Validity of cycle test in air compared to underwater cycling.

M. ALMELING¹, L. SCHEGA², F. WITTEN¹, P. LIRK³, K. WULF³

¹University of Göttingen, Department of Anaesthesiology, Division of Sports Medicine at the Department of Sports, Sprangerweg 3, 37075 Göttingen, Germany; ²Catholic University of Leuven, Department of Rehabilitation Science, Faculty of Physical Education and Physiotherapy, 3001 Leuven, Belgium; ³Medical University of Innsbruck, Department of Anaesthesiology and Critical Care Medicine, Anichstrasse 35, 6020 Innsbruck, Austria

Almeling M, Schega L, Witten F, Lirk P, Wulf K. Validity of cycle test in air compared to underwater cycling. Undersea Hyerb Med 2006; 33(1):45-53. According to international guidelines, fitness to dive is generally assessed using a bicycle stress test (BST) in air. To date, there is no study explicitly addressing the question whether the results of a BST in air really predict performance status under water. Therefore, the aim of the present study was twofold: first, to design an experimental setting allowing the examination of physical performance status under water, and second, to examine whether there is an association of response to exercise in air compared to exercise under water using self contained underwater breathing apparatus (SCUBA). We constructed and evaluated a measurement technique for a bicycle ergometry and for gas analysis under water. Part of the work was the development of a new valve system which allowed to collect the exhaled air in total and to transport it to the spirometer next to the pool. Twenty-eight healthy male divers underwent a BST. Compared to a given workload in air, gross capacity decreased significantly by about 50% underwater. High performance in air was associated with a high performance underwater. The examinations were carried out without any complications. In conclusion, our experimental setting allowed the safe and reliable examination of physical performance status under water. First results indicate that the results of a BST in air correlate well with the cardio-circulatory performance status underwater. A subsequent study with a larger sample size will enable us to more precisely model this correlation.

INTRODUCTION

Fitness to dive both for professional and sports divers is generally assessed with physical fitness tests (1,2). The consensus paper of the European Diving Technology Committee states that tests such as a cycle ergometer test provide an adequate means of fitness assessment (1). However, satisfactory performance in a bicycle ergometer test of exercise does not guarantee corresponding reactions under immersed conditions. Important physiological changes in ventilation, blood volume distribution and stimulation of heartbeat, known as diving response (19), might influence the results. Therefore, the aim of the study was to design an experimental setup to allow the examination of physical performance status underwater, and to examine the association of response to exercise using a bicycle stress test both in air and under water.

Materials and Methods

The institutional review board of the University of Göttingen approved the present study. Written and informed consent was obtained from all subjects prior to the experiments. For examinations carried out under water, a safety diver was placed next to the subjects.

Subjects

Thirty-three healthy volunteers participated in the study carried out in May 2001. Thirty-one subjects completed all tests, among them 28 men and three women. All
subjects were certified divers with valid fit-to-dive certification. Due to the small number of females, the analysis was limited to male subjects.

<table>
<thead>
<tr>
<th>Sex</th>
<th>n</th>
<th>age (years)</th>
<th>length (cm)</th>
<th>weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>female</td>
<td>3</td>
<td>28.0 (17-41)</td>
<td>165.3 (162-68)</td>
<td>61.0 (50-70)</td>
</tr>
<tr>
<td>male</td>
<td>28</td>
<td>39.9 (26-62)</td>
<td>180.2 (170-90)</td>
<td>79.1 (65-95)</td>
</tr>
</tbody>
</table>

Table 1. Anthropometrical details of the tested group; in clippings minimal and maximum values

The mean age of the subjects was 40 years (range: 26-62 years), mean body height was 180 cm (range: 170-190 cm), mean body weight was 79 kg (range: 65-95 kg), mean systolic and diastolic blood pressure was 127 mmHg and 81 mmHg, respectively (range: 107-165 mmHg, and 65-94 mmHg, respectively).

None of the subjects was on antihypertensive medication.

**Experimental design**

The *underwater experimental setup* is shown schematically in Fig.1. We adapted a standard mechanical ergometer for underwater use in whole body immersion (Monark, Vansbro, Sweden) (Fig. 1,a). The ergometer was placed in a pool having a depth of 3 m. A second bicycle was placed outside the pool (EOS-Sprint 900, Jaeger, Höchberg, Germany) (b). Both ergometers were connected by chains (c). Between the latter, an electric separator was interposed for safety reasons (d). Heart rate, ECG and blood pressure were followed on a monitor (e). The exhaled air was collected in a spirometer next to the pool (f) to which it was conducted by a tube (g). A safety diver was placed next to the subject (h). The principal

![Fig. 1. Test set up showing: a. ergometer under water and b. on land, c. transmission with a chain, d. electric separation, e. ECG monitor, f. spirometer, g. tubes for expiration gas, h. safety diver, i. watch glass for test leader, j. splash wall.](http://archive.rubicon-foundation.org)
investigator could monitor the activities under water through a watch glass (i). A splash wall was used to protect the equipment outside the pool from getting wet (j). The air temperature was kept constant at 20°C and the water temperature at 27°C, respectively.

**Blood pressure** was recorded with an automatic system adapted for the use under water (BOSO-TM-2420, Bosch and Son, Jungingen, Germany). A special suspension was developed to adapt the pressure in this recorder to the level of the blood pressure cuff. The blood pressure was measured continuously. An underwater video system allowed its visualization on a monitor outside the pool. The data were registered automatically.

**ECG** electrodes were fixed on the subject under water and were isolated against water. The ECG was shown on a monitor (Hellige Ergomed, Freiburg, Germany) outside the pool. It was printed continuously and analyzed by a physician throughout the examination.

For the **gas analysis**, the subject on the ergometer was equipped with an ordinary scuba system as it is commonly used in professional diving (Mares, Rapallo, Italy). To collect the exhaled air and transport it to the spirometer next to the pool, we constructed a special valve system, adapting the expiration valve of the scuba regulator to ambient pressure. This system was patented (Patent DE 10016772.1., 2000).

To calculate the oxygen uptake, the measured volumes were corrected according to the pressure difference (test at 117 kPa, spirometer at sea level, 100 kPa). Samples were taken every 15 seconds. Oxygen and carbon dioxide in the exhalation air of the diver were measured in Douglas sac method (3).

**Time course of the examination**

At day one, the subject exercised with the ergometer on dry land. The workload was increased stepwise by 50 Watts (W) every three minutes until the subject reached the maximum tolerable workload which was defined as a blood pressure heart rate of 220 minus the subject’s age (4, 5).

At day eight, the subject exercised against the resistance of the mechanical ergometer under water. The performance of the subject was registered by the connected ergometer outside the pool (Fig. 1). The setting was increased stepwise by 30 W every three minutes until the subject reached the maximum tolerable workload (see above).

**Freewheeling resistance**

Before starting the tests under water, the resistance during freewheeling was measured. Using a pendulum generator turning 55 rpm, the ergometer setup including the passively moving subject shows a hydrodynamic resistance of about 34 W (6). Then the subject had to spin at 55 rpm without ergometer resistance. During this procedure the oxygen uptake was measured. This value, showing the water resistance of the set up including the subject, was defined as step “zero watt” during the following tests.

**Gross capacity**

The set up described above provided the parameters which were needed to calculate the efficiency of workload on the bicycle ergometer, namely the respiratory quotient and the oxygen uptake. Gross capacity (p) was calculated as shown in the formula below:

\[
p = \frac{\mathrm{\text{VO}}_2 \times (5.1567 \times \text{RQ} + 15.974)}{0.06}
\]

Results of ergometry in air could not be compared directly to the results of underwater ergometry due to the higher resistance in the latter setting. We assumed that the same capacity of a subject leads to a comparable oxygen uptake. Therefore, a comparable capacity in W was measured. Then, the 34 W while freewheeling was added to the gross capacity underwater of the subject. The
The sum was termed *gross capacity underwater (GC-W)* and compared to the *gross capacity in air (GC-A)*.

**Statistics**

All data were entered into a computerized database and analyzed using statistical software (Jump, SAS). Parameters were compared using the t-test. P values less than 0.05 were regarded to be statistically significant.

**RESULTS**

All subjects completed ergometry in both air and under water without complications. Fig. 2 shows the number of measurements completed per gross capacity step. Under water, the maximum step reached was 180 W compared to 350 W in air.

The average and maximum GC-W reached was 53 % of the GC-A. The average GC-W was significantly lower than the average GC-A (123 W vs. 234 W, p<0.001). High performance in air was associated with high performance under water (Fig.3).

The relationship between performance and oxygen uptake was highly linear (Figs. 4 and 5). Maximum oxygen uptake ranged between 1.78 and 4.53 litres per minute, showing the inter-individual differences in performance among the subjects (Figs. 6 and 7, page 50). The average oxygen uptake was 2.86 litre in air and 2.51 litre under water (p = 0.007).

Although in nearly all cases the maximum heart rate of the subject was higher in air compared to underwater, all heart rates at comparable workload steps underwater were higher (Fig. 8, page 50). This difference proved to be significant at the 50 W and 100 W step (p < 0.005) and also at the 150 watt step (p = 0.028).
Figs. 4 & 5. Oxygen-uptake was 0.5 litres per minute higher on all stress steps in water (figure 5) than on land (figure 4). This is expressed in the parallel shift of the regression line comparing the test results on land to the results in immersion.
Net exercise capacity underwater is reduced due to viscosity, density, heat conduction, heat capacity and hydrostatic pressure compared to equivalent work levels in air. Application of formula 1 showed that to reach 120 watt net capacity an average over all tests of 542 W in air and 686 W underwater was needed (Fig.9). The known efficiency of a bicycle ergometer in air of 22.1% is reduced to 17.5% when cycling underwater (7,8,9,10). The reduction is mainly due to higher loss of thermal energy and a higher loss for ventilation work (1.5 W in dynamic ventilation of 50 l/min as an average at 120 W and 3.5 W as additional workload for ventilation resistance of tubes and regulator).

**DISCUSSION**

The present study directly correlates exercise tolerance in a bicycle stress test both underwater and in air. The main finding is that bicycle stress tests conducted in air predict general cardio-circulatory ability of a diver. However, it was not possible to assess specific workload. The bicycle stress test is well documented in literature and is internationally standardised (4, 5, 7). However, even though featured prominently in fit-to-dive consensus guidelines (1, 11), bicycle stress tests in air have not been directly compared to underwater tests.

For a reasonable comparison of workload on a bicycle ergometer in air to a diver’s workload on a bicycle ergometer under water, both heart rate and blood pressure need to be measured. Secondly, workload has to be defined in both procedures. Measuring the oxygen uptake and assuming that the same uptake leads to the same workload can approximate this. With the set-up employed...
in the present study, we were able to calculate the capacity of the ergometer under water and directly compare the physiological response of the tested test persons with the results found in air.

This contrasts with some previous literature measuring energy turnover in relation to swimming or diving velocity (15-21). Previous publications show that a comparison between spiro-ergometric testing, expressing the capacity in W, and a test procedure trying to express capacity in terms of velocity (meter per second) is not possible (12, 13). Since mechanical power is the product of force and velocity ($P_{\text{mech}} = F \times V$), the force ($F$) in test conditions in water could not be determined, as hydrodynamic resistance of water, as a main limitation factor in water performance, was not measurable. For example, Chen 1996 (14) tested subjects on a bicycle in head out water immersion and without calculating water resistance as a main factor for different results in efficiency. Similarly, Dwyer and Pilmanis used a setup where the diver pushed a board against resistance underwater (29). Resistance was measured by compressing a spring while swimming at different velocities. The subjects showed higher heart rates in relation to higher stress levels compared to a bicycle test in air. The investigators were no able to calculate the workload of different test situations. They concluded that heart rate and ventilation are not suited to estimate diver’s capacity.

Comparing equivalent workload situations, our test results show that heart rate in whole body immersion is higher than in air. This is important since nearly all studies on heart rate in immersion show a reduction, the so called “dive response” (22). Only a very small number of studies tried to stress subjects in immersion, mainly in head out water position (23-28).

The main problem with these studies is that the face itself contains the pressure and temperature receptors, which are the main triggers of the dive response (22). Furthermore, most studies did not show significant results due to the small sample size. We postulate that this increase is due to typical diver’s pressure breathing. Positive end-expiratory pressure reduces central venous flow. Reduced venous flow subsequently reduces the volume per heartbeat, which is then compensated by increasing heart rate. The results lead to the conclusion that any testing procedure which tries to estimate workload in a situation where the subject is in whole body immersion will not be reliable. Nevertheless, our results show that the capacity measured on a bicycle stress test in air has a predictive value for the same underwater test setup. Therefore, it may be stated that the bicycle stress test is an exact but non-specific testing setup, with an important role in the determination of fitness to dive. However, bicycle test results do not reflect workplace specific capacity of a diver’s workplace. In correlation to sport specific testing, it seems to be clear that neither bicycle nor running ergometric test setups correlate with the specific load of a person swimming (10, 30, 31). Assuming that fin swimming under water is a main part of a diver’s work, there is still no workload specific testing procedure for this group. Some actual studies were able to measure energy take up while fin swimming (32, 33).

The subject’s limited performance under water, mainly due to water resistance, in our opinion shows that comparable standard workload above water leads to high or very high levels of workload performed underwater.

In conclusion, the results of our study indicate that the results of a BST in air correlate well with the cardio-circulatory performance status underwater. A subsequent study with a larger sample size will enable us to model this correlation more precisely.

REFERENCES


