Cardio-pulmonary Characteristics during Land and Swimming Exercise

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Abstract Cardio-pulmonary response was compared in nine American swimmers (18-21 year) during tethered swimming and land exercise. VE was significantly higher in land (P<.05) than in swimming due to the higher f. At a comparable VO₂ greater HR was observed in land exercise during submaximal work. However, during maximal work the difference disappeared. The DLco increased linearly with VO₂ during land exercise but plateaued out during swimming so that compared to land DLco was higher in swimming at submaximal work. There was a linear increase in Vc with increase in VO₂ in both swimming and land exercise. The Vc during swimming was significantly higher (P<.01) than that in land exercise over all work loads. During submaximal work VE, HR, DLco, and Vc were affected by the water immersion and posture. However, during maximal work in spite of higher Vc in swimming the DLco was almost the same as that in land exercise. It was postulated that the stimulus for an adequate oxygen uptake is governed by the work demand which overcomes any influence from other sources such as water immersion or posture.

INTRODUCTION

Many physiological phenomena have been attributed to the under water exercise as a result of their chronic intermittent exposure to work in aquatic environment. Work performance on “land” has also unique characteristics compared to under water exercise. In order to investigate any possible functional adaptation to under water exercise, comparisons of the physiological response to land and under water exercise have been made. However, there are several factors complicating any comparison of exercise on land and water such as immersion, temperature regulation, work efficiency and ventilatory restriction. More recently, there has been considerable interest in the cardio-respiratory response to submaximal as well as maximal work during under water exercise and land exercise (McARDLE et al., 1969; HOLMÉR, 1972; NADEL et al., 1974). The maximal oxygen uptake has been compared during swimming and land exercise (MAGEL, 1967). DIXON and FAUKNER (1971), utilizing the CO₂ rebreathing method, reported that cardiac output while swimming did not differ when compared to their land exercise at the level of maximal work. In the present investigation cardio-pulmonary response including the pulmonary gas exchange (diffusing capacity of the lung and pulmonary
capillary blood volume) was compared during swimming and land exercise. More specifically, the study was designed to see the interaction between ventilatory response and pulmonary diffusing capacity.

METHODS

The present study was designed to examine the relationship of cardio-pulmonary adaptation during swimming and land exercise. The subjects consisted of nine American swimmers between the ages of 18–21 year. All the tests were conducted of the University of Wisconsin in U. S. A. (March~July, 1973). The antropometric and resting pulmonary functions measurements were obtained at random according to the subjects' schedule.

The tethered swimming test was similar to that used by Magel et al. (1967). The test was administered in a 7 m (length) ×4 m (width) ×1.5 m (depth) swimming tank. The water temperature was set to that experienced in a swimming situation (27–29°C). The front crawl style was employed by all subjects. After entering the water the subject was given the mouth piece with a two-way valve which was attached to a snorkel type head frame and the noseclip. Then the subject was fitted to a gymnastic type canvas belt around his waist which was connected to a restraining line. The line was directed rearward of the subject over a ball-bearing pulley which was linked to the weight resistance apparatus. The testing work load was initially set at 1.1 kg. The work load was increased at each level by 1.1 kg increments until the subject could no longer support the weight during the 4–6 min swim. The subjects were instructed to maintain the normal breathing pattern that they would use in a swimming situation.

The land exercise using treadmill followed a modified Balke progressive test (Balke, 1963). The test started at a 2.5% grade at 3 mph and the grade was increased by 2.5% each two minutes except during the measurements of oxygen intake (V̇O₂), diffusing capacity of the lung (DLco), and pulmonary capillary blood volume (Vc) until the maximal voluntary work capacity was attained. After 2–3 minutes from the each level of exercise, expired gas was collected for V̇O₂; then the subject was turned into the CO gas mixture for DLco and Vc as described by Ogilve and Forster (1957). Oxygen consumption was determined for each exercise load utilizing an open circuit and was calculated from the volume VI and VE, ECO₂ and FO₂. The minute ventilation and breathing frequency (f) were measured through a gas volume meter and recorded continuously. Heart rates were counted from the QRS complex of the ECG tracing recorded on the polygraph. DLco during exercise was measured by the steady-state method as described by Bates (1955). Vc was determined using Roughton-Forster' equation (1957). The expired CO₂, O₂, and CO concentrations were determined by analysis with a Quintron gas chromatograph Model M-3. The analyzer was calibrated with gases of known concentration obtained volumetrically by GallenkampLloyd (Instrumentation Assoc. Inc.)
RESULTS

The physical characteristics for the respective groups are listed in Table 1. The heights, weights, and pulmonary function measurements at rest are in agreement with previously reported data on college swimmers (Andrew et al., 1972; Mostyn et al., 1963; Reddan, 1966). Compared to a normal population (Andrew et al., 1972), the height, weight, and vital capacity were higher in the present subjects. Resting DLco and Vc, measured by single-breath

Table 1. Physical characteristics

<table>
<thead>
<tr>
<th>Subj</th>
<th>Age (Year)</th>
<th>Ht  (cm)</th>
<th>Wt  (kg)</th>
<th>VC  (L)</th>
<th>% Pred. 1)</th>
<th>DLco  (mL/mmHg/min)</th>
<th>% Pred. 2)</th>
<th>Vc  (mL)</th>
<th>% Pred. 3)</th>
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<tr>
<td>J M</td>
<td>18.6</td>
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<td>38.4</td>
<td>116.0</td>
<td>143.0</td>
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<td>72.3</td>
<td>6.00</td>
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<td>183.5</td>
<td>68.2</td>
<td>5.37</td>
<td>95.6</td>
<td>41.2</td>
<td>132.0</td>
<td>121.1</td>
<td>152.9</td>
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<tr>
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<td>171.4</td>
<td>70.9</td>
<td>6.13</td>
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<td>78.2</td>
<td>6.03</td>
<td>108.4</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>MS</td>
<td>23.0</td>
<td>175.6</td>
<td>66.4</td>
<td>5.29</td>
<td>110.8</td>
<td>39.8</td>
<td>138.2</td>
<td>124.6</td>
<td>167.0</td>
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<td>AO</td>
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<td>182.1</td>
<td>73.6</td>
<td>6.22</td>
<td>114.1</td>
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<td>140.9</td>
<td>170.8</td>
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<td>181.0</td>
<td>74.1</td>
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<td>129.7</td>
<td>128.9</td>
<td>156.1</td>
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<tr>
<td>SD</td>
<td>1.98</td>
<td>4.49</td>
<td>4.81</td>
<td>0.41</td>
<td>12.17</td>
<td>4.56</td>
<td>12.28</td>
<td>19.50</td>
<td>18.59</td>
</tr>
</tbody>
</table>

1) Weng, T. (1969) \( \text{VC} = 1.46\times e^{-0.20\times \text{Ht}} \)
2), 3) Bucci, G. et al. (1961)

\[
\text{DLco} = \text{Antilog} (0.656(\text{Ht}) + 0.308) \\
\text{VC} = \text{Antilog} (0.684(\text{Ht}) + 0.674)
\]

Fig. 1. Minute ventilation (\( \dot{V_E} \)) in relation to \( \dot{V_O_2} \) during swimming and land exercise.
**Table 2.** Regression equations for Ventilation ($\dot{V}E$), Breathing frequency ($f$), Heart Rate (HR), Tidal Volume (VT), Diffusing Capacity (DLco), Membrane Diffusion (Dm), and Pulmonary Capillary Blood Volume (Vc).

<table>
<thead>
<tr>
<th>Dependent Variable ($Y$)</th>
<th>Coef. of Independ. Vari. ($a$)</th>
<th>Constant ($b$)</th>
<th>Correlation ($r$)</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{V}E$ (STPD)</td>
<td>Land</td>
<td>26.55</td>
<td>-10.90</td>
<td>.896</td>
</tr>
<tr>
<td>($l/min$)</td>
<td>Swim</td>
<td>23.47</td>
<td>-12.30</td>
<td>.915</td>
</tr>
<tr>
<td>$f$</td>
<td>Land</td>
<td>8.36</td>
<td>10.21</td>
<td>.751</td>
</tr>
<tr>
<td>(Breaths/min)</td>
<td>Swim</td>
<td>7.44</td>
<td>6.03</td>
<td>.725</td>
</tr>
<tr>
<td>HR</td>
<td>Land</td>
<td>21.94</td>
<td>89.55</td>
<td>.679</td>
</tr>
<tr>
<td>(Beats/min)</td>
<td>Swim</td>
<td>25.59</td>
<td>64.42</td>
<td>.920</td>
</tr>
<tr>
<td>VT (BTxS)</td>
<td>Land</td>
<td>.51</td>
<td>1.52</td>
<td>.700</td>
</tr>
<tr>
<td>($t$)</td>
<td>Swim</td>
<td>.27</td>
<td>1.94</td>
<td>.552</td>
</tr>
<tr>
<td>DLco</td>
<td>Land</td>
<td>6.21</td>
<td>32.0</td>
<td>.589</td>
</tr>
<tr>
<td>($ml/mmHg/min$)</td>
<td>Swim</td>
<td>3.51</td>
<td>68.1</td>
<td>-.312</td>
</tr>
<tr>
<td>Dm</td>
<td>Land</td>
<td>9.04</td>
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<td>.280</td>
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<td>($ml/mmHg/min$)</td>
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<td>113.4</td>
<td>.178</td>
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<tr>
<td>Vc</td>
<td>Land</td>
<td>17.22</td>
<td>95.2</td>
<td>.373</td>
</tr>
<tr>
<td>($ml$)</td>
<td>Swim</td>
<td>22.7</td>
<td>124.8</td>
<td>.553</td>
</tr>
</tbody>
</table>

*** $P < 0.001$
** $P < 0.01$
* $P < 0.05$

Independent Variable $x = \dot{V}O_2$ ($l/min$)
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Table 3. A comparison of Ventilation (VE), Breathing Frequency (f), Heart Rate (HR), Tidal Volume (VT), Diffusing Capacity (DLCO) Pulmonary Capillary Blood Volume (VC) with increasing oxygen consumption (VO₂ l/min) during swimming and land exercise.

<table>
<thead>
<tr>
<th>VO₂ (l/min)</th>
<th>~2.5</th>
<th>2.6~3.5</th>
<th>3.6~</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swim</td>
<td>Land</td>
<td>Swim</td>
<td>Land</td>
</tr>
<tr>
<td>VE(STPD) (l/min)</td>
<td>X</td>
<td>33.2</td>
<td>36.8</td>
</tr>
<tr>
<td>f (Breaths/min)</td>
<td>SD</td>
<td>9.2</td>
<td>7.8</td>
</tr>
<tr>
<td>HR (Beats/min)</td>
<td>X</td>
<td>20.4</td>
<td>23.2</td>
</tr>
<tr>
<td>VT (BTPS) (l)</td>
<td>SD</td>
<td>5.0</td>
<td>5.1</td>
</tr>
<tr>
<td>DLCO (ml/mmHg/min)</td>
<td>X</td>
<td>109.9</td>
<td>129.7**</td>
</tr>
<tr>
<td>VC (ml)</td>
<td>SD</td>
<td>14.2</td>
<td>13.9</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>2.27</td>
<td>2.06</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.41</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>64.2***</td>
<td>46.9</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>13.2</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>172.0**</td>
<td>110.6</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>42.3</td>
<td>34.9</td>
</tr>
</tbody>
</table>

*** P < 0.001
** P < 0.01
* P < 0.05

Fig. 3. Heart rate (HR) in relation to VO₂ during swimming and land exercise.
method (OGILVIE et al., 1957), exceed the normal predicted values (WENG, 1969; Bucci et al., 1961) by 13.4–70.8%.

Correlation coefficients for the regression analysis indicated a significant linear relationship between VE and VO$_2$ during both water and land exercise (Table 2). VE was significantly higher in land than swimming except VO$_2$ of 2.5 l below (P < 0.05, Table 3). The increase in VE with submaximal work during land exercise was accomplished by a comparable linear increase in $\dot{f}$ (Fig. 2). During swimming there was considerable variation in the

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**Fig. 4.** DLco in relation to VO$_2$ during swimming and land exercise.

**Fig. 5.** Pulmonary capillary blood volume (Vc) in relation to VO$_2$ during swimming and land exercise.
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VT with increasing work load. However, over the submaximal range of energy expenditure the VT was higher in swimming than land exercise. A significantly linear relationship was observed between HR and $\dot{V}O_2$ both in swimming and land exercise (Table 2). At a equal $\dot{V}O_2$, greater HR was observed in land exercise during submaximal exercise ($P < 0.01$, Table 3).

However, there was no significant difference in HR during maximal level (Table 3).

DLco increased linearly with increasing $\dot{V}O_2$ during land exercise (Fig. 4). However, there was no positive relationship between DLco and $\dot{V}O_2$ during swimming. At the low work loads, DLco was significantly higher in swimming than in land exercise ($P < 0.001$, Table 3). Pulmonary capillary blood volume ($V_c$) was obtained in both swimming and land exercise (Fig. 5). There was a linear increase in $V_c$ with increase in $\dot{V}O_2$ in both swimming and land exercise. The $V_c$ during swimming was significantly higher than land exercise over all work loads ($P < 0.01$, Table 3). Although $V_c$ was higher in swimming, there was similar increase in $V_c$ (30%) from the lowest to the highest work load in both swimming and land exercise.

DISCUSSION

In this study, there was no significant difference in HR during maximal work load. However, most of the subjects had considerably lower HR at a given $\dot{V}O_2$ during submaximal swimming. There are several factors inherent in both exercise that must be considered. On the land, exercise elicits a greater SV and a slower HR in supine as compared to upright position (Bevegard et al., 1966; Ekelund and Holmgren, 1967; Stenberg, 1967). The slower HR might be due to the supine position in the present study. A similar posture occurring in swimming would suggest better venous return and greater cardiac filling which would result in a larger SV and lower HR. It has been shown that cardiac output was higher during submaximal exercise in the water than in the sitting position (Cerny, 1972), and the lower HR, therefore, may be an effect of immersion and the supine posture. Dixon (1971) showed a lower HR with no significant difference in cardiac output between swimming and land exercise during maximal effort. Bradycardia associated with breath-hold diving (Harding et al., 1965; Hunting, 1968; Irving, 1963) or water temperature (Craig and Dvorak, 1966) might also account for the lower HR during swimming.

A lower VE during swimming compared to land exercise has been observed previously (Åstrand and Saltin, 1961; Holmér, 1972). The authors explained that the decrease in both respiratory rate and tidal volume was a result of the limited number of strokes per minute since all swimmers breathed in a one breath to one stroke ratio. Other possible factors contributing to a depressed VE include the effect of hydrostatic pressure on the thorax (Faulkner, 1966; Karpovich, 1939) creating a lower lung volume, an increase
in flow resistance (Karrovich, 1939), on
the involvement of the respiratory muscles
in the arm stroke (Counsilman 1968; Faulkner, 1966).

A lower \( f \) and higher VT in swimming
compared to land exercise during sub-
maximal work was apparent in the
present study. However, during heavy
work load, in order to maintain the higher
work load the subjects had to increase
their arm strokes per minute. Therefore,
they may have limited their ability to
attain a higher VT. Although there were
great individual variations, the difference
in VT disappeared during higher work
load.

The linear increase of steady-state dif-
fusing capacity (DLco) during land exer-
cise observed in this study is general
agreement with previously reported studi-
es (Bates et al., 1955; Donevan, 1959;
Mostyn et al., 1963). The absolute
values in the present study at comparable
\( \dot{V}O_2 \) are also in good agreement. The
linear increase of DLco with increasing
\( \dot{V}O_2 \) indicates a normal expansion of
the pulmonary capillary bed. Johnson
(Johnson et al., 1965) has shown that
DLco plateaus or falls beyond that
causing max \( \dot{V}O_2 \) due to the fall in
cardiac output. DLco is not limited by
the ability to increase capillary blood
flow. This is not apparent in the present
study. The absolute DLco during land
exercise was identical to that reported by
Donevans (1959). In contrast to the
linear increase of DLco with increasing
\( \dot{V}O_2 \) during land exercise, DLco in swim-
ning had already reached almost its
highest value at the first workload and
showed no further increase. An early
plateau in DLco, i.e., the higher DLco
during swimming compared to land exer-
cise at low work load could be due to a
greater VC during swimming because of
the supine posture (Danzer et al., 1968)
and vascular engorgement from water
pressure produced by an increased SV
and higher cardiac output (Guyatt et
al., 1965). VC and DM during water and
land exercise in this study agree with
previous reports of higher VC during
sitting exercise in immersion at sub-
maximal work load (Cerny, 1972). VC
during heavy work load has not been
reported. The magnitude of the VC at-
tained at the maximal work load closely
approximates physiological estimate of
the maximal size of the bed. However,
in spite of higher VC with added effects
of the posture and immersion during
swimming, the DLco at the higher work
load was almost the same as land exercise.
This suggests that the stimulus for an
adequate oxygen uptake is governed by
the work demand which overcomes any
influence from other sources such as water
immersion or posture.

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Cardio-pulmonary Characteristics during Exercise


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Water immersion 時における 呼吸循環機能が 陸上運動時と比較し、どのような因子で影響されるかをけん引負荷水泳とトレッドミル運動時において検討した。対象は Age group 水泳クラブに所属するアメリカ人男子 9 名（18-21才）で、それぞれけん引負荷水泳とトレッドミル運動の二つの状態において, $\dot{V}O_2$, $VE$, $VT$, $f$, $HR$, $DLC0$, $Vc$ を測定した。$VE$ は陸上と同じ運動強度において水泳運動時の低い値を示した。これは運動体位と immersion による Bradycardia の影響と考えられる。しかし Maximal 運動時においてその差はほとんどなくなかった。水泳運動時の DLC0 は運動強度に関係なく常に最大に近い値を示し、従って運動負荷による $\dot{V}O_2$ の増大にも無関係であった。一方、陸上運動時の DLC0 は従来言われているとく $\dot{V}O_2$ の増大に比例して増加するのが認められた。Maximal DLC0 については両運動時ににおいて、ほぼ同じ値を示した。$Vc$ に関しては陸上運動、水泳運動時とも $\dot{V}O_2$ と直線関係を示したが、水泳運動時の方が常に高い値を示した。以上の事から Submaximal 運動時において VE, HR, DLC0, Vc は immersion, posture 等の影響をうけるが、Maximal 運動時における HR, DLC0 は陸上運動とほぼ同じで immersion, posture 等の影響より $O_2$ demand により直接的関与があると推測された。