Physiology of man during a 10-day dry heliox saturation dive (SEATOPIA) to 7 ATA. I. Cardiovascular and thermoregulatory functions

M. MATSUDA, H. NAKAYAMA, A. ITOH, N. KIRIGAYA, F. K. KURATA, R. H. STRAUSS, and S. K. HONG.

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Matsuda, M., H. Nakayama, A. Itoh, N. Kirigaya, F. K. Kurata, R. H. Strauss, and S. K. Hong. 1975. Physiology of man during a 10-day dry heliox saturation dive (SEATOPIA) to 7 ATA. I. Cardiovascular and thermoregulatory functions. Undersea Biomed. Res. 2(2):101-118.–Cardiovascular functions, energy metabolism, and body heat exchange were studied in 7 male subjects during a 10-day stay in a dry heliox hyperbaric environment (7 days at 7 ATA and 3 days of decompression). Temperature was maintained at 28-29°C except during the 4th and 5th days at 7 ATA when it was lowered to 25-26°C in order to study the effects of cold. The daily caloric intake remained at about 3000 kcal throughout the dive. The pulse rate was about 20% below the predive level; lowering the temperature did not augment this bradycardia. There were slight increases in systolic and diastolic blood pressures. Both the rectal and skin temperatures decreased at 7 ATA (28-29°C) with a further reduction at 25-26°C. A decrease in mean body temperature was mainly due to the lowered peripheral skin temperatures. The urinary excretion of catecholamines showed no marked changes. During a standard submaximal exercise (500 kilopond meter/min); the O_2-pulse was greater and the ventilatory equivalent was lower compared to their respective predive values. Diurnal changes in the body temperatures and $\dot{V}_{O_2}$ became more exaggerated at depth. Toward the end of the 7-day period at 7 ATA, the pulse rate and body temperatures tended to return to the predive level, suggesting a possible adaptation to hyperbarism.

blood pressures	pulse rate
caloric intake	rectal temperature
hyperbarism	saturation dive
oxygen consumption	skin temperatures

During the last decade at least 15 saturation diving experiments (some dry and others coupled with wet dives) have been carried out throughout the world. As a result, we now know that men can live, at least for 80 min at a depth equivalent to 2000 fsw (PHYSALIE VI dive conducted by COMEX Hyperbaric Research Center, Marseilles, France). We also know that men are able to perform rather strenuous tasks in an environment with the gas density equivalent to a 5000-ft heliox environment (Lambertsen 1972). These studies are extremely important in exploring the ultimate diving depth which man can survive for limited lengths of time. However, many other dives to shallower depths but for longer durations than the above indicate alterations in certain physiological functions such as heart rate (Hamilton, MacInnis, Noble, and Schreiner 1966; Raymond, Bell, Bondi, and Lindberg 1968; Schaefer, Carey, and Dougherty 1970; Salzano, Rausch, and Saltzman 1970;

Bühlmann, Matthys, Overrath, Bennet, Elliott, and Gray 1970; Moore, Morlock, Lally, and Hong 1972), body heat balance (Raymond et al. 1968; Moore et al. 1972; Webb *in press*; Raymond, Thalmann, Lindgren, Langworthy, Spaur, Crothers, Braithwaite, and Berghage 1975), and body fluid balance (Hamilton et al. 1966; Moore et al. 1972; Bennett and Gray 1971). Admittedly, the changes in the above functions are subtle but, if sustained, could affect man's performance at depth.

The present investigation was undertaken to systematically document cardiovascular functions, energy metabolism, and body heat exchange during a 10-day (7 days at 7 ATA) stay in a hyperbaric dry heliox environment with special emphasis on the diurnal rhythms of the physiological functions noted above.

METHODS

Two identical dives were carried out in Yokosuka, Japan, under the auspices of the Japan Marine Science and Technology Center (JAMSTEC) during July 13-28 (Dive I) and July 30-August 14 (Dive II), 1973. This was the first cooperative dive between JAMSTEC and the University of Hawaii, based on a joint research plan formulated in 1972.

SUBJECTS

From a number of applicants, seven subjects (3 for Dive I and 4 for Dive II) were selected on the basis of rigorous physical and physiological examinations. Their physical characteristics are given in Table 1. All subjects were trained scuba divers and one of them (Subject C) had been employed in a 2-day dry saturation dive to 4 ATA in 1972. In addition to these subjects, one investigator stayed inside the chamber in Dive I to serve as a medical officer as well as to carry out physiological measurements.

TABLE 1

Physical characteristics of subjects

Subject & Dive		Age (yrs)	Height (cm)	Weight (kg)	Surface Area (m^2)	Skinfold thickness* (mm)
A	I	25	167.7	57.25	1.66	36
B	I	24	162.2	59.65	1.65	37
C	I	22	168.1	60.06	1.71	40
D	II	25	162.0	55.00	1.59	52
E	II	26	163.5	55.00	1.60	61
F	II	27	163.7	59.40	1.65	33
G	II	24	162.4	57.43	1.64	63
mean		25	164.2	57.68	1.64	46

* Represents the sum of measurements from six sites (see METHODS)

HABITAT AND DIVE PROFILE

The hyperbaric chamber, 7.0 m (23 ft) long, 2.0 m (6.6 ft) wide, 2.0 m (6.6 ft) high, consists of three sections (sleeping quarters, laboratory, shower and toilet) and can be pressurized to 11 ATA. Moreover, the chamber is equipped with temperature and humidity control units as well as other life support systems.

Compression started at 1100 hours and was completed at 1400 hours. The chamber was first compressed with air to a depth of 4 m (13.2 ft) at a rate of 1 m (3.3 ft) per min, followed by compression with pure helium to a depth of 60 m (200 ft; 7 ATA) at a rate of 1 m per 3 min. Therefore, the total pressure of 7 ATA at depth was attributed to He (5.5 ATA), N_2 (1.2 ATA), and O_2 (0.3 ATA).

The chamber pressure was maintained at 7 ATA by a continuous supply of O_2 for exactly 7 days. Decompression started at 1400 hours on Day 11; the average rate of decompression was approximately 30 m (100 ft) per day. As shown in Fig. 1, decompression was not carried out during 0000-0600 hours and 1400-1600 hours. It thus took 3 days to return to the surface.

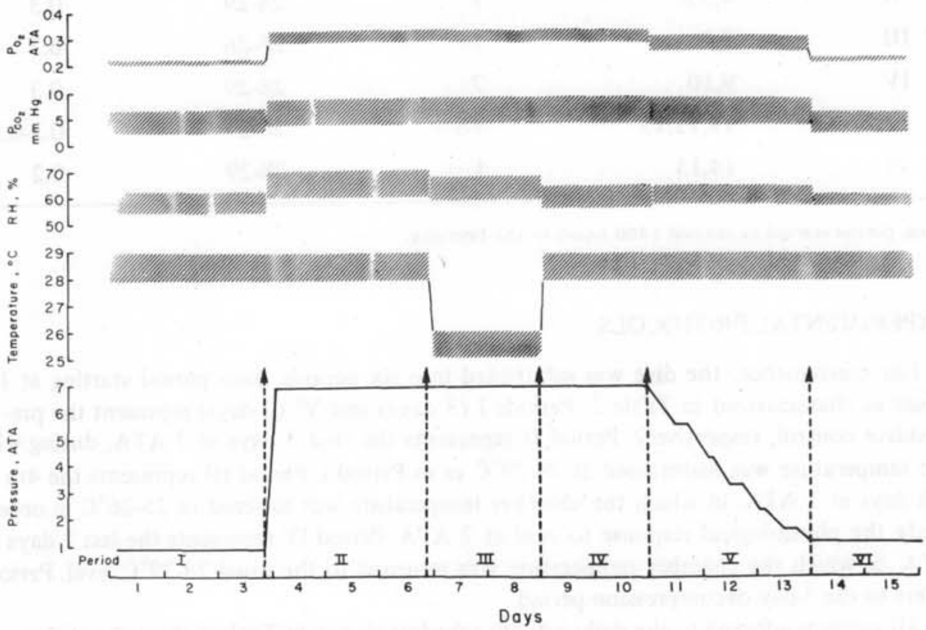

Fig. 1. Dive profile and environmental parameters.

ENVIRONMENTAL PARAMETERS

As shown in Fig. 1, the chamber temperature was maintained at 28-29°C[1], except during 2 days (4th and 5th days at 7 ATA; Period III) when it was lowered to 25-26°C. The relative

[1] This temperature was selected because we felt it would be close to a comfort zone for 7-ATA heliox environment based on the prediction by Webb (1970). During pre- and postdive control periods at this temperature, the subjects felt somewhat warm and elected to wear shorts only; no visible sweating was observed. On the other hand, in the 7-ATA heliox environment, the subjects felt somewhat cold and elected to wear additional clothing. Therefore, the subjects were advised to remove additional clothing 15 min before the measurements of skin and rectal temperature.

humidity, determined by the difference in dry and wet bulb temperatures, was maintained at 60 ± 10%. The P_{O_2} of the chamber gas was raised and maintained at 0.3 ATA during the dive. Although the original plan was to maintain the level of P_{CO_2} below 7 mm Hg inside the chamber, the CO_2 scrubber system was not fully satisfactory and P_{CO_2} often increased to nearly 10 mm Hg. Moreover, the fluctuations in P_{CO_2} were rather large.

TABLE 2

Designation of experimental periods

Periods	Dive days	Total pressure (ATA)	Temperature range (°C)	P_{O_2} (ATA)
I	1,2,3	1	28-29	0.2
II	4,5,6	7	28-29	0.3
III	7,8	7	25-26	0.3
IV	9,10	7	28-29	0.3
V	11,12,13	7-1	28-29	0.3-0.2
VI	14,15	1	28-29	0.2

Each period started at around 1400 hours of the first day.

EXPERIMENTAL PROTOCOLS

For convenience, the dive was subdivided into six periods, each period starting at 1400 hours as characterized in Table 2. Periods I (3 days) and VI (2 days) represent the pre- and postdive control, respectively. Period II represents the first 3 days at 7 ATA, during which the temperature was maintained at 28-29°C as in Period I. Period III represents the 4th and 5th days at 7 ATA, in which the chamber temperature was lowered to 25-26°C in order to study the physiological response to cold at 7 ATA. Period IV represents the last 2 days at 7 ATA, in which the chamber temperature was returned to the usual 28-29°C level. Period V refers to the 3-day decompression period.

All subjects adhered to the daily activity schedule shown in Table 3 throughout the entire experimental period.

By weighing every dish immediately before and after each meal, a complete record of the food consumed by each subject was kept. Food in each dish was subsequently homogenized and analyzed for carbohydrate, lipid, protein, water, Na, and K in the Morinaga Nutrition Laboratory, Tokyo. Each subject was given soybean sauce (shoyu) contained in a 10-ml plastic syringe to quantify its consumption. Since soybean sauce contains a considerable amount of NaCl, salt grain was not separately given.

Body weight was measured to within ± 50 gm, after the urinary bladder was emptied at 0600 hours each morning. The measurements of pulse rate, blood pressure, body temperatures, and oxygen consumption were made at rest in a sitting position. The blood pressure was measured by using an anaeroid sphygmomanometer. Both the rectal (T_r) and

TABLE 3
Daily activity schedule inside the chamber

Hours	Activity
0600	Rise out of bed; empty urinary bladder; measurements of body weight, skinfold thickness, pulse rate, blood pressure, rectal and skin temperatures, and oxygen consumption; draw venous blood sample (10 ml).
0730	Breakfast
1030	Empty urinary bladder; measurements of pulse rate, blood pressure, rectal and skin temperatures, and oxygen consumption.
1200	Lunch
1500	Empty urinary bladder; repeat the same measurements carried out at 1030.
1630	Supper
1800	Submaximal exercise test (once in each period except Period V).
1930	Repeat the same measurements carried out at 1030.
2030	Snack
2200	Empty urinary bladder; retire to bed.

skin temperatures were measured to within ± 0.1°C using a YSI telethermometer (Yellow Springs Instrument Co., Model 46). The skin temperatures were measured at the forehead, chest, abdomen, back, upper arm, hand, thigh, calf, and foot and the mean skin temperature ($\overline{T}_s$) was computed by a formula of Consolazio, Johnson, and Pecora (1963). The mean body temperature ($\overline{T}_B$) was computed by a formula: $\overline{T}_B = (2/3)T_r + (1/3)\overline{T}_s$.

Oxygen consumption was determined by an open-circuit method. During the final 2 min of a 10-min breathing period, the expired gas was collected in a Douglas bag which had been rinsed twice with the expired gas during the first 8 min. The volume of expired gas was measured by a dry gas meter (A. H. Thomas Co., Philadelphia) which had been calibrated in both 1- and 7-ATA environments. A portion of the mixed expired gas was passed through a needle valve in the chamber wall for the analyses of O_2 and CO_2 concentrations by a gas chromatograph[2] (Shimazu Manufacturing Co., Japan). The inspired chamber gas was also sampled through a needle valve for analysis. Appropriate corrections for pressure, temperature, and water vapor were made to express the values of $\dot{V}_{O_2}$ in STPD.

Skinfold thickness was measured by using a caliper (Hemco, Holland, Michigan) which read from 0-40 mm in 0.1-mm increments. The following sites were selected: chest (at the juxta nipple), abdomen (one adjacent to the umbilicus and the other on midaxillary line at umbilicus level), arm (at the posterior midpoint between acromion and the tip of olecranon), subscapula (below the tip of the scapula), and knee (above the patella).

Each subject freely voided urine into a container during each of the four intervals (0601-1030, 1031-1500, 1501-2200, 2201-0600 hours next day). As soon as each container

[2]The accuracy of CO_2 and O_2 measurements was ± 0.02 and 0.04%, respectively.

was locked out at the end of each interval, the volume was recorded; then an aliquot of about 30-ml was poured into a polyethylene vial containing sodium metabisulfite and was frozen immediately. Catecholamines were determined only in Dive I by the spectrophotofluorometric method of Shore and Olin (1958), using a Technicon Auto Analyzer.

Submaximal exercise tests were carried out using a bicycle ergometer (Monark, Verberg, Sweden). During the final 2 min of a 10-min exercise period at 500 kilopond meter/min, the heart rate, $\dot{V}_E$, and $\dot{V}_{O_2}$ were determined: the heart rate by the use of EKG, and $\dot{V}_E$ and $\dot{V}_{O_2}$ using an open-circuit method as described above. The subject breathed through a standard commercial mouthpiece double-hose assembly (U.S. Divers, Santa Ana, California). No exercise tests were performed during the decompression period. Although the test was performed in both dives, complete measurements of cardiorespiratory functions were made only in Dive I.

RESULTS

CALORIC INTAKE

The average daily caloric intake during various periods is summarized in Table 4. During the predive control period (Period I) the daily caloric intake amounted to approximately

TABLE 4

Caloric intake and dietary composition

Periods (n)	Caloric intake (kcal/day)	Caloric intake		
		carbohydrate (%)	*lipid* (%)	*protein* (%)
	(*mean* ± SE)			
I (21)	3080 ± 697	63	18	19
II (21)	3126 ± 702	58	22	20
III (14)	3270 ± 917	59	21	20
IV (14)	2826 ± 788	62	19	19
V (21)	2913 ± 660	55	23	22
VI (14)	2702 ± 755	63	17	20

3000 kcal. Although there were small variations in the magnitude of daily caloric intake during various dive periods, no significant changes were noted. On the average, 60% of the calories were contributed by carbohydrates and 20% each by lipids and proteins. The body weight also fluctuated randomly during the experiment without showing any significant trend (Fig. 2). Total skinfold thickness (the sum of skinfold thickness measured at five sites; *see* METHODS) did not show any significant changes.

PULSE RATE AND BLOOD PRESSURES

The average values of pulse rate and blood pressures measured daily four different times are shown in Fig. 2. In this graph the early morning (0600 hours) values obtained during the

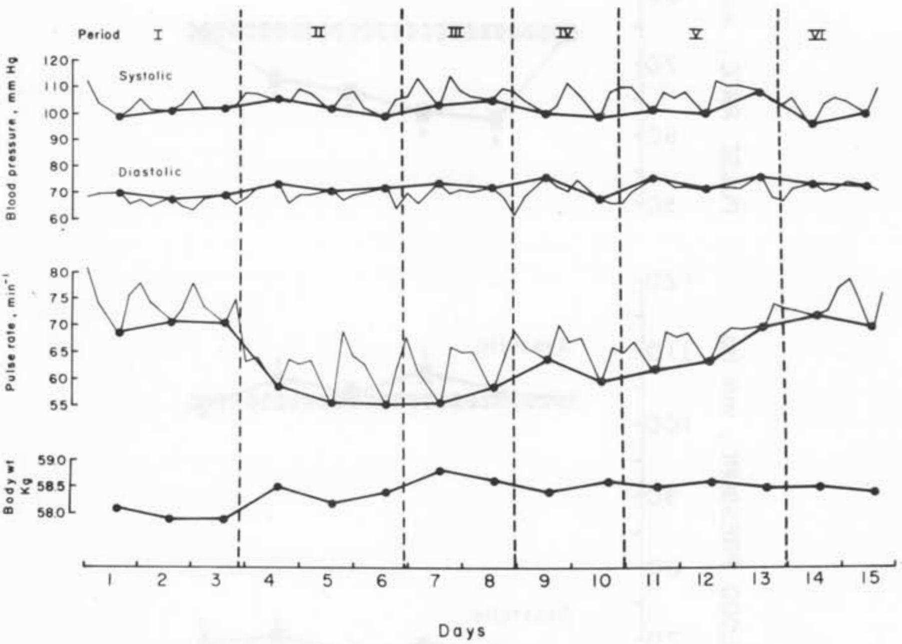

Fig. 2. Daily changes in blood pressures, pulse rate, and body weight. In this and Fig. 4, each point represents the average for seven subjects; the early morning values (0600 hours) are connected by thick lines; and the four values obtained each day are connected by thin lines which represent diurnal variations.

entire period are connected by thick lines and the four values obtained for each day by thin lines. In other words, the thick lines indicate the overall trend while the thin lines represent the diurnal changes. For the statistical evaluation of the data, the grand mean (± SE) was computed for each period and is shown in Fig. 3.

The pulse rate during 3 days of predive control (Period I) was stable, with a mean of 74 ± 1 beats per minute. Upon compression to 7 ATA without changing the environmental temperature (Period II), the pulse rate decreased by approximately 20% and remained at this level. Moreover, a reduction in the chamber temperature to 25-26°C at 7 ATA (Period III) failed to decrease the pulse rate further. It is, however, interesting to note that the pulse rate tended to increase again during decompression and returned to the predive control (Period VI). In general, the pulse rates measured in the early morning were lower than that in the late morning and afternoon throughout the experiment.

As compared to Period I, the systolic blood pressure increased significantly during Periods III ($P < .01$) and V ($P < .05$). The diurnal changes were qualitatively similar to those of the pulse rate. The diastolic blood pressure tended to increase during Periods II-V, but a significant increase was noted only during Period V ($P < .05$). The diastolic pressure also remained elevated during Periods VI ($P < .05$). The pattern of diurnal changes in the diastolic pressure were opposite to those of pulse rate and systolic blood pressure throughout the entire experimental period.

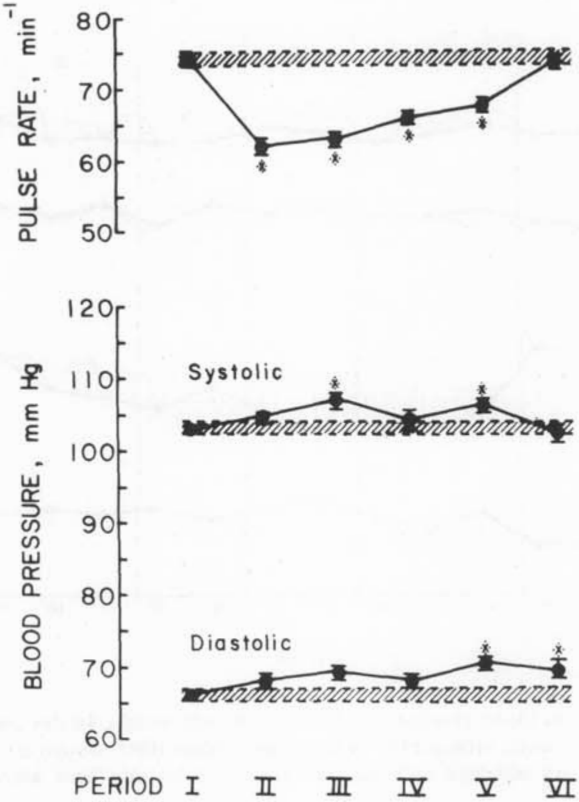

Fig. 3. Changes in the average pulse rate and blood pressures during the six experimental periods (See Table 2 for designation of experimental periods.) In this and Fig. 5, each point represents the mean (± SE) of all measurements taken four times a day from seven subjects during the respective period. The shaded area indicates the predive control values (mean ± SE) taken during Period I. ※ denotes a significant difference ($P < .05$ on nonpaired t test) from the corresponding control (Period I).

BODY TEMPERATURES

The early morning body temperatures as well as the diurnal rhythm are shown in Fig. 4, using the same convention for the construction as in Fig. 2. Mean values for each period are shown in Fig. 5.

The early morning rectal temperature decreased slightly from 36.6°C during Period I to about 36.3°C during Period II. The mean rectal temperature for Period II (36.8 ± 0.04°C) was significantly lower than that for Period I (37.0 ± 0.03°C). No further reduction in the rectal temperature was noted during Period III after which the rectal temperature tended to increase slowly toward the predive control level. On the other hand, the mean skin temperature decreased more drastically during Period II ($P < .01$) and, moreover, showed a further reduction during Period III ($P < .01$). As in the case of the rectal temperature, the mean skin temperature began to increase slowly toward the predive control after Period III.

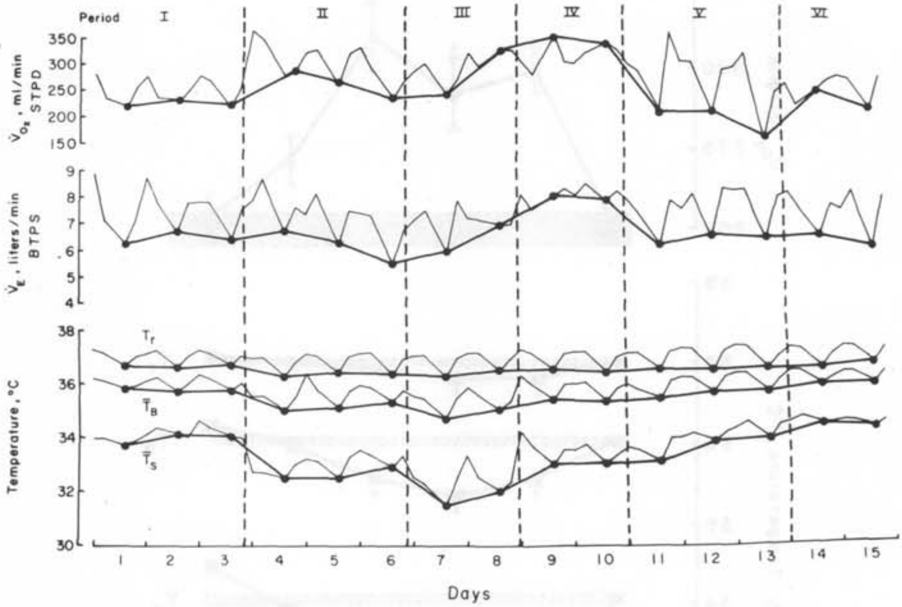

Fig. 4. Daily changes in oxygen consumption ($\dot{V}_{O_2}$), minute volume ($\dot{V}_E$), and rectal (T_r), mean body ($\bar{T}_B$), and mean skin ($\bar{T}_S$) temperatures.

The mean body temperature changed in a manner similar to that of the mean skin temperature. A maximal reduction in the mean body temperature was 0.7°C observed during Period III ($P < .01$).

As expected, both rectal and mean skin temperatures were always lowest during the early morning and were elevated during the rest of the day. The magnitude of this diurnal variation, as calculated by the difference between the highest and lowest temperatures in a given day, was 0.5-0.6°C during Period I for both rectal and mean skin temperatures, as shown in Table 5. There were significant increases in the magnitude of the diurnal variations of the rectal, mean skin, and mean body temperatures during Periods II-V ($P < .05$).

The marked reductions in mean skin temperature observed at 7 ATA are primarily due to reductions in the peripheral skin temperatures as shown in Fig. 6. In this figure, the skin temperatures of 10 different regions obtained from Subject C in 1- and 7-ATA environments are shown. In the 1-ATA, 28°C environment the regional difference in skin temperature was less than 2°C. In the 7-ATA, 28°C environment the skin temperatures of the forehead and the trunk (e.g. chest, abdomen, and back) were lowered only slightly but those of the extremities (e.g. upper arm, lower arm, hand, thigh, calf, and foot) were lowered rather markedly, thereby increasing the regional difference in the skin temperature almost twofold. These changes in regional skin temperatures were magnified in the 7-ATA, 26°C environment.

OXYGEN CONSUMPTION

The average $\dot{V}_E$ remained at about 7.5 liters/min (BTPS) throughout the entire experimental period, while the $\dot{V}_{O_2}$ increased significantly ($P < .05$) during Periods II-IV, as

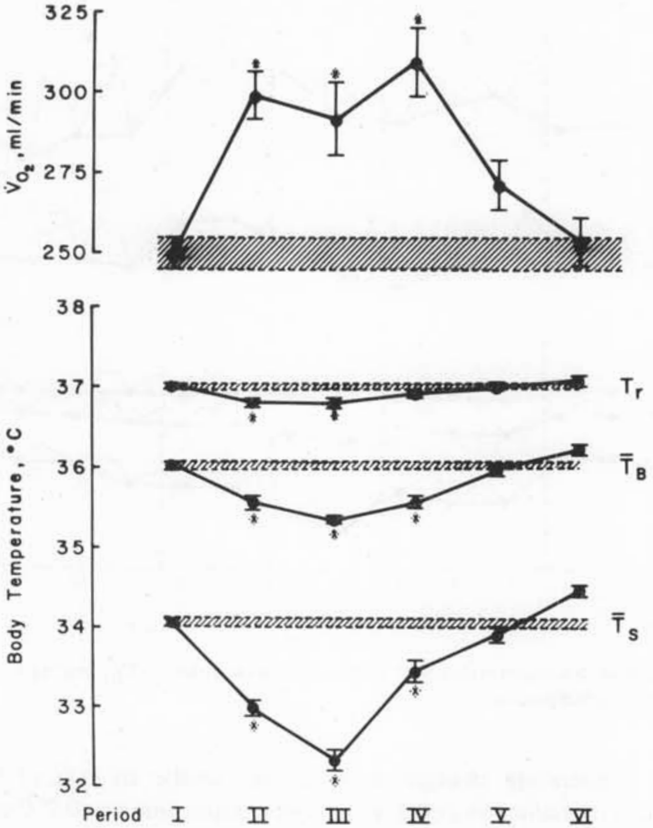

Fig. 5. Changes in the average oxygen consumption ($\dot{V}_{O_2}$) and body temperatures during the six experimental periods. ※ denotes a significant difference ($P < .05$ on nonpaired t test) from the corresponding control (Period I).

TABLE 5

Diurnal variations of body temperature and $\dot{V}_{O_2}$

Periods (n)	ΔT_r (°C)	$\Delta \bar{T}_s$ (°C)	$\Delta \bar{T}_B$ (°C)	$\Delta \dot{V}_{O_2}$ (ml/min–STPD)
		(*mean* ± SE)		
I (21)	0.6 ± 0.04	0.5 ± 0.05	0.5 ± 0.04	69 ± 8
II (21)	0.8 ± 0.03*	0.8 ± 0.06*	0.7 ± 0.03*	109 ± 10*
III (14)	0.8 ± 0.04*	1.3 ± 0.11*	0.9 ± 0.04*	126 ± 19*
IV (14)	0.7 ± 0.06	1.0 ± 0.14*	0.8 ± 0.08*	106 ± 13*
V (21)	0.8 ± 0.05*	0.7 ± 0.07*	0.7 ± 0.05*	147 ± 14*
VI (14)	0.8 ± 0.06	0.5 ± 0.05	0.6 ± 0.04	104 ± 19

* Significantly different ($P < .05$ on nonpaired t test) from the corresponding value obtained during Period I.

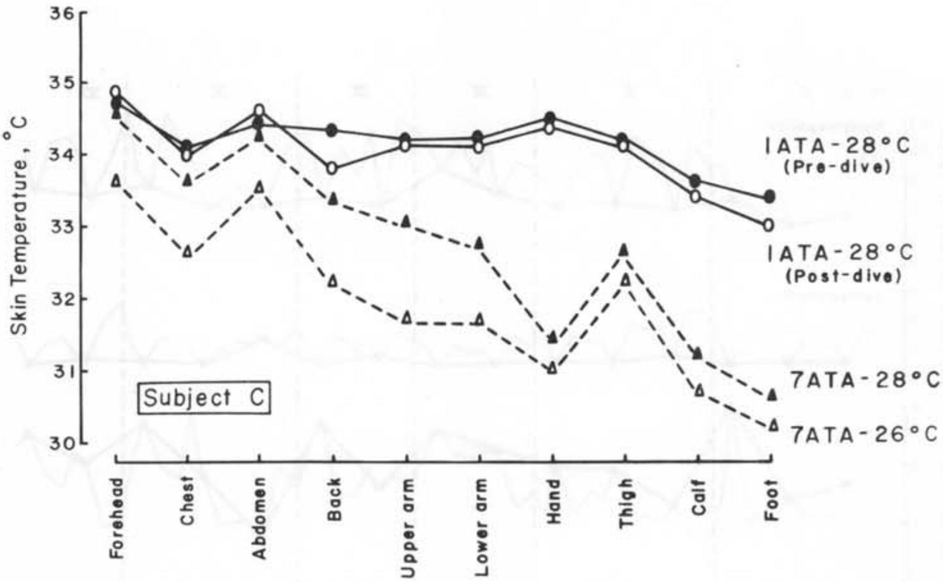

Fig. 6. Regional skin temperature profiles at 1 and 7 ATA in one subject ("C").

compared to Period I (Figs. 4 and 5). The magnitude of increase was about 20% of the predive control level. Interestingly, the $\dot{V}_{O_2}$ during Period III was not different from that during Periods II and IV. For both $\dot{V}_E$ and $\dot{V}_{O_2}$, distinct diurnal variations were observed, except during Period IV when the $\dot{V}_E$ rhythm was damped while the $\dot{V}_{O_2}$ rhythm was reversed for some unknown reason(s). The magnitude of this diurnal variation for $\dot{V}_{O_2}$ was 69 ml/min (STPD) during Period I but significantly increased during Periods II-V ($P < .05$), as shown in Table 5.

CATECHOLAMINE EXCRETION

The urinary excretion of catecholamines showed marked diurnal variations. As shown in Fig. 7, the rate of catecholamine excretion was lowest at night and nearly tripled during the daytime. The daily excretion of epinephrine remained at about 8 μg/day throughout the experimental period, except during Period II when a significant increase was noted ($P < .05$) (Table 6). The daily excretion of norepinephrine was also maintained fairly constant throughout the entire experimental period.

CARDIORESPIRATORY RESPONSES TO SUBMAXIMAL EXERCISE

The average values of heart rate, $\dot{V}_E$ and $\dot{V}_{O_2}$ determined during the last 2 min of the 10-min exercise at 500 kilopond-meter/min are summarized in Table 7. The heart rate was significantly lower during Periods II and III as compared to Period I ($P < .05$). Although $\dot{V}_E$ values during Periods II-IV tended to be lower than the control, no statistical significance was noted. The $\dot{V}_{O_2}$ was significantly higher during Period IV as compared to Period I ($P < .05$), resulting in a higher O_2-pulse ($\dot{V}_{O_2}$/heart rate; $P < .05$) and a lower ventilatory equivalent ($\dot{V}_E/\dot{V}_{O_2}$; $0.05 < P < 0.10$) during Period IV.

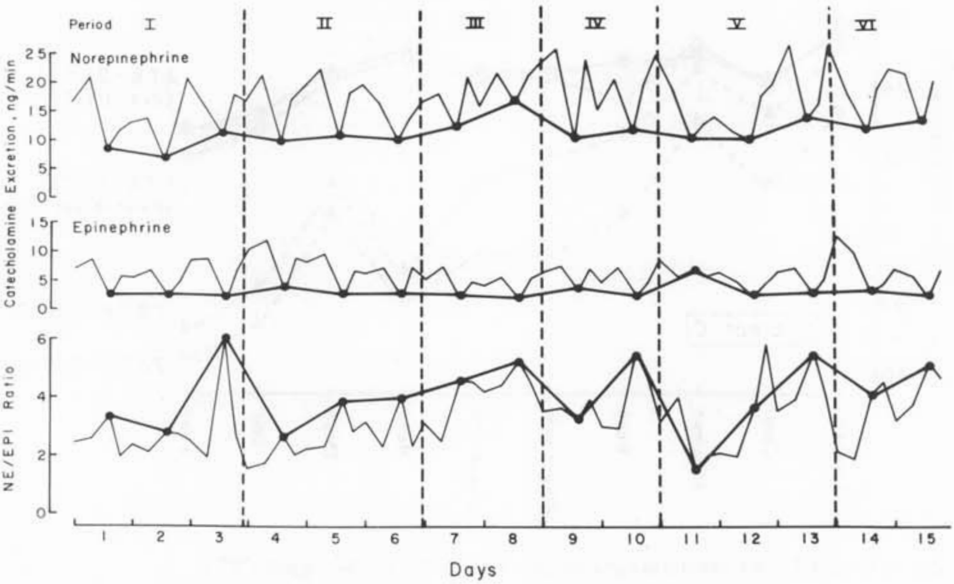

Fig. 7. Daily changes in urinary excretion of norepinephrine and epinephrine. Each point represents the average for three subjects in Dive I. The early morning values (0600 hours) are connected by thick lines; thin lines represent diurnal variations.

TABLE 6

Daily excretion of catecholamines in urine

Periods (n)	Norepinephrine (μg/day)	Epinephrine (μg/day)
	(*mean* ± S.E.)	
I (9)	19.0 ± 1.6	7.8 ± 0.4
II (9)	21.6 ± 1.6	9.9 ± 0.8*
III (6)	22.9 ± 1.2	6.4 ± 0.7
IV (6)	24.6 ± 3.6	7.5 ± 0.7
V (9)	21.3 ± 2.4	7.7 ± 0.6
VI (6)	24.5 ± 2.3	8.8 ± 1.1

*Significantly different ($P < .05$ on nonpaired t test) from the corresponding control (Period I).

TABLE 7

Cardiorespiratory responses to a submaximal exercise
(500 kilopond meter/min)

Period	Heart rate (per min)	$\dot{V}_E$ (liters/min–BTPS)	$\dot{V}_{O_2}$ (ml/min–STPD)	$\dot{V}_{O_2}$/Heart rate (ml/beat)	$\dot{V}_E/\dot{V}_{O_2}$ (liters/100 ml)
I	127 ± 10	43.6 ± 7.9	1,836 ± 170	14.4 ± 0.6	2.36 ± 0.22
II	113 ± 6*	36.9 ± 6.9	1,621 ± 174	14.4 ± 2.2	2.29 ± 0.49
III	99 ± 10*	30.4 ± 4.4	1,529 ± 184	15.7 ± 3.6	2.00 ± 0.33
IV	114 ± 10	34.4 ± 5.9	2,031 ± 223*	17.7 ± 0.3*	1.68 ± 0.10
VI	124 ± 11	45.4 ± 6.1	1,756 ± 249	14.2 ± 2.0	2.58 ± 0.05

Each value represents mean (± SE) on three subjects. Only one measurement was made during each period on each subject.

*Significantly different ($P < .05$ on paired t test) from the corresponding values obtained during Period I.

DISCUSSION

The basic design of the present investigation is unique in that: (1) various physiological functions such as energy metabolism, cardiovascular adjustments, and body heat balance were measured four different times each day, and (2) the physiological responses to a subtle cold stress were studied in a hyperbaric environment. As a result, one cannot only assess the overall changes in these physiological functions with more confidence but the possible changes in the diurnal rhythm can also be detected. Moreover, the duration of the saturation dive was sufficiently long (7 full days at 7 ATA) to gain insight into the possible adaptation to living in a hyperbaric heliox environment. The provision of 3-day predive and 2-day postdive control periods also enabled us not only to have a solid baseline for each function, but also to gain more insight into the recovery pattern of the affected physiological functions observed during the hyperbaric period.

ENERGY BALANCE

Although approximately 4000 kcal in food was offered daily, their caloric intake averaged 3000 kcal a day throughout the entire experimental period (Table 4). Even when the chamber temperature was lowered by 3°C (Period III) and the mean body temperature decreased almost by 0.7°C (Fig. 5), the increase in caloric intake was insignificant. The above level of caloric intake is considerably lower than the values reported in other dives where the depth of dive is deeper than in the present dive. For instance, in a dry heliox saturation dive to 500 fsw conducted in Hawaii, the average daily caloric intake amounted to 4000 kcal (Moore et al. 1972). In a dive to 1200 fsw conducted by the University of Pennsylvania, the divers consumed about 3500 kcal a day and yet their body weight decreased by 4 kg (Webb *in press*). Such a high level of caloric intake is usually attributed to continuous heat drains in the hyperbaric helium environment (*see below*). Perhaps in the present dive the depth is relatively shallow and, hence, the magnitude of heat drain is considerably less than in the above dives. Evidently, 3000 kcal a day was sufficient for the subjects since body weight and skinfold thickness remained fairly constant.

CARDIOVASCULAR ADJUSTMENTS

In agreement with previous reports (Hamilton et al. 1966; Raymond et al. 1968; Schaeffer et al. 1970; Salzano et al. 1970; Bühlman et al. 1970; Moore et al. 1972), a distinct hyperbaric bradycardia was observed in the present work (Figs. 2 and 3). The appearance of this bradycardia was already noted in the first measurement of pulse rate, taken 1 hour after the completion of the compression to 7 ATA. Moreover, the degree of bradycardia remained the same even when the chamber temperature was lowered to 25-26°C (Period III) from 28-29°C at 7 ATA, suggesting that the cold stress associated with the hyperbaric heliox environment may not be causally related to hyperbaric bradycardia. Such a finding is at variance with the report of Moore et al. (1972) who observed an attenuation of bradycardia upon raising the chamber temperature from 27.8 to 29°C at 500 fsw.

Both systolic and diastolic blood pressures increased slightly at depth. Although some of these increases were statistically significant (Fig. 3), it is difficult to interpret these changes in the absence of knowledge on the stroke volume and the peripheral blood flow.

BODY HEAT BALANCE

The rate of resting heat production, based on the measurement of $\dot{V}_{O_2}$ (Figs. 4 and 5), increased by 20% at 7 ATA. Despite this increase in heat production, both the rectal and skin temperatures decreased significantly (Figs. 4 and 5). As briefly discussed in the preceding sections, the greater thermal conductivity of the hyperbaric heliox environment is

TABLE 8

Thermal characteristics of gaseous environment

	1-ATA air	7-ATA mixed gas
	O_2–0.2 ATA N_2–0.8 ATA	O_2–0.3 ATA N_2–1.2 ATA He–5.5 ATA
ρ, g/liter	1.150	2.648
C_P, cal/g · °C	0.256	1.027
ρC_P, cal/liter · °C	0.295	2.719
Relative heat capacity	1.0	9.2
Convective character*	1.0	40.8

ρ = density; Cp = specific heat at constant pressure; $\rho \cdot$Cp = heat capacity.
*See Webb (1970).

responsible for this negative heat balance. As shown in Table 8, the heat capacity and the convective character of the hyperbaric gas mixture (5.5 ATA He + 1.2 ATA N_2 + 0.3 ATA O_2) are 9.2 and 40.8 times greater than the corresponding values of 1-ATA air. On the basis of $\Delta\dot{V}_{O_2}$ and $\Delta\overline{T}_B$ observed at 7 ATA, the magnitude of the total extra heat loss over and above the level at Period I was estimated to be 2500 kcal during 7 days at 7 ATA. Since the caloric intake remained fairly constant during the experimental period, one would theoretically expect about 280 gm of body fat to be mobilized to make up for this extra heat loss.

Obviously, this loss of body fat is too small to be picked up by the measurement of body weight.

In previous dives where body temperature was measured, reductions in rectal (or oral) and skin temperatures were observed (Raymond et al. 1968; Moore et al. 1972), although the opposite phenomenon was reported in other dives (Hock, Bond, and Mazzone 1966; Webb 1972). Results very similar to those obtained in the present work were reported by Moore et al. (1972), who also observed a significant increase in respiratory heat loss in a hyperbaric heliox environment. According to their work, the increase in respiratory heat loss is rather small at 7 ATA and, hence, was not measured in the present work. They also noted a strong vasoconstriction of peripheral vessels at 500 fsw, which could not be reversed even during a usual cold pressor test.

Webb (*in press*) observed during a dive to 1200 fsw that rectal temperature was higher during the early morning but was lower during the afternoon as compared to the predive level, indicating a damping of the diurnal rhythm. However, the present work indicates an exaggeration of the diurnal rhythms for both body temperature and oxygen consumption (Table 5). More experiments are needed in the future to resolve this conflict in observations.

CATECHOLAMINE EXCRETION

The saturation divers were subjected to a considerable psychological stress throughout the dive, especially during the decompression period. In addition, they were exposed to a cold stress even when the chamber temperature was high enough according to the 1-ATA air standard (Webb 1970). One would, therefore, expect an increase in the release of catecholamines during a saturation dive. On the other hand, the inhibitory effect of helium on the catecholamine system, as recently proposed by Raymond, Weiskopf, Halsey, Goldfein, Eger, and Severinghaus (1972), would tend to counteract the above stimulatory effect. In the present investigation, the urinary excretion of norepinephrine was not significantly elevated during the dive while that of epinephrine showed a significant increase only during Period II (Table 6). In several previous dry heliox saturation dives (Bühlmann, Ziegler, and Müller 1972; Waldvogel and Bühlmann 1968) the daily excretion of catecholamines tended to decrease.

CARDIORESPIRATORY RESPONSES TO EXERCISE

Both the heart rate and $\dot{V}_E$ during a standardized submaximal exercise were lower during Periods II-IV as compared to those during Period I (Table 7). As a result, the O_2-pulse increased while the ventilatory equivalent decreased during Periods II-IV. These findings are in agreement with previous reports (Hamilton et al. 1966; Salzano et al. 1970; Moore et al. 1972; Strauss, Wright, Peterson, Lever, and Lambertsen 1972). These changes in heart rate and $\dot{V}_E$ tended to be exaggerated during Period III but a simultaneous reduction in $\dot{V}_{O_2}$ makes the interpretation of the data difficult. A maintenance of lower heart rate during exercise in the hyperbaric environment than in 1-ATA air is certainly a manifestation of hyperbaric bradycardia for which no acceptable explanations are available at present (*see above*). Nevertheless, it is important to ask if a lower heart rate during exercise in the hyperbaric environment indicates a correspondingly lower cardiac output. If it does, the maximal work capacity is certainly expected to be affected in the hyperbaric environment. The answer to this important question is not available. The lower $\dot{V}_E$ during exercise in the hyperbaric environment is most likely due to the high gas density. As shown in Table 8, the gas density at 7 ATA is 2.5 times greater than that at 1-ATA air. While the work of breathing undoubtedly increases as the density of breathing gas increases, it does not seem to limit the divers' work capacity (Strauss et al. 1972).

PHYSIOLOGICAL RESPONSES TO COLD IN HYPERBARIC HELIOX

One objective of this investigation was to document the physiological responses to a small reduction in the chamber temperature at 7 ATA from 28-29°C to 25-26°C for 2 days. By comparing the data obtained during Period III with those obtained during Periods II and IV, one can draw certain conclusions pertaining to the above objective. During Period III the mean skin temperature showed a further reduction ($P < .01$) while the systolic blood pressure tended to increase (Figs. 3 and 5). Caloric intake, pulse rate, diastolic blood pressure, rectal temperature, and $\dot{V}_{O_2}$ did not change significantly (Table 4 and Figs. 3 and 5). However, urinary excretion of epinephrine decreased ($P < .001$ for Period II vs. III; $P > .10$ for Period III vs. IV), while the norepinephrine changed insignificantly, thereby increasing the urinary norepinephrine-epinephrine ratio.

It should be re-emphasized that the subjects were already in a state of negative body heat balance even before Period III and showed significant changes in the pulse rate, blood pressure, and $\dot{V}_{O_2}$. Evidently, the lowering of chamber temperature from 28-29 to 25-26°C is not sufficient to induce marked changes in cardiovascular and metabolic functions.

ADAPTATION TO HIGH PRESSURE

Although the duration of the present dive was only 7 days on the bottom, one may gain insight into the possible adaptation of physiological systems to the hyperbaric heliox environment by comparing the results obtained during Period II with those obtained during Period IV. As compared to Period II, pulse rate and rectal, skin, and mean body temperatures were significantly higher during Period IV ($P < .05$, Figs. 3 and 5), whereas other measured functions such as $\dot{V}_{O_2}$ and blood pressure were not different between Periods II and IV. The urinary excretion of epinephrine was lower ($P < .05$) while that of norepinephrine tended to be higher during Period IV than during Period II and, thus, the urinary norepinephrine-epinephrine ratio increased during Period IV (Table 6). The latter findings may indicate an endocrine adaptation to cold stress at 7 ATA. Similar increases in the urinary norepinephrine-epinephrine ratio have been noted in cold-acclimated men (Kang, Han, Paik, Park, Kim, Kim, Rennie, and Hong 1970; Gale 1973). The O_2-pulse during exercise tended to increase while the ventilatory equivalent tended to decrease in all subjects during Period IV as compared to Period II (Table 7). Whatever the underlying mechanisms for these changes, the apparent efficiency of the cardiorespiratory system to deliver O_2 to the working muscle seems to be higher during Period IV. In other words, even during 7 days of stay in the hyperbaric heliox environment, there appears to develop subtle endocrine and cardiorespiratory adaptations.

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Matsuda, M., H. Nakayama, A. Itoh, N. Kirigaya, F. K. Kurata, R. H. Strauss, and S. K. Hong. 1975. Physiologie humaine au cours d'une plongée fictive à saturation de 10 jours à 7 ATA en hélium-oxygène (SEATOPIA). I. Fonctions cardiovasculaires et thermorégulatrices. Undersea Biomed. Res. 2(2):101-118.–Les fonctions cardiovasculatires, le métabolisme énergétique, et l'échange de la chaleur corporelle ont été étudiés chez sept sujets mâles au cours d'un sejour de 10 jours en hélium-oxygène (plongée fictive; 7 jours à 7 ATA et 3 jours de décompression). La température ambiante a été maintenue à 28-29°C sauf pendant les 4^e^ et 5^e^ journées à 7 ATA, quand elle a été réduite à 25-26°C pour étudier les effets du froid. La ration calorique quotidienne est restée à 3000 kcal pendant la plongée. La fréquence cardiaque a été environ 80% de celle controlée avant la plongée; la réduction de la température n'a pas augmenté cette bradycardie. Les températures rectale et cutanée ont diminué à 7 ATA, avec une diminution encore plus prononcée à 25-26°C. La diminution de la température corporelle moyenne a été attribuée à la reduction des températures cutanées périphériques. L'excrétion urinaire des catecholamines n'a pas changé. Au cours d'une épreuve d'exercise sous-maximal standard (500 kilopond meter/min) on a remarqué un plus grand $\dot{V}_{O_2}$ et un equivalent ventilatoire plus restreint par rapport aux valeurs controlées avant la plongée. Les changements diurnes de la température corporelle et de $\dot{V}_{O_2}$ s'exaggeraient aux profondeurs. Vers la fin de la periode à 7 ATA, la fréquence cardiaque et la température corporelle manifestaient une tendance à revenir aux valeurs d'avant la plongée, ce qui suggérerait une adaptation possible à l'hyperbarie.

pression sanguine	fréquence cardiaque
ration calorique	température rectale
hyperbarie	plongée à saturation
consommation d'oxygène	température cutanée

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