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CARDIORESPIRATORY RESPONSES

TO SUBMAXIMAL EXERCISE IN WATER

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CARDIORESPIRATORY RESPONSES
TO SUBMAXIMAL EXERCISE IN WATER

BY
KAREN ANN CARLBERG
B.S., University of Washington, 1972

THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Biology

in the Graduate School of
The University of New Mexico
Albuquerque, New Mexico

December, 1976

ACKNOWLEDGEMENTS

The planning, conduct and writing of a study such as this one require the cooperation of many people, and I am indebted to a number of individuals for their assistance.

Dr. Loren Myhre was extremely helpful with the conception and initial planning of the study.

Dr. Ulrich Luft and his staff at the Lovelace Foundation were very generous with their advice and the use of their facilities.

The four subjects, Jim Butscher, Steve Silbaugh, Butch Stackpole and Joe Valles, deserve a great deal of thanks for the considerable time and effort they contributed to the study. In addition, Ron Contreras, Michael Lipkan and Joanne Santiago were most helpful in assembling the equipment and conducting the tests.

Dr. Earl Bourne, Dr. Eric Toolson and Dr. Waneta Tuttle were very helpful with interpretation of the data and the writing of the thesis.

And my biggest thanks go to Dr. Marvin Riedesel, whose infinite patience and encouragement throughout all phases of the project were very much appreciated.

CARDIORESPIRATORY RESPONSES
TO SUBMAXIMAL EXERCISE IN WATER

BY
Karen Ann Carlberg

ABSTRACT OF THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Biology
in the Graduate School of
The University of New Mexico
Albuquerque, New Mexico
December, 1976

ABSTRACT

Maximal oxygen consumption is consistently lower when measured during swimming than during running or bicycling. A number of factors could contribute to this difference, including size of active muscle mass, body position, heat exchange mechanisms, breathing patterns and adjustments to water immersion.

In this study, the effects of water immersion on submaximal exercise were isolated by having subjects perform identical work in air and water. The exercise consisted of rowing on a rowing machine, with rate of movement controlled so that the subjects always worked at the same relative workload and oxygen consumption. To compare the physiological responses to exercise in air and water, measurements and calculations were made of oxygen consumption, carbon dioxide production, respiratory exchange ratio, minute ventilation, respiratory rate, tidal volume, recovery heart rate and lactic acid accumulation.

The experiment was conducted in three phases. In Phase I, the subjects' maximum oxygen consumptions were measured with a standard bicycle ergometer test. Phase II determined the rate of work on the rowing machine required for each subject to attain 70 to 80% of his maximum oxygen consumption. Water resistance necessitated a slower work rate in the water than in the air. Phase III provided the data for comparing physiological responses to exercise in air and water. In this final phase, each subject performed one test in air and one in water, with nearly identical oxygen consumptions in both tests.

Responses to exercise in air and water were quite similar. There was no significant difference between any of the measurements made during

the exercise, including oxygen consumption, carbon dioxide production, respiratory exchange ratio, minute ventilation, respiratory rate and tidal volume. Recovery heart rates were similar. Lactic acid concentration, measured during the fifth minute of recovery, was slightly, but significantly, greater following the water tests.

The oxygen cost of each pull on the rowing machine was calculated by dividing the oxygen consumption per minute by the number of pulls per minute. Rowing in the water required 50 to 60% more oxygen than rowing in air. This may be a good estimate of the additional energy expenditure required for underwater work.

It is concluded that water immersion per se has little effect on the response to submaximal exercise. The reduction in maximal oxygen consumption during swimming compared to running or bicycling must be due to differences other than immersion, such as size of active muscle mass, body position, breathing patterns or heat loss mechanisms.

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INTRODUCTION

Maximum oxygen consumption is consistently lower when measured during swimming than during treadmill running or bicycling (Dixon and Faulkner, 1971; McArdle, Glaser, and Magel, 1971; Holmér, 1972; Holmér, and Bergh, 1974). Well-trained competitive swimmers, as well as non-competitive swimmers, display this reduced maximal work capacity while swimming (Holmér, Lundin, and Erikson, 1974a; Holmér et al., 1974b).

A number of factors could explain this difference between swimming and other forms of exercise: (i) a smaller muscle mass may be used in swimming than in running or bicycling, (ii) the horizontal body position of most other types of exercise, (iii) some styles of swimming limit breathing frequency, (iv) heat exchange mechanisms are different in the water than in the air, and (v) water immersion itself results in several physiological changes.

This investigation is concerned with the effects of water immersion on exercise. Does immersion in water, by itself, cause significant changes in the cardiovascular, respiratory and metabolic responses to submaximal exercise?

To isolate the effects of water immersion on exercise, human subjects were asked to exercise in both air and water, with all other conditions as similar as possible. Rowing on a rowing machine was selected for the exercise. Work rate was controlled so that each subject would be working at the same workload in each environment. To detect any differences in the response to exercise in the two environments, measurements and calculations of oxygen consumption, carbon dioxide production, respiratory exchange ratio, minute ventilation, respiratory rate, tidal volume, recovery heart rate and blood lactic acid concentration were made.

LITERATURE REVIEW

The lower maximum oxygen consumption observed during swimming has been attributed to a number of factors. Immersion in water has been shown to have various effects on cardiovascular and respiratory function. Temperature of the water is a determinant of the response to immersion. Differences in body position and size of active muscle mass used during swimming may also contribute to the disparity in physiological responses to swimming and running or bicycling.

I. Maximum Oxygen Consumption (\dot{V}_{O_2}) During Swimming

When human subjects' maximum oxygen consumptions (\dot{V}_{O_2}) measured during swimming have been compared with their maximum \dot{V}_{O_2} 's measured during treadmill running or bicycling, most investigators have found the swimming maximum \dot{V}_{O_2} to be lower (Åstrand and Rodahl, 1970; Holmér, 1972; Holmér and Bergh, 1974). Holmér et al., (1974a) found the maximum \dot{V}_{O_2} during swimming to be 6% less than during treadmill running. Young female competitive swimmers were reported by Åstrand et al. (1963) to have maximum \dot{V}_{O_2} 's during swimming averaging 92.5% of their maximum \dot{V}_{O_2} 's during bicycling. An 11% decrement in maximum \dot{V}_{O_2} was observed by McArdle et al. (1971) when swimming was compared with treadmill walking. Swimming maximum \dot{V}_{O_2} was reported to be 15% lower than running maximum \dot{V}_{O_2} by Holmer et al. (1974b). Åstrand and Saltin (1961) found swimming maximum \dot{V}_{O_2} 's to be between 73 and 95% of their subjects' maximum \dot{V}_{O_2} 's during bicycling. Highly trained competitive swimmers, as well as recreational swimmers, have maximum \dot{V}_{O_2} 's during swimming which are lower than their maximum \dot{V}_{O_2} 's measured during running or bicycling (Åstrand et al., 1963; Holmér et al., 1974a; Holmér et al., 1974b). Better swimmers,

however, appear to have swimming maximum \dot{V}_{O_2} 's closer to their maximum \dot{V}_{O_2} 's during running or bicycling (McArdle et al., 1971).

Some investigators have found that, at least for highly trained swimmers, there is no significant difference between maximum \dot{V}_{O_2} measured during swimming and treadmill running (Magel and Faulkner, 1967). Dixon and Faulkner (1971) reported that maximum \dot{V}_{O_2} during swimming was not significantly different from maximum \dot{V}_{O_2} during treadmill running for trained swimmers, but for recreational swimmers the value for swimming was 19 to 25% lower.

Moore et al. (1970) reported a higher \dot{V}_{O_2} during water immersion than in air at several workloads, including maximal work. However, water temperatures were below the point where other investigators have reported an increase in \dot{V}_{O_2} due to cold exposure.

The reduced maximal oxygen consumption during swimming has been attributed to many factors. These include a reduced active muscle mass, the horizontal body position, different conditions for heat exchange, and decreases in cardiac output, heart rate, stroke volume, arteriovenous oxygen difference, minute ventilation and ventilation coefficient. Studies of these factors will be discussed in the following sections.

II. Effects of Water Immersion

A. Cardiovascular Effects

Immersion in water results in a number of changes in the cardiovascular system: differences in heart rate are usually observed, and changes in blood volume distribution and peripheral vascular resistance often result in altered blood pressure, stroke volume, cardiac output and lung capillary volume.

1. Heart Rate

Heart rate usually decreases upon submersion in thermoneutral water (Keatinge and Evans, 1961; Faulkner, 1965; Faulkner, 1968; Hood et al., 1968). The effects of non-thermoneutral water immersion will be discussed in a later section. Wells (1932) reported an average drop in resting heart rate of 11 beats/min after immersion. Mean reductions of 11 beats/min in resting heart rate in the sitting position and 14 beats/min in the standing position were observed by Tuttle and Corleaux (1935). Tuttle and Templin (1943) reported a 12% mean decrease in resting heart rate. The size of the reduction appears to depend on the temperature of the water (Tuttle and Corleaux, 1935) and the subject's resting heart rate: the lower the resting heart rate, the smaller the decrease during immersion (Tuttle and Templin, 1943).

Exercise heart rates are lower in water than in air for comparable workloads (Dixon and Faulkner, 1971) and comparable oxygen consumptions (McArdle et al., 1971). Maximal heart rates during maximal exercise are consistently lower during swimming than during exercise in air (Faulkner, 1968; Holmér, 1972; Holmér and Bergh, 1974; Holmér et al., 1974a; Holmér et al., 1974b). Åstrand and Saltin (1961) observed heart rates during maximal swimming which were 3 to 10 beats/min slower than during bicycling. McArdle et al. (1971) suggested that the lower maximal heart rate during swimming may be accounted for by the easier dissipation of metabolic heat, the horizontal body position, or a smaller active muscle mass.

The cause of the reduced heart rate during immersion is not certain, but some investigations of its origin have been made. All vertebrates studied have shown some degree of bradycardia as part of a diving reflex when submerged, including natural divers, non-divers and humans (Anderson,

1966). Feigle and Folkow (1963) attributed diving bradycardia to three factors: a specific nervous reflex resulting from submersion of the head, hypercapnia and hypoxia. When Anderson (1966) submerged ducks at various levels, it appeared that bradycardia was precipitated by submersion of an area around the nostrils and nasal cavity. This response was obliterated with bilateral section of the trigeminal nerve; the ophthalmic branch appeared to be the most important. Humans display bradycardia during submersion of only the face (Anderson, 1966). Anderson (1966) concluded that diving bradycardia is a medullary reflex, because decerebrated animals exhibit a reduced heart rate as readily as before decerebration. Feigle and Folkow (1963) found that electrical stimulation of the mesencephalon elicited diving-like responses, including bradycardia. Heart rate appears to be slowed during immersion by vagal activity which prolongs diastole; the response is abolished by vagotomy (Anderson, 1966). Hollenberg and Uvnas (1963) reported that diving bradycardia was obliterated by denervation of the carotid chemoreceptors and baroreceptors.

2. Blood Redistribution

Immersion in water results in a redistribution of the blood volume, with a larger proportion of the blood moving into the thorax. Arborelius et al. (1972) reported an average increase of 0.7 liters in central blood volume during immersion. According to Gauer (1973), 25% of the total blood volume is shifted into the thorax upon immersion, causing an increase of 3 to 15 mmHg in central venous pressure. Guyatt et al. (1965) observed, as a result of blood redistribution, an average increase of 47% in pulmonary capillary blood volume and an average increase of 16.2% in diffusing capacity of the lung. Arborelius et al. (1972) explain the blood redistribution in this manner: the transmural pressure gradient

exerted by the weight of the blood column below the diaphragm is not only completely balanced by the external water column, but a reversed pressure gradient is created above the level of the diaphragm. The result is a net movement of blood toward the upper parts of the body, above the diaphragm.

Along with the increased volume of blood in the thorax during immersion, increases in heart volume and stroke volume are often observed. Gauer (1973) noted an increase in heart volume averaging 180 ml. While sitting in water, stroke volume has been reported to be 30% (Gauer, 1973) to 35% (Arborelius et al., 1972) greater than while sitting in air. During swimming, stroke volume has been found to be the same as during running (Holmér et al., 1974b) or 5% larger than while running (Dixon and Faulkner, 1971). Hood et al. (1968) suggested that the increased stroke volume results from bradycardia during immersion.

The effects of immersion on cardiac output are variable, presumably because the decrease in heart rate and increase in stroke volume are not always comparable. At rest, a 30% (Gauer, 1973) to 32% (Arborelius et al., 1972) increase in cardiac output has been observed. During exercise, Denison et al. (1972) reported a 10% increase in both heart rate and cardiac output, but these results may have been due to their high water temperature. Holmér et al. (1974b) found that during submaximal work cardiac output was similar in swimming and running. However, in maximal work, cardiac output was 10% lower during swimming, resulting from a lower heart rate and unchanged stroke volume. They attributed the lower maximal heart rate and cardiac output to the smaller active muscle mass used in swimming. Dixon and Faulkner (1971) reported recreational swimmers' maximal cardiac output was 25% below the running value. This resulted

from decreases in both heart rate and stroke volume during swimming. However, in trained swimmers they found that a 5% increase in stroke volume compensated for the decreased heart rate, such that cardiac output was the same in swimming and running. They suggested that only trained swimmers can maintain a large enough blood flow through the arm, shoulder and chest muscles to maintain a high venous return.

B. Respiratory Effects

During immersion in water, the work of breathing appears to be increased by the hydrostatic pressure on the thorax and abdomen. The displacement of blood into the thorax reduces the space available in the lungs for alveolar air. As a result of these factors, the depth of inspiration and total ventilation are often reported to be reduced during immersion.

1. Changes in Breathing During Immersion

Maximum pulmonary ventilation has often been demonstrated to be lower during swimming than during running (Magel and Faulkner, 1967; Holmér et al., 1974a), walking (McArdle et al., 1971) or bicycling (Åstrand and Saltin, 1961; Holmér, 1972). The ratio of pulmonary ventilation to oxygen consumption during maximal swimming is also lower than during bicycling (Åstrand et al., 1963). Holmér et al. (1974b) reported that ventilation was 111.0 liters/min during maximal swimming and 154.2 liters/min during maximal running; alveolar ventilation was 101.8 liters/min in maximal swimming and 111.2 liters/min in maximal running.

Evidence of alveolar hypoventilation has been observed in subjects exercising in water. Trained swimmers studied by Dixon and Faulkner (1971) tended to hypoventilate, resulting in a high oxygen extraction and a high level of CO_2 in expired air. These swimmers had a low

arteriovenous oxygen difference, which the authors suggest may reflect a low arterial P_{O_2} rather than a high mixed venous oxygen content. The low arterial P_{O_2} may partly explain the lower maximal \dot{V}_{O_2} in swimming compared to bicycling (Åstrand and Rodahl, 1970). In contrast, Holmér et al. (1974b) reported that despite the relative hypoventilation in swimming, gas exchange was sufficient to maintain arterial oxygenation similar to running. Denison et al. (1972) found no changes in alveolar ventilation or end-tidal P_{O_2} in immersed exercising subjects.

Some investigators have found pulmonary ventilation to be similar while exercising in water and air, especially at submaximal workloads. Dixon and Faulkner (1971) reported that trained swimmers had similar maximal ventilations swimming and running, but recreational swimmers had a significantly lower ventilation swimming than running. At submaximal workloads, Craig and Dvorak (1969), Moore et al. (1970) and McArdle et al. (1971) have observed similar ventilations in water and air. Craig and Dvorak (1969) suggest that smaller ventilations have been measured during swimming because the subjects' breathing was restricted in some way.

Lung volumes are usually reduced in resting subjects immersed in water. Prefault, Lupi-H, and Anthonisen (1976) found that total lung capacity decreased slightly after immersion; they attributed this to the shift of blood into the chest and the hydrostatic pressure which reduces the maximum static transpulmonary pressure that can be generated. Vital capacity has been reported to decrease by 9% (Agostoni et al., 1966), by 350 ml (Karpovich, 1939) and from 5.33 liters to 5.10 liters (Craig and Ware, 1967). Tidal volume remains unchanged (Hong et al., 1969). The tidal volume range moves toward expiration, implying an increase in

inspiratory reserve volume (Miles, 1969) and decreases in expiratory reserve volume (Beckman et al., 1961; Hong et al., 1969) and functional residual capacity (Prefault et al., 1976). These changes may be due to a cranial displacement of the abdomen and diaphragm (Agostoni et al., 1966; Prefault et al., 1976) or the additional pressure on the chest which disturbs the balance between chest elasticity and lung elasticity (Miles, 1969). As a result, 300 to 400 ml of air may be driven out of the lungs (Miles, 1969).

During exercise in water, the pattern of breathing is often different than during exercise in air. Tidal volume during maximal swimming is less and breathing frequency is higher than during maximal running (Craig and Dvorak, 1969; Dixon and Faulkner, 1971; McArdle et al., 1971). The combination of these changes can result in either a lower (McArdle et al., 1971) or the same (Dixon and Faulkner, 1971) ventilation as in running. In submaximal swimming, McArdle et al. (1971) observed a lower breathing rate and higher tidal volume than during treadmill walking at low workloads, and similar breathing rates at higher workloads. The reduced tidal volume during swimming is due to hydrostatic pressure, increased airflow resistance, position of the chest cage and involvement of the intercostal muscles in the arm stroke (Dixon and Faulkner, 1971; McArdle et al., 1971).

Use of artificial inspiratory resistances during exercise produces changes in breathing similar to the changes during swimming. Decreases in tidal volume and breathing frequency were reported by Craig, Blevins, and Cummings (1970) and Lynne-Davies et al. (1971). Flook and Kelman (1973) observed changes in breathing patterns similar to those observed by McArdle et al. (1971) with swimmers: tidal volume was increased

during light exercise, unchanged during moderate exercise and reduced during heavy exercise; breathing frequency and minute ventilation both decreased.

2. Increased Work of Breathing During Immersion

The energy, or oxygen, cost of breathing increases during immersion due to the hydrostatic pressure on the chest and the increased airway resistance. Hong et al. (1969) estimated that the total work of breathing for a tidal volume of one liter increased by approximately 60% .

Computations of the work of breathing during immersion are difficult to evaluate. Karpovich (1939) performed a set of calculations to determine the amount of pressure on the thoracic cavity of a swimmer and the extra work of breathing in the water: Because water exerts 200.0 g of pressure per 6.5 cm^2 for each 30.5 cm of depth, the total pressure exerted on the body depends on depth. If the surface area of the movable part of the chest is 625 cm^2 , and the median line of the body is 12.5 cm deep, then the water pressure which has to be overcome for inspiration is $625 \times 12.5 = 7812 \text{ g}$. If inhaling 500 ml of air moves the chest 1 cm, then the extra work performed is $0.01 \text{ m} \times 7.8 \text{ kg} = 0.078 \text{ mkg}$. Another method for calculating the extra work of breathing in the water is to measure oxygen consumption while lying on land and lying in water; the difference is the amount of oxygen used to overcome water pressure. The difference ranged from 1.3 to 2.3 ml of oxygen for every liter of air, which is equivalent to 0.00065 to 0.014 cal or 2.77 to 5.97 mkg. The dissimilarity in these two values for the extra work of breathing indicates the imprecision in making such an estimate.

The effort required for inspiration during swimming may be even greater than predicted by calculations. Because inhalation interferes with the propelling movements of swimming, there is a tendency to inhale as

quickly as possible, further increasing the work of breathing (Karpovich, 1939).

Increased airway resistance is another factor increasing the work of breathing during immersion. The decrease in lung volume reduces airway diameter, increasing airway resistance by an estimated 58% (Agostoni et al., 1966).

In addition to water pressure on the chest, the space available for alveolar air is reduced by the increased volume of blood in the lungs during immersion. Begin et al. (1976) demonstrated an increase in pulmonary capillary blood flow in subjects seated in water. Hamilton and Mayo (1944) reported that water pressing on the veins increases venous return sufficiently to increase the load of blood in the lungs and decrease the space available for air.

Swimmers and divers often have larger than average lung volumes. The highly trained girl swimmers studied by Åstrand et al. (1963) had above average total lung capacities, functional residual capacities, vital capacities and residual volumes. All volumes except residual volume were increased by an average of 11 to 15%, approximately one standard deviation, over normal. Hong et al. (1963) found that the Ama, the Korean diving women, had vital capacities 25% larger than would be predicted from body size. This was due entirely to an increased inspiratory capacity. Their maximum breathing capacities and maximal inspiratory pressure for any given lung volume were also significantly higher than normal. Carey, Schaefer, and Alvis (1956) measured vital capacities 15% over predicted values in diving instructors at an Escape Training Tank. Because vital capacity appears to increase significantly with training, they suggest that the large capacities are developed through aquatics rather than inherited. The mechanism of this increase is probably

strengthening of the inspiratory muscles resulting from the high inspiratory resistance due to hydrostatic pressure on the chest.

3. Adaptations to Increased Work of Breathing During Immersion

Minute ventilation increases linearly with increasing workload up to about 50% of the maximum work capacity, and then it rises disproportionately to very high levels as the maximum work capacity is approached (Ouellet, Poh, and Becklake, 1969). The energy cost of breathing rises exponentially rather than linearly with increasing ventilation (Riley, 1954; Rossier, Buhlmann, and Wiesinger, 1960). Despite the high cost of breathing at near maximal workloads, ordinarily the limiting factor to work capacity is cardiac output rather than ventilatory capacity (Miles, 1957) because maximum voluntary ventilation usually exceeds the ventilation at maximal oxygen consumptions (Ouellet et al., 1969). However, during exercise in water the energy cost of breathing is greater for any given level of ventilation. Therefore, maximum breathing capacity may become the limiting factor in maximal work (Miles, 1957), and ventilation may even be inadequate at modest workloads in swimming and diving (Faulkner, 1968).

The high cost of breathing during exercise in water can be reduced by alveolar hypoventilation (Faulkner, 1968). This will increase the efficiency of breathing because respiratory work per liter of alveolar ventilation is reduced (Rossier et al., 1960). Under these conditions alveolar and arterial P_{CO_2} are elevated (Rossier et al., 1960). There is a level of ventilation, however, above which alveolar P_{CO_2} is only further elevated due to the extra work of the respiratory muscles (Riley, 1954). Therefore, there is always an optimal level of ventilation which results in maximal oxygen available to the tissues and minimal alveolar

P_{CO_2} . During exercise in air this optimal level is reached and alveolar hypoventilation develops at oxygen consumptions of 3 to 4 liters/min (Rossier et al., 1960). Because the work of breathing during immersion is greater for any level of ventilation, presumably alveolar hypoventilation would develop at a lower level of work.

C. Metabolic Effects

1. Respiratory Exchange Ratio (RER)

The ratio of carbon dioxide production to oxygen consumption (RER) during maximal swimming is lower than during maximal treadmill walking (McArdle et al., 1971) or running (Magel and Faulkner, 1967). Åstrand et al. (1963) measured a mean RER of 0.96 during maximal swimming compared to 1.11 during maximal bicycling. The lower RER indicates a relative hypoventilation during swimming which could be explained by altered mechanical conditions of breathing or increased resistance in the air collection apparatus (Åstrand et al., 1963). Because part of the expired CO_2 is derived from the HCO_3^- pool as a result of lactic acid accumulation (Åstrand and Rodahl, 1970), the lower RER during swimming could also result from a smaller lactic acid accumulation.

2. Lactic Acid

In a resting subject, the amount of lactic acid in the blood is less than 20 mg/100 ml of blood (Wells, Balke, and Van Fossan, 1956). During light to moderate exercise the level of lactic acid remains fairly constant, and then at some critical level of exercise lactate production starts increasing (Hermansen and Stensvold, 1972), at first slowly, then rapidly (Wells et al., 1956). This critical level has been reported to be at an oxygen consumption between 1.5 and 2.0 liters/min (Wells et al., 1956), and at various percentages of the maximum oxygen consumption: 50%

for untrained subjects and 60 to 65% for trained subjects (Åstrand and Rodahl, 1970), 60% (Knuttgen and Saltin, 1972), two-thirds (Margaria, Edwards, and Dill, 1933) and 60 to 80% (Hermansen and Stensvold, 1972). During maximal exercise, lactic acid accumulation may reach 100 mg/100 ml of blood (Wells et al., 1956) to 130 to 220 mg/100 ml of blood (Hermansen and Stensvold, 1972).

At the end of exercise lactic acid concentration is higher at its site of production in the active muscles than in the arterial blood (Knuttgen and Saltin, 1972). It takes a few minutes for the lactate to diffuse from the muscles to the blood so that it becomes evenly distributed throughout the body (Margaria and Edwards, 1934). The peak in blood lactate occurs when lactate concentration has equilibrated between muscle and blood, but lactate removal has still been minimal. This peak has been reported to occur at various intervals after the end of exercise: 2 to 5 min (Hermansen and Stensvold, 1972), 5 min (Gisolfi, Robinson, and Turrell, 1966; Belcastro and Bonen, 1975), 5 to 10 min (Åstrand and Rodahl, 1970), 5 to 20 min (Newton and Robinson, 1966), 6 min (Knuttgen and Saltin, 1972) and 7 to 10 min (Margaria et al., 1933).

Lactic acid formation during swimming is either the same or lower than during other types of exercise. When Åstrand and Saltin (1961) compared blood lactate after maximal efforts in seven types of exercise, values were consistently lowest after swimming. However, when Åstrand et al. (1963) tested highly trained swimmers in maximal swimming and bicycling, blood lactate levels were of the same order of magnitude after both types of exercise.

III. Water Temperature

Physiological responses to immersion are very much dependent on

water temperature. Changes in water temperature can create changes in metabolic rate, heart function, peripheral circulation, breathing and body temperature.

A. Effects on Oxygen Consumption

Most investigators have found that \dot{V}_{O_2} is least at a neutral water temperature and rises at higher or lower temperatures. Occasionally water temperature has been reported to have no effect on \dot{V}_{O_2} . Temperature effects on \dot{V}_{O_2} have been noted both at rest and during exercise. Goff et al. (1956) reported that \dot{V}_{O_2} was affected more by average skin temperature than by immersion per se during both rest and mild exercise.

In resting subjects, Craig and Dvorak (1966) found that \dot{V}_{O_2} increased at water temperatures below 28C (due to shivering) and above 37C. Goff et al. (1956) reported little effect on resting \dot{V}_{O_2} of water 29 to 33C, and an increase above 33C of approximately one liter/m²/hr.

During exercise in water, Craig and Dvorak (1969) observed that \dot{V}_{O_2} for a given workload was the same at 30 to 35C as in air, 0.14 liter/min higher at 25C, and higher still at 22C. They attributed the higher \dot{V}_{O_2} in cold water to increased voluntary muscle activity and increased resting muscle tension. Moore et al. (1970) measured higher \dot{V}_{O_2} 's during exercise in water at 22 and 16C than at 30C. McArdle et al. (1976) found a \dot{V}_{O_2} response to exercise in 33C water the same as in air, but higher in water of 18 and 25C. During submaximal and maximal swimming, Holmér and Bergh (1974) reported a higher \dot{V}_{O_2} at a given velocity in 18C water than at 26 or 34C. Nadel et al. (1974) found a lower \dot{V}_{O_2} response to submaximal and maximal swimming at 26 than 18C, and an even lower \dot{V}_{O_2} at 33C. They suggested that the increased cost of swimming in cold water was largely due to shivering.

No temperature effects on \dot{V}_{O_2} were seen by Costill (1966) in subjects swimming at 18, 25 and 32C or at 17.4, 26.8 and 33.1C (Costill, Cahill, and Eddy, 1967).

B. Cardiovascular Effects

The heart rate response to immersion depends on the temperature of the water (Tuttle and Corleaux, 1935; Goff et al., 1956). Generally, heart rate is slower in moderately cool water (Craig and Dvorak, 1968; Faulkner, 1968; Craig and Dvorak, 1969; Moore et al., 1970) and faster in very cold (Keatinge and Evans, 1961; Faulkner, 1968) and warm water (Tuttle and Corleaux, 1935; Tuttle and Templin, 1943).

Reductions in resting heart rate have been recorded in water at 25C (Keatinge and Evans, 1961), 18 to 29C (Tuttle and Templin, 1943) and below 35C (Craig and Dvorak, 1966). Wells (1932) measured an average drop of 4 beats/min between 38 and 27C. Exercise heart rates are also lower in cool water. Moore et al. (1970) recorded the lowest exercise heart rates at 16C. Craig and Dvorak (1969) reported that heart rate at a given \dot{V}_{O_2} was 10 beats/min slower in 25C water than in air. When McArdle et al. (1976) plotted heart rate against \dot{V}_{O_2} , they obtained similar graphs for air and 33C water, but the graph shifted to the right for 18 and 25C water. Faulkner (1965) noted that the reduced exercise heart rate in 27 to 32C water was not related to training. Costill et al. (1967) observed that recovery heart rate following submaximal swimming was lower with 17.4C water than with water at 26.8 or 33.1C.

Resting heart rate consistently rises in warm water. An average resting heart rate of 120 beats/min was recorded by Wells (1932) in 43C water. Keatinge and Evans (1961) noted a steady rise in heart rate in water of 37.8C. Craig and Dvorak (1966) observed an increased heart rate

at 36 to 37C which they attributed to heat stress.

Other cardiovascular effects of immersion in cool water include a constricted peripheral vascular field (Keatinge and Evans, 1961), reduced blood flow to the skin and slightly lower systolic blood pressure (Craig and Dvorak, 1966). McArdle et al. (1976) noted that because cardiac output remains the same for a given \dot{V}_{O_2} at water temperatures between 18 and 33C, an increase in stroke volume must accompany the slower heart rate at low temperatures.

Conversely, immersion in warm water results in peripheral vasodilation (Faulkner, 1965; Faulkner, 1968), decreased systolic and diastolic blood pressure and increased pulse pressure (Craig and Dvorak, 1966).

C. Effects on Breathing

Immersion in cold water consistently produces hyperventilation during both rest and exercise (Faulkner, 1965). Keatinge and Evans (1961) reported that in subjects immersed at 5 and 15C, pulmonary ventilation was initially high and end-tidal P_{CO_2} low, and then end-tidal P_{CO_2} returned to near normal. Costill (1966) observed a greater hyperventilation during maximal swimming at 18C than at 25C. Subjects exercising in 30C water had ventilations similar to exercise in air, but at 22 and 16C ventilation increased (Moore et al., 1970). Craig and Dvorak (1969) had subjects exercise with a high workload in air and water at 25, 30 and 35C. Ventilation was lowest in air, intermediate in 30 and 35C water and highest in 25C water. Respiratory frequency was lowest in air and highest in 25C water. Tidal volume was lowest in 35C water and highest in 25 and 30C water. When ventilation was plotted against \dot{V}_{O_2} , there was no significant difference between the various conditions.

D. Neutral Water Temperature

Upon immersion at a neutral water temperature, all physiological changes

are due to immersion alone and not to temperature effects. Neutral water temperatures have been reported to be 33.5 to 34.5C (Echt, Lange, and Gauer, 1974), 35C (Arborelius et al., 1972), 35.0 to 35.5C (Craig and Dvorak, 1966), 37C (Tuttle and Corleaux, 1935) and 38 to 41C (Wells, 1932).

IV. Active Muscle Mass

Measurement of maximum \dot{V}_{O_2} requires the use of a large muscle mass, so that there are enough active cells to maximally utilize the cardiovascular system. One explanation often given for the lower maximum \dot{V}_{O_2} measured during swimming is that a smaller muscle mass is used than in running or bicycling (McArdle et al., 1971; Holmér et al., 1974a; Holmér et al., 1974b). Unlike running or bicycling, swimming is predominantly arm work. Faulkner (1965) estimates that the arms perform 70% of the work in swimming. Another factor reducing the active muscle mass in swimming is buoyancy; a swimmer doesn't have to support himself in the water (Faulkner, 1968; Åstrand and Rodahl, 1970; Holmér et al., 1974b).

A disadvantage of a small active muscle mass is a reduced muscle pump assisting venous return. The resulting decreases in stroke volume and cardiac output help reduce maximal \dot{V}_{O_2} (Dixon and Faulkner, 1971). Well-trained swimmers can maintain a higher blood flow through the muscles of the arms, shoulders and chest, thus maintaining a larger venous return. The large venous return enables them to more closely approach their maximal running \dot{V}_{O_2} while swimming (Dixon and Faulkner, 1971). Holmér and Åstrand (1972) measured maximum \dot{V}_{O_2} during treadmill running and swimming on two identical twins; both were athletes but only one was a trained swimmer. Their maximum \dot{V}_{O_2} 's while running were identical, but the swimmer had a 49% higher \dot{V}_{O_2} in the swimming test.

A number of studies have been conducted comparing maximal work with

arms only and legs only. Maximal \dot{V}_{O_2} using arms only has been measured as 63% (Bar-Or and Zwiren, 1975), 68% (Reybrouck, Heigenhauser, and Faulkner, 1975) and 69 to 71% (Åstrand and Saltin, 1961) of maximal \dot{V}_{O_2} using legs only. Heart rate is higher during arm work for any given \dot{V}_{O_2} (Asmussen and Hemmingsen, 1958; Astrand and Saltin, 1961). Asmussen and Hemmingsen (1958) suggest that, presuming cardiac output is the same for arm and leg work, heart rate increases during arm work to compensate for a reduced stroke volume which results from a smaller venous pump. Bar-Or and Zwiren (1975) propose that maximum \dot{V}_{O_2} is less during arm work because the central circulatory functions do not reach their maximum. Reybrouck et al. (1975) attribute the lower maximum \dot{V}_{O_2} during arm work to a reduced cardiac output resulting from reduced skeletal muscle blood flow.

V. Horizontal Body Position

The horizontal body position has been cited as a contributing factor to the lower maximum \dot{V}_{O_2} measured during swimming (Faulkner, 1968; Åstrand and Rodahl, 1970; Holmér et al., 1974a). When Åstrand and Saltin (1961) compared bicycle ergometer exercise in sitting and supine positions, the maximum \dot{V}_{O_2} attained while supine was 83 to 89% of the maximum \dot{V}_{O_2} in the sitting position.

The slower heart rate associated with swimming has also been attributed to the horizontal body position. This position aids venous return, so that stroke volume and cardiac output increase, resulting in a reduced heart rate (Dixon and Faulkner, 1971; McArdle et al., 1971).

MATERIALS AND METHODS

I. Subjects

Four healthy male students served as subjects. One subject, B.S., was a competitive weightlifter who seldom engaged in aerobic sports. The other three were not competitive athletes but participated in recreational aerobic activities a few days a week. The subjects' heights, weights and ages are listed in Table 1.

II. Rowing Machine

The exercise apparatus was a rowing machine built especially for the study. It consisted of a metal frame, a seat that could be pushed backward against a spring, and a pair of handles that could be pulled backward against springs. Figure 1 illustrates the rowing machine and the movements of an exercising subject.

The rectangular steel frame measured 124 cm by 41 cm. A pair of footrests were attached to the front of the frame.

The seat had a wooden and metal base, a wooden back, and four wheels mounted on the corners of the base. A rope attached to the front of the seat extended forward to a pulley at the front of the frame and then back to a heavy-duty spring attached to the rear of the frame. With his feet pushing against the footrests, the subject could push the seat backward, with the spring providing a considerable resistance. When the subject relaxed, the spring brought the seat forward again. The seat was prevented from lifting up off the frame by a pair of metal rods attached to the sides of the frame and running through spaces on the sides of the seat.

A pair of padded handles were attached to ropes extending forward

Table 1. Subject data

Subject	Height cm	Weight kg	Age years
J.B.	180	77	24
S.S.	183	75	26
B.S.	173	79	24
J.V.	170	70	27

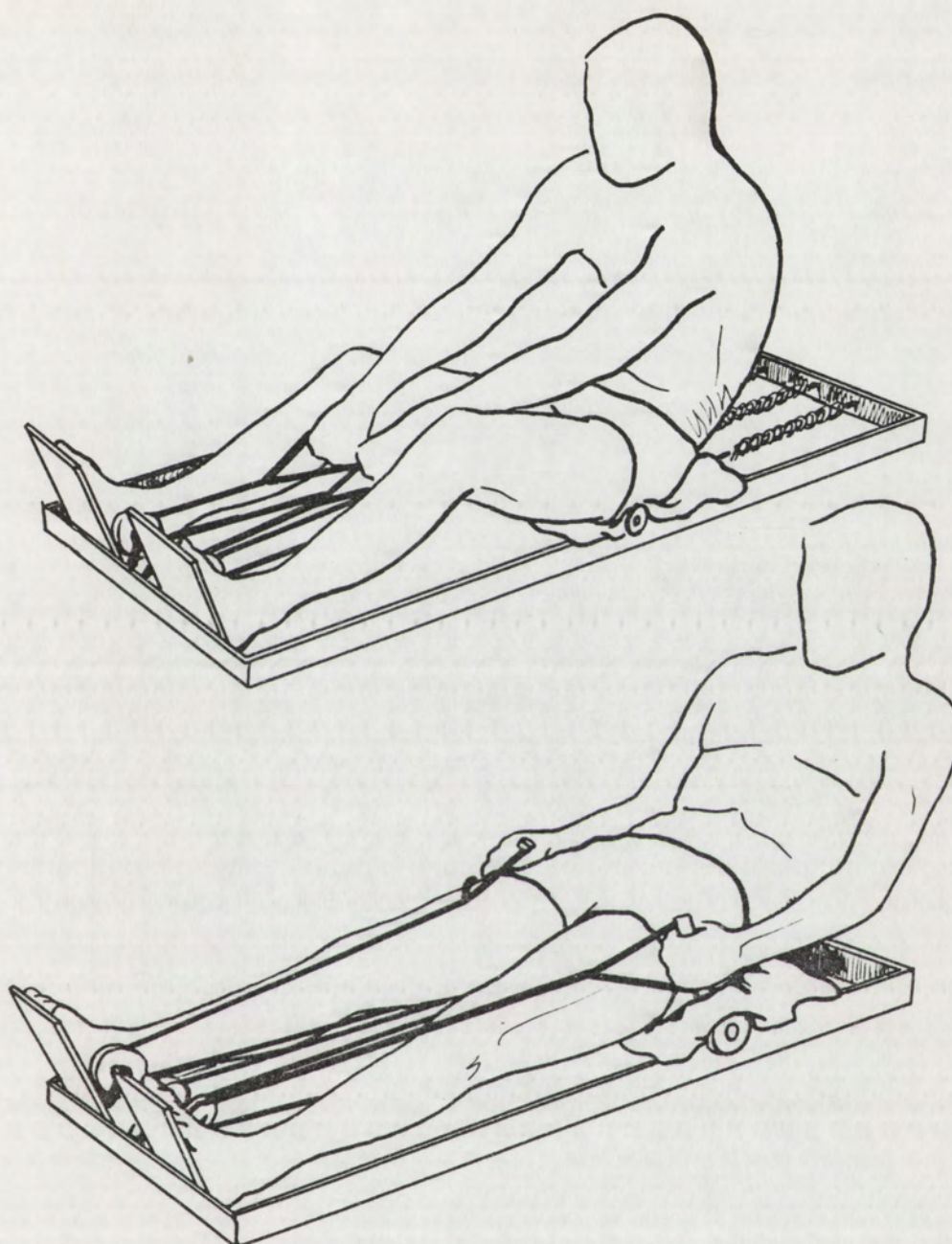


Figure 1. Subject
exercising on the
rowing machine

to pulleys at the front of the frame and then back to lightweight springs at the rear of the frame. The springs provided resistance when the subject pulled the handles back, and brought them forward again when the subject relaxed.

III. The Exercise

The exercise was designed to use a large muscle mass, including arm, leg and trunk muscles, to ensure reasonably high oxygen consumptions and to prevent excessive fatigue in any one muscle group.

The subjects exercised by moving back and forth on the rowing machine. During the backward movement they pushed the seat back until their legs were extended, pulled the handles back to their crotch and leaned back until their shoulders touched the wall behind the rower. During the forward movement they allowed the springs to pull the seat and handles forward and they leaned forward with their shoulders.

The pattern of movement was standardized as much as possible in the air and in the water for each subject. It proved impractical, however, to standardize the pattern of movement between different subjects due to differences in height and strength.

The work performed per minute was varied by altering the work rate, or number of pulls per minute. A metronome aided the subjects in maintaining a constant rhythm. To compensate for the added resistance of the water, work rate was always slower in the water than in air. This provided similar rates of oxygen consumption in both environments.

IV. Experimental Protocol

The experiment was conducted in three phases. The subjects' maximum oxygen consumptions were determined in Phase I with a bicycle ergometer test. In Phase II, a series of tests were conducted with the rowing

machine in the air and in the water to establish an appropriate rate of work for the final tests in Phase III. An appropriate work rate was considered to be one that resulted in an oxygen consumption between 70 and 80 percent of the subject's maximum oxygen consumption. In Phase III, one test was conducted in each environment for each subject, with the workloads being as nearly equal as possible. The data collected in Phase III provide the basis for this study.

Maximum oxygen consumption was determined in Phase I with a bicycle ergometer test. Each subject was asked to pedal the bicycle until reaching exhaustion. The workload was increased by 75 mkg each minute. Expired air was collected in Douglas bags, and measured for oxygen content, carbon dioxide content, and volume. Other measurements included heart rate, blood pressure, and respiratory rate.

The object of Phase II was to determine how many pulls per minute on the rowing machine were required for the subjects to reach 70 to 80 percent of their maximal oxygen consumptions. This proportion of their capacities was selected because it was strenuous enough to produce consistent cardiovascular and respiratory responses, but still attainable with the rowing machine. A number of tests were conducted with the rowing machine in the air and in the water with varying work rates until the desired rate of oxygen consumption was reached. Work rate was always slower in the water due to the added resistance to movement. For each test, a subject exercised on the rowing machine for three to five minutes, until a steady state was attained. One to four bags of expired air were collected for thirty-second periods during the last portion of the exercise. The oxygen content, carbon dioxide content and volume of the air were measured, and oxygen consumption was calculated.

The final tests of Phase III provided the data used in this study for assessing the physiological responses to exercising in air and water environments. Each subject performed at least one test in the air and one in the water. A test was accepted as a final test if the oxygen consumption was between 70 and 80 percent of the subject's maximum oxygen consumption, and the air and water tests had to have oxygen consumptions within five percent of one another. Before a test began, the subject's heart rate was required to be at the resting level. For each test, the subject exercised on the rowing machine for five minutes. Expired air was collected in Douglas bags for four thirty-second periods during the last two minutes of exercise. Respiratory rate was counted during these four thirty-second periods. Heart rate was measured during the first three minutes of recovery. Between the fourth and fifth minutes of recovery a venous blood sample was withdrawn for measurement of lactic acid concentration.

V. Water and Air Environments

A stainless steel tank, measuring 1.52 m by 1.52 m, was used for exercising in the water. Water level was at the jugular notch. Water temperature was maintained between 34 and 35C. This range of temperatures is considered to be thermoneutral, with no physiological changes attributable to temperature alone (Craig and Dvorak, 1966; Echt et al., 1974; McArdle et al., 1976).

The tests in the air were conducted in an area adjacent to the tank. All aspects of equipment set-up and data collection were similar in both environments.

VI. Expired Air Collection

The subjects breathed into and out of a mouthpiece and two-way valve

connected to inspiratory and expiratory hoses about two meters in length. The end of the inspiratory hose was open to room air, and the expiratory hose was connected to a Douglas bag.

During the water tests the hoses were extended outside the tank. The subjects wore a face mask to prevent water from splashing into their eyes and nose.

VII. Gas Analysis

The percentages of oxygen and carbon dioxide in the expired air were measured with a Scientific Research Instruments MEDSPECT (MS8) mass spectrometer. A Tissot spirometer (120 liters) was used to measure the volume of air in the Douglas bags. With these data, oxygen consumption, carbon dioxide production, respiratory exchange ratio, minute ventilation and tidal volume were calculated. Oxygen consumption and carbon dioxide production were expressed under STPD conditions (standard temperature, pressure, dry). Minute ventilation and tidal volume were expressed under BTPS conditions (body temperature, pressure, saturated).

VIII. Heart Rate Measurement

Recovery heart rate was counted by two methods. Immediately after finishing the exercise, the subject was given a stopwatch and asked to count his pulse for the last ten seconds of each 15 second period for three minutes. An electrocardiogram was recorded during the first three minutes of the recovery period using either telemetry equipment or conventional EKG equipment.

IX. Lactic Acid Measurement

Blood was withdrawn from a superficial elbow vein. One ml of blood was immediately pipetted into two ml of 0.6 N perchloric acid to denature

the lactate dehydrogenase, ensuring that the level of lactic acid would remain stable. The mixture was centrifuged and the cellular material discarded.

The supernatant, containing plasma and perchloric acid, was prepared for measurement with a Lactate Test Combination kit purchased from Boehringer Mannheim Corporation. Absorbance measurements were made with a Beckman DU spectrophotometer, and lactic acid concentration was calculated in mg/100 ml of blood.

X. Statistical Analysis

The one-tailed paired-design t-test was applied to determine the statistical significance of any differences between the responses to exercise in air and water.

RESULTS

Phase I test results determined each subject's maximum oxygen consumption. Phase II results specified the rates of work required for the subjects to reach 70 to 80% of their maximum oxygen consumptions on the rowing machine, enabling all subjects to work at the same relative workload in both environments. Phase III results provided the data for assessing physiological responses to exercise in air and water, and are presented in greatest detail.

I. Phase I

Maximum oxygen consumptions of the four subjects ranged from 2.64 to 3.72 liters/min. Data collected during the Phase I tests are presented in Tables 2-5. Maximum oxygen consumptions and maximum oxygen consumptions per kg of body weight are listed separately in Table 6.

II. Phase II

Oxygen consumptions achieved at various work rates on the rowing machine during Phase II are presented in Tables 7-10. Work rates used in the Phase III tests are shown in Table 11. In the air, work rates for Phase III ranged from 44 to 55 pulls/min, and in the water they ranged from 28 to 44 pulls/min.

III. Phase III

Data collected during the last two minutes of the Phase III tests in air and water are presented in Tables 12-19. Mean values for the four thirty-second periods of data collections for each test are given in Table 20. Table 21 lists the mean values and standard deviations for all four subjects for the air and water tests.

Mean oxygen consumptions during the Phase III tests ranged from 1.93 to 2.67 liters/min. All mean oxygen consumptions fell between 68

Table 2. Last three minutes of data collection,
Phase I test, Subject J.B.

Minute	Heart rate beats/min	Systolic pressure mmHg	Diastolic pressure mmHg	\dot{V}_{O_2} liters/min	CO ₂ production liters/min	RER	Minute ventilation liters/min	Respiratory rate breaths/min	Tidal volume liters
15	178	196	84	2.16	2.43	1.12	73.4	30	2.5
17	192	208	106	2.70	3.06	1.14	105.1	40	2.6
18	195	214	98	2.94	2.40	1.16	129.7	48	2.7

Table 3. Last three minutes of data collection,
Phase I test, Subject S.S.

Minute	Heart rate beats/min	Systolic pressure mmHg	Diastolic pressure mmHg	\dot{V}_{O_2} liters/min	CO ₂ production liters/min	RER	Minute ventilation liters/min	Respiratory rate breaths/min	Tidal volume liters
12	192	214	94	1.95	2.08	1.01	67.4	26	2.6
14	201	226	90	2.41	2.61	1.09	88.2	36	2.5
15	207	230	90	2.67	3.01	1.12	111.1	46	2.4

Table 4. Last three minutes of data collection,
Phase I test, Subject B.S.

Minute	Heart rate beats/min	Systolic pressure mmHg	Diastolic pressure mmHg	$\dot{V}O_2$ liters/min	CO ₂ production liters/min	RER	Minute ventilation liters/min	Respiratory rate breaths/min	Tidal volume liters
11	144	186	96	1.80	1.90	1.06	59.3	34	1.7
14	162	198	104	2.24	2.51	1.12	88.9	40	2.2
15	167	202	108	2.64	3.26	1.24	120.2	48	2.5

Table 5. Last three minutes of data collection,
Phase I test, Subject J.V.

Minute	Heart rate beats/min	Systolic pressure mmHg	Diastolic pressure mmHg	$\dot{V}O_2$ liters/min	CO ₂ production liters/min	RER	Minute ventilation liters/min	Respiratory rate breaths/min	Tidal volume liters
15	176	222	88	3.72	3.78	1.02	126.6	32	4.0
17	185	228	84	3.33	3.57	1.07	122.5	36	3.4
18	186	—	90	3.30	3.49	1.06	126.6	36	3.5

Table 6. Maximum oxygen consumptions (\dot{V}_{O_2})

Subject	Maximum \dot{V}_{O_2} liters/min ²	Maximum \dot{V}_{O_2} per kg body weight
J.B.	2.94	0.038
S.S.	2.67	0.036
B.S.	2.64	0.033
J.V.	3.72	0.053

Table 7. Phase II test results, Subject J.B.

Air tests			Water tests		
Work rate pulls/min	Mean \dot{V}_{O_2} liters/min	Mean % of max \dot{V}_{O_2}	Work rate pulls/min	Mean \dot{V}_{O_2} liters/min	Mean % of max \dot{V}_{O_2}
40	1.42	48.4	32	2.06	69.9
45	1.68	57.0	34	2.01	68.2
50	2.34	79.6	34	2.48	84.0
50	1.90	64.7	34	2.00	68.1
			35	2.63	89.3
			35	2.14	72.8
			36	2.01	68.3
			36	2.63	89.3
			36	2.76	93.7

Table 8. Phase II test results, Subject S.S.

Air tests			Water tests		
Work rate pulls/min	Mean \dot{V}_{O_2} liters/min	Mean % of max \dot{V}_{O_2}	Work rate pulls/min	Mean \dot{V}_{O_2} liters/min	Mean % of max \dot{V}_{O_2}
50	2.21	82.9	29	1.34	50.3
45	1.57	58.9	34	1.85	69.3
50	1.96	73.4	35	1.82	68.0
49	2.28	85.1	38	2.07	77.3
51	2.31	86.3	30	2.26	84.6
47	1.79	67.1	28	2.07	77.4
44	1.81	67.8	28	1.66	62.0
46	1.90	71.1	30	2.01	75.3
47	1.90	71.2	30	1.86	69.7
48	2.25	84.3			

Table 9. Phase II test results, Subject B.S.

Air tests			Water tests		
Work rate pulls/min	Mean \dot{V}_{O_2} liters/min	Mean % of max \dot{V}_{O_2}	Work rate pulls/min	Mean \dot{V}_{O_2} liters/min	Mean % of max \dot{V}_{O_2}
45	2.10	79.5	30	2.02	76.5
45	2.18	82.7	30	2.28	86.2*
44	2.00	75.6	28	2.14	81.0
44	2.03	76.8	26	1.69	64.0
44	2.09	79.2			
45	2.09	79.1			
43	2.02	76.4			

Table 10. Phase II test results, Subject J.V.

Air tests			Water tests		
Work rate pulls/min	Mean \dot{V}_{O_2} liters/min	Mean % of max \dot{V}_{O_2}	Work rate pulls/min	Mean \dot{V}_{O_2} liters/min	Mean % of max \dot{V}_{O_2}
50	1.90	51.0	33	2.46	65.9
55	2.63	70.6	35	2.35	63.1
56	2.72	72.9	43	2.25	60.4
57	3.09	82.9	45	2.54	68.1
56	2.94	79.0	47	3.08	82.7
56	3.45	92.7			
52	3.14	84.4			

Table 11. Rates of work for Phase III tests

Subject	Air test pulls/min	Water test pulls/min
J.B.	55	36
S.S.	47	32
B.S.	44	28
J.V.	48	44

Table 12. Phase III test in air, last two minutes, Subject J.B.

Minute	\dot{V}_{O_2} liters/min	% of max \dot{V}_{O_2}	CO ₂ pro- duction liters/min	RER	Minute ventilation liters/min	Respiratory rate breaths/min	Tidal volume liters
3'-3'30"	1.98	67.3	2.13	1.08	72.1	33	2.2
3'30"-4'	2.18	74.1	2.36	1.08	83.3	32	2.6
4'-4'30"	2.11	71.6	2.27	1.08	79.9	30	2.7
4'30"-5'	2.23	75.7	2.29	1.03	84.4	32	2.6

Table 13. Phase III test in water, last two minutes, Subject J.B.

Minute	\dot{V}_{O_2} liters/min	% of max \dot{V}_{O_2}	CO ₂ pro- duction liters/min	RER	Minute ventilation liters/min	Respiratory rate breaths/min	Tidal volume liters
3'-3'30"	2.26	76.9	2.36	1.04	82.2	38	2.2
3'30"-4'	2.20	74.8	2.36	1.07	86.1	36	2.3
4'-4'30"	—	—	—	—	—	33	—
4'30"-5'	—	—	—	—	—	36	—

Table 14. Phase III test in air, last two minutes, Subject S.S.

Minute	\dot{V}_{O_2} liters/min	% of max \dot{V}_{O_2}	CO ₂ pro- duction liters/min	RER	Minute ventilation liters/min	Respiratory rate breaths/min	Tidal volume liters
3'-3'30"	1.94	72.6	2.25	1.16	93.7	48	2.0
3'30"-4'	1.94	72.5	2.07	1.07	88.6	52	1.7
4'-4'30"	2.00	74.9	2.12	1.06	86.4	52	1.7
4'30"-5'	2.19	81.8	2.09	0.96	85.5	48	1.8

Table 15. Phase III test in water, last two minutes, Subject S.S.

Minute	\dot{V}_{O_2} liters/min	% of max \dot{V}_{O_2}	CO ₂ pro- duction liters/min	RER	Minute ventilation liters/min	Respiratory rate breaths/min	Tidal volume liters
3'-3'30"	2.14	79.9	2.10	0.98	78.0	39	2.0
3'30"-4'	2.12	79.3	2.23	1.05	90.2	39	2.3
4'-4'30"	1.99	74.4	2.09	1.05	85.2	42	2.0
4'30"-5'	2.10	78.7	2.20	1.05	94.4	43	2.2

Table 16. Phase III test in air, last two minutes, Subject B.S.

Minute	\dot{V}_{O_2} liters/min	% of max \dot{V}_{O_2}	CO ₂ pro- duction liters/min	RER	Minute ventilation liters/min	Respiratory rate breaths/min	Tidal volume liters
3'-3'30"	1.85	70.1	2.12	1.14	75.9	48	1.6
3'30"-4'	1.76	66.7	2.05	1.17	79.3	42	1.9
4'-4'30"	2.00	75.6	2.26	1.13	88.8	42	2.1
4'30"-5'	2.11	79.8	2.37	1.13	96.9	44	2.2

Table 17. Phase III test in water, last two minutes, Subject B.S.

Minute	\dot{V}_{O_2} liters/min	% of max \dot{V}_{O_2}	CO ₂ pro- duction liters/min	RER	Minute ventilation liters/min	Respiratory rate breaths/min	Tidal volume liters
3'-3'30"	1.84	69.7	1.57	0.85	59.9	28	2.1
3'30"-4'	1.96	74.2	1.78	0.91	67.3	28	2.4
4'-4'30"	2.01	76.3	1.97	0.98	80.1	26	3.1
4'30"-5'	2.00	75.7	1.92	0.96	80.5	28	2.9

Table 18. Phase III test in air, last two minutes, Subject J.V.

Minute	\dot{V}_{O_2} liters/min	% of max \dot{V}_{O_2}	CO ₂ pro- duction liters/min	RER	Minute ventilation liters/min	Respiratory rate breaths/min	Tidal volume liters
3'-3'30"	2.80	75.2	2.56	0.91	97.3	24	4.1
3'30"-4'	2.54	68.2	2.31	0.91	87.7	24	3.7
4'-4'30"	2.72	72.9	2.53	0.93	93.3	21	4.4
4'30"-5'	2.62	70.4	2.33	0.89	86.2	24	3.6

Table 19. Phase III test in water, last two minutes, Subject J.V.

Minute	\dot{V}_{O_2} liters/min	% of max \dot{V}_{O_2}	CO ₂ pro- duction liters/min	RER	Minute ventilation liters/min	Respiratory rate breaths/min	Tidal volume liters
3'-3'30"	2.37	63.5	2.40	1.02	100.9	36	2.8
3'30"-4'	2.70	72.5	2.62	0.97	103.9	40	2.6
4'-4'30"	2.56	68.8	2.41	0.94	97.7	40	2.4
4'30"-5'	2.54	68.1	2.35	0.93	97.2	40	2.4

Table 20. Mean values, Phase III tests,
each subject

	J.B. air	J.B. water	S.S. air	S.S. water	B.S. air	B.S. water	J.V. air	J.V. water
$\dot{V}O_2$ liters/min	2.12	2.23	2.02	2.09	1.93	1.95	2.67	2.54
% of max $\dot{V}O_2$	72.2	75.9	75.5	78.1	73.1	74.0	71.7	68.2
CO ₂ production liters/min	2.26	2.36	2.13	2.10	2.20	1.81	2.43	2.45
RER	1.07	1.06	1.06	1.03	1.14	0.93	0.91	0.97
Minute ventilation liters/min	79.9	84.2	88.6	87.0	85.2	72.0	91.1	99.9
Respiratory rate breaths/min	32	37	50	41	44	28	23	39
Tidal volume liters	2.5	2.2	1.8	2.1	2.0	2.6	3.9	2.6

Table 21. Mean values, Phase III tests, all four subjects

Measurement	Air tests	Water tests
\dot{V}_{O_2} liters/min	2.18 \pm 0.33	2.20 \pm 0.25
% of max \dot{V}_{O_2}	73.1 \pm 1.7	74.1 \pm 4.2
CO ₂ production liters/min	2.26 \pm 0.13	2.18 \pm 0.29
RER	1.05 \pm 0.10	1.00 \pm 0.06
Minute ventilation liters/min	86.2 \pm 4.8	85.7 \pm 11.5
Respiratory rate breaths/min	37 \pm 12	36 \pm 6
Tidal volume liters	2.5 \pm 1.0	2.4 \pm 0.2
Lactic acid mg/100 ml	39.0 \pm 5.8	44.3 \pm 4.7*

*excluding Subject B.S.

and 78% of the subjects' maximum oxygen consumptions. For each subject, the mean oxygen consumption for the water test was within 5% of the mean oxygen consumption for the air test. Three subjects, J.B., S.S. and B.S., had a slightly greater mean oxygen consumption in water than in air, while subject J.V. had a higher mean oxygen consumption in air.

Mean carbon dioxide productions for the Phase III tests ranged from 1.81 to 2.45 liters/min. Subjects S.S. and B.S. had greater mean CO₂ productions in air than in the water, and subjects J.B. and J.V. had higher CO₂ productions in the water. A higher mean CO₂ production did not necessarily accompany a higher mean oxygen consumption; only one subject, J.B., had a higher mean CO₂ production in the same test in which mean oxygen consumption was highest.

Mean respiratory exchange ratios (RER) ranged from 0.91 to 1.14. Three subjects, J.B., S.S. and B.S., had higher RER's in the air than in the water, but the difference was not significant ($t = 0.83$, $p \geq 0.1$).

Minute ventilation was similar in air and water. Mean values ranged from 72.0 to 99.1 liters/min, with two subjects, S.S. and B.S., having a higher ventilation in air and two, J.B. and J.V., higher in water.

Respiratory rates differed considerably during the two Phase III tests for three of the subjects. There was a difference of 16 in mean number of breaths per minute for two subjects, B.S. and J.V., and a difference of nine for subject S.S. The air and water environments appeared to affect the subjects' respiratory patterns differently, however; two subjects, S.S. and B.S., had higher respiratory rates in the air and the other two, J.B. and J.V., were higher in the water. One subject, B.S., consistently breathed at the same rate as his rate of work, exhaling each time he pulled back on the rowing machine. Subject J.B.

appeared to do this during his air test. The other two subjects' respiratory rates were unaffected by rate of work.

Mean tidal volumes were similar in the air and water. Subjects J.B. and J.V. had larger tidal volumes in the air, and subjects S.S. and B.S. were higher in water. A subject's higher tidal volume never occurred in the same test as the higher respiratory rate. That is, if tidal volume was higher in the air, respiratory rate was higher in the water, and vice versa. The test with the higher minute ventilation was always the one with the higher respiratory rate and smaller tidal volume.

For three of the subjects, S.S., B.S. and J.V., mean CO_2 production, mean RER, mean minute ventilation and mean respiratory rate were all highest during the same test. This occurred during the air test for subjects S.S. and B.S. and during the water test for subject J.V. Subject J.B.'s pattern of response was similar; his CO_2 production, minute ventilation and respiratory rate were highest during his water test, and his RER was only 0.01 less in water than in air.

Recovery heart rates were similar in air and water. Any difference in heart rate response during the first two minutes of recovery was diminished or reversed by the third minute of recovery. Subjects J.B. and B.S. had, on the average, identical heart rate responses in air and water. Subject S.S.'s heart rate was consistently lower in the water. Subject J.V. had a recovery heart rate consistently, but only very slightly, higher in water than in air. Figure 2 illustrates heart rate changes during the first three minutes of recovery.

Lactic acid concentrations are presented in Table 22. Three of the four subjects had greater lactate accumulations after the water tests than the air tests. The fourth subject, B.S., had an unusually low

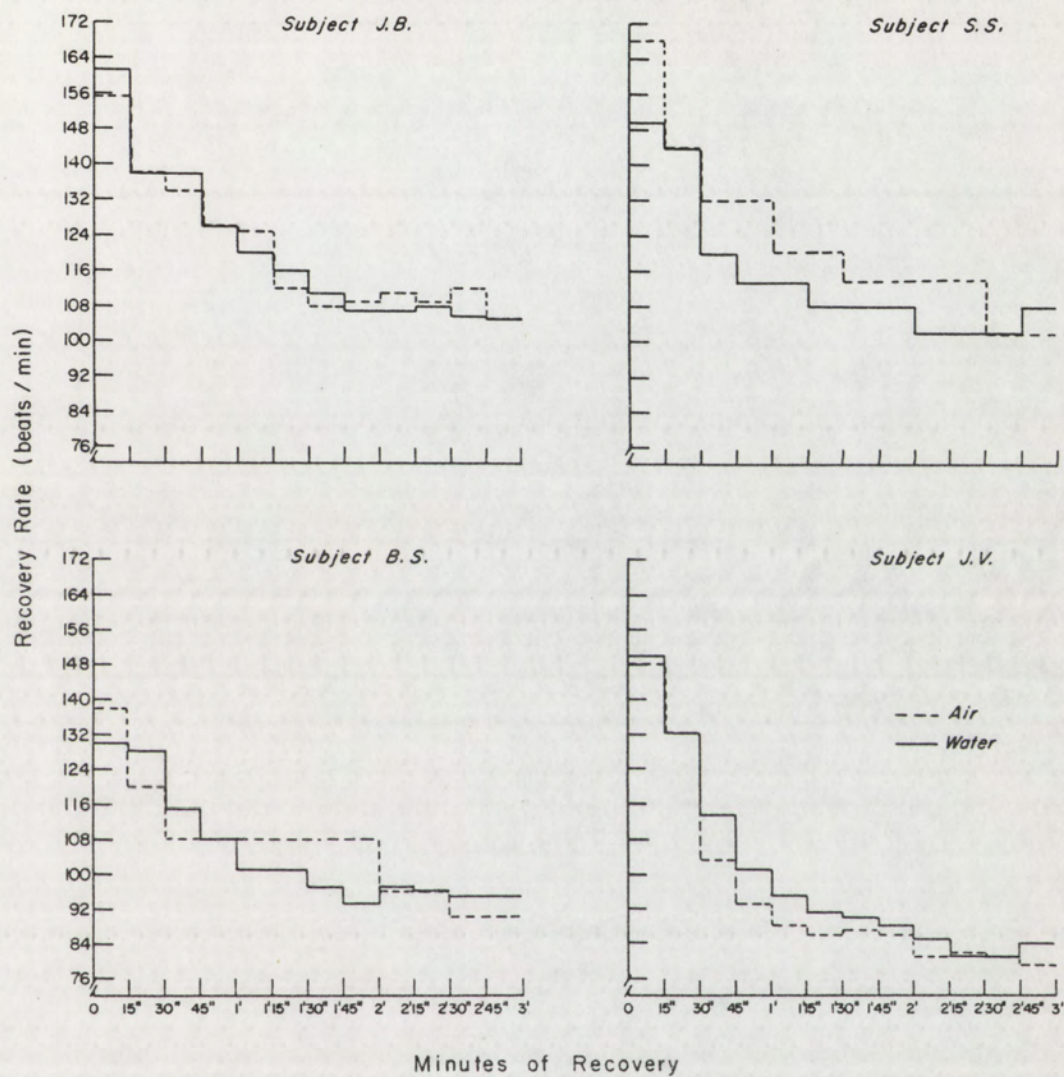


Figure 2. Recovery heart rates

Table 22. Lactic acid concentrations
Phase III tests

Subject	Air tests mg/100 mg	Water tests mg/100 ml
J.B.	36.1	43.1
S.S.	47.4	49.5
B.S.	38.2	8.9
J.V.	34.4	40.4

Table 23. \dot{V}_{O_2} per pull

Subject	Air test liters of O_2	Water test liters of O_2	% increase in water
J.B.	0.039	0.062	59.0
S.S.	0.043	0.065	51.2
B.S.	0.044	0.070	59.1
J.V.	0.056	0.058	3.6
Mean, all 4 Subjects	0.046	0.064	39.1
Mean Subjects J.B., S.S., & B.S.	0.042	0.066	57.1

lactate value after the water test; this result will be considered further in the Discussion. The higher lactate values following the water tests, excluding B.S.'s values, were significant ($t = 3.37$, $0.025 \leq p \leq 0.05$).

The aerobic work performed with each pull on the rowing machine can be estimated by dividing the mean oxygen consumption per minute for each test by the number of pulls per minute during that test. These values are listed in Table 23. The oxygen consumption per pull ranged from 0.039 to 0.056 liters during the air tests, and from 0.058 to 0.070 liters during the water tests. The percent increase in oxygen consumption per pull for the water tests over the air tests ranged from 51 to 59% for subjects J.B., S.S. and B.S. Subject J.V., however, increased his oxygen consumption per pull by only 3.6% in the water.

DISCUSSION

Because metabolic rates and patterns of exercise were nearly identical while rowing in air and in water, this study provided an ideal opportunity to isolate and measure the effects of immersion in water. The similarities in physiological responses in the two environments suggest that differences observed during swimming and running or bicycling are due primarily to factors other than water immersion.

I. Maximum Oxygen Consumptions

Although three of the four subjects had maximal oxygen consumptions during the Phase I tests which were lower than the average, it appears that all four tests accurately measured the subjects' capacities. Subject J.V.'s maximal \dot{V}_{O_2} , 3.72 liters/min, was higher than the average and was undoubtedly an accurate measurement. His maximal \dot{V}_{O_2} occurred during the 15th minute of an 18 minute test, and during the last three minutes of the test his \dot{V}_{O_2} decreased while the workload continued to increase; this is always a clear indication that the maximal \dot{V}_{O_2} has been reached. The other three subjects reached their maximal \dot{V}_{O_2} during their last minute of exercise. Both their RER's and subjective observation indicated that they had reached their maximum capacities. According to Issekutz, Birkhead, and Rodahl (1962), maximal \dot{V}_{O_2} is attained when ΔRER reaches 0.40. The ΔRER is defined as work RER - 0.75, and work RER is the respiratory exchange ratio during exercise. Therefore, a work RER of 1.15 should represent maximal work. Subjects J.B. and B.S. had maximal RER's of 1.16 and 1.24, respectively, indicating that they did reach their maximum capacities. Subject S.S.'s maximal RER was only 1.12, but he appeared completely exhausted at the end of the test, as did subjects J.B. and J.V., indicating

a maximal effort.

II. Recovery Heart Rates

Three of the subjects had recovery heart rates after the Phase III water tests which were similar to or lower than their recovery heart rates in air. The fourth subject, J.V., had a recovery heart rate slightly higher in the water than in air. The cause may have been emotional. He complained several times that he was uncomfortable performing the exercise in the water, whereas the other three subjects preferred the water tests to the air tests.

III. Metabolic Measurements

One of the lactic acid measurements, after subject B.S.'s Phase III water test, was exceptionally low: 8.9 mg/100 ml of blood, compared to a range of 34.4 to 49.5 mg/100 ml of blood for the other seven tests. This is at the low end of the range for normal resting blood lactate values. It could not be determined whether this represented a true value or an error in measurement. There was no source of error evident. However, all of B.S.'s other responses to this test were within the expected range, so it seems unlikely that his lactate accumulation was actually this low.

For three of the subjects, mean CO_2 production, mean RER, mean minute ventilation and mean respiratory rate were all highest during the same Phase III test (Table 20). The response of the fourth subject was similar, but his RER was 0.01 lower in the test in which the three other values were highest. These responses demonstrate the importance of CO_2 in the regulation of ventilation.

IV. Comparison of Rowing in Air and Water

There appeared to be little significant difference between the

subjects' cardiovascular, respiratory and metabolic responses to exercise in air and in water. This is in contrast to the findings of investigators who have compared swimming with running or bicycling. Two explanations are possible: 1) the difference in responses to swimming and running or bicycling are due to factors other than being immersed in water, or 2) there were some differences between exercising on the rowing machine in air and in water which compensated for the effects of immersion.

A. Comparison of Exercise Types

There are a number of important differences between swimming and running or bicycling which may contribute to the lower maximum \dot{V}_{O_2} attained during swimming. Swimming differs from running and bicycling in that there is a horizontal body position, a smaller active muscle mass, a limit to breathing frequency, different mechanisms of heat exchange and hydrostatic pressure on the body surface.

The form of exercise used in this study was selected to minimize the differences between exercising in air and water, in order to isolate water immersion as the only difference between the two environments. Rowing in the water utilized the same muscle mass and body position as rowing in air. Breathing frequency was not limited. The only differences between rowing in air and water should have been those due to water immersion: hydrostatic pressure on the body surface and different mechanisms of heat exchange.

The hydrostatic pressure on the chest while rowing in water may not have been as great as it would be during swimming. The tank in which the water tests were conducted was relatively small, so that the back and forth movement of the subject's torso generated considerable wave

action in the water. This caused the water level to fluctuate within a range of one to one and a half feet, so that sometimes the water level was near the middle or lower part of the subject's rib cage and other times the water splashed over his head. Thus the hydrostatic pressure on the chest was intermittent and variable.

B. Respiratory and Metabolic Responses

Minute ventilations were similar while rowing in air and water. Other investigators have often found minute ventilation to be lower while exercising in water than in air. The lack of discrepancy here may be explained by the intermittent nature of the hydrostatic pressure on the chest during the water tests or the freedom of breathing frequency in both environments. Because workloads and minute ventilations were submaximal, the work of breathing may not have reached a level where hydrostatic pressure on the chest would have a noticeable effect.

Since minute ventilation was apparently adequate in both environments, metabolism was predominantly aerobic in both cases, and little difference was observed in the various respiratory and metabolic responses. Respiratory rate, tidal volume, and RER, all measured during the exercise, were similar in both environments. Lactic acid concentration in the blood during the fifth minute of recovery was slightly greater following the water tests than the air tests. These results may indicate that, although anaerobic metabolism was somewhat elevated during the water tests, the movement of lactic acid from the muscles into the circulatory system was similar during the exercise in both air and water, and only during recovery did the excess lactate formed in the water tests enter the blood. Because work rate was always lower in water than air, the muscle pump assisting venous blood return may have been less effective

during the water tests, resulting in a slower equilibration of lactate throughout the body. Consequently, P_{CO_2} of the blood was probably the same during exercise in both air and water, precluding any differences in minute ventilation, respiratory rate, tidal volume or RER.

C. Recovery Heart Rates

Overall, recovery heart rates were similar after rowing in the air and in the water. This is in contrast to most other studies, which have demonstrated a slower heart rate in the water than in air, both at rest and during exercise.

According to Feigle and Folkow (1963), the reflex bradycardia during immersion is caused by a specific neural reflex resulting from submersion of the head, hypercapnia and hypoxia. None of these conditions were present during the water tests in this study. The subjects were submerged only to the jugular notch. Water did splash over their heads while they were rowing, but the areas around their nose and eyes were protected by a face mask. Prior to the start of each test, heart rates were at the resting level and similar in both environments, indicating that just sitting in the water had little effect on heart rates. Because minute ventilation was apparently adequate, hypercapnia and hypoxia did not develop. Thus, the classical "diving reflex" probably did not play a role in determining heart rate response in this study.

The major change occurring in the cardiovascular system upon immersion is a net movement of blood from the peripheral to the central areas of the body as a result of hydrostatic pressure on the body surface. At rest, this will produce an increase in stroke volume and a reduction in heart rate. During recovery from exercising on the rowing machine, however, the increased central blood volume appeared to have little effect

on heart rate. Recovery heart rate is normally controlled by a number of factors, including severity and duration of work, excess body heat, and levels of circulating lactic acid and epinephrine. Presumably all of these factors, with the exception of lactic acid, were the same following exercise with the rowing machine in the air and in the water because oxygen consumption was the same in both cases. At rest, the increased central blood volume during immersion is probably associated with an increase in central blood pressure which contributes to a reduction in heart rate. During recovery from exercise, however, blood pressure may be determined more by peripheral vascular resistance than by central blood volume. Heart rate, therefore, would depend on factors related to the severity and duration of work, rather than any change in blood distribution. This appears to have been the case with the subjects in this study: recovery heart rates following the water tests were similar to heart rates after the air tests because the demands of the work were the same. The metabolic requirements of the exercise played a greater role in determining cardiovascular function than did any blood redistribution resulting from immersion.

The lower heart rates reported during swimming than during running or bicycling are more likely due to differences in size of active muscle mass, body position or heat exchange than to immersion per se. The diving reflex may also have some importance during swimming because the entire face is usually exposed to the water.

D. Work to Overcome Water Resistance

Subjects J.B., S.S. and B.S. used an average of 57% more oxygen per pull on the rowing machine in the water than in the air. This represents the extra work performed in overcoming the resistance of the

water to the movement of the torso. Most types of underwater work require additional energy expenditure for overcoming water resistance; this value may be a good estimate of the extra work involved whenever a large body surface area is moved through water.

Subject J.V. used only 3.6% more oxygen per pull in the water than in the air. This was probably because he did not move his torso through as great a range in water as he did in the air. Most of his movement during the water test was with his arms rather than with his whole upper body. The other three subjects used the same pattern and range of movement in both environments. Since J.V.'s maximum oxygen consumption was considerably higher than that of the other three subjects, he had to use a higher work rate in order to reach 70% of his capacity. While moving through the full range of movement with his torso in the water he was unable to achieve a work rate high enough to attain 70% of his maximum oxygen consumption. The only way he was able to reach 70% was by diminishing his range of movement and increasing his work rate.

CONCLUSIONS

1. Unlike the typical response during swimming, minute ventilation was as high while rowing in water as it was in the air. Three explanations are probable: (i) the intermittent hydrostatic pressure on the chest was insufficient to hinder inspiration, (ii) breathing frequency was not limited, and (iii) the work of breathing at the workloads used was not great enough for hydrostatic pressure to have a noticeable effect.

2. Lactic acid production may have been greater during the water tests than the air tests. Blood levels of lactate and CO_2 , however, were probably similar during the exercise, with diffusion into the blood of excess lactate formed in the water tests occurring only after the end of exercise.

3. Because oxygen consumption, blood levels of CO_2 and minute ventilation were similar in both environments, there were no significant differences in RER, respiratory rate or tidal volume.

4. Recovery heart rates appeared to be determined more by the metabolic demands of the exercise than by blood volume distribution, and therefore heart rates were similar after exercise in both environments.

5. When a large body surface area is moved through water, the oxygen requirement of work appears to increase by approximately 50 to 60%.

6. Immersion per se did not greatly alter the response to submaximal exercise when all other parameters were held constant. Other factors such as size of active muscle mass, body position, limits to breathing frequency and water temperature must contribute significantly to the differences in cardiovascular, respiratory and metabolic responses to swimming and running or bicycling.

LITERATURE CITED

1. Agostoni, E., G. Gurtner, G. Torri, and H. Rahn. Respiratory mechanics during submersion and negative-pressure breathing. *J. Appl. Physiol.* 21:251-258. 1966.
2. Anderson, Harald T. Physiological adaptations in diving vertebrates. *Physiol. Rev.* 46:212-243. 1966.
3. Arborelius, M., Jr., U.I. Balldin, B. Lilja, and C.E.G. Lundgren. Hemodynamic changes in man during immersion with the head above water. *Aerospace Med.* 43:592-598. 1972.
4. Asmussen, E., and I. Hemmingsen. Determination of maximum working capacity at different ages in work with legs or with the arms. *Scand. J. Clin. Lab. Invest.* 10:67-71. 1958.
5. Åstrand, P.-O., L. Engstrom, B.O. Eriksson, P. Karlberg, I. Nylander, B. Saltin, and C. Thoren. Girl swimmers, with special reference to respiratory and circulatory adaptation and gynaecological and psychiatric aspects. *Acta Paediat. Suppl.* 147:1-75. 1963.
6. Åstrand, Per-Olaf, and Kaare Rodahl. Textbook of work physiology. McGraw-Hill Book Co., New York. p. 279-305, 343-369, 545-546. 1970.
7. Åstrand, Per-Olaf, and Bengt Saltin. Maximal oxygen uptake and heart rate in various types of muscular activity. *J. Appl. Physiol.* 16:977-981. 1961.
8. Bar-Or, O., and L.D. Zwiren. Maximal oxygen consumption test during arm exercise--reliability and validity. *J. Appl. Physiol.* 38:424-426. 1975.
9. Beckman, E.L., K.R. Coburn, R.M. Chambers, R.E. Deforest, W.S. Augerson, and V.C. Benson. Physiologic changes observed in human subjects during zero G simulation by immersion in water up to neck level. *Aerospace Med.* 32:1031-1041. 1961.
10. Begin, Raymond, Murray Epstein, Marvin A. Sackner, Robert Levinson, Richard Dougherty, and David Duncan. Effects of water immersion to the neck on pulmonary circulation and tissue volume in man. *J. Appl. Physiol.* 40:293-299. 1976.
11. Belcastro, Angelo N., and Arend Bonen. Lactic acid removal rates during controlled and uncontrolled recovery exercise. *J. Appl. Physiol.* 39:932-936. 1975.
12. Carey, Charles R., Karl E. Schaefer, and Harry J. Alvis. Effects of skin diving on lung volumes. *J. Appl. Physiol.* 8:519-523. 1956.
13. Costill, David L. Effects of water temperature on aerobic working capacity. *Res. Quart.* 39:67-73. 1966.

14. Costill, D.L., P.J. Cahill, and D. Eddy. Metabolic responses to submaximal exercise in three water temperatures. *J. Appl. Physiol.* 22:628-632. 1967.
15. Craig, Albert B., Jr., and Maria Dvorak. Thermal regulation during water immersion. *J. Appl. Physiol.* 21:1577-1585. 1966.
16. Craig, Albert B., Jr., and Maria Dvorak. Thermal regulation of man exercising during water immersion. *J. Appl. Physiol.* 25:28-35. 1968.
17. Craig, A.B., Jr., and M. Dvorak. Comparison of exercise in air and water of different temperatures. *Med. Sci. Sports* 1:124-130. 1969.
18. Craig, A.B., Jr., and D.E. Ware. Effect of immersion in water on vital capacity and residual volume of the lungs. *J. Appl. Physiol.* 23:423-425. 1967.
19. Craig, F.N., W.V. Blevins, and E.G. Cummings. Exhausting work limited by external resistance and inhalation of carbon dioxide. *J. Appl. Physiol.* 29:847-851. 1970.
20. Denison, D.M., P.D. Wagner, G.L. Kingaby, and J.B. West. Cardio-respiratory responses to exercise in air and underwater. *J. Appl. Physiol.* 33:426-430. 1972.
21. Dixon, Robert W., Jr., and John A. Faulkner. Cardiac outputs during maximum effort running and swimming. *J. Appl. Physiol.* 30:653-656. 1971.
22. Echt, Martin, Lothar Lange, and Otto H. Gauer. Changes of peripheral venous tone and central transmural venous pressure during immersion in a thermoneutral bath. *Pflugers Archiv* 352:211-217. 1974.
23. Faulkner, John A. Physiology of swimming. *Res. Quart.* 37:41-54. 1965.
24. Faulkner, John A. Physiology of swimming and diving, p. 415-446. In Harold B. Falls, *Exercise Physiology*. Academic Press, New York. 1968.
25. Feigle, E., and B. Folkow. Cardiovascular responses in 'diving' and during brain stimulation in ducks. *Acta Physiol. Scand.* 57: 99-110. 1963.
26. Flook, V., and G.R. Kelman. Submaximal exercise with increased inspiratory resistance to breathing. *J. Appl. Physiol.* 35:379-384. 1973.
27. Gauer, Otto H. Recent advances in the physiology of whole body immersion. *Proceedings of the Fifth International Symposium on Basic Environmental Problems of Man in Space*. Ed. A. Graybill. NASA. Washington, D.C. 8 p. 1973.

28. Gisolfi, C., S. Robinson, and E.S. Turrell. Effects of aerobic work performed during recovery from exhausting work. *J. Appl. Physiol.* 21:1767-1772. 1966.
29. Goff, L.G., H.F. Brubach, H. Specht, and N. Smith. Effect of total immersion at various temperatures on oxygen uptake at rest and during exercise. *J. Appl. Physiol.* 9:59-61. 1956.
30. Guyatt, A.R., Faith Newman, F.F. Cinkotai, J.I. Palmer, and M.L. Thomson. Pulmonary diffusing capacity in man during immersion in water. *J. Appl. Physiol.* 20:878-881. 1965.
31. Hamilton, W.F., and J.P. Mayo. Changes in the vital capacity when the body is immersed in water. *Amer. J. Physiol.* 141:51-53. 1944.
32. Hermansen, Lars, and Inger Stensvold. Production and removal of lactate during exercise in man. *Acta Physiol. Scand.* 86:191-201. 1972.
33. Hollenberg, N.K., and B. Uvnas. The role of the cardiovascular response in the resistance to asphyxia of avian divers. *Acta Physiol. Scand.* 58:150-161. 1963.
34. Holmér, Ingvar. Oxygen uptake during swimming in man. *J. Appl. Physiol.* 33:502-509. 1972.
35. Holmér, Ingvar, and Per-Olaf Astrand. Swimming training and maximal oxygen uptake. *J. Appl. Physiol.* 33:510-513. 1972.
36. Holmér, Ingvar, and Ulf Bergh. Metabolic and thermal response to swimming in water at varying temperatures. *J. Appl. Physiol.* 37:702-705. 1974.
37. Holmér, Ingvar, Anders Lundin, and Bengt O. Eriksson. Maximum oxygen uptake during swimming and running by elite swimmers. *J. Appl. Physiol.* 36:711-714. 1974a.
38. Holmér, Ingvar, Elliott M. Stein, Bengt Saltin, Bjorn Ekblom, and Per-Olaf Åstrand. Hemodynamic and respiratory responses compared in swimming and running. *J. Appl. Physiol.* 37:49-54. 1974b.
39. Hong, S.K., P. Cerretelli, J.C. Cruz, and H. Rahn. Mechanics of respiration during submersion in water. *J. Appl. Physiol.* 27:535-538. 1969.
40. Hood, W.B., Jr., R.H. Murray, C.W. Urschel, J.A. Bowers, and J.K. Goldman. Circulatory effects of water immersion upon human subjects. *Aerospace Med.* 39:579-584. 1968.
41. Issekutz, B., Jr., N.C. Birkhead, and K. Rodahl. Use of respiratory quotients in assessment of aerobic work capacity. *J. Appl. Physiol.* 17:47-50. 1962.

42. Karpovich, Peter V. Respiration in swimming and diving. *Res. Quart.* 10:3-14. 1939.
43. Keatinge, W.R., and M. Evans. The respiratory and cardiovascular response to immersion in cold and warm water. *Quart. J. Exp. Physiol.* 46:83-94. 1961.
44. Knuttgen, Howard G., and Bengt Saltin. Muscle metabolites and oxygen uptake in short-term submaximal exercise in man. *J. Appl. Physiol.* 32:690-694. 1972.
45. Lynne-Davies, P., J. Couture, L.D. Pengelly, and J. Milic-Emili. Immediate ventilatory response to added inspiratory elastic loads in cats. *J. Appl. Physiol.* 30:512-516. 1971.
46. Magel, John R., and John A. Faulkner. Maximum oxygen uptakes of college swimmers. *J. Appl. Physiol.* 22:929-938. 1967.
47. Magel, John R., Guido F. Foglia, William D. McArdle, Bernard Gutin, Gary S. Pechar, and Frank I. Katch. Specificity of swim training on maximum oxygen uptake. *J. Appl. Physiol.* 38:151-155. 1975.
48. Margaria, R., and H.T. Edwards. The removal of lactic acid from the body during recovery from muscular exercise. *Amer. J. Physiol.* 107:681-686. 1934.
49. Margaria, R., H.T. Edwards, and D.B. Dill. The possible mechanisms of contracting and paying the oxygen debt and the role of lactic acid in muscular contraction. *Amer. J. Physiol.* 106:689-715. 1933.
50. McArdle, William D., Roger M. Glaser, and John R. Magel. Metabolic and cardiorespiratory response during free swimming and treadmill walking. *J. Appl. Physiol.* 30:733-738. 1971.
51. McArdle, William D., John R. Magel, George R. Lesmes, and Gary S. Pechar. Metabolic and cardiovascular adjustment to work in air and water at 18, 25, and 33°C. *J. Appl. Physiol.* 40:85-90. 1976.
52. Miles, S. The effect of changes in barometric pressure on maximum breathing capacity. *J. Physiol. (London)* 137:85P-86P. 1957.
53. Miles, Stanley. *Underwater Medicine*. J.B. Lippincott Co., Philadelphia. p. 75-80. 1969.
54. Moore, T.O., E.M. Bernauer, G. Seto, Y.S. Park, S.K. Hong, and E.M. Hayashi. Effect of immersion at different water temperatures on graded exercise performance in man. *Aerospace Med.* 41:1404-1408. 1970.
55. Nadel, E.R., I. Holmér, U. Bergh, P.-O. Åstrand, and J.A.J. Stolwijk. Energy exchanges of swimming man. *J. Appl. Physiol.* 36:465-471. 1974.

56. Newton, J.L., and S. Robinson. The distribution of blood lactate and pyruvate during work and recovery. Final Scientific Report to NASA, Grant NSG 408, Part V. 17 p. 1966.
57. Ouellet, Yvon, S.C. Poh, and Margaret R. Becklake. Circulatory factors limiting aerobic exercise capacity. J. Appl. Physiol. 27:874-880. 1969.
58. Prefault, Christian, Eulo Lupi-H, and N.R. Anthonisen. Human lung mechanics during water immersion. J. Appl. Physiol. 40:320-323. 1976.
59. Reybrouck, Tony, George F. Heigenhauser, and John A. Faulkner. Limitations to maximum oxygen uptake in arm, leg, and combined arm-leg ergometry. J. Appl. Physiol. 38:774-779. 1975.
60. Riley, Richard L. The work of breathing and its relation to respiratory acidosis. Ann. Int. Med. 41:172-176. 1954.
61. Rossier, P.H., A.A. Buhlmann, and K. Wiesinger. Respiration: physiologic principles and their clinical applications. The C.V. Mosby Co., St. Louis. p. 230-235. 1960.
62. Tuttle, W.W., and John F. Corleaux. The response of the heart to water of swimming pool temperature. Res. Quart. 6:24-26. 1935.
63. Tuttle, W.W., and Joyce L. Templin. A study of normal cardiac response to water below body temperature with special reference to a submersion syndrome. J. Lab. Clin. Med. 28:271-276. 1943.
64. Wells, George. The effect of external temperature changes on heart rate, blood pressure, physical efficiency, respiration, and body temperature. Res. Quart. 3:108-121. 1932.
65. Wells, J. Gordon, Bruno Balke, and Donald D. Van Fossan. Lactic acid accumulation as a factor in determining work capacity. Air University, School of Aviation Medicine, USAF, Randolph AFB, Texas, 56-121. 9 p. 1956.