work task sufficiently increases heart rate, ventilatory volumes and carbon dioxide retention to induce a state of perceptual narrowing in the working divers. This reduced mental acuity decreases the divers' ability to assess his situation while working underwater. From these results, one would expect the diver's judgement to become further impaired with increased depth where the also increasing work of breathing would require accurate assessment of the work rate being performed. In view of these discrepancies, it appears that the divers' subjective opinions cannot be relied upon to accurately monitor their physical safety while working underwater. The divers were obviously unaware of the physiological stress under which they were working and this would prove unsafe at greater depths and/or with increased workloads.

SUMMARY AND CONCLUSION

To summarize the data presented in the previous chapter, a consistent increase, r = .70, exists in a number of physiological parameters for divers working underwater at a constant rate at increasing depths. These relationships include increasing heart rates with increasing depth, increasing respiratory responses, i.e. $\dot{V}O2$, $\dot{V}E$ STPD and 02 pulse with increasing depth, and increasing CO2 tensions with increasing depth. An inverse relationship exists for 02 tensions and work efficiency rates which decrease with increasing depth. These relationships appear to be under the influence of individual baroreceptic respnses in the divers, the hydrostatic imbalance across the pulmonary structures as a result of increased external ambient pressures, increased resistance to flow of compressed air at increased depths, and decreased gas diffusion rates at depth.

Continuation of the task at conservative depths approaching 70 feet in freshwater would expose the subject to a hydrostatic imbalance approximately three times that of normal surface working conditions. By extrapolating the current results in the relationships indicated, a diver performing a similar block-lifting task at 70 feet would have a heart rate approaching 150 to 160 beats/minute with an oxygen uptake of approximately 2.5 to 3.0 litres/minute. These values are approaching 75 to 80% of the maximal aerobic work capacity determined for the divers used in this study, and they do not take into account the increasing work of breathing evident with increases in depth. Increased resistance to breathing air at raised ambient pressures is present in open circuit SCUBA equipment having ideal resistive characteristics (Milne and Morrison, 1979). The danger of overexertion, the main cause of diving accidents, is immanent under these conditions as the divers' concentration upon the task to be completed impairs their ability to perceive increased personal physiological demands, i.e. increased heart rates, increased inspiratory and expiratory volumes. Therefore, it is the investigator's opinion that a monitoring device be applied to the diver and monitored by surface personnel during the execution of underwater tasks which are being conducted at depths beyond 30 feet or for prolonged periods of time, i.e. longer than 15 minutes. In this way, any anomalies in the divers' condition may be recognized quickly and appropriate action may be taken whether this requires the cessation of the task or the mobilization of safety divers. The principle consideration in any diving operation, sport or commercial, should be the safety of the divers.

It is the investigator's opinion that the current trend toward utilizing open circuit SCUBA systems common to recreational diving for so-called light underwater work be more closely examined in view of the present study. The advantages of using more readily available equipment requiring less training, less maintenance and fewer personnel thereby reducing administrative costs may be outweighed by the inability to perform the required task and maintain diver safety.

It is felt that more studies should continue to be conducted in the field, whether in freshwater or saltwater. Although numerous setbacks are experienced in this type of research, the data obtained are more readily applicable to the aqueous environment where research is needed.

APPENDIX A

CONSENT FOR PARTICIPATION IN GRADUATE RESEARCH

UNIVERSITY OF WINDSOR

I, ________________________________, authorize the said Examiner, ________________________ of ________________________, to administer and conduct an exercise fitness test designed to determine my maximal physical work capacity and to collect data providing indices of my physical work capacity in a freshwater underwater environment at the depths mentioned below.

I understand that I will perform on a motor-driven treadmill at increasing inclination and constant speed until my maximal oxygen uptake is achieved as determined through the analysis of the expired oxygen and carbon dioxide. During the performance of the test and during recovery, my heart rate will be monitored.

I understand that I will be required to perform moderate physical work (40% of maximal $\dot{V}O2$ as determined from the treadmill test results) on land and underwater in 3 work situations; 1) at a depth of 6 feet, 2) at a depth of 15 feet, and 3) at a depth of 30 feet in an open water freshwater environment. During these tasks, my expired gases will be collected for later analysis of oxygen, carbon dioxide and nitrogen content, and my heart rate will be continually monitored. I understand that the above mentioned Examiner will provide the required safety equipment and personnel for the safe execution of the underwater tasks. Some of the standard precautions to be taken include the use of two safety divers in addition to the Examiner, auxiliary air supplies available to the subjects at all times while underwater, reference lines for descents and ascents, conservative use of the no-decompression limits to ensure safe bottom times and surface personnel trained in diver rescue with the constant availability of rescue equipment to be present for all open water sessions.

I understand that as a volunteer, I will be able to discontinue any of the above mentioned tasks if I become distressed for any reason. I understand that every effort will be made to conduct the tests in such a way as to minimize the discomfort and risk. However, I understand that just as with other types of fitness tests, there are potential risks. These include episodes of transient lightheadedness, chest discomfort, leg cramps and nausea to name a few.

____

Date

____

Subject (Signature)

____

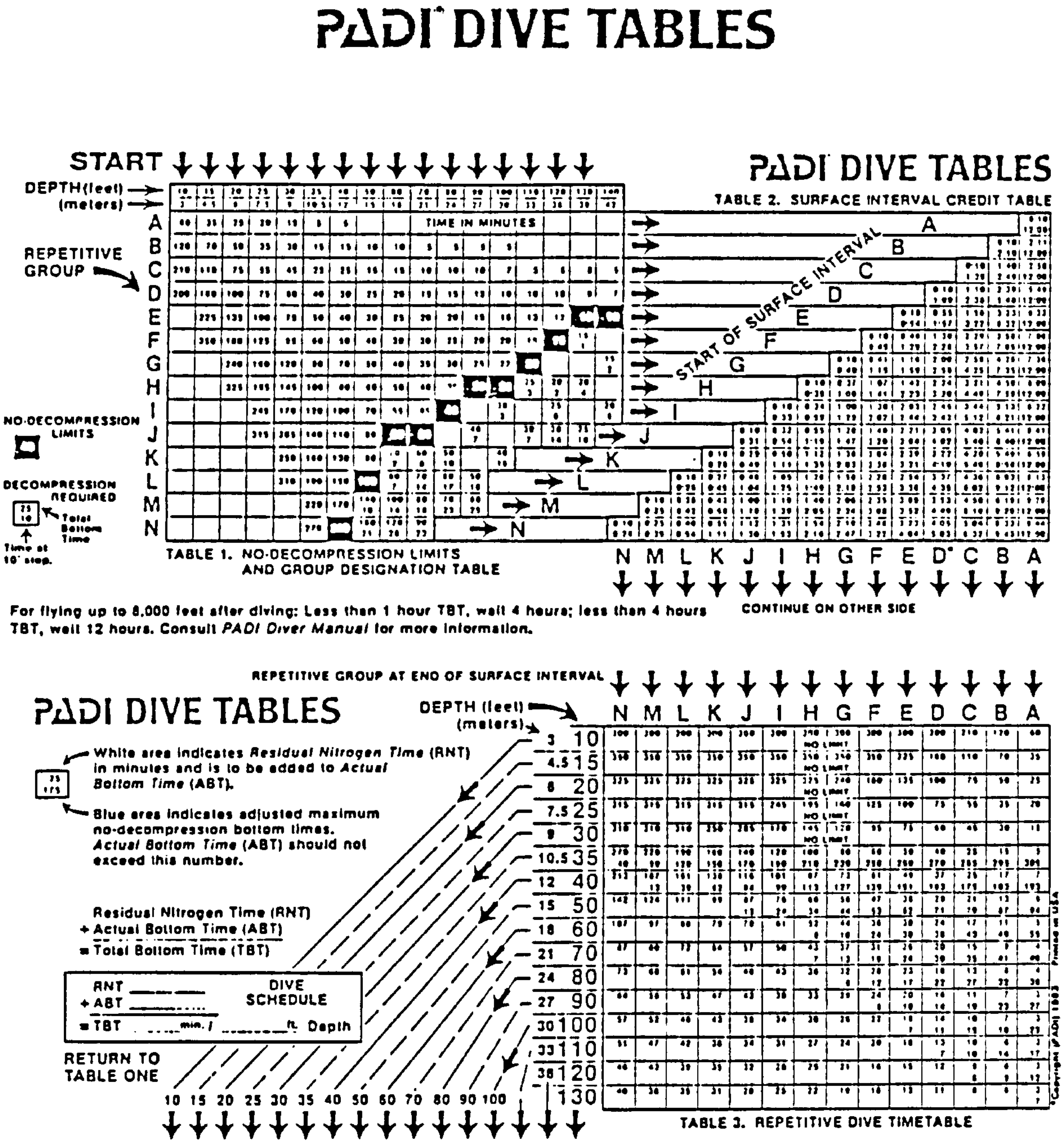
Level of SCUBA Certification

____

Witness

APPENDIX B

NO-DECOMPRESSION DIVE TABLES



(Graver, 1980, p 200)

APPENDIX C

CALCULATED PRESSURE PER SQUARE INCH AT VARIOUS DEPTHS

The following pressures were calculated using the equation;

Pressure per square inch (psi) = Depth (feet) x 0.432

(Graver, 1980, p.14)

Depth (feet)	Pressure (psi)
6	2.60 *
7	3.03
8	3.46
9	3.90
10	4.32
11	4.76
12	5.19
13	5.63
14	6.06
15	6.49 *
16	6.93
17	7.36
18	7.79
19	8.23
20	8.66
21	9.09
22	9.53
23	9.95
24	10.39
25	10.83
26	11.26
27	11.69
28	12.12
29	12.56
30	12.99 *

* Experimental Depths

APPENDIX D

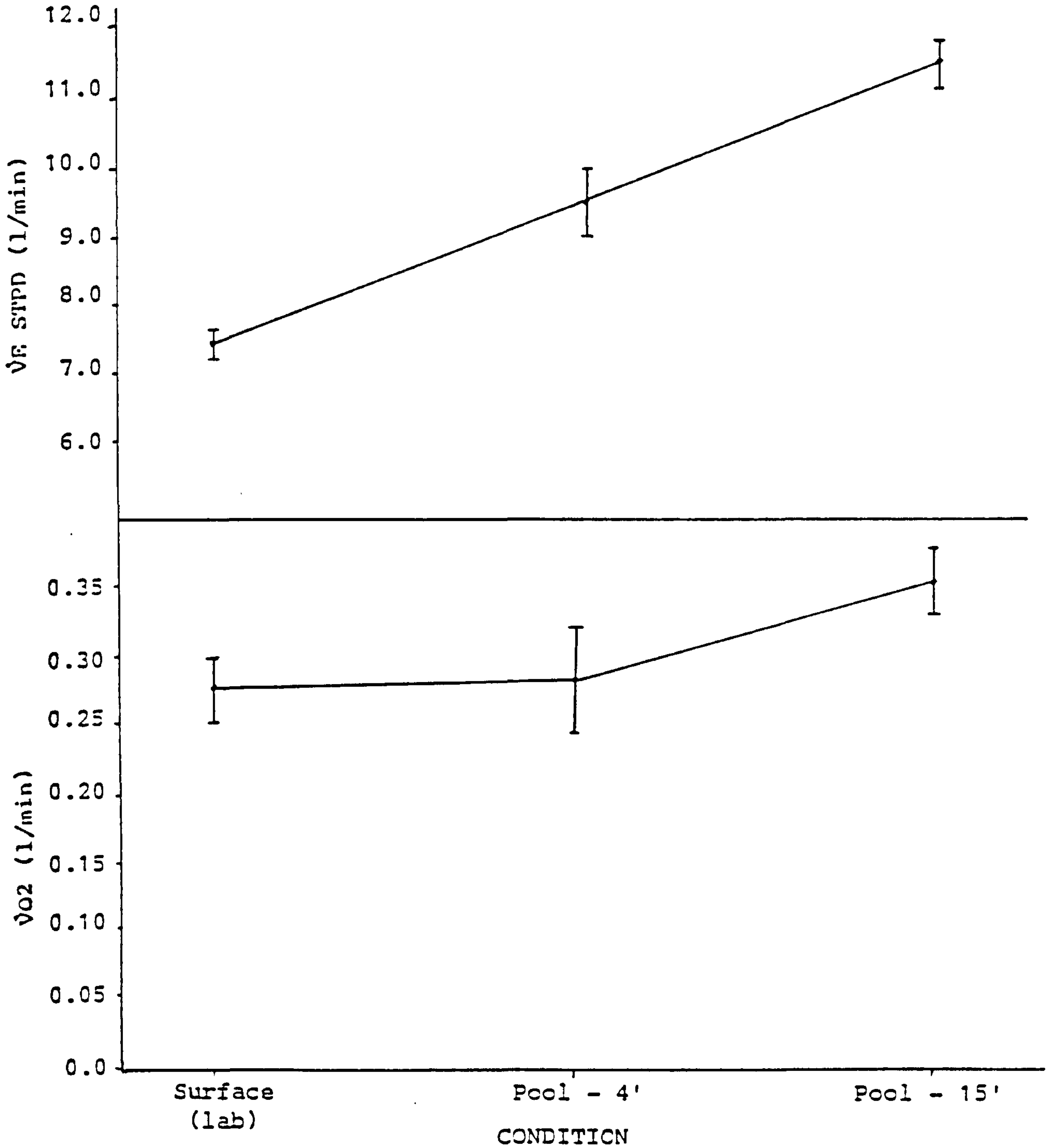
COMPARISON OF RESTING $\dot{V}O2$ VALUES

Condition	Trial	$\dot{V}E$ STPD (l/min)	FE02 (%)	FEC02 (%)	$\dot{V}O2$ (l/min)	(ml/min/kg)
Surface (lab)	1	7.95	17.94	1.75	0.26	3.27
	2	7.86	17.96	1.70	0.26	3.27
	3	8.13	17.72	2.01	0.29	3.60
	4	6.34	17.36	2.73	0.24	3.49
	5	6.77	17.28	2.83	0.26	3.27
	6	7.40	17.22	2.92	0.29	3.60
	Mean:	7.41	17.58	2.32	0.27	3.42
	Std. Dev.:	±0.63	±0.30	±0.53	±0.04	±0.01
Pool - 4'	1	9.93	18.41	2.01	0.27	3.27
	2	11.08	18.49	1.91	0.29	3.54
	3	6.92	18.02	2.11	0.22	2.71
	4	7.27	17.16	2.19	0.31	3.82
	5	6.57	17.61	2.16	0.24	2.99
	6	7.53	17.74	2.03	0.26	3.30
	7	7.44	17.69	2.01	0.27	3.32
	8	11.70	18.57	1.67	0.30	3.73
	9	11.07	18.64	1.83	0.27	3.35
	10	11.16	18.54	1.84	0.28	3.54
	11	12.41	18.61	1.79	0.31	3.83
	12	11.52	18.92	1.21	0.24	3.00
	Mean:	9.55	18.20	1.90	0.27	3.37
	Std.Dev.:	±2.11	±0.52	±0.23	±0.04	±0.30

Condition	Trial	$\dot{V}E$ STPD (l/min)	FEO2 (%)	FECO2 (%)	$\dot{V}O2$ (l/min)	(ml/min/kg)
Pool - 15'	1	11.17	18.21	2.05	0.33	4.06
	2	11.61	18.26	2.04	0.33	4.14
	3	11.08	18.13	2.10	0.33	4.14
	4	10.86	17.61	2.14	0.40	4.94
	5	10.25	17.98	2.00	0.33	4.11
	6	10.16	17.94	2.03	0.33	4.13
	7	10.60	17.75	2.28	0.36	4.55
	8	9.46	17.68	2.11	0.34	4.21
	9	13.56	18.62	1.85	0.33	4.14
	10	13.49	18.57	1.79	0.34	4.25
	11	13.84	18.91	1.39	0.31	3.81
	12	13.84	18.74	1.50	0.33	4.12
	Mean:	11.66	18.20	1.94	0.34	4.22
	Std.Dev.:	±1.52	±2.84	±0.25	±0.03	±0.21

APPENDIX E

COMPARISON OF RESTING $\dot{V}O2$ VALUES



The mean and standard deviation values were obtained from one subject and represent 6 trials in the laboratory and 12 trials per underwater condition to validate the underwater expired gas collection system. The table of results has been included in Appendix D, p 53.

APPENDIX F

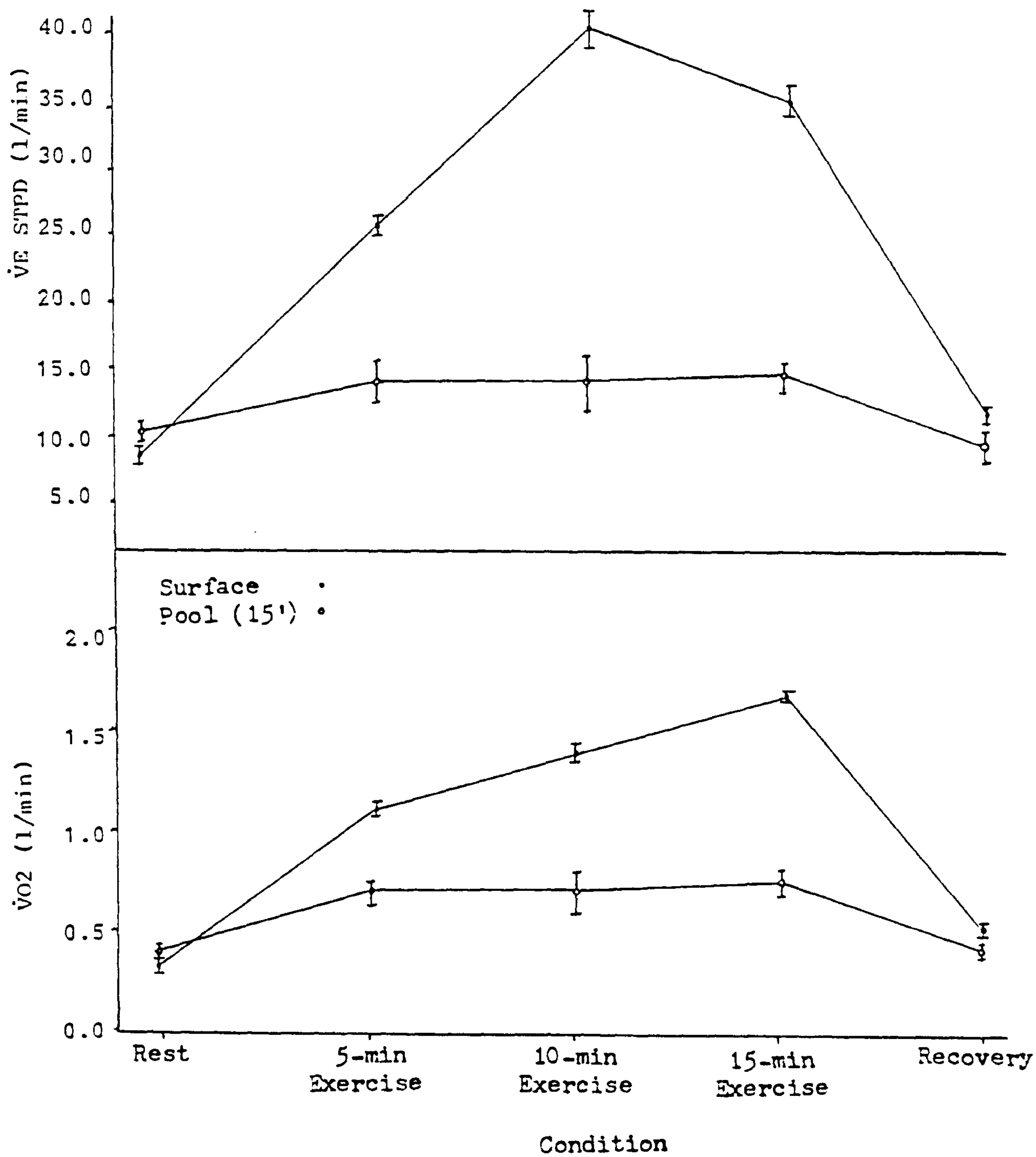
COMPARISON OF TEST PROTOCOL PILOT STUDIES

Condition	Sample	$\dot{V}E$ STPD (l/min)	FE02 (%)	FEC02 (%)	$\dot{V}O2$ (l/min)	$\dot{V}O2$ (ml/min/kg)
Surface I.	Rest	6.34	17.36	2.73	0.24	3.00
	5-min.Exercise	24.21	16.60	3.08	1.13	14.18
	10-min.Exercise	42.09	16.84	3.62	1.17	14.63
	15-min.Exercise	36.89	16.79	3.52	1.59	19.88
	Recovery	12.11	17.28	3.04	0.46	5.75
II.	Rest	6.81	17.55	2.49	0.25	3.09
	5-min.Exercise	23.18	16.42	3.59	1.10	13.80
	10-min.Exercise	35.51	16.69	3.60	1.57	19.61
	15-min.Exercise	31.75	16.64	3.59	1.42	17.79
	Recovery	11.53	17.18	3.07	0.45	5.67
Mean:	Rest	6.58	17.46	2.61	0.25	3.05
		±0.10	±0.41	±0.12	±0.05	±0.17
	5-min.Exercise	23.70	16.51	3.34	1.12	13.99
		±0.17	±0.09	±0.18	±0.11	±3.10
	10-min.Exercise	38.80	16.77	3.61	1.37	17.12
		±3.29	±0.40	±0.01	±0.20	±2.49
	15-min.Exercise	34.32	16.72	3.56	1.51	18.83
		±2.57	±0.40	±0.19	±0.09	±0.95
	Recovery	11.82	17.23	3.06	0.46	5.69
		±0.29	±0.06	±0.17	±0.07	±0.48

Condition	Sample	V̇E STPD (l/min)	FE02 (%)	FEC02 (%)	V̇O2 (l/min)	V̇O2 (ml/min/kg)
Pool	I. Rest	7.95	17.94	1.75	0.26	3.27
	5-min.Exercise	11.88	16.10	2.99	0.63	7.92
	10-min.Exercise	13.94	16.75	2.66	0.64	8.00
	15-min.Exercise	13.85	16.83	2.63	0.62	7.79
	Recovery	6.34	18.12	1.63	0.20	2.50
	II. Rest	8.13	17.72	2.01	0.29	3.60
	5-min.Exercise	12.42	16.28	3.00	0.63	7.92
	10-min.Exercise	13.13	17.03	2.36	0.57	7.09
	15-min.Exercise	12.87	16.63	2.96	0.60	7.50
	Recovery	8.31	17.39	2.24	0.32	4.04
Mean:	Rest	8.04	17.83	1.88	0.28	3.44
		±0.67	±0.11	±0.13	±0.05	±0.08
	5-min.Exercise	12.15	16.19	2.99	0.63	7.92
		±0.27	±0.09	±0.17	±0.00	±0.00
	10-min.Exercise	13.54	16.89	2.51	0.61	7.55
		±0.17	±0.14	±0.15	±0.07	±0.36
	15-min.Exercise	13.36	16.73	2.80	0.61	7.65
		±0.49	±0.10	±0.03	±0.01	±0.24
	Recovery	7.33	17.76	1.94	0.26	3.27
		±0.95	±0.21	±0.27	±0.06	±0.77

APPENDIX G

COMPARISON OF TEST PROTOCOL PILOT STUDIES



The mean and standard deviation values were obtained from one subject to confirm the ability to replicate the work task in both a dry land and an aqueous environment. The table of results has been included in Appendix F, p 56.

APPENDIX H

CORE TEMPERATURES AT 50% OF MAXIMAL V̇02 WORKLOADS

Subject A. Age 22. Weight 80 kg. Maximal V̇O2 65 m./min/kg.
Subject B. Age 27. Weight 83.2 kg. Maximal V̇O2 59.5 ml/min/kg.

Workload = 5.5 mph @ 2.5% gradient on treadmill
(approx. 50% of max. V̇O2).

Time (min)	Core Temp.(°C) A	B	Time (min)	Core Temp (°C) A	B
0	37.5	37.6	16	38.5	38.4
1	37.6	37.6	17	38.5	38.4
2	37.6	37.7	18	38.5	38.3
3	37.7	37.7	19	38.5	38.4
4	37.8	37.7	20	38.4	38.4
5	37.8	37.8	21	38.5	38.5
6	37.9	37.8	22	38.5	38.5
7	37.9	37.9	23	38.6	38.4
8	38.0	37.9	24	38.5	38.5
9	38.0	38.0	25	38.6	38.5
10	38.2	38.0	26	38.6	38.6
11	38.3	37.9	27	38.6	38.5
12	38.3	38.0	28	38.7	38.6
13	38.3	38.2	29	38.7	38.6
14	38.2	38.3	30	38.8	38.7
15	38.4	38.3			
			Mean:	38.3	38.2
			Std.Dev.:	±0.37	±0.34

APPENDIX I

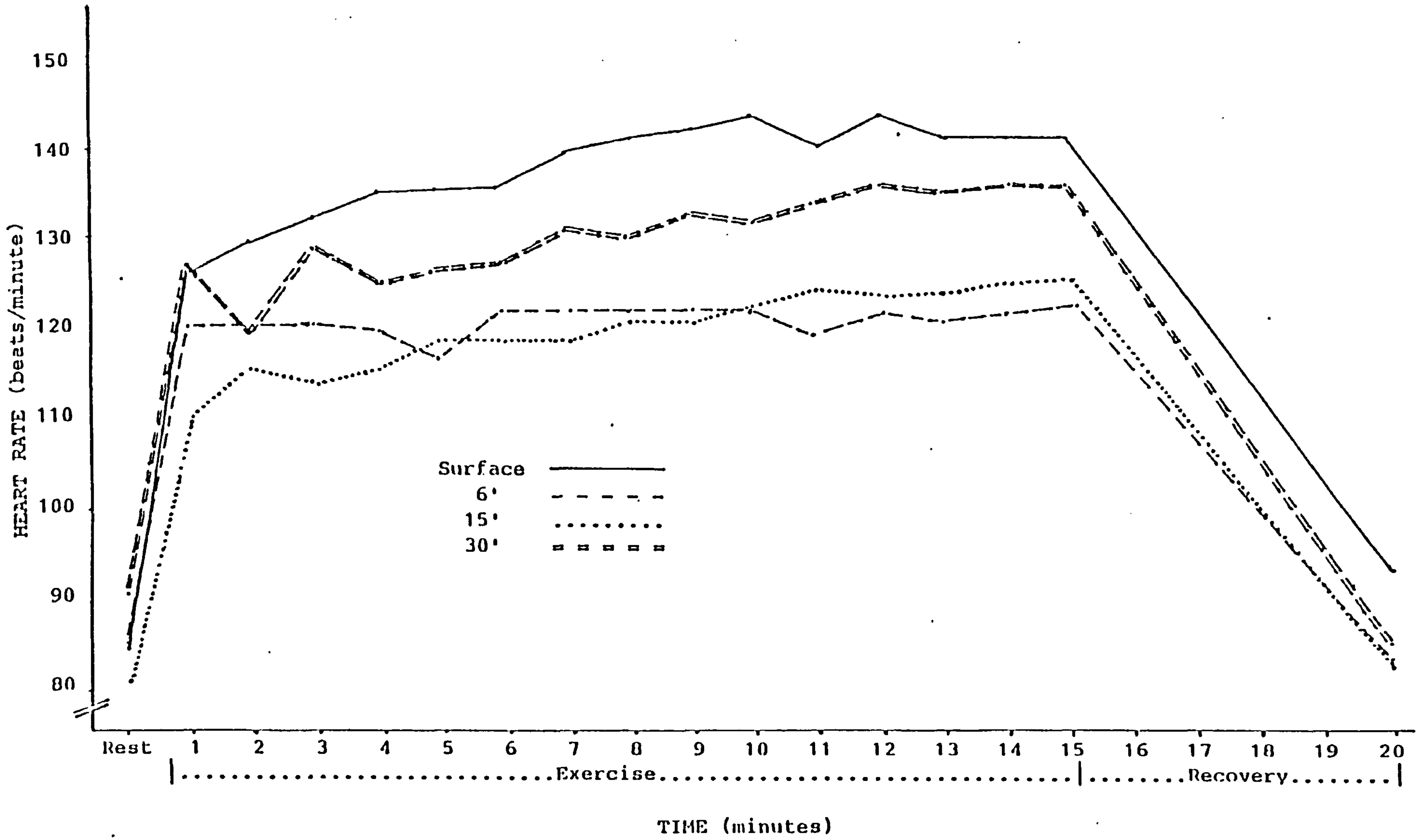
OBSERVED HEART RATES (beats/minute).

Condition	Subject	Rest	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	5 Minute Recovery
			Time (minutes)															
Surface (lab)	KB	74	128	120	117	120	121	118	123	124	120	128	117	127	116	119	120	88
	JN	72	118	123	123	123	123	126	128	134	133	131	132	128	131	130	130	84
	DB	98	126	133	152	149	147	144	148	152	159	159	156	164	161	164	157	96
	GA	84	128	137	139	145	150	155	162	162	161	161	161	158	158	159	158	104
	GE	93	131	134	133	138	138	136	136	133	141	140	138	140	141	136	142	93
6'	KB	89	132	116	121	114	99	118	105	111	113	108	108	114	121	118	127	82
	JN	88	116	115	118	121	120	126	129	124	126	126	120	121	115	116	114	88
	DB	78	119	119	122	113	114	115	119	117	114	112	112	118	113	111	112	76
	GA	88	126	131	128	130	126	126	129	127	126	125	127	129	128	128	130	93
	GE	84	108	121	115	119	124	120	124	127	128	135	124	126	127	132	130	80
15'	KB	77	111	108	91	97	101	105	103	108	109	108	111	108	119	130	121	77
	JN	87	111	113	116	115	116	121	117	116	117	113	119	123	116	117	115	87
	DB	88	118	119	120	120	118	117	120	119	121	123	125	116	119	120	123	77
	GA	82	121	128	125	124	124	121	124	128	123	122	121	130	133	128	136	97
	GE	74	89	116	120	125	131	128	129	133	133	141	144	140	137	136	135	76
30'	JN	91	134	124	127	120	122	123	124	121	127	125	131	139	134	136	134	94
	DB	97	126	115	127	124	131	130	139	133	137	137	137	138	139	138	139	82
	GA	86	121	120	127	126	126	128	129	133	132	130	133	132	133	136	135	81

At the time of testing, heart rates were recorded each minute on an underwater slate as observed on an Exersentry Heart Rate monitor sealed inside a water-proof plexiglass housing. The monitor was linked to electrodes worn under the dry suit of each subject by 10 foot length of wire which allowed full movement patterns during each trial.

Subjects KB and GE participated in the first three conditions only.

APPENDIX J. HEART RATE VERSUS TIME.



This figure illustrates the mean heart rate values obtained at each level. The complete table of raw data is provided in Appendix I.

APPENDIX K

EXPIRED GAS CONCENTRATION DATA

Condition	Sample	$\dot{V}E$ STPD (1/min)	FEO2 (%)	FECO2 (%)	$\dot{V}O2$ (1/min)	$\dot{V}O2$ (ml/kg)	02 Pulse
SUBJECT KB:							
Surface	Rest	6.92	17.39	2.76	0.26	3.40	3.51
	7-min. Exercise	28.83	16.59	3.58	1.31	17.18	10.23
	15-min. Exercise	27.67	16.59	3.51	1.26	16.55	10.50
	Recovery	15.57	16.86	3.17	0.67	8.79	7.61
6'	Rest	7.16	17.68	2.51	0.25	3.25	2.81
	7-min. Exercise	15.88	17.38	2.87	0.59	7.66	5.32
	15-min. Exercise	19.32	17.18	3.15	0.76	9.86	5.98
	Recovery	14.23	17.26	2.93	0.55	7.14	6.71
15'	Rest	9.49	17.45	2.91	0.35	4.54	4.55
	7-min. Exercise	19.82	17.05	3.15	0.81	10.51	7.50
	15-min. Exercise	16.37	16.94	3.18	0.69	8.96	5.70
	Recovery	15.93	17.22	2.89	0.63	8.18	8.18

Appendix K (cont'd.)

Expired Gas Concentration Data

Condition	Sample	$\dot{V}E$ STPD (l/min)	FEO2 (%)	FECO2 (%)	$\dot{V}O2$ (l/min)	$\dot{V}O2$ (ml/kg)	02 Pulse
SUBJECT GE:							
Surface	Rest	4.07	16.50	3.94	0.19	2.43	2.04
	7-min. Exercise	29.65	16.22	4.38	1.43	18.24	10.21
	15-min. Exercise	27.33	16.15	4.43	1.33	17.06	9.37
	Recovery	6.40	16.34	4.28	0.30	3.84	3.23
6'	Rest	5.00	17.22	2.82	0.20	2.60	2.38
	7-min. Exercise	15.18	16.45	3.51	0.72	9.37	5.67
	15-min. Exercise	26.53	16.60	3.34	1.22	15.88	9.39
	Recovery	16.18	16.51	3.47	0.76	9.89	9.50
15'	Rest	11.38	17.33	2.97	0.48	6.25	6.49
	7-min. Exercise	28.26	16.88	3.98	1.15	14.97	8.65
	15-min. Exercise	33.67	16.75	3.91	1.44	18.74	10.67
	Recovery	24.79	16.84	3.99	1.02	13.27	13.42

Appendix K (cont'd.)

Expired Gas Concentration Data

Condition	Sample	$\dot{V}E$ STPD (l/min)	FEO2 (%)	FECO2 (%)	$\dot{V}O2$ (l/min)	$\dot{V}O2$ (ml/kg)	02 Pulse
SUBJECT JN:							
Surface	Rest	6.40	17.64	2.75	0.22	2.63	3.06
	7-min. Exercise	30.24	16.38	4.08	1.42	17.02	10.84
	15-min. Exercise	30.82	16.30	4.24	1.46	17.56	11.23
	Recovery	6.98	16.50	4.00	0.32	3.82	3.81
6'	Rest	5.06	17.75	2.72	0.17	2.04	1.93
	7-min. Exercise	19.20	16.94	3.51	0.79	9.47	6.37
	15-min. Exercise.	16.49	16.48	4.01	0.76	9.11	6.67
	Recovery	15.19	16.66	4.00	0.66	7.91	7.50
15'	Rest	6.74	17.62	2.80	0.23	2.76	2.64
	7-min. Exercise	29.25	16.99	3.58	1.18	14.15	10.17
	15-min. Exercise	28.04	16.91	3.75	1.15	13.79	10.00
	Recovery	10.95	16.87	3.79	0.45	5.40	5.17

Appendix K (cont'd.)

Expired Gas Concentration Data

Condition	Sample	V̇E STPD (l/min)	FEO2 (%)	FECO2 (%)	V̇O2 (l/min)	V̇O2 (ml/kg)	02 Pulse
Subject JN (cont'd.)							
30'	Rest	13.60	18.37	2.22	0.36	4.32	3.96
	7-min. Exercise.	34.68	17.63	2.84	1.19	14.27	9.84
	15-min. Exercise	25.75	17.38	3.22	1.05	12.58	7.09
	Recovery	22.19	17.54	2.96	0.77	9.23	8.19
SUBJECT DB:							
Surface	Rest	9.22	17.63	2.55	0.32	4.90	3.27
	7-min. Exercise	35.74	16.94	3.29	1.43	21.67	8.99
	15-min. Exercise	32.86	17.01	3.26	1.35	20.46	8.60
	Recovery	12.11	17.26	2.96	0.47	7.09	4.90
6'	Rest	12.33	17.58	2.79	0.43	6.55	5.51
	7-min. Exercise	20.67	17.28	2.95	0.79	12.03	6.75
	15-min. Exercise	25.02	17.13	3.01	1.01	15.38	9.02
	Recovery	13.96	17.34	2.92	0.53	8.07	6.97

Appendix K (cont'd.)

Expired Gas Concentration Data

Condition	Sample	$\dot{V}E$ STPD (1/min)	FEO2 (%)	FECO2 (%)	$\dot{V}O2$ (1/min)	$\dot{V}O2$ (ml/kg)	02 Pulse
Subject DB (cont'd.)							
15'	Rest	10.39	17.91	2.54	0.33	5.02	3.75
	7-min. Exercise	24.48	17.88	2.61	0.78	11.87	6.56
	15-min. Exercise	21.66	17.42	2.85	0.80	12.18	6.50
	Recovery	20.50	17.58	2.81	0.72	10.96	9.35
30'	Rest	20.07	17.68	2.53	0.69	10.50	7.11
	7-min. Exercise	45.60	17.25	2.91	1.77	26.95	13.31
	15-min. Exercise	39.51	17.13	3.03	1.59	24.21	11.44
	Recovery	26.36	17.38	2.89	0.98	14.92	11.95
SUBJECT GA:							
Surface	Rest	7.52	17.88	2.15	0.25	3.96	2.98
	7-min. Exercise	39.32	16.84	3.82	1.64	26.14	10.19
	15-min. Exercise	31.81	16.78	3.79	1.35	21.58	8.54
	Recovery	8.67	16.98	3.69	0.35	5.59	3.37

Appendix K (cont'd.)

Expired Gas Concentration Data

Condition	Sample	V̇E STPD (l/min)	FEO2 (%)	FECO2 (%)	V̇O2 (l/min)	V̇O2 (ml/kg)	02 Pulse
Subject GA (cont'd.)							
6'	Rest	9.97	18.32	2.01	0.28	4.43	3.18
	7-min. Exercise	29.29	17.75	2.52	0.99	15.67	7.80
	15-min. Exercise	31.31	17.19	3.28	1.21	19.15	9.31
	Recovery	28.27	17.62	2.77	0.98	15.51	10.54
15'	Rest	17.71	17.74	2.53	0.60	9.50	7.32
	7-min. Exercise	37.34	17.86	2.59	1.15	18.20	8.98
	15-min. Exercise	30.19	17.64	2.75	1.04	16.46	7.65
	Recovery	20.43	17.98	2.46	0.63	9.97	6.50
30'	Rest	25.01	17.62	2.74	0.87	13.77	10.12
	7-min. Exercise	38.15	17.28	3.30	1.43	22.63	11.09
	15-min. Exercise	36.76	17.25	3.33	1.39	22.00	10.30
	Recovery	19.59	17.94	2.38	0.62	9.82	7.65

APPENDIX L

WORK OUTPUT AND WORK INPUT CALCULATIONS

A. Calculated Work Output (kilocalories).

Subject	Surface	6'	15'	30'
KB	0.25	0.25	0.25	*
GE	0.24	0.24	0.25	*
JN	0.30	0.30	0.30	0.30
DB	0.22	0.22	0.22	0.22
GA	0.26	0.26	0.26	0.26

*Subject did not participate in 30' testing.

B. Calculated Work Input (kilocalories).

Subject	Surface		6'		15'		30'	
Time:	7	15	7	15	7	15	7	15
KB	5.25	5.00	1.70	2.55	2.30	1.70	*	*
GE	6.20	5.70	2.60	5.10	3.25	4.80	*	*
JN	6.00	6.20	3.10	2.95	4.75	4.37	4.15	3.45
DB	5.55	5.15	1.80	2.90	2.25	2.35	5.40	4.50
GA	6.95	5.50	3.55	4.65	2.75	2.20	2.80	2.60

* Subject did not participate in 30' testing.

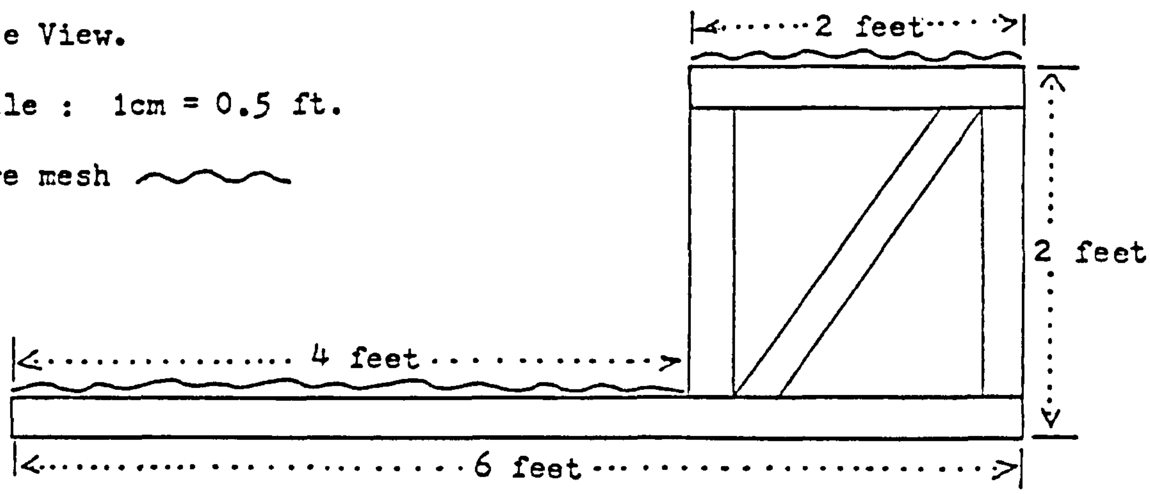
APPENDIX M

SPECIFICATIONS OF WORK PLATFORM

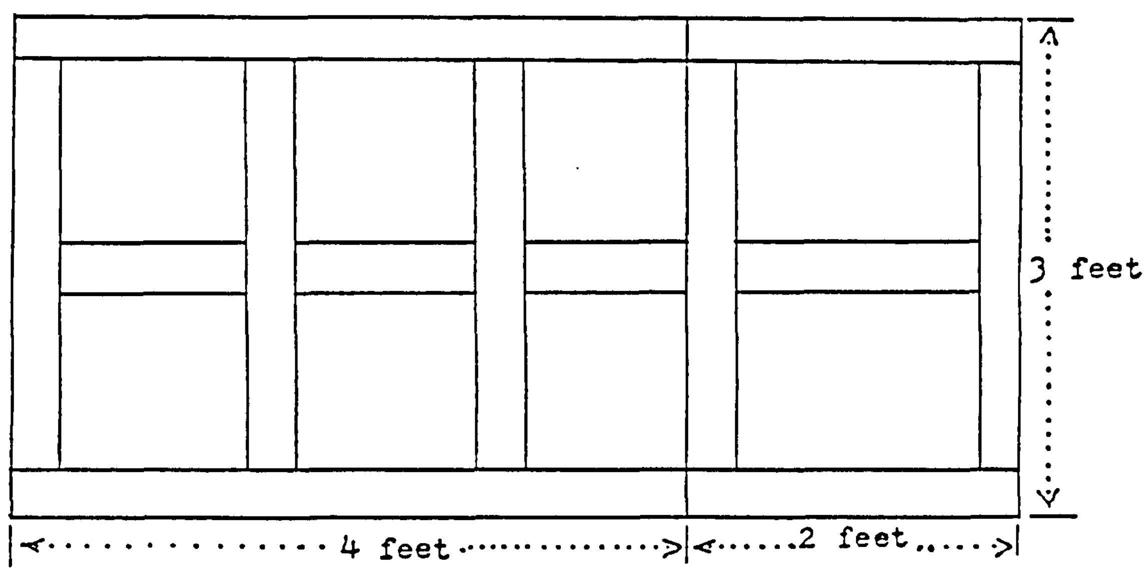
A. Side View.

Scale : 1cm = 0.5 ft.

Wire mesh



B. Top View.



Heavy gauge wire mesh covered the lower portion of the platform (see A) where the divers stood and the elevated end upon which the block was lifted during the work task. The frame was constructed of pressure treated pine 4" X 4" 's.

Overall weight was approximately 70 lbs and required 250 lbs of lead distributed evenly around the frame to be anchored securely in the clay sediment.

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