SIMULATED MULTIDAY UNDERWATER HABITATION IN HYPERBARIC HELIUM-OXYGEN ENVIRONMENT

BY

Atsushi Ito\textsuperscript{91}

ABSTRACT

During the last decade underwater habitations have been planned and carried out in several countries. In Japan, an underwater habitation of 60 meters by 4 men for 7 days (named “Seatopia” project) was carried out by the Japan Marine Science and Technology Center (JAMSTEC) in 1973. Before the actual project, safety check of the equipment and selection of candidates were required from the viewpoint of medical sciences. After that, 7 subjects, candidates for “aquanauts” lived in a hyperbaric chamber of 7 atmosphere absolute pressure air and helium simulating an underwater habitat of 60 m depth, for 7 days (in total 15 days including 3 days of control before compression, 3 days of decompression, 2 days after decompression). Physiological functions of all the subjects were examined for more than 2 weeks. Effects of high pressure and thermal conductivity on cardiorespiratory system, renal function and metabolism were evaluated with the findings of 1) decreased heart rate and forced expiratory volume; 2) increased urine volume; 3) decreased rectal and skin temperature with increased heat production and 4) the more trained the diver, the lower the skin temperature and the lower the heat production.

INTRODUCTION

Exposure to a high-pressure atmosphere causes serious interrelated physical reactions which limit the usefulness of the air for deep and prolonged underwater operations. Air will always remain important for shallow water and short duration diving activities. However, for deep diving its use is progressively limited by the narcosis produced by its high partial pressure of nitrogen\textsuperscript{1}, by increased respiratory resistance for its density\textsuperscript{2}, and a prolonged decompression is required because of high solubility of air into the tissues and its slow elimination rate from the tissues\textsuperscript{3,4}. The oxygen toxicity itself imposes restriction of both duration and depth of dive, if the compressed natural air was used. Several days of exposure to the saturated status with air should eventually cause pulmonary oxygen

\textsuperscript{91} 伊藤敦之：Department of Hygiene (Chief: Prof. H. KITA), School of Medicine, Tokyo Medical and Dental University (Tokyo Ika Shika Daigaku). Received for publication, May 14, 1974.
poisoning if the water depth exceeds 10 m (corresponding to the air
1,500 mm Hg and oxygen 500 mm Hg)\(^5\). At a greater depth this intoxica-
tion develops more rapidly not only in the respiratory system but also in
the central nervous system\(^6,7\). Because of these troubles, helium is used as
a main component of an artificial breathing gas mixture. In the case of
"Seatoopia project"\(^8\), environmental gas was composed of He:5.5 atm-
ospheres absoluie (ATA), N\(_2\):1.2 ATA, O\(_2\):0.3 ATA. Comparison of this gas
mixture to the air is shown in Table 1. The heat capacity and convective
character of this gas mixture are far greater than those of the air\(^8\) and,
therefore, during the multiday exposure, the study of reaction to the stress
of hyperbaric helium was necessary prior to a further underwater habitation
program\(^9\). Though until recently several underwater habitations have
been tried (including "Seatoopia" project in 1972\(^10\))^\(^11\), durations were rather
short, and the measurement and number of subjects were insufficient for
adequate data. The present investigation was undertaken to examine the
physical functions of seven subjects under 7 ATA for 7 days for actual com-
pression and several days for control. Thus each physiological function was
measured frequently and systematically for seven subjects, four times/day
for 15 days, i.e., more than 400 times to obtain statistical reliability.

**Method**

(A) Subjects: Seven adult males were selected as "aquanauts" from
a number of candidates. As summarized in Table 2, their physical states
were almost similar to each other. All these subjects were professional
divers, especially these in Group 1 (subjects A~C) are more trained than
the others. The first simulated habitation was started by Group 1 with one
physician for medical care and instruction for physiological examinations.

\(^*2\) "Seatoopia" project: (sea + utopia) one of the national projects for ocean development,
sponsored by the Science and Technology Agency, and the experiments were carried
out by the Japan Marine Science and Technology Center (JAMSTEC). The experi-
ments were started in 1971 and repeated once a year. In 1972, habitation experiment
for 4 subjects, for 2 days, at the sea bottom of 30 m depth, and in 1973, for 4 subjects,
for 1 week, at 60 m depth, ended with success.
Table 2. Physical characteristics of subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (yrs.)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Surface area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>25</td>
<td>167.7</td>
<td>57.25</td>
<td>1.66</td>
</tr>
<tr>
<td>B</td>
<td>24</td>
<td>162.2</td>
<td>59.65</td>
<td>1.65</td>
</tr>
<tr>
<td>C</td>
<td>22</td>
<td>168.1</td>
<td>60.06</td>
<td>1.71</td>
</tr>
<tr>
<td>Group 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>25</td>
<td>162.0</td>
<td>55.00</td>
<td>1.59</td>
</tr>
<tr>
<td>E</td>
<td>26</td>
<td>163.5</td>
<td>55.00</td>
<td>1.60</td>
</tr>
<tr>
<td>F</td>
<td>27</td>
<td>163.7</td>
<td>59.40</td>
<td>1.65</td>
</tr>
<tr>
<td>G</td>
<td>24</td>
<td>162.4</td>
<td>57.43</td>
<td>1.64</td>
</tr>
</tbody>
</table>

The second simulated habitation was undertaken by the members of Group 2.

(B) Simulator of habitation: To simulate the environment of the habitat at 60 m depth, deck decompression chamber (DDC) was prepared. This was originally used for decompression of divers after long duration of dive to prevent decompression sickness. Dimensions of the DDC were as follows:

- **Size**: 7 m x 2 m³
- **Volume**: 15 m³(main) + 6 m³(sub)
- **Capacity**: 4 person
- **Pressure**: 0.0 ~ 10.3 kg/cm²
- **Temperature**: 25 ~ 35°C
- **Relative humidity**: 60 ~ 80%

(C) Time schedule: The compression started at 11:00 on the day named "X"**, air inside the chamber was compressed with air to that corresponding to 4-m depth at the rate of 1 m/2.5 min, followed by compression with pure helium to 60 m-depth at the rate of 1 m/3 min**. Therefore, partial pressure of each gas was 5.5 ATA He, 1.2 ATA N₂ and 0.3 ATA O₂, a total of 7.0 ATA. The pressure was maintained by continuous oxygen supply and carbon dioxide absorption, for full 7 days. The decompression started at 14:00 on (X+7) day. The rate of decompression was 1.5 m/hr for surfacing from the depth of 60 to 30 m, 1.2 m/hr for 30 to 15 m, and 0.9 m/hr for 15 m to the sea level**. Decompression was interrupted from 24:00 to 06:00 and from 14:00 to 16:00, so it took 71 hr to return to the surface. During the experiment, the chamber temperature was always maintained at 28°C except when it was lowered to 26°C for 48 hr for the experiment from (X+3) to (X+5) day. Relative humidity was kept at 60%.

The phase of experiment was divided into six according to the environmental conditions in the simulator as shown in Table 3. All the subjects followed the schedule as shown in Table 4 throughout the entire experimental phase.

(D) Measurement: Water and food intake was recorded for each sub-

---

**X** day was made as follows:

- X₁ (for Group 1), July 16, and X₂ (for Group 2), August 2, 1973.
Table 3. Environmental conditions during the experiments

<table>
<thead>
<tr>
<th>Phase</th>
<th>Date</th>
<th>No. of days</th>
<th>Pressure (ATA)</th>
<th>Temp. (°C)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>(X-3.)~X.</td>
<td>3</td>
<td>1</td>
<td>28</td>
<td>Control before compression</td>
</tr>
<tr>
<td>II</td>
<td>X</td>
<td>~ (X+3.)</td>
<td>3</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>(X+3.)~(X+5.)</td>
<td>2</td>
<td>7</td>
<td>26</td>
<td>Cold stress</td>
</tr>
<tr>
<td>IV</td>
<td>(X+5.)~(X+7.)</td>
<td>2</td>
<td>7</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>(X+7.)~(X+10.)</td>
<td>3</td>
<td>7~1</td>
<td>28</td>
<td>Decompression</td>
</tr>
<tr>
<td>VI</td>
<td>(X+10.)~(X+12.)</td>
<td>2</td>
<td>1</td>
<td>28</td>
<td>Control after decompression</td>
</tr>
</tbody>
</table>

Table 4. Daily schedule

<table>
<thead>
<tr>
<th>Time schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>06:00 Rising, going to lavatory</td>
</tr>
<tr>
<td>Measurements:</td>
</tr>
<tr>
<td>(a) Body weight, skinfold thickness</td>
</tr>
<tr>
<td>(b) Heart rate, blood pressure, body temperature, oxygen consumption, and urine volume</td>
</tr>
<tr>
<td>07:30 Breakfast</td>
</tr>
<tr>
<td>10:30 Measurements: items (b)</td>
</tr>
<tr>
<td>11:30 Lunch</td>
</tr>
<tr>
<td>15:00 Measurements: items (b)</td>
</tr>
<tr>
<td>16:30 Supper</td>
</tr>
<tr>
<td>18:00 Exercise test, respiratory function tests</td>
</tr>
<tr>
<td>19:30 Measurements: items (b) except urine volume</td>
</tr>
<tr>
<td>21:00 Tests concerning fatigue</td>
</tr>
<tr>
<td>22:00 Going to bed after urine volume measurement</td>
</tr>
</tbody>
</table>

Subject. Body weight was measured just after the urination at 06:00. The skinfold thickness was measured by using calipers (Hemko, Holland, Michigan, U.S.A.) with a range of 0.0~40.0 mm at the measuring points shown in Fig.1. The measurements of heart rate, blood pressure, body temperature, and oxygen consumption were made at rest in a sitting position. The heart rate was measured by palpation at Radial artery, the blood pressure with aneroid sphygmomanometer of Tycos type. Body temperatures, both rectal and skin, were measured with telethermometer (Yellow Spring Instrument, Model 46, Yellow Spring, U.S.A.). The mean value of skin temperature was calculated from the values of 10 measuring points (A~J) as shown in Fig. 1, from the following formula (Consolazio et al.15).

\[
\text{Mean skin temperature} = 0.07 \cdot A + 0.35 \left( \frac{B+C+D}{3} \right) + 0.14 \left( \frac{E+F}{2} \right) + 0.05 \cdot G + 0.19 \cdot H + 0.13 \cdot I + 0.07 \cdot J
\]

\[
\text{Mean body temperature} = \frac{1}{3} \text{ skin temperature} + \frac{2}{3} \text{ rectal temperature}
\]

The oxygen consumption ($V_{O_2}$) was measured from expired gas volume ($V_A$).
and the difference of oxygen volume percent between inspired and expired gas, which was collected into a Douglas bag during the final 2 min of 10 min breathing. The bag was washed with expired gas during the preceding 8 min. The volume of expired gas was measured with a dry gas meter (A.H. Thomas, Model 113, Philaderphia, U.S.A.) which had been calibrated at both 1 ATA and 7 ATA. Oxygen volume (%) of the expired gas was measured with a gas chromatograph (Shimadzu, Model 3BT, Kyoto, Japan). As an exercise test, heart rate and oxygen consumption were measured during the last 2 min of 10 min exercise at 500 kpm/min with bicycle ergometer (Monark, Varberg, Sweden); Heart rate was measured by ECG and expired gas volume and oxygen consumption were measured by the same way as described above. Fatigue was measured by a flicker test, reaction time to a drop stick, color definition time, etc. General physical status was examined by two physicians (including the author) from head to foot by observation, auscultation, percussion, palpation, etc., before compression and after decompression.

Results

Environmental conditions in the chamber are shown in Fig. 2 (a~d). The daily fluctuation of average heart rate, measured four times a day in seven subjects during the day (connected with a solid line) and the minimum value of heart rate measured every hour in sleep at night (broken line) are shown in Fig. 3-a, and blood pressure is summarized in Table 5. Respiratory function: Vital capacity (VC), forced expiratory volume in 1.0 sec
Fig. 2. Environmental conditions in the chamber

(Group 1 — , Group 2 —— )
Fig. 3. Physiological functions of the subjects (Group 1: horizontally hatched), (Group 2: vertically hatched)
(FEW₁₆), and maximum voluntary ventilation (MVV) are shown in Fig. 4. Average rectal temperature of seven subjects with standard deviation is shown in Fig. 3-a. In this figure, the result of mean skin temperature of each subject in Group 1 is covered with horizontal hatching and those of Group 2 with vertical hatching. The heat production (kcal/m²·hr) was calculated from oxygen consumption and body surface area¹⁰, as shown in Fig. 3-c. Water balance (water intake—output by urine) is shown in Fig. 5.

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Systolic pressure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group 1</td>
<td>104.8±1.43</td>
<td>103.0±2.50</td>
<td>106.3±1.63</td>
<td>107.7±2.88</td>
<td>111.2±1.71*</td>
<td>106.2±2.44</td>
</tr>
<tr>
<td>Group 2</td>
<td>101.2±0.97</td>
<td>103.6±2.08</td>
<td>108.6±1.46*</td>
<td>100.8±1.11</td>
<td>102.8±1.07</td>
<td>100.1±1.59</td>
</tr>
<tr>
<td><strong>Diastolic pressure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group 1</td>
<td>71.6±0.81</td>
<td>74.1±2.57</td>
<td>75.3±1.27</td>
<td>74.8±2.04</td>
<td>76.6±1.65*</td>
<td>76.7±1.75</td>
</tr>
<tr>
<td>Group 2</td>
<td>63.3±0.93</td>
<td>63.3±0.90</td>
<td>65.5±1.09</td>
<td>64.1±1.28</td>
<td>66.7±0.85*</td>
<td>65.2±1.19</td>
</tr>
</tbody>
</table>

* Significantly different (p<0.05) from Phase I

---

![Graphs](Figures/fig_4.png)

**Fig. 4.** Respiratory function  (Group 1— , Group 2— )
and excretion rate and specific gravity of urine in Table 6. Cardiorespiratory response to exercise is shown in Table 7, the daily caloric intake in Fig. 6, body weight in Fig. 7, and skinfold thickness (the total amount of the values obtained at five points in Fig. 1) is shown in Fig. 8.

Measurements concerning fatigue were made during the experiment, but the results fluctuated irregularly, no correlation to the pressure and
Table 7. Cardiorespiratory responses to exercise (500 kpm/min)

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate (per min)</td>
<td>127 ± 3.8</td>
<td>110 ± 3.4*</td>
<td>102 ± 3.9*</td>
<td>112 ± 4.8*</td>
<td>123 ± 3.7</td>
</tr>
<tr>
<td>$\dot{V}_e$ (l/min-ATPS)</td>
<td>44.5± 2.67</td>
<td>36.4± 2.19</td>
<td>30.1± 1.40*</td>
<td>32.0± 1.70*</td>
<td>45.4± 2.87</td>
</tr>
<tr>
<td>$\dot{V}_O_2$ (ml/min-STPD)</td>
<td>1753±38</td>
<td>1748±99</td>
<td>1580±42*</td>
<td>1924±83</td>
<td>1716±86</td>
</tr>
</tbody>
</table>

ATPS= Ambient Temperature and Pressure Saturated with water vapor
STPD= Standard conditions of Temperature (0°C), Pressure (760 mm Hg) and Dry gas
Subjects=7, Mean ±S.E.
* Significantly different (p<0.05) from Phase I

Fig. 6. Food intake (Group 1—; Group 2——)

Temperature being obtained. General physical examination: All the subjects showed no abnormalities before compression but, after decompression, facial edema and exaggerated knee jerk and Achilles' jerk were revealed in three (one in Group 1 and two in Group 2) of them for a few days.
Fig. 7. Body weight

Fig. 8. Skinfold thickness

**DISCUSSION**

This investigation is very unique for the following reasons: (1) Many kinds of physiological functions were examined four times a day; (2) compression was maintained for sufficiently long time (seven subjects, for seven days, at 7 ATA) to investigate the adaptability to living in a helium oxygen
hyperbaric environment; (3) chamber was always kept at 28°C, except lowered to 26°C on the middle two days of seven-day compression by the design of the experiment. This lowering of temperature was useful for examining the effect of cold stress on the human body. As the chamber has a capacity for four divers, seven divers were divided into two groups and compression was made two times, but the environment was controlled the same in both cases as shown in Fig. 2.

(I) Cardiovascular function: Hyperbaric bradycardia was noted in a previous “Seatopia” project of 30 m depth for two days in 1972(10). Similar reports are seen in other projects abroad(11). The cause of hyperbaric bradycardia has not yet been clarified in such reports. In the present experiment, bradycardia was already recognized at the first measurement, just 1 hr after the compression to 7 ATA and the degree of bradycardia remained in the same level even when the chamber temperature was lowered to 26°C. This result suggests that the cold stress may not be a pulse rate-decreasing factor. Gradual increase of heart rate was seen in the latter phase of 7 ATA. This phenomenon suggests that there is an adaptation to hyperbaric stress. In spite of the expectation, before this experiment, that blood pressure might rise by cold exposure, i.e., by higher thermal conductivity of helium, there was only a slight difference between the pressure in phases II and I. However, rather distinct rise of pressure was observed during the decompression (phase V). In animal experiment before the previous underwater habitation in 1972, same tendency was recognized(10). It may be explained by considering that blood viscosity is increased by the dehydration(17), and that there are other hemodynamic changes by supersaturation of the gas.

(II) Respiratory function: Static function (for instance vital capacity) did not change throughout the entire phase of the experiment (phase I~VI), because no change of structure occurred in the respiratory system, but dynamic functions (forced expiratory volume, maximum voluntary ventilation) decreased by 10–15% at 7 ATA and recovered soon after decompression. This is due to the enlarged airway resistance by increased density of breathing gas(2,17), but the decrease of these functions under the helium environment was not so great compared with that the 7 ATA of air.

(III) Heat balance and metabolism: Rectal temperature of each subject with equal pattern all through the experiment. Skin temperature and heat production of the subjects of Group 1 and Group 2 changed with the same tendency all through the experiment but, as shown in Figs. 3–b and 3–c, the differences of these phenomena between Group 1 and 2 were so distinct that it was unnecessary to prove stochastically.

(IV) Water balance: The water intake and output were well bal-
anced before compression and after decompression, at the stage of 7 ATA and during decompression, the output of water increased and the intake decreased, and the specific gravity of urine decreased. Hong et al. (joint workers of "Seatopia" project) measured urea-N, creatinine, urine osmolality, and calculated Na+/K+ ratio in urine, and they suggest hyperbaric diuresis may be due to disturbance of tubular reabsorption\textsuperscript{19,20}. Though insensible perspiration was impossible to measure, this suggests that there may occur an active dehydration in the body during the exposure to 7 ATA. This phenomenon was accelerated by the lowering of the chamber temperature to 26°C. Due to dehydration, specific gravity of urine increased during and after decompression.

(V) Cardiorespiratory responses to exercise: Increase of heart rate $\dot{V}_o$ by exercise under the pressure of 7 ATA was smaller than that under 1 ATA air. These phenomena were also observed at rest both at 7 and 1 ATA. This may be due to the fact the higher partial pressure of oxygen at 7 ATA than that in the air of 1 ATA.

(VI) Physiological responses to cold in hyperbaric helium-oxygen environment: During the seven-day compression, temperature in the chamber was lowered from 28°C to 26°C for two days according to experiment plan. Because the thermal conductivity of helium is far greater than that of air, the same temperature reduction had more effect on the human body than that at 1 ATA air. When the data of these phases were compared, the difference in urine excretion rate and in skin temperature between phase III and phases II and IV was significant. Hong et al.\textsuperscript{19,20} suggested that the increase in urine excretion rate was most likely to be further inhibition of ADH system. In parallel to the decrease of chamber temperature from 28°C to 26°C, the skin temperature also decreased in proportion to the expansion of the difference between chamber and core temperature.

(VII) Adaptation to high environmental pressure: As stated repeatedly, the most typical stress of helium-oxygen environment is the loss of body heat by the large heat conductivity of helium. Thus, exposure to the helium-oxygen environment may give a result similar to cold stress, although the atmospheric temperature is relatively higher. The mechanism of human body to cold stress is generally classified into two types, one is a decrease in thermal radiation from the skin surface, decreasing the skin temperature by vasoconstriction, and the other is an increase in heat production. Some people develop radiation-inhibiting system more, and others adapt to the cold stress with higher heat production. The former is called the "insulative type" and the latter, the "metabolic type"\textsuperscript{21}. The more trained divers (Group I) react to the cold stress with a more developed in-
hibiting system of thermal conduction, i.e., they depend on the lowering of skin temperature primarily and scarcely rely on the increase of heat production. On the other hand, the group of metabolic type (Group 2) tolerate the cold stress by increase of heat production. Food intake did not parallel the increased heat production; although meal of 4000 kcal was supplied to each subject each day, intake was 8000 kcal/day throughout the entire experimental period. Even when environmental temperature in the chamber was lowered from 28°C to 26°C and mean body temperature decreased about 1°C, neither caloric intake, nor body weight and skinfold thickness paralleled heat production. In this experiment, type of reaction to hyperbaric helium-oxygen environment was divided into two\(^{25,26}\), the problem of whether their reaction type is incidental by nature or it can be converted with further training will be solved in the near future.

**CONCLUSION**

Seven Japanese divers, who were divided into 2 groups by their diving ability, spent 15 days in a chamber and compressed for seven days to 7 ATA with a gas mixture of helium and oxygen to simulate underwater habitation for a prolonged period. Various physiological functions, such as cardiorespiratory functions, body temperature, heat production, and water balance were examined. Results obtained are as follows:

1) The heart rate was reduced by 20% in both groups at 7 ATA, but blood pressure increased during the decompression.

2) Though forced expiratory volume in 1.0 sec decreased by 10% under 7 ATA, vital capacity remained unchanged throughout the entire experimental period.

3) The rectal temperature changed according to the compression and decompression equally in both groups. The skin temperature of Group 1 (well-trained divers) decreased far more than that of Group 2 (not so well trained divers). On the other hand, the increase of heat production of Group 2 was more than that of Group 1.

4) The urine volume increased while the water intake decreased at 7 ATA. The specific gravity of urine increased during and after decompression. There occurred a severe dehydration in the hyperbaric environment.

5) During the exercise under 7 ATA, heart rate and \( \dot{V}_o \) were less than that under 1 ATA air.

6) During the reduction of chamber temperature (28–26°C) only the skin temperature decreased and urine volume increased. Other functions
scarcely changed or remained unchanged.

7) The difference of skin temperature and heat production between skilled divers and ordinary ones suggests that there are some differences in the mechanism of reaction to the stress of hyperbaric helium-oxygen environment.

ACKNOWLEDGEMENT

Grateful acknowledgement is made to Professor H. Kita of this Department for his cordial guidance and revision of this paper, and to Dr. M. Matsuda, Director for Medical Research, Japan Marine Science and Technology Center, Chief of “Seatopia” project, for his kindness in arranging the author to join this project. Thanks are also expressed to Prof. S. K. Hong, Department of Physiology, School of Medicine, State University of Hawaii, international joint worker of this project, for his kind advice on methods and techniques.

Some part of this article was reported by permission of JAMSTEC at the 44th Annual Meeting of the Japanese Society for Hygiene, April 3, 1974.

REFERENCES