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Maximal physical-work capacity of man at 43.4 ATA

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Dwyer, J., H. A. Saltzman, and R. O'Bryan. 1977. Maximal physical-work capacity of man at 43.4 ATA. Undersea Biomed. Res. 4(4): 359–372.—Four U.S. Navy divers performed submaximal and maximal work in 4.4 °C water on an underwater-cycle ergometer at 1.6 and 43.4 ATA (1400 fsw). The $\dot{V}O_{2max}$ (the $\dot{V}O_2$ at the maximally tolerated 6-min work load) under control conditions at 1.6 ATA was 2.86–3.00 liter · min^{-1} in three divers, and decreased to 1.81–2.36 liter · min^{-1} at the maximal depth. The fourth diver increased his $\dot{V}O_{2max}$ from 1.53 liter · min^{-1} at 1.6 ATA to 1.90 liter · min^{-1} at 43.4 ATA. Reductions in maximal external-work performance on the ergometer averaged 30% at depth; measured work performance on the ergometer averaged 30% at depth; measured work on the ergometer was generally restricted to 75 watts or less. End-tidal P_{CO_2} increased concordantly with $\dot{V}O_2$ at depth but did not exceed 50 mmHg. Carbon dioxide retention was not a significant factor in work limitation. The $\dot{V}E$ during maximal work did not remain a fixed percentage of the maximum voluntary ventilation (MVV) at 43.4 ATA, but there was no consistent tendency for the divers to respire nearer their MVV. Dyspnea was severe at depth during exercise and the perceived effort expended to breathe was at the extreme limit for each man. The observed severe restriction of work capacity and $\dot{V}O_{2max}$ underwater at 43.4 ATA is in sharp contrast to extrapolations based on observations in dry chambers, where subjects breathed gases of comparable or greater densities at lesser depths.

exercise in water
oxygen consumption
carbon dioxide
dyspnea
maximum voluntary ventilation
pulmonary ventilation

In 1973 a simulated dive to 50 ATA (1600 fsw) revealed unanticipated physiological responses to exercise in normal immersed men breathing from a semiclosed-circuit underwater breathing system[1] (Spaur 1974; Spaur, Raymond, Knott, Crothers, Braithwaite, Thalman, and Uddin 1977). The unexpected observations included: 1) an unusually rapid heart rate at relatively low levels of O_2 consumption ($\dot{V}O_2$); 2) a very low $\dot{V}O_2$ at the maximally tolerated level of work without significant change in Pa_{CO_2} pH, and lactate concentration in the blood; 3) subjective appreciation of severe breathlessness and impending blackout at these low levels of $\dot{V}O_2$; and 4) the inability of the subjects to perform work under these conditions was not accompanied by the usual features of alveolar hypoventilation encountered when large volumes of dense gas are respired.

Respiratory acidosis, hypoxemia in arterial blood, and altered mechanical properties of the lungs were apparently ruled out as possible causes of the subjective sensations that led to voluntary termination of exercise. Spaur and colleagues (1977) suggested that the mechanical consequences of respiring a dense gas through the added resistance of an appropriate breathing assembly led to pulmonary hyperinflation, analogous to what is observed in an acute asthmatic attack. Under these conditions, the known mechanical inefficiency of ventilation (Sharp, Danon, Druz, Goldberg, Fishman, and Machnach 1974) may have led to sensations of inspiratory insufficiency and dyspnea in the experimental subjects.

The scheduling of a subsequent dive to 1400 fsw (43.4 ATA) provided an opportunity for us to extend and assess the observations of Spaur and his co-workers (1977) under nearly comparable conditions with use of an underwater breathing apparatus designed to minimize external resistance to gas flow. Under the conditions of this experiment, in the evaluation of immersed men at 43.4 ATA, the respiratory physiological goals were to determine: 1) the effective $\dot{V}O_{2max}$; 2) what percentage of the $\dot{V}O_{2max}$ at sea level may be utilized at depth under otherwise comparable conditions; 3) whether maximally tolerated work correlated with elevations of the end-tidal P_{CO_2} ($P_{ET_{CO_2}}$); and 4) what percentage of the effective maximum voluntary ventilation (MVV) may be utilized during maximal exercise.

METHODOLOGY

The simulated dive was conducted in the U.S. Navy Experimental Diving Unit Ocean Simulation Facility in Panama City, Florida. The chamber complex consists of five interconnected chambers, each averaging 3.7 m in length and 2.5 m in diameter (total volume 67.58 m³). The center chamber was connected by a trunk to a large wet-pot chamber in which data acquisition apparatus and dive tenders were stationed. The wet pot, measuring 4.6 m in diameter and 14.75 m long, was filled with water maintained at 4.44 °C. An especially modified ergometer[2] was mounted on a frame 3 ft below the water surface. The exercise and respiration experiments described in this report were part of an experimental program designed to investigate several aspects of deep saturation diving with considerable time spent underwater (Fig. 1).

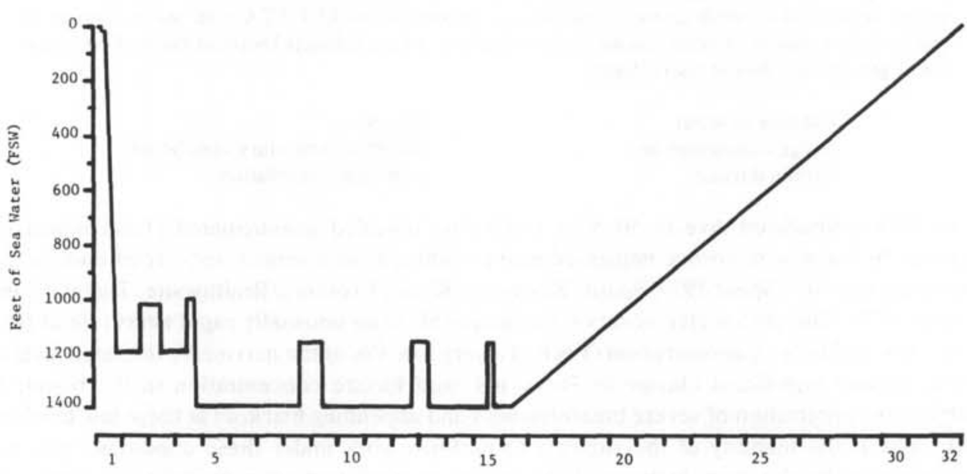

Fig. 1. Planned dive profile in days and feet of seawater (fsw). Pressure at maximum depth was 1400 fsw (43.4 ATA). Because of decompression sickness, the profile was modified and lengthened substantially after the 21st day.

The subjects were four of six experienced, healthy male divers selected to participate in this experiment. Exclusion of two subjects was based on our failure to obtain adequate physiological data at depth. Physical characteristics of the men are depicted in Table 1. In preparation for this experiment, all subjects performed calisthenics and a 7.25-km run, 5 days a week during the six weeks preceding the simulated dive. As an additional part of the training, each man performed four underwater work cycles, similar to the experimental protocol, during the two weeks preceding compression.

The diver wore a full-face mask with an oral compartment and breathed through a low-resistance directional valve.[3] Large-diameter hoses (7 cm) connected the inspiration and expiration ports of the breathing valve to gas-tight bags enclosed in a Plexiglas® gas-tight box (Fig. 2). Expired gas entered the Plexiglas compartment at a pressure greater than ambient, circulated around the bags, and leaked out a side arm of the expiratory hose into the water at the level of the diver's mouth. Thus, hydrostatic pressure differences were approximately equalized in a uniform manner. The gas bag containing inspired gas was maintained manually at an appropriate volume. Expired gas vented through the Plexiglas box into the water except during the measure of $\dot{V}_E$. To obtain a 1-min sample of $\dot{V}_E$, we collected the exhaled gas in the appropriate gas-tight bag.

The experimental sequence was performed in an identical manner during the control studies at 1.6 ATA (20 fsw) and at 43.4 ATA (1400 fsw). The diver was dressed in a hot-water heated suit and positioned comfortably on the underwater ergometer during rest and exercise periods. Throughout the 70 min of immersion required for each full experimental sequence, the divers remained subjectively warm; measured temperatures in the rectum and at multiple locations on the skin did not vary significantly from normal control measurements.

The first portion of the experimental sequence was a 10-min rest period. All measurements were made during the final minute. Six-minute work periods, separated by four minutes of rest, were scheduled at 25, 50, 75, 100, and 125 W. Although work-output levels are represented as watts measured on the ergometer, the actual work output of the diver was much higher due to the additional work of moving the limbs against the water and the constraints of the hot-water suit. On the basis of the work of Costill (1971), we estimated that the resistive-fluid medium alone increased the energy requirements of cycling on the ergometer by 33–42%. Therefore, the actual work performed to overcome the combined resistances of the ergometer, water, and thermal suit may have increased the net work output to perhaps twice the indicated load on the ergometer. The amount of useful work that a diver was able to apply to his underwater task, however, was that measured on the ergometer.

TABLE 1

DESCRIPTIVE CHARACTERISTICS OF THE TEST DIVERS

Diver*	Age, yr	Height, cm	Predive Weight, kg	Postdive weight, kg	Body-surface** area, m²	Diving experience, yr
1	42	175.26	71.82	69.09	1.87	9
2	23	175.24	80.00	76.14	1.96	5
3	29	190.50	103.18	94.09	2.32	5
4	35	182.88	78.86	73.18	2.01	12

*Data on two of the six test divers were not included in this study because researchers were unable to obtain adequate physiological data at depth.

**Computed with predive weight by method of DuBois and DuBois (1915):

$BSA\ (m^2) = Ht^{0.725} \cdot Wt^{0.425} \cdot 71.84 \cdot 10^{-4}$.

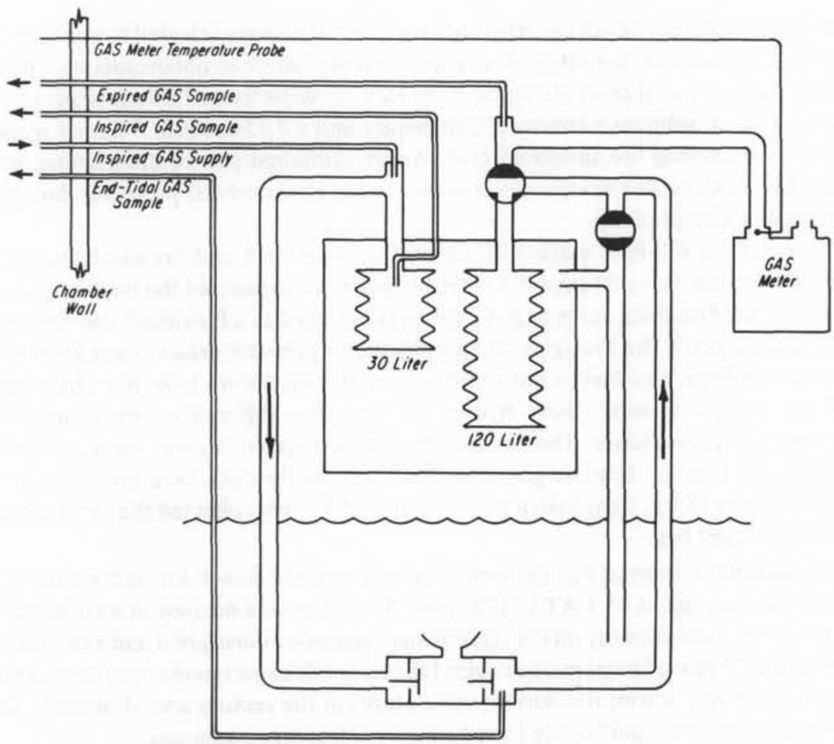

Fig. 2. Low-resistance breathing system for expired-gas collection and volume measurements.

The early failure of divers to perform moderate loads at maximum depth presented an opportunity for us to make repeated measurements at a light work load. In cases where a diver was unable to perform more than 5 min of work, however, no data were obtained. Ten minutes after completion of the exercise sequence, the diver performed two 15-s maximal voluntary ventilation tests (MVV_{15}) while remaining immersed. The expired gas during the two tests was collected and measured as in the exercise studies. The divers chose their own breathing rates for these tests.

Base-line exercise sequences during immersion and MVV measurements were obtained during the two weeks preceding the simulated dive. During this base-line period, subjects were exposed to the control conditions at 1.6 ATA (20 fsw) for 6 h each day. Immersion exposures were sufficient for each diver to become thoroughly familiar with the experiment and procedures. During the base-line measurements, air was the breathing gas ($P_{I_{O_2}}$ of 260.3 mmHg, $P_{I_{CO_2}}$ of 0.59 mmHg, density of 1.822 g · liter^{-1} BTPS). At the maximum pressure of 43.4 ATA (1400 fsw), 0.98% O_2 in helium was respired ($P_{I_{O_2}}$ of 323.6 mmHg, $P_{I_{CO_2}}$ of 0.7 mmHg, density of 7.338 g · liter^{-1} BTPS).[4]

Conventional ECG leads were fastened to fixed locations for measurements of the heart rate during the experiments at 43.4 ATA. Pressure at the mouth was monitored continuously from a pressure transducer attached to the directional breathing valve. Expired gas vented through a small-bore tube at an appropriate rate of flow to a mass spectrometer[5] located outside the chamber. Throughout portions of the experimental sequence, continuous recordings were obtained of heart rate, respiratory rate, pressure at the mouth, and the O_2 and CO_2 fractions in the expirate.

During the intervals when full data were obtained, the exhaled gas was collected in a gas-tight bag for a known period of time. Samples of mixed-expired gas and inspired gas were transferred outside the chamber through small-bore lines and collected in glass syringes lubricated with a dilute lactic acid solution. The expired gas volume was measured by passing the contents of the expired gas bag through a dry-gas meter, located within the chamber, at an approximate but fixed gradient of 69 mmHg. A thermometer within the gas meter indicated the temperature of the gas. The composition of the mixed-expired gas was determined on gas chromatographs using a catherometer-sensing principle. The oxygen column of one chromatograph was lengthened to 4.3 m. The calibration of experimental gas samples was calculated to have an error of less than ± 50 ppm for O_2 and less than ± 10 ppm for CO_2. Standard equations (Otis 1964) were used to calculate the primary data:

$$R = \frac{(1 - FI_{O_2})FE_{CO_2} - (1 - FE_{O_2})FI_{CO_2}}{(1 - FE_{CO_2})FI_{O_2} - (1 - FI_{CO_2})FE_{O_2}} \quad (1)$$

$$\dot{V}CO_2 = \dot{V}E\ STPD \cdot FE_{CO2} - \left(\frac{FE_{He}}{FI_{He}} \cdot FI_{CO2}\dot{V}E\right) \quad (2)$$

$$\dot{V}O_2 = \dot{V}CO_2/R \quad (3)$$

$$PET_{CO_2} = (PB - PH_2O)FET_{CO_2} \quad (4)$$

RESULTS

One partial experimental sequence was obtained for each of four divers at maximum depth and was compared to the base-line measurement obtained during the 2 weeks preceding the simulated dive. Two of the four subjects were able to complete only the 50-W work load at maximum depth. They did repeat the 25-W load after a suitable rest, however, providing two sets of data for that particular work level. The other two divers were able to complete the 75-W work load at maximum depth. Under the control conditions, all four divers completed work through 75 W; three of the four subjects were able to complete the 100-W load as well, and one man performed his assigned task at a 125-W load.

Data for oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), and respiratory exchange ratio (R) are presented in Table 2. At rest $\dot{V}O_2$ values were within the expected range. No consistent differences occurred at depth. Values for R at rest were generally greater than 1.0 at depth.

Analysis of data for $\dot{V}O_2$ and R during exercise at depth revealed no consistent increases or decreases for a given level of work compared to control data. Three of the four divers were unable to equal at depth their maximum control $\dot{V}O_2$ under otherwise comparable conditions. One of the four divers had a greater maximal $\dot{V}O_2$ at depth, however. The maximum $\dot{V}O_2$ obtained at depth was 2.36 liter · min^{-1}. Increments in $\dot{V}O_2$ with increasing levels of ergometric work were variable and followed the anticipated linear relationship only in Diver 2.

The PET_{CO_2} did not correlate closely with achieved effort at depth (Table 3). There was a general tendency for the PET_{CO_2} to increase concordantly with $\dot{V}O_2$, but the correlation coefficient between these parameters computed with individual data points for all four divers was 0.14 at 1.6 ATA; this value was 0.83 at 43.4 ATA (Table 4). At both depths, the standard errors of estimating the PET_{CO_2} from $\dot{V}O_2$ ($Sy \cdot x$) are sufficiently large and the calculated regression

TABLE 2

OXYGEN CONSUMPTION ($\dot{V}O_2$), CARBON DIOXIDE PRODUCTION ($\dot{V}CO_2$), AND RESPIRATORY EXCHANGE RATIO (R) DURING REST AND WORK UNDERWATER AT 1 .6ATA (20 fsw) AND 43.4 ATA (1400 fsw). REPEATED MEASUREMENTS WERE OBTAINED ON DIVERS 3 AND 4 AT 25 W.

Condition	Diver	$\dot{V}O_2$, liter · min^{-1} STPD		$\dot{V}CO_2$, liter · min^{-1} STPD		R	
		1.6 ATA	43.4 ATA	1.6 ATA	43.4 ATA	1.6 ATA	43.4 ATA
Rest	1	—	0.36	0.30	0.33	—	0.94
	2	0.42	0.29	0.35	0.38	0.84	1.30
	3	0.29	0.29	0.25	0.34	0.87	1.17
	4	0.30	0.25	0.21	0.35	0.70	1.40
25 W	1	1.29	1.27	1.14	1.10	0.88	0.87
	2	1.49	1.45	1.35	1.38	0.90	0.95
	3	1.40	1.68	1.13	1.34	0.81	0.80
	4	1.31	1.39	0.96	1.24	0.73	0.89
50 W	1	1.27	1.83	1.17	1.65	0.92	0.90
	2	1.97	2.00	1.53	1.87	0.77	0.93
	3	2.22	1.81	1.90	1.36	0.85	0.74
	4	1.53	1.90	1.14	1.73	0.74	0.91
75 W	1	2.28	2.06	2.49	2.10	1.08	1.02
	2	2.48	2.36	2.00	2.30	0.80	0.97
	3	1.53	—	1.44	—	0.93	—
	4	1.53	—	1.32	—	0.86	—
100 W	1	3.00	—	3.43	—	1.14	—
	2	2.86	—	2.65	—	0.92	—
	3	2.64	—	2.28	—	0.86	—
	4	—	—	—	—	—	—
125 W	3	2.97	—	2.84	—	0.95	—
Repeated measurements							
25 W	3	—	1.56	—	1.14	—	0.72
	4	—	1.36	—	1.33	—	0.98

slopes sufficiently low that definite effective interaction cannot be concluded even though the correlation coefficient exceeded 0.80 at the maximum depth.

Regression lines for the four divers are presented in Fig. 3. Diver 1 (Fig. 3A) had a low correlation and regression slope at 1.6 ATA, but both coefficients were larger as pressure was raised to 43.4 ATA. In Diver 2 the $P_{ET_{CO_2}}$ also remained relatively constant but was slightly elevated over a wide range of oxygen consumption (0.49 to 2.86 liter · min^{-1}) at 1.6 ATA. At 43.4 ATA, however, a correlation approaching unity was found, and the regression line indicates that $P_{ET_{CO_2}}$ was progressively elevated as the $\dot{V}O_2$ increased from 1.45 to 2.36 liter · min^{-1}. The maximum recorded $P_{ET_{CO_2}}$ at depth for this diver, however, did not exceed 50 mmHg at the 75 W level of ergometric work. The remaining two divers (Figs. 3C and 3D) had positive correlation coefficients and parallel regression lines at both depths. The intercept was lower in each case at the maximum depth, however.

TABLE 3

PULMONARY VENTILATION($\dot{V}_E$), END-TIDAL P_{CO_2} ($P_{ET_{CO_2}}$), AND HEART RATE (HR) DURING REST AND WORK UNDERWATER AT 1.6 ATA (20 fsw) AND 43.4 ATA (1400 fsw). REPEATED MEASUREMENTS WERE OBTAINED ON DIVERS 3 AND 4 AT 25 W.

Condition	Diver	$\dot{V}_E$, liter · min⁻¹ BTPS		$P_{ET_{CO_2}}$, mmHg		HR, b · min⁻¹	
		1.6	43.4	1.6	43.4	1.6	43.4
Rest	1	36.44*	14.96	—	—	—	74
	2	14.39	14.32	—	—	—	86
	3	10.54	10.56	39.4	30.6	—	102
	4	28.50*	15.76	—	31.3	—	72
25 W	1	45.79	26.10	—	38.2	—	124
	2	39.55	36.88	46.4	39.8	—	122
	3	39.79	37.00	37.7	37.9	—	134
	4	24.99	35.57	49.9	38.3	—	116
50 W	1	51.41	34.89	37.8	36.9	—	138
	2	40.70	40.77	47.1	46.8	—	136
	3	46.79	37.00	42.8	34.6	—	136
	4	42.50	47.51	46.7	38.2	—	128
75 W	1	83.70	44.81	31.7	41.5	—	160
	2	55.15	48.14	44.6	49.7	—	154
	3	36.58	—	44.2	—	—	—
	4	51.90	—	41.2	—	—	130
100 W	1	109.63	—	38.8	—	—	166
	2	72.96	—	46.1	—	—	—
	3	54.07	—	48.9	—	—	—
	4	—	—	—	—	—	—
125 W	3	76.02	—	46.2	—	—	—
Repeated measure-ments							
25 W	3	—	33.52	—	34.9	—	—
	4	—	38.91	—	37.5	—	—

*These unusually large volumes for pulmonary ventilation are presumably due to admixture of the collected expired minute volume with inspired gas.

The relationship between exercise ventilation ($\dot{V}_{E_{max}}$) and the maximum voluntary ventilation (MVV) was examined by computing the percentage of the MVV which could be respired at the maximally tolerated work load. Table 5 indicates that the $\dot{V}_{E_{max}}$ did not remain a fixed percentage of the effective MVV at depth. Furthermore, there was no consistent tendency in this study for the four divers to use more of their effective MVV at maximum depth.

Due to technical problems, it was not possible to measure the heart rate during the base-line studies. The relationship between heart rate values in Table 3 and the $\dot{V}_{O_2}$ at depth was not unusual and overlapped with previous observations of men working underwater (Craig and Dvorak 1969; Dwyer and Pilmanis *in press*).

TABLE 4

CORRELATION COEFFICIENTS (r) BETWEEN PET_{CO2} AND $\dot{V}O_2$ AT 1.6 ATA AND 43.4 ATA FOR EACH DIVER AND ALL DIVERS COMBINED. REGRESSION EQUATIONS INDICATE SLOPE AND INTERCEPT OF THE STATISTICAL RELATIONSHIP BETWEEN THE TWO PARAMETERS.

Condition	Diver	r	Regression equation	$Sy \cdot x$*
1.6 ATA	1	+.034	$y' = 0.015x + 36.07$	2.04
	2	−.450	$y' = -0.790x + 47.79$	0.94
	3	+.776	$y' = 3.326x + 37.08$	2.64
	4	+.570	$y' = 4.700x + 38.80$	4.00
	All	+.144	$y' = 0.939x + 41.28$	4.83
43.4 ATA	1	+.508	$y' = 2.970x + 33.76$	3.83
	2	+.991	$y' = 9.130x + 27.86$	1.11
	3	+.855	$y' = 3.700x + 29.69$	1.89
	4	+.949	$y' = 4.500x + 30.61$	1.27
	All	+.830	$y' = 6.600x + 28.62$	3.18

*$Sy \cdot x$ is the standard error of PET_{CO_2} (y) estimated from $\dot{V}O_2(x)$.

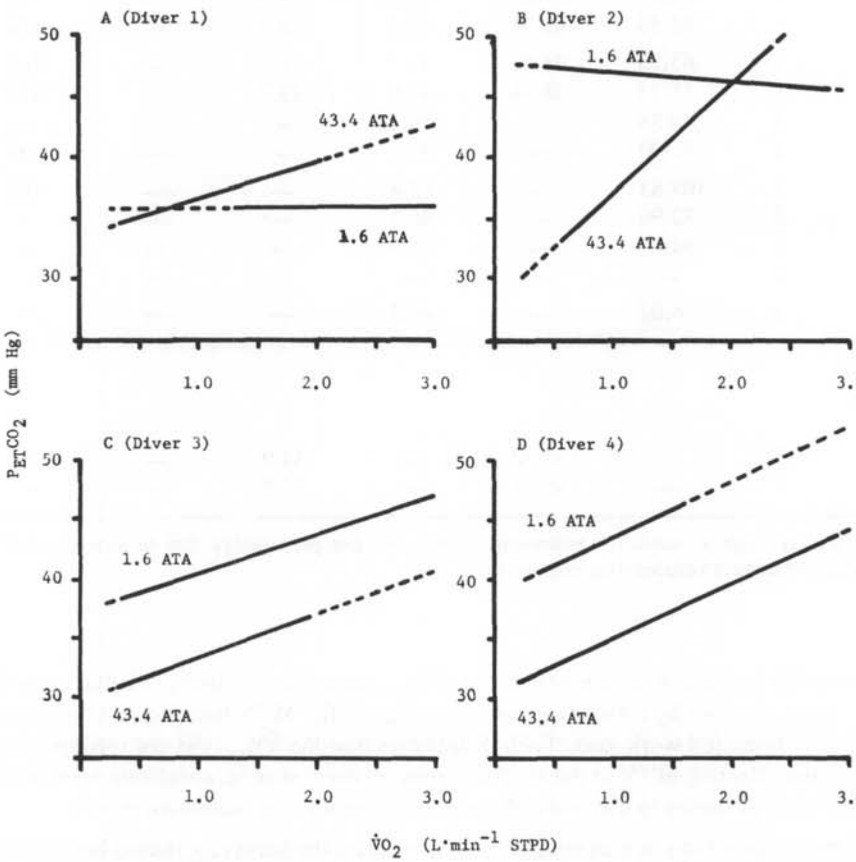

Fig. 3. Regression lines for PET_{CO_2} and $\dot{V}O_2$ at 1.6 and 43.4 ATA, computed with individual data points from 4 divers. Broken portions of lines represent extrapolation by regression equation.

TABLE 5
PULMONARY VENTILATION DURING MAXIMALLY TOLERATED WORK ($\dot{V}E_{max}$), MAXIMAL VOLUNTARY VENTILATION (MVV), AND PERCENTAGE OF MVV THAT COULD BE RESPIRED DURING MAXIMAL WORK AT 1.6 ATA (20 fsw) AND 43.4 ATA (1400 fsw).

Diver	$\dot{V}E_{max}$, liter · min^{-1} BTPS)		MVV, liter · min^{-1} BTPS		$\dot{V}E_{max}$ · MVV^{-1} · 100	
	1.6	43.4	1.6	43.4	1.6	43.4
1	109.63	44.81	151.28	86.70	72	52
2	72.96	48.14	115.69	72.74	63	66
3	76.02	37.00	99.87	50.65	76	73
4	51.90	47.51	128.55	79.16	40	49

*MVV measurement is the highest value of two tests. $\dot{V}E$ at the maximum work load was measured once at each depth.

Subjective impressions

Each of the divers experienced some degree of respiratory distress that limited their work capacity. An inability to "catch up on the breathing" was commonly reported after the dive. Some of the divers experienced leg fatigue, but the inability to inhale sufficient gas per breath to relieve the sensation of breathlessness plus the sense of needing to expend an excessive effort to meet the subjective ventilatory needs of the work load were the symptoms most closely associated with cessation of exercise. Two divers described their degree of difficulty in breathing during exercise as extreme. One diver also felt a lack of energy at 43.4 ATA (1400 fsw), while in another inspiratory insufficiency was the predominant symptom.

DISCUSSION

The criteria for maximal aerobic power ($\dot{V}O_{2max}$) and maximal physical-work capacity have been outlined by Astrand and Rodahl (1970). The experimental standards for maximal work tests established by these investigators and others (Astrand and Saltin 1961; Karlsson and Saltin 1970) could not be applied in the present study, however. We were unable to measure the blood-lactate concentration, to obtain more than a few measurements of heart rate or to administer two or more supramaximal work loads. Therefore, the highest work load the individual divers could tolerate for one 6-min trial was regarded as the maximal physical-work capacity, and the O_2 consumption during the final minute at that load represents the effective maximal O_2 uptake or aerobic power (herein designated $\dot{V}O_{2max}$).

A comparison of data at 1.6 ATA and 43.4 ATA indicates that the effective $\dot{V}O_{2max}$ at the greater depth in considerably reduced from control measurements. At 43.4 ATA the O_2-uptake rates ranged from 1.81 to 2.36 liter · min)7. In a previous dive to 50 ATA, using indentical underwater exercise, Spaur et al. (1977) found that three divers could work at 1.81 liter · min)7 but only one could work at a level requiring 1.92 liter · min)7. Comparison to control performance was not possible, however, since no predive $\dot{V}O_2$ data were given.

Morrison (1973) also studied O_2 uptake during underwater work (trapeze swimming) at maximum sustainable effort with O_2–N_2 mixtures at 6–176 fsw. In contrast to the present study, his results showed no prominent tendency for $\dot{V}O_{2max}$ to be reduced at the deeper depth.

Morrison's divers were able to consume 1.7 to 3.2 liter · min^{-1} at 176 fsw. Dwyer and Pilmanis (*in press*) and Kurenkov (1973) have also demonstrated that a relatively high $\dot{V}O_2$ (3.5 to 4.8 liter · min^{-1}) may be reached at 4–7 ATA in open-water swims. Furthermore, Fagraeus (1974) and Anthonisen, Utz, Kryger, and Urbanetti (1976) found no decrement in $\dot{V}O_{2max}$ at 6 ATA during bicycle exercise in air. Since the inspired gas densities in some of these studies were similar to that prevailing at 43.4 ATA of $He-O_2$, it appears that the observed reduction in $\dot{V}O_{2max}$ at the maximum depth must be due to some other factor in the hyperbaric environment. Nevertheless, the subjective reports of the divers suggest that the increased gas density was a factor contributing to reduced performance of work.

Large reductions in maximal physical-work capacity were found in all divers. Diver 3 completed the 125-W work level near the surface, but he was unable to perform more than 50 W at 43.4 ATA. The other divers performed 25 to 33% less work at maximum depth. The decrement in $\dot{V}O_{2max}$ at 43.4 ATA also averaged 30% in three divers (range 39.1 to 17.5%), although one diver apparently increased his aerobic power at the maximum depth. The limited $\dot{V}O_{2max}$ performance at depth was similar to that reported by Spaur et al. (1977) at 50 ATA but differed considerably from observations in dry chambers, suggesting no decrement in aerobic power at simulated depths of 6 ATA in air and 18.6 ATA in $He-O_2$. In the present study, the cumulative effects of apprehension related to the underwater breathing assembly, confinement, and deconditioning and the enervating effects of vibration may have contributed significantly to the observed decrement in work performance. These factors, combined with the known effects of dense gas on the work and perceived effort of breathing, may have been additive in their effects at 43.4 ATA, producing a performance decrement not normally found in dry chambers when divers breathe gases of comparable density during simulated dives. Furthermore, the direct effects of hydrostatic pressure, high inert gas tension, and the increased loss of heat into the expired helium may also play some significant role in limiting the work capacity of divers at great depths.

On the basis of reports by several investigators (Jarrett 1966; Wood and Bryan 1969; Cook 1970; Miller, Wangensteen, and Lanphier 1971, 1972; Morrison 1973; Fagraeus 1974; Dwyer and Pilmanis *in press*), it was expected that the $P_{ET_{CO_2}}$ would increase with $\dot{V}O_2$ at 43.4 ATA after further increments in $\dot{V}_E$ were constrained by the relatively low maximal expiratory flow possible under the given experimental conditions. Presumably higher values for the Pa_{CO_2} would lead to impaired performance as a consequence of narcotic effects. We did not find a $P_{ET_{CO_2}}$ above 50 mmHg, however, and there was no statistical indication that an elevated $P_{ET_{CO_2}}$ was closely related to $\dot{V}O_{2max}$ even though many positive correlation coefficients were found (Table 4).

In Morrison's study (1973) the $P_{ET_{CO_2}}$ was not measured, but four of six divers at 176 fsw reported sensations of breathing difficulty and headache, which suggests that significant CO_2 retention had occurred at the point of maximal work. Similar symptoms and dizziness were reported by Dwyer and Pilmanis (*in press*) during heavy work at 4 ATA in the open sea when $P_{A_{CO_2}}$ exceeded 57 mmHg in some divers. None of the divers in the present study experienced headache or dizziness after the exercise test. Furthermore, none of the observed values for $P_{ET_{CO_2}}$ was sufficiently high to implicate respiratory acidosis in the restriction of work capacity.

Fagraeus (1974) supports the view that blood-lactate concentration, rather than hypercapnia, is more closely related to $\dot{V}O_{2max}$. In his study, $\dot{V}O_{2max}$ and lactate did not change significantly as pressure was raised to 6 ATA. The $P_{ET_{CO_2}}$ also increased with pressure but, as in the present study, it showed large variability among the divers. We were unable to measure blood lactate due to restrictions imposed by the divers' protective suits and breathing systems.

Although CO_2 retention has been identified by several investigators as a cause of reduced performance (Jarrett 1966; Cook 1970; Miller et al. 1971; Dwyer and Pilmanis *in press*), the factors limiting work under the conditions of this experiment apparently led to termination of exercise before marked hypercapnia occurred.

There are obvious limitations to using $P_{ET_{CO_2}}$ as an index of Pa_{CO_2} or tissue P_{CO_2}. No experimental data are available to evaluate the correspondence of these parameters under the conditions of this study. Furthermore, the methods used to obtain samples of end-tidal gas from the immersed diver may have allowed some gas mixing to occur within the sampling system, resulting in a lowering of the true $P_{ET_{CO_2}}$. If our $P_{ET_{CO_2}}$ values are a valid index of Pa_{CO_2}, however, then our results generally support Spaur et al. (1977) who reported no disturbance in Pa_{CO_2} or arterial pH at 50 ATA at a point where $\dot{V}_{O_2}$ was restricted to low levels and sensations of respiratory insufficiency were extreme.

Our finding that the maximum pulmonary ventilation ($\dot{V}_{E_{max}}$) did not equal the MVV at 43.4 ATA is generally in agreement with Fagraeus and Linnarsson (1973) and Anthonisen et al. (1976). In contrast, Miller et al. (1971) and Lambertsen (1976a) have found some divers can respire their MVV during 4–6 min of heavy exercise while breathing dense gases. Anthonisen et al. (1976) reported one diver who could respire his MVV at 4 ATA in air during heavy exercise, but five others used 80% of their MVV. Similar results were found during a simulated saturation dive to 18.6 ATA (He–O_2) by Dressendorfer, Hong, Morlock, Pegg, and Respicio (1976). The reason for differences in ventilation capacity during heavy exercise among divers may be found in the patterns of breathing utilized during exercise and the MVV test.

The concept that MVV data may indicate accurately the maximal volume of gas that can be ventilated in a given experimental setting is based on the following assumptions: 1) respiration rate and tidal volume were controlled by the subjects to maximum advantage in terms of ventilation volume; 2) the major portion of each expiration was effort-independent; and 3) the end-expiratory lung volume under these conditions was determined in an optimal manner by the value for static recoil pressure of the lung ($P_{st(l)}$) and transpulmonary pressure (P_{max}) at the point that effort-independent expiratory flow initially attained a maximum value. This value for P_{max} cannot be exceeded advantageously because greater transpulmonary pressures are not accompanied by increased expiratory-flow rates, presumably because concurrent dynamic-airway compression counteracts increments in flow that otherwise would occur.

When MVV is performed at high lung volumes, expiratory flow is maximal because $P_{st(l)}$ is high and P_{max} is greater at higher lung volumes (Mead, Turner, Macklem, and Little 1967). The mechanical efficiency of the inspiratory muscles (intercostals and diaphragm) is significantly reduced at high lung volumes (Sharp et al. 1974), however, sharply reducing the gain in maximal inspiratory flow for a given expenditure of effort. As a consequence, the advantages during expiration of breathing at a high lung volume are offset and MVV limits are attained sooner than would otherwise be the case.

The same mechanical limitations apply to ventilation during maximal exercise, even though the stimuli for ventilation are different. When a deeper breathing pattern is used with a resultant smaller end-expiratory lung volume, a more favorable mechanical advantage is obtained for inspiratory muscles, thus allowing a higher inspiratory flow. At that lower lung volume, however, the altered expiratory mechanics reduce maximum expiratory flow (MEF). By contrast, if inspiration begins from a higher functional residual capacity (FRC), the subsequent increase in $P_{st(l)}$ and P_{max} results in higher expiratory rates; however, the mechanical effort expended to inspire increases disproportionately. Possibly the limit in this physiologic choice is set not only by P_{max} but also by the maximal level of ventilatory muscular effort that can be sustained long enough to accomplish the assigned task. If ventilatory muscular exhaustion limits performance under these conditions, then appropriate endurance training of the ventilatory musculature might be functionally advantageous, as has been reported (Leith and Bradley 1976).

Divers who are unable to approach their MVV during exercise under pressure may be using different breathing patterns in each test, which would result in different ventilation values even though expiration is limited by the same mechanical factors (Miller et al. 1972). Spaur and his co-workers (1977) have reported data strongly supporting the hypothesis that divers breathe more deeply and concomitantly raise their FRC's during MVV tests at 49.5 ATA. If the divers in this experiment also raised their FRCs, as is likely, and if different breathing patterns were employed during the MVV and $\dot{V}E_{max}$ tests at 43.4 ATA, the disparate pulmonary mechanics would have resulted in these two parameters being dissimilar.

On the basis of a limited number of observations, the data indicate that maximal physical-work capacity and $\dot{V}O_{2max}$ were significantly restricted underwater at 43.4 ATA. Termination of exercise in this experiment clearly was unrelated to alveolar hypoventilation and CO_2 retention. The severe dyspnea during exercise presumably was due to the inspiratory mechanical effort at higher lung volumes. Whether this perception of dyspnea was effected directly through proprioceptive afferent impulses or indirectly as a consequence of inspiratory muscle fatigue is not clear. If the latter hypothesis is correct, the failure mode may have reflected perceived exhaustion of ventilatory musculature. No data are available to assess the validity of this speculation.

Although valuable physiologic information can be obtained from dry-chamber studies in which respiratory gas densities in a $He-O_2$ environment at extreme depths are simulated by exposure to denser gases at comparatively shallow depths (Lambertsen 1976a), the respiratory responses of immersed men breathing gases of comparable density at greater depths differ significantly (aside from one brief report [Lambertsen 1976b]). As a consequence, the capacity to do work while immersed at 1400–5000 fsw appears to have been overestimated (Lambertsen 1976a; Anthonisen et al. 1976) and is in sharp contrast to the observed severe restriction of human physical-work capacity and aerobic power during immersion at 43.4–49.5 ATA. Furthermore, the apparent limited capacity for O_2 consumption under these conditions in the deep underwater environment does not fully reflect the severe limitation imposed on useful external physical work. A large portion of the O_2 consumed is expended to pay the costs of breathing dense gas through underwater breathing assemblies and in overcoming the drag of the surrounding water and the constraints imposed by the protective thermal suit.

Only a fraction of the $\dot{V}O_2$ during deep dives in cold water can be expended as useful work. Under these conditions at 43.4 ATA, trained divers found it difficult to perform more than 50 W of ergometric work. Therefore, the fraction of utilized oxygen available for performing external work is an important consideration in assessing the capacity of a diver to accomplish useful tasks at great depths. Contemporary underwater breathing apparatus designs, superimposed upon other factors known to affect ventilation adversely, contribute to this very low estimate for useful work that divers can perform in cold water at comparable depths.

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Dwyer, J., H. A. Saltzman, and R. O'Bryan. 1977. Performance maximale de l'homme à 43,4 ATA. Undersea Biomed. Res. 4(4): 359–372.—Quatre plongeurs de la Marine americaine ont accompli des tâches de travail ergométrique sous-maximal et maximal pendant l'immersion. La température de l'eau était de 4,4°C, la pression 1,6 ou 43,4 ATA (1400 fsw). La consommation d'oxygène ($\dot{V}O_{2max}$) au travail maximal toléré pendant 6 minutes à 1,6 Ata était 2,86–3,00 liter · min^{-1}, et 1,81–2,36 liter · min^{-1} au fond chez trois plongeurs. Chez le quatrième plongeur, la consommation d'oxygène a augmenté de 1,53 liter · min^{-1} à 1,6 ATA jusqu'à 1,90 liter · min^{-1} à 43,4 ATA. Le travail ergométrique accompli a diminué de 30% en moyen à la profondeur maximale. Le travail mesuré à l'ergomètre n'a pas dépassé 30 watts en général. La pression partielle de CO_2 a augmenté en fonction du $\dot{V}O_2$ à la profondeur maximale, mais n'a jamais dépassé 50 mmHg. La rétention de CO_2 n'a pas limité le travail de façon significative. La ventilation minute pendant le travail maximal n'est pas resté un pourcentage fixe de la ventilation volontaire maximale (VVM) à 43,4 ATA, mais on n'a pas constaté une tendance des plongeurs à respirer plus près de la VVM. La dyspnée au fond était sévère pendant le travail, et l'effort perçu de la respiration était à la limite personnelle de chaque sujet. La limitation sévère de la capacité de travail et la consommation d'oxygène que nous avons observées pendant ces expériences semblent contredire les extrapolations basées sur les expériences en chambres sèches, en mélanges de densité comparable et à des profondeurs moins grandes.

travail pendant l'immersion	dyspnée
consommation d'oxygène	ventilation volontaire maximale par minute
dioxyde de carbone	ventilation pulmonaire

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[1]U.S. Navy MK 10 apparatus.

[2]Collins pedal-mode ergometer modified for underwater use (James 1976).

[3]Collins Triple J valve. At 43.4 ATA, the maximum recorded positive expiratory pressure was less than 8 cmH_2O during performance of the 100-W workload while divers were immersed; under comparable conditions the maximum negative inspiratory pressure was 22 cmH_2O.

[4]Calculated as in Radford (1964) and Handbook of Chemistry and Physics (1967–68).

[5]Med Spec. (Calculated to be accurate to liter $\cdot$ 10^{-4}; modified for 0–1% CO_2 range.)