EFFECTS ON MAN OF HIGH CONCENTRATIONS OF CARBON DIOXIDE IN RELATION TO VARIOUS OXYGEN PRESSURES DURING EXPOSURES AS LONG AS 72 HOURS[1]

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The limits of 3% carbon dioxide and 17% oxygen in ambient air have been accepted in the American Submarine Service as compatible with efficient performance of personnel for extended periods of time. Although considerable experimental data have accumulated on the influence of carbon dioxide on respiration (1–4), the investigations, with the exception of those of Miller (5), have been limited to short-term exposures. Furthermore, other than the studies of Case and Haldane (6), little attempt has been made to correlate the changes in respiration caused by combined oxygen deficiency and carbon dioxide excess with psycho-physiological functions.

With respect to the oxygen saturation of blood, the prime consideration is not the partial pressure of oxygen in ambient air, but the much lower alveolar oxygen pressure. If the lungs could be more effectively ventilated, it should be possible to raise the alveolar oxygen pressure to levels approaching that in the ambient air. The problem is to determine the carbon dioxide concentration in the ambient air that will bring about maximal pulmonary ventilation without undue physical impairment. This will permit the alveolar oxygen pressure to approximate the partial pressure of oxygen in ambient air.

TEST PROCEDURES

General

In six experiments of 35 to 72 hours' duration, groups of 4 to 77 male subjects (age range 18 to 45 years) occupied sealed steel chambers which allowed a free air space of approximately 500 cu. ft. per man. The first experiment was an indoctrination run. In the second experiment of 52 hours' duration (4 subjects), the exhaled carbon dioxide was not absorbed and oxygen was not replenished. In the third experiment (4 subjects), carbon dioxide likewise was not absorbed but the ambient oxygen was not permitted to fall below 19%. In the fourth experiment of 72 hours' duration (4 subjects), carbon dioxide in excess of 5% was absorbed; oxygen was not replenished. In experiments 5 and 6, the carbon dioxide in excess of 5% was again absorbed; oxygen was not replenished. In experiment 5, 37 men breathed recirculated air for 60 hours and in experiment 6, 77 men were subjected to similar conditions for 50 hours.

[1] The material in this article should be construed only as the personal opinions of the writers and not as representing the opinion of the Navy Department officially.

In the first four experiments an Effective Temperature of approximately 85° was maintained to simulate hot tropical conditions with a dry bulb of 90° F. and a relative humidity of 75%. In experiment 5, the Effective Temperature averaged 75° with a dry bulb of 80° F. and a relative humidity of 65%; in experiment 6, the Effective Temperature averaged 59°, with a dry bulb of 60° F. and a relative humidity of 90%.

Biochemical, physiological and psychological measurements and observations were made. The following daily schedule was followed in the first four experiments and slight modifications were made in experiments 5 and 6.

0800–1030	psychological tests	1400–1800	test program repeated
1030–1130	physiological tests	1800–2000	dinner—rest period
1130–1200	biochemical tests	2000–2400	test program repeated
1200–1400	lunch—rest period	2400–0800	sleep period—breakfast

Biochemical

In the early experiments, blood was drawn from the brachial artery. Due to the frequency of needle insertion as well as technical difficulties, samples of 'arterialized' venous blood were drawn in the later experiments. These were obtained by immersing the hand in hot water (45°C.) for 20 minutes and with the hand still immersed, drawing blood from one of the dorsal veins of the hand (7). Blood obtained in this manner was used for gas analysis in lieu of arterial blood.

Alveolar air samples were taken according to the technic described by Dill (8). All subjects were trained for several days before the start of the experiments to insure proper sampling technic.

The plasma pH was calculated by means of the Henderson-Hasselbalch equation from data obtained from analysis of alveolar air and arterial blood or 'arterialized' venous blood (9, 10).

Physiological

The following measurements were made in the course of the experiments: pulse rate, blood pressure, body temperature, pulse rate response to exercise and respiratory rate and minute volume. The observers followed a strict routine in making all measurements in order to reduce to a minimum the variability in data usually obtained with inexperienced subjects. During a typical test procedure, the subject reclined quietly for 15 minutes, after which the pulse rate, blood pressure and body temperature were obtained. He was next allowed to assume a sitting position while the respiratory measurements were made. Finally, he engaged in light activity for the purpose of recording response to exercise.

Pulse beats were counted for 30 seconds. Blood pressure was measured by auscultation, the diastolic pressure being taken at the point of sound disappearance. Pulse pressure was computed as the difference between systolic and diastolic pressures. Body temperature was obtained with standard clinical thermometers, rectal temperatures being employed in the first four experiments, and oral temperatures in the last two. To obtain the respiratory data in the first four experiments, expired air was collected by means of a face mask connected to a Tissot spirometer; dry gas meters were employed in experiments 5 and 6 in place of spirometers. The respiratory rate was counted for a full minute and minute volume was measured for a period of 5 minutes. Exercise response was evaluated on the basis of performance in the step-up test (11). For this test the subject stepped up and down, using the same leg, on an 18-inch box, 20 times in 30 seconds, pulse counts being made immediately after and two minutes after cessation of exercise. A 'cardiovascular score' was computed by the formula (11):

C.V.S. = (5″ to 20″ pulse count) plus (1′45″ to 2′15″ pulse count).

Psychological

Fourteen different tests were used in the psychological battery. Principles which guided the selection of tests were: that test procedures cover a wide range of functions; that tests have high enough reliability to make possible an evaluation of individual performance; and that tests be used that were known to be satisfactory as criteria of anoxia. The functions tested were:

Vision. Foveal flicker frequency was measured as one significant aspect of central photopic vision (12). The dark-adapted form-acuity threshold was measured with a T-shaped test object similar to that of the Navy radium plaque adaptometer (13).

Audition. Measures were made of the ability to discriminate differences in pitch and loudness (14), and of the absolute auditory threshold over a wide range of pitch.

Equilibrium. Ability to stand still and erect was measured by recording anterior-posterior body sway with eyes open and closed (15). Ability to maintain balance during movement was measured by requiring the subject to walk a one-inch rail without shoes (15).

Hand-arm steadiness. This was measured by the ability to keep the end of a rod in a fixed position.

Eye-hand coordination. Two tests of this function were used: the Koerth pursuit rotor, which requires a smooth continuous pattern of movement for one hand; and a complex tapping test, which requires irregular and non-symmetrical movement of both hands simultaneously (16).

Strength. A Smedley hand dynamometer was used, following a procedure that requires steadily increasing outputs of energy to the point where the subject is no longer able to improve (17).

Symbolic functions. Three paper-and-pencil tests were used: the Johnson Code Test, which requires continuous application and attention in a series of letter-for-letter translations (18); the computation test, which is a series of mixed addition and subtraction problems (18); and the number-checking test, which requires the comparison of pairs of numbers to determine whether they are alike or different (19).

Except in experiment 6 and on one test in experiment 5, all subjects had extended practice on the tests before the experiments began, in order to minimize the effect of rapid learning and irregular adaptation to test conditions. Control of motivation was not possible, but there was reason to believe that motivation was relatively high and constant. The subjects knew the purpose and nature of the research and knew approximately, if not exactly, how well they were doing on each test. There were no special rewards or inducements to good performance but a general social facilitation and normal competitive spirit developed among the subjects; i.e., morale was judged to be good.

EXPERIMENTAL DATA AND DISCUSSION

General

The cost of maintaining adequate oxygenation of hemoglobin when the ambient oxygen is as low as 12% and carbon dioxide as high as 5% is an approximate $2\frac{1}{2}$-fold increase in minute breathing volume, a rise in pulse rate of approximately 10 beats per minute, some impairment in specific sensorimotor performance, headache affecting 20% of the personnel, and occasionally nausea. Throughout all experiments involving 130 man exposures, only three men were removed from the closed spaces. One of these men showed apprehension; another, exhaustion; and a third, a steadily increasing blood pressure. At no time were these men in a critical condition.

TABLE 1. *Summary of conditions to which the subjects were exposed*

EXPERIMENT NUMBER	NUMBER OF MEN	DURATION	HIGHEST CO_2	LOWEST O_2	HOUR WHEN AMBIENT CO_2 APPROACHED 5%
		hrs.	*per cent*	*per cent*	
1	4	34	5.95	14.18	29
2	4	52	6.54	13.45	34
3	4	51	6.75	19.22	37
4	4	72	5.42	10.45	32
5	37	60	5.27	12.21	34
6	77	50	5.18	13.21	34

The period immediately following inhalation of outside air may be attended by transient dizziness and headache. Observers exposed periodically for one to two hours to the recirculated compartment air repeatedly developed headaches and experienced a transient taste and smell of ammonia upon leaving the compartment. However, the apparently complete recovery of both subjects and observers was rapid.

The data (table 1) show that the highest carbon dioxide concentration was 6.75%, the lowest oxygen concentration 10.45%. Although these concentrations were tolerated, the symptoms of headache and respiratory difficulty, especially during physical effort, sharply increased whenever the carbon dioxide rose appreciably above 5%.

Special significance is attached to experiment 3 in which the oxygen was maintained at a level approaching normal although the carbon dioxide was permitted to approach 7%. In this experiment it was found that measurable improvement over the performance in other experiments did not result from the added oxygen.

The remarkably consistent values of carbon dioxide output per man, of 0.326 l/min. STP (0.69 cu. ft/hour) and oxygen consumption 0.387 l/min. STP (0.82 cu. ft/hour), agree with those obtained by previous investigators in tests performed during and subsequent to the first World War.

It is noteworthy that the alveolar carbon dioxide pressure, respiratory minute volume, and pulse rate show very little change until the atmospheric carbon dioxide approaches the 3% level. Above the 3% level, these functions begin to increase rather sharply.

Biochemical Data

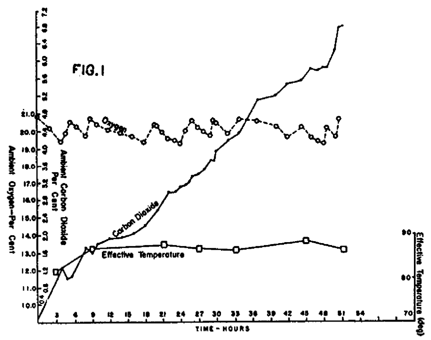
Ambient carbon dioxide and oxygen concentrations. In experiment 3, the carbon dioxide rose to a value of 6.75 at the end of 51 hours but the oxygen was maintained at a level of 20% ± 0.8 during this period (fig. 1). In experiment 4, carbon dioxide absorption was begun at the end of 45 hours to maintain the carbon dioxide level at 5% until the termination of the test at the end of 72 hours. Oxygen was not added and the concentration fell to 12.8% during the 56th hour where it remained for several suceeding hours (fig. 2). At this time, nitrogen was added at a constant rate to compensate for outboard leakage. In experiments 5 and 6, carbon dioxide absorption was begun during the 35th hour when the concentration reached 5% and continued for 25 and 15 additional hours, respectively (fig. 3, 4).

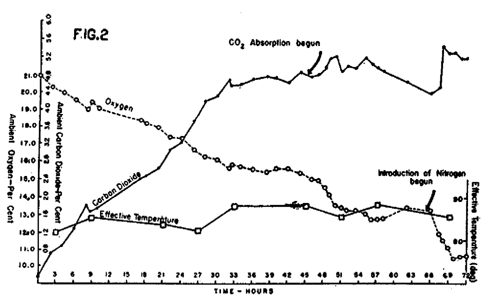
Comparison of values of ambient with alveolar carbon dioxide and oxygen concentrations. As a result of the increased ventilation, the oxygen percentage in the lungs during the rebreathing of air falls at a slower rate than it does in the ambient air. The difference between ambient and alveolar oxygen pressures (ΔpO_2) varies from 40 to 52 mm. Hg at the beginning of the tests and declines steadily to values ranging from 11 to 19 mm. Hg at the conclusion of the experiment (table 2, fig. 5). The difference between alveolar and ambient carbon dioxide (ΔpCO_2) diminishes similarly from about 42 mm. Hg (chamber open to outside air) to about 10 mm. Hg when the ambient carbon dioxide reaches 46 mm. Hg (exp. 2, table 2).

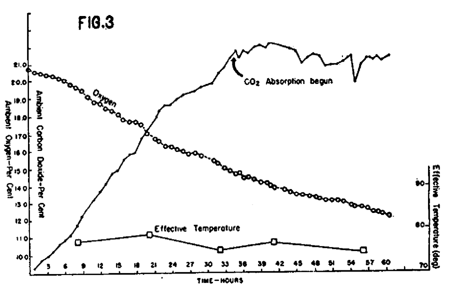
Effects of high carbon dioxide concentrations on plasma pH and carbon dioxide content. The plasma pH values (table 3) indicate a slight increase in acidity, 7.44 to 7.38 in one experiment and 7.40 to 7.38 in another, when the carbon dioxide of the ambient air increased from 0.03% to 5%. Plasma carbon dioxide increased from 58.6 to 59.5 vols. % in one experiment, and from 58.2 to 64.6 vols. % in another. These changes may be classified as slight and are at variance with the results obtained by Miller (5). They further illustrate the remarkable rôle played by hyperventilation in protecting the body against the accumulation of carbon dioxide in the presence of high ambient concentrations of this gas.

Oxygen concentrations in ambient and alveolar air and the corresponding equivalent altitudes. An ambient oxygen pressure of 100 mm. Hg without increased carbon dioxide in the air is associated with an alveolar oxygen pressure of 58 mm. Hg. Corresponding values are found at simulated altitudes of 10,000 feet (20). The same ambient oxygen pressure (100 mm. Hg), however, in combination with 5% carbon dioxide in air is associated with an alveolar pressure of 86 mm. Hg. This value corresponds to a simulated altitude of but 4000 feet (fig. 6).

Effects of carbon dioxide on oxygen saturation of blood. The percentages of oxyhemoglobin in two experiments (4 and 5) when carbon dioxide in ambient







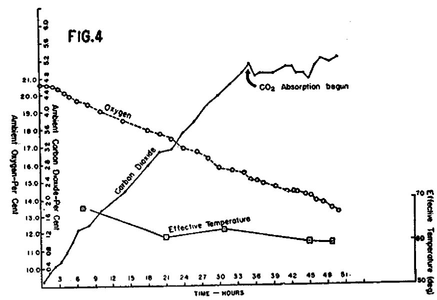


FIG. 1. Experiment 3, the rise in CO_2 maintaining constant O_2 during 52 hours recirculation of compartment air.

FIG. 2. Experiment 4, the rise in CO_2 and fall in O_2 during 72 hours recirculation of compartment air. During the 65th hour nitrogen and some carbon dioxide was introduced into the compartment.

FIG. 3. Experiment 5, the rise in CO_2 and fall in O_2 during 60 hours recirculation of compartment air.

FIG. 4. Experiment 6 the rise in CO_2 and fall in O_2 during 50 hours recirculation of compartment air.

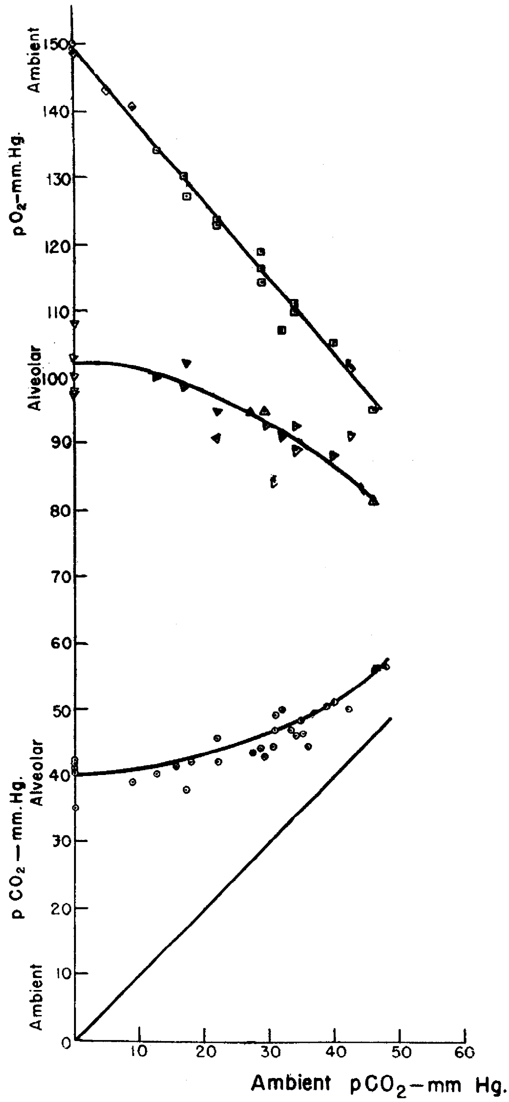
air is 5% show considerable elevation over percentages expected in the absence of CO_2 when the oxygen pressure in inhaled air is reduced (table 3, fig. 7). These relatively high saturation values are due to the maintenance of a high alveolar oxygen pressure (table 2) resulting from hyperventilation. In association with an ambient carbon dioxide pressure of 36 mm. Hg an oxygen pressure of 72.5 mm. Hg (corresponding to that at a simulated altitude of 17,000 feet) saturates hemoglobin 87% (fig. 7). In the absence of carbon dioxide in the inhaled air, the saturation of hemoglobin would have been of the order of 76%. However, on the basis of the data submitted no further gain in alveolar oxygen or hemoglobin saturation is to be expected by increasing the ambient carbon dioxide

TABLE 2. *Effects of increased ambient carbon dioxide on alveolar air*

NUMBER EXPERIMENT	NUMBER OF SUBJECTS	DATE	HOURS OF EXPOSURE	AMBIENT AIR				ALVEOLAR AIR				ΔpCO_2[1]	ΔpO_2[1]
				CO_2	O_2	pCO_2	pO_2	CO_2	O_2	pCO_2	pO_2		
		1944		*Per cent*		*mm. Hg*		*Per cent*		*mm. Hg*		*mm. Hg*	*mm. Hg*
1	4	11 May	Rest	0.03	20.94	0.2	150.1	5.76	14.18	40.8	100.4	40.6	49.7
	4		4	1.28	19.62	9.2	140.5	5.49	14.60	39.3	103.7	30.1	36.8
	4		10	2.41	18.32	17.3	131.2	5.94	13.75	42.3	98.5	25.0	32.7
	4	12 May	23	3.84	16.63	27.5	119.1	5.81	13.28	43.5	95.0	16.0	22.1
	4		28	4.79	15.50	34.3	111.0	6.50	13.01	46.4	92.5	12.1	18.5
	4		34	5.95	14.18	42.6	101.5	7.08	12.55	50.4	89.3	7.8	12.2
2	4	17 May	Rest	0.03	20.94	0.2	150.1	5.92	14.55	41.9	103.0	41.7	47.0
	4		4	0.75	20.23	5.3	143.4	4.90	16.05	33.7	112.8	26.6	30.6
	4		10	1.79	18.97	12.6	134.4	5.74	14.20	40.4	100.0	27.8	34.4
	4	18 May	22	3.15	17.48	22.3	123.7	5.95	13.49	42.2	95.2	19.9	28.5
	4		28	4.07	16.42	28.8	116.3	6.22	13.09	44.1	92.9	15.3	23.4
	4		34	4.83	15.50	34.1	109.6	6.61	12.95	46.3	89.0	12.2	20.0
	4	19 May	46	5.66	14.52	40.0	102.8	6.93	12.39	49.3	88.2	12.3	18.4
	4		51	6.54	13.45	46.2	95.2	7.87	11.45	55.8	81.4	9.6	13.8
3	4	25 May	Rest	0.03	20.94	0.2	150.1	5.81	13.85	41.1	98.1	39.9	52.0
	4		18	2.21	19.34	15.9	138.5	5.85	14.84	41.4	105.6	25.5	32.9
	4		34	4.32	20.57	31.0	147.5	6.57	17.79	46.8	127.0	15.8	20.5
	4	26 May	42	5.41	19.54	38.8	140.0	7.10	16.86	50.7	123.7	11.9	16.3
	4		51	6.72	20.52	48.2	147.2	7.92	18.98	56.7	135.8	8.5	11.4
4	4	31 May	Rest	0.03	20.94	0.2	148.5	4.95	15.08	35.5	108.2	35.3	40.3
	4	1 June	17.5	2.47	18.13	17.4	127.5	5.39	14.50	38.0	102.2	20.6	25.3
	4		28	4.19	16.25	29.4	114.4	6.14	13.53	42.9	95.0	13.4	19.4
	4	2 June	42	4.60	15.22	32.3	106.8	6.54	13.01	46.0	91.2	13.5	15.6
	4		52	4.98	13.27	35.0	93.2	6.64	10.85	46.5	76.1	11.5	17.1
	4		58	4.78	12.45	33.6	87.3	6.54	10.73	45.9	73.5	12.3	13.8
	4	3 June	66	4.36	13.21	30.6	92.6	6.33	10.04	44.4	70.5	13.8	22.1
	4		72	5.13	10.45	36.2	73.5	6.35	8.72	44.5	60.7	8.3	12.8
5	10	13 July	Rest	0.03	20.94	0.2	148.8	5.96	13.77	42.3	97.6	42.0	51.2
	8	14 July	19	3.07	17.53	22.2	122.7	6.38	12.73	45.5	90.6	22.3	32.1
	10	15 July	31	4.32	15.50	30.7	110.0	6.98	11.91	49.6	84.4	18.9	25.6
	7	16 July	54	4.98	12.83	35.2	90.8	6.88	10.23	48.5	72.1	13.3	18.7

[1] ΔpCO_2 and ΔpO_2 are defined as the difference between ambient and alveolar pO_2 or pCO_2.

above 36 mm. Hg. An increase of carbon dioxide beyond 36 mm. Hg failed to decrease ΔpO_2 and a level is reached where the law of diminishing returns applies (fig. 6).



mm. Hg.			
Ambient Air		Alveolar Air	
pCO_2	pO_2	pCO_2	pO_2
0.2	150.1	40.8	100.4
9.2	140.5	39.3	103.7
17.3	131 20	42.3	985
275	119.1	435	950
343	111.0	46.4	925
42.6	101.5	504	893
02	150.1	41.9	103.0
53	1434	—	—
12.6	1343	40.4	1000
223	1237	422	952
288	116.3	441	929
34.1	1096	46.3	890
40.0	102.8	493	883
46.2	952	55.8	81.4
02	150.1	41.1	981
15.9	—	41.4	—
31.0	—	46.8	—
388	—	50.7	—
48.2	—	56.7	—
0.2	1485	35.5	108.2
17.4	1275	38.0	1022
29.4	114.4	42.9	950
323	1068	460	91.2
350	—	46.5	—
33.6	—	45.9	—
30.6	—	44.4	—
362	—	44.5	—
02	1488	42.3	976
222	122.7	45.5	906
307	—	49.6	—
352	—	48.5	—

Note: All alveolar points are averages of from 4 - 10 subjects.

FIG. 5. Effects of carbon dioxide on alveolar air at various oxygen concentrations.

TABLE 3. *Effects of increased ambient carbon dioxide on gas equilibria in blood*

EXPERIMENT NO.	DATE	TIME	AMBIENT AIR		ALVEOLAR AIR		BLOOD				PLASMA	
			pCO_2	pO_2	pCO_2	pO_2	O_2 cont.	O_2 cap'y	HbO_2	CO_2 cont.	CO_2 cont.	pH
			mm. Hg		*mm. Hg*		*vol. %*	*vol. %*	*% sat.*	*vol. %*	*vol. %*	
4[1]	6/6	0830	0.2	149.0	39.2	101.3	18.68	19.63	95.3	47.8	58.6	7.44
	6/1	0800	17.4	127.5	38.0	102.2	19.79	20.85	95.0	48.4	58.9	7.45
	6/2	0800	32.3	106.8	46.0	91.2	18.71	20.22	92.6	51.2	59.9	7.38
	6/3	0800	32.4	92.6	44.3	70.5	19.24	21.27	90.5	50.2	60.4	7.40
	6/3	1400	36.0	73.5	44.6	61.2	18.16	20.33	89.3	48.9	59.5	7.38
5[2]	7/13	0830	0.2	149.0	42.4	97.3	19.94	20.34	95.5	47.9	58.2	7.40
	7/16	0700	35.2	90.8	48.5	72.1	18.44	19.93	92.5	53.3	64.6	7.38

[1] Average of 4 subjects.
[2] Average of 5 subjects.

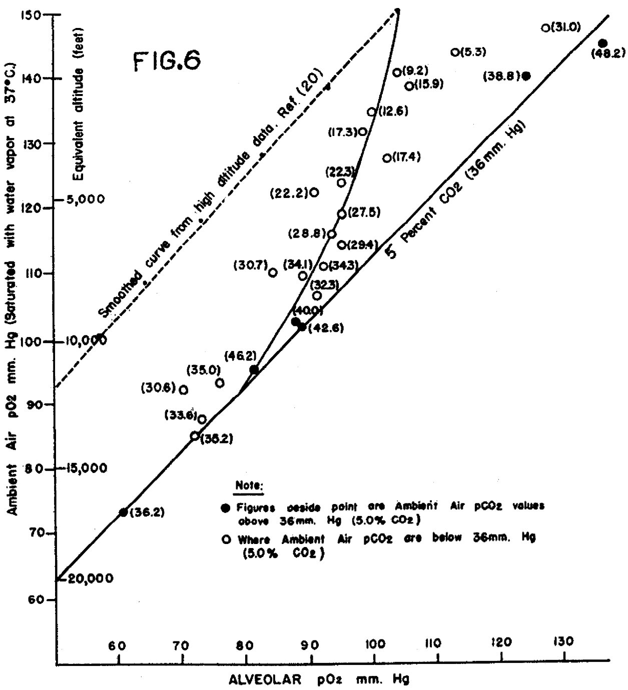


FIG. 6. Effects of carbon dioxide on oxygen pressure in alveoli at various ambient oxygen concentrations.

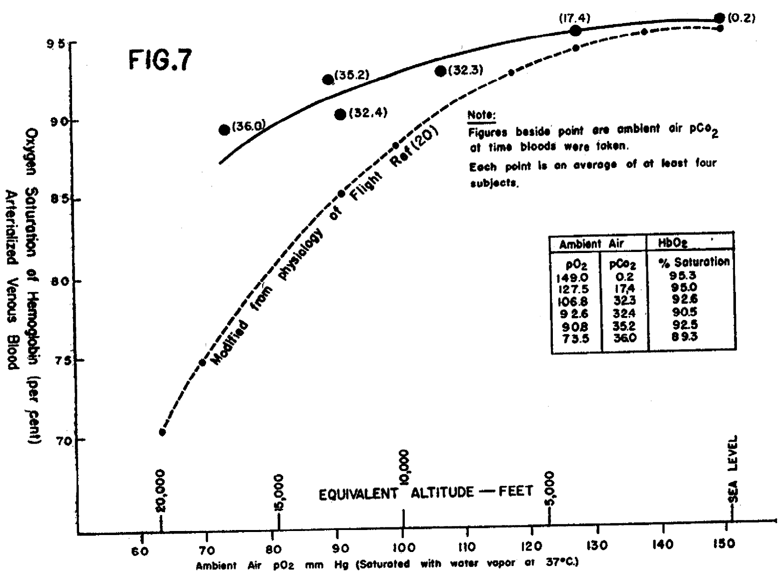


FIG. 7. Effects of carbon dioxide on oxygen saturation of hemoglobin at various ambient oxygen concentrations.

Physiological Data

High concentrations of carbon dioxide in the ambient air impose a physiological stress by raising the alveolar carbon dioxide pressure and thereby reducing the pressure gradient which is so favorable to the unloading of this gas from the

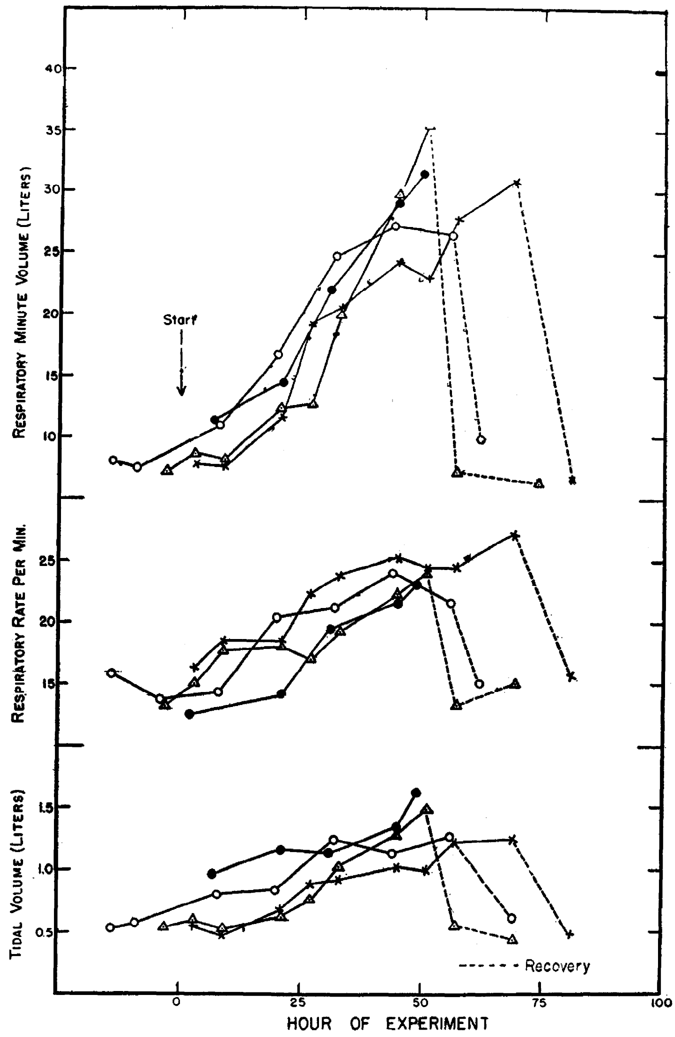


FIG. 8. Effects of carbon dioxide on mean respiration rate, tidal and minute volume. Experiment 3 = △, 4 = x, 5 = ○, and 6 = ●.

pulmonary blood. Hence with heightened alveolar carbon dioxide pressure, it can be assumed that the amount of carbon dioxide unloaded from each unit of blood passing through the alveolar capillaries is reduced. To overcome the barrier imposed by the high ambient carbon dioxide the organism responds by increasing pulse rate, respiratory rate and tidal volume. The pulse rate response is probably indicative of an increased cardiac output which augments the rate of carbon dioxide transport from the tissues to the lungs, while the respiratory response ensures a more effective removal of carbon dioxide from the alveoli.

Respiration. The most prominent physiologic response to the altered oxygen and carbon dioxide concentrations was the change in respiration. In the course of each experiment, the respiratory rate and the tidal volume approximately doubled and the minute volume was two to three times its normal value (figure 8). It was found that an increase in normal ventilation minute volume of over 300% can be maintained for many hours without serious or persistent effects. Some subjects complained of soreness of the respiratory musculature at the end of the experiments but this symptom disappeared within one or two days.

The increase in respiratory minute volume produced by 3% carbon dioxide was of the order of one and a half times normal, compared with a two to three-fold increase brought about by 5% carbon dioxide.

Pulse rate. A characteristic mean increase of approximately 10 beats per minute over the normal resting rate occurred when the carbon dioxide concentration reached 5% (fig. 9). That this increase was in response to the increased carbon dioxide pressure rather than to the lowered ambient oxygen pressure was proved by experiment 3, in which the rising carbon dioxide concentration was accompanied by a similar rise in pulse rate, although the oxygen concentration was maintained between 19 and 21%. Figure 9 also shows an approximate difference of 10 beats per minute at equivalent carbon dioxide concentrations between experiments 3 and 4, and 5 and 6. This difference is attributed to effect of temperature on pulse rate. Experiments 3 and 4 were carried out at Effective Temperatures of 85 and 88°, and experiments 5 and 6 at 75 and 60°, respectively (fig. 1–4). Regardless of the effect of temperature on pulse rate, a rise always accompanied an increase in carbon dioxide concentration.

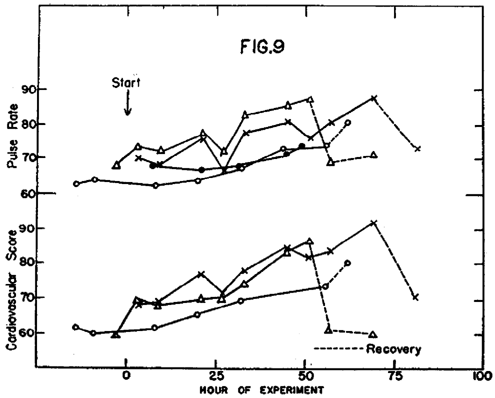
Pulse rate response to exercise paralleled the increase in carbon dioxide (fig. 9). This finding, as in the case of the resting pulse rate, cannot be attributed to the decreased ambient oxygen pressure. It will be noted that in experiment 5 there was a sharp rise of about 8 points in the C. V. S. obtained two hours after the chamber was opened and ventilation with outside air started (recovery point)[2]. In other experiments the C. V. S. was not ascertained until 6 to 9 hours after exposure to outside air. It appears therefore that the exposure to outside air results in a rise in the C. V. S. (two-hour measurement) followed by a fall to pre-experimental level at the end of 6 to 9 hours. Explanation of this rise is difficult, but it can be said that the return to outside air was the most drastic change to which the subjects were exposed, and which in part is reflected by the increased pulse rate response to exercise.

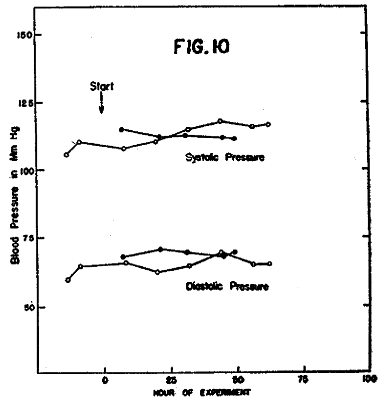
Blood pressure. There were no characteristic changes in blood pressure (fig. 10). In two of the experiments, both the systolic and diastolic pressures showed a tendency to increase but pulse pressure did not change.

Body temperature. Rectal and oral temperatures require separate considera-

[2] The period of re-exposure to outside air.

tion (fig. 11). In experiments 3 and 4, involving few subjects, rectal temperatures were taken, while in experiments 5 and 6 convenience dictated the use of oral thermometers. In the control observations oral temperatures were, as has been commonly observed, roughly one-half degree lower than rectal temperatures. In experiments 3 and 4, the rectal temperatures rose within 5 to 10 hours after the





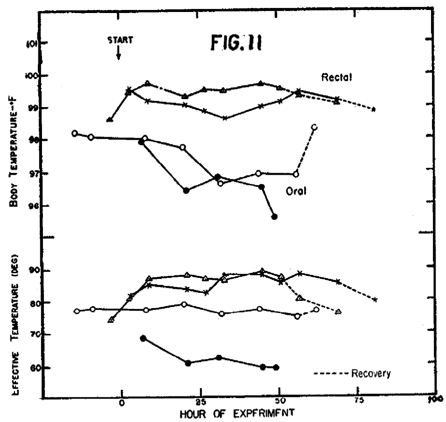


FIG. 9. Effects of carbon dioxide on mean pulse rate and cardiovascular score. Experiment 3 = △, 4 = x, 5 = ○ and 6 = ●.

FIG. 10. Effects of carbon dioxide on mean systolic and diastolic pressure. Experiment 5 = ○ and 6 = ●.

FIG. 11. Mean oral and rectal temperatures and compartment Effective Temperatures. Experiment 3 = △, 4 = x, 5 = ○ and 6 = ●.

start of an experiment to higher levels and dropped almost as rapidly at the close of an experiment. This rise is attributed to the high Effective Temperatures of the experimental chamber (88 and 85°). On the other hand, experiment 5 (Effective Temperature, 75°) and experiment 6 (Effective Temperature, 60°) imposed a heat conservation problem as indicated by the considerable decrease in oral temperature. The subjects were inadequately clothed, particularly in experiment 6, and felt cold. The fall in oral temperature may in part be due to mouth breathing which many subjects found necessary at high ambient carbon dioxide concentrations as well as to the increased heat loss due to hyperventilation.

TABLE 4. *Subjective symptoms with respect to the subjects, recorded as a fraction (personnel affected/personnel interviewed)*

	HOUR OF TEST	AMBIENT AIR		CEREBRAL FULLNESS	HEADACHE[1]	NASAL CONGESTION	NAUSEA	SORE THROAT	DRY THROAT	DRY OR SORE THROAT	FELT GOOD	FELT FAIR
		CO_2	O_2									
		per cent										
Exp. 5												
Chamber closed	46.5	4.8	13.5		15/35	14/34	5/35			16/34		
	58.5	5.0	12.5		16/34		2/34					
Chamber open	1.5 hr. after test	0.03	20.9		7/34		1/34					
Exp. 6												
Chamber closed	3	0.5	20.5	—	2/20	3/20		1/20	0/20		19/20	1/20
	7	1.3	19.5	1/18	0/18	0/18		0/18	0/18		17/18	1/18
	11	1.9	18.6	1/15	0/13	0/15		0/15	0/15		15/15	0/15
	15	2.4	18.3	1/16	0/16	3/16		1/16	0/16		16/16	0/16
	19	2.8	17.7	1/35	0/35	0/35		3/35	0/35		31/35	4/35
	23	3.3	17.3	1/17	0/17	1/17		0/17	0/17		17/17	0/17
	27	3.9	16.5	0/17	3/17	4/17		1/17	0/17		15/17	2/17
	29	4.2	15.9	1/10	2/10	2/10		0/10	1/10		6/10	4/10
	31	4.4	15.6	1/18	1/18	1/18		0/18	2/18		15/18	3/18
	35	5.0	15.1	0/16	0/16	1/16		0/16	0/16		16/16	0/16
	39	4.8	14.6	0/14	4/14	4/14		2/14	1/14		11/14	3/14
	43	4.8	14.1	4/16	3/16	0/16		0/16	0/16		8/16	8/16
	47	5.1	13.7	1/10	3/10	0/10		0/10	3/10		8/10	2/10
	50	5.2	13.2	6/76	18/76	8/76		6/76	18/76		50/76	23/76[2]
Chamber open	1.5 hr. after test	0.03	20.9	4/76	3/76	—		—	—		—	—

[1] Headaches were for the most part transient and not severe. One man was removed from the chamber because of headache, nausea, vomiting, and a blood pressure rise to 146 mm.

[2] All personnel were in good condition the following morning. Only 3 of 76 individuals complained of malaise at the 50th hour.

Mouth breathing and increased heat loss. The increased rates of ventilation encountered in these experiments caused an increase in rate of heat loss via the lungs. In experiment 6, the subjects were exposed to uncomfortably low temperatures and high humidities. If we assume the temperature to be 61°F., the relative humidity to be 90% and the minute volume of a seated man to be 30 liters, then each man loses about 41.9 cal. per hour through the lungs (21). The metabolic rate of a seated man weighing 70 kgm. is roughly 100 calories per hour. Hence, under these conditions a man loses about 42% of the heat which he is producing via the lungs. When he is breathing at a more normal rate of 10 liters per minute, he loses only 14% of his heat via this channel. Consequently, thermal insulation adequate for normal breathing becomes inadequate when the rate of ventilation is increased without concurrent increase in rate of metabolism.

In experiments 3 and 4 the subjects breathed humid air at a temperature of over 90°F. Under these conditions the heat loss via the lungs was negligible. Thus, it can be seen that with respect to temperature regulation an increased rate of ventilation without coincident increase in the rate of heat production is a definite liability at low temperatures and is not an appreciable asset at high temperatures unless the relative humidity is low.

Subjective symptoms. Subjective reactions were recorded in experiments 5 and 6 (table 4). The usual symptoms, sore throat, nasal congestion and headache, were experienced about 40 hours after the start of the experiments. In experiment 5, about 40% of the subjects complained of all these symptoms; in experiment 6, dry throats and headaches occurred in 18%, and nasal congestion in about 10%. However, all personnel felt well the morning after the conclusion of each experiment. In the first four experiments, transient headaches occurred frequently after leaving the sealed spaces. A phenomenon of interest was the fleeting smell and taste of ammonia when outside air was breathed following exposure in high carbon dioxide atmospheres.

Psychological

Although there were some unquestionable decrements in test performance in these experiments, the results lead to an interpretation that the losses, when they occur, were not of such magnitude or character as to interfere appreciably with efficiency of personnel performing naval tasks. Five per cent carbon dioxide is not a comfortable concentration for prolonged inhalation, but the data show that its depressing effect is not great. Compensatory mechanisms appear to come into play to mitigate the adverse effects of long exposures. Other conditions, e.g., the extreme Effective Temperature in the early experiments may also have operated to reduce efficiency. Since these conditions would be expected to affect test scores in the same direction as increased carbon dioxide or reduced oxygen, the changes found are maximal if attributed to the major variables of carbon dioxide excess and oxygen deficiency.

The psychological test data have been analyzed to answer five questions.

What changes in performance occurred during the experiments (table 5)? There was no consistent significant effect upon any of the auditory or visual functions measured, nor upon any of the paper-and-pencil test scores, after the subjects practiced. The eye-hand coordination tests showed a slight decline in most cases. Hand dynamometer scores declined 3 to 10% in well-practiced subjects. Even though statistically significant, these changes are believed to be of small practical importance. The amount of body sway consistently increased, and, for the most part, the increases approach statistical significance. Some part, at

TABLE 5. *The difference in performance between the first and last test in the closed chamber*

Each column presents the data for an experiment. Description of the time and conditions of each test period is given at the head of the columns. Items and group means relating to the first test are in the lines labeled (1); those concerning the last test, in (2).

		EXPERIMENT					
		1	2	3	4	5	6
Time to middle of test period from closing chamber	(1)	1¼ hr.	1¼ hr.	1¼ hr.	1¼ hr.	7½ hr.	6 hr.
	(2)	31½ hr.	49½ hr.	49½ hr.	69 hr.	57½ hr.	49 hr
Per cent CO_2 (av.) during test	(1)	0.5	0.6	0.5	0.5	1.1	1.1
	(2)	5.4	6.1	6.0	5.3	4.8	5.1
Per cent O_2 (av.) during test	(1)	20.2	20.4	20.4	20.5	19.6	19.7
	(2)	14.8	14.0	19.8	11.2	12.5	13.4
Number of subjects		4	3	3	4	2	12
Critical flicker frequency (flashes per sec.)	(1)	41.0	43.8		44.5		
	(2)	40.7	40.4		42.9		
	t	<1.0	1.86		1.72		
Dark adaptation threshold (log $\mu\mu$ lamberts)	(1)					3.7	
	(2)					3.7	
	t					0.0	
Pitch discrimination (decile rank)[3]	(1)	2.0	3.0	4.0			
	(2)	4.5	6.3	4.7			
	t	1.35	4.94[1]	<1.0			
Loudness discrimination (decile rank)[3]	(1)	5.2	6.3	4.0			
	(2)	8.2	6.3	4.3			
	t	2.22	0.0	<1.0			
Audiometer, 128 dv. (decibels)[3]	(1)				18.1		
	(2)				13.8		
	t				<1.0		
Audiometer, 1024 dv. (decibles)[3]	(1)				18.8		
	(2)				18.1		
	t				<1.0		
Audiometer, 8192 dv. (decibels)[3]	(1)				−2.5		
	(2)				3.1		
	t				5.02[1]		
Body sway, eyes open (mm. in 2 min.)[3]	(1)	223	500	200	251	174	
	(2)	390	865	244	394	204	
	t	2.75	3.95	1.24	3.07	1.55	

TABLE 5—*Continued*

		EXPERIMENT					
		1	2	3	4	5	6
Body sway, eyes closed (mm. in 2 min.)[3]	(1)	364	714	421	304	216	
	(2)	566	1214	737	550	308	
	t	2.36	1.76	3.12	2.19	2.38	
Railwalking (feet walked in 10 trials)	(1)	47	49	56		46	
	(2)	36	51	49		40	
	t	1.28	<1.0	2.18		1.57	
Hand-arm steadiness (contacts per min.)[3]	(1)	48.4	16.0	54.9	31.8	50.0	
	(2)	133.8	87.8	123.5	98.7	100.2	
	t	15.59[1]	3.72	10.04[1]	2.50	11.76[1]	
Complex tapping (contacts per min.)	(1)	164	170	188	195	159	
	(2)	148	143	179	163	164	
	t	1.40	3.24	<1.0	1.17	<1.0	
Pursuit rotor (contact during 30 sec.)	(1)	24.65	25.90	27.37	26.35	12.85[4]	
	(2)	22.08	25.34	26.31	24.79	16.77	
	t	2.09	<1.0	2.59	1.90	5.31[1]	
Hand dynamometer (kgm.)	(1)	54.5	55.7	56.3	52.6	56.1	56.6[4]
	(2)	49.2	52.0	54.7	49.0	51.8	57.6
	t	2.50	1.58	2.52	2.51	4.26[1]	<1.0
Computation (problems in 6 min.)	(1)	87.8	73.3	116			
	(2)	69.2	78.7	118			
	t	3.48[1]	<1.0	<1.0			
Computation (problems in 10 min.)	(1)				165	167	
	(2)				154	155	
	t				1.0	2.46[1]	
Code test—15 min. (letters per 90 sec.)	(1)	26.7	25.9	32.2			
	(2)	25.1	27.7	32.8			
	t	<1.0	<1.0	<1.0			
Code test—30 min. (letters per 90 sec.)	(1)				28.5	29.3	26.5[4]
	(2)				27.7	29.7	30.2
	t				<1.0	1.05	4.45[1]
Number checking (number correct in 3 min.)	(1)	51.8	55.3	67.0			
	(2)	47.2	55.3	64.3			
	t	<1.0	0.0	<1.0			

[1] Values for *t* and *N* show that the difference between these means is significant at the .05 level of confidence, or lower.

[2] Number of subjects in experiment 5 was 17, except as follows: dark adaptation, 4; body sway, 5; hand-arm steadiness, 15.

[3] A lower score indicates better performance.

[4] The subjects had little or no practice before the experiment.

least, of this increase is a result of heavy breathing. Control of gross body movement is not so severely affected by heavy breathing as is static equilibrium, for railwalking scores showed only an inconsistent trend downward. Of the functions measured, hand-arm steadiness showed the greatest change, but again

TABLE 6. *Comparison of performance at the beginning and the end of the time during which the CO_2 concentration was approximately 5%*

Each column presents the data for an experiment. Description of the time and conditions compared is given at the head of each column. Items and group means of performance relating to the beginning of the time at 5% CO_2 are in the lines labeled (1); those concerning the end of the time at 5% CO_2 are labeled (2).

		EXPERIMENTS		
		4	5	6
Time to middle of test period since closing chamber	(1)	37½ hr.	34 hr.	31 hr.
	(2)	61½ hr.	58½ hr.	48 hr.
Per cent CO_2 (av.) during test	(1)	4.7	4.8	4.1
	(2)	5.2	4.8	5.0
Per cent O_2 (av.) during test	(1)	15.6	15.1	15.8
	(2)	12.0	12.5	13.5
Number of subjects		4	2	12
Critical flicker frequency (flashes per sec.)	(1)	41.8		
	(2)	43.0		
	t	2.43		
Audiometer, 128 dv. (decibels)[3]	(1)	26.0		
	(2)	10.6		
	t	3.37[1]		
Audiometer, 1024 dv. (decibels)[3]	(1)	16.8		
	(2)	18.4		
	t	<1.0		
Audiometer, 8192 dv. (decibels)[3]	(1)	1.2		
	(2)	6.0		
	t	<1.0		
Body sway, eyes open (mm. in 2 min.)[3]	(1)	260	248	
	(2)	368	204	
	t	2.82	1.73	
Body sway, eyes closed (mm. in 2 min.)[3]	(1)	353	415	
	(2)	490	308	
	t	2.25	2.22	
Hand-arm steadiness (contacts per min.)[3]	(1)	99.1	90.7	
	(2)	104.9	100.2	
	t	<1.0	1.58	

TABLE 6—*Continued*

		EXPERIMENTS		
		4	5	6
Complex tapping (contacts per min.)	(1)	202	153	
	(2)	182	164	
	t	1.38	2.54[1]	
Pursuit rotor (contact during 30 sec.)	(1)	26.39		
	(2)	24.16		
	t	1.44		
Hand dynamometer (kgm.)	(1)	47.6	53.8	58.3[4]
	(2)	48.0	51.8	57.6
	t	<1.0	1.56	<1.0
Computation (problems in 10 min.)	(1)	161	156	
	(2)	162	155	
	t	<1.0	<1.0	
Code test—30 min. (letters per 90 sec.)	(1)	27.9	28.8	29.4[4]
	(2)	28.6	29.7	30.2
	t	<1.0	3.16[1]	1.22

[1] Values for t and N show that the difference between these means is significant at the .05 level of confidence, or lower.

[2] Number of subjects in experiment 5 was 17, except as follows: body sway, 5; hand-arm steadiness, 15.

[3] A lower score indicates better performance.

[4] The subjects had no practice before the experiment.

body movements, resulting from heavy breathing, were obviously an important determining factor.

To what extent does performance change when oxygen percentage gradually decreases and carbon dioxide is maintained at 5% (table 6)? The data of experiments 4, 5, and 6 are relevant to this question. The statistical analysis consisted in comparing performance when the carbon dioxide first reached 5% with performance just prior to return to normal air. In using the data of experiment 4, the small number of cases made advisable the averaging of the scores of the first two and the last two test periods during the 40 hours that the carbon dioxide was at a 5% level.

The results (table 6) show very few changes of significance. Only three of the comparisons show differences significant below the .05 level of confidence, and that for the audiometer (128 double vibrations[3]) is questionable because of mechanical difficulties during the testing. The other two show improvement. The conclusion to be drawn from this analysis is that the subjects were able to maintain their performance levels in all tests during prolonged exposure to 5% carbon dioxide even when the ambient oxygen percentage was decreasing to 12. Further-

[3] Hereinafter, 'dv.'

more, there is evidence in some tests of adaptation to the conditions of the experiments, with consequent improvement in performance during the last 20 hours.

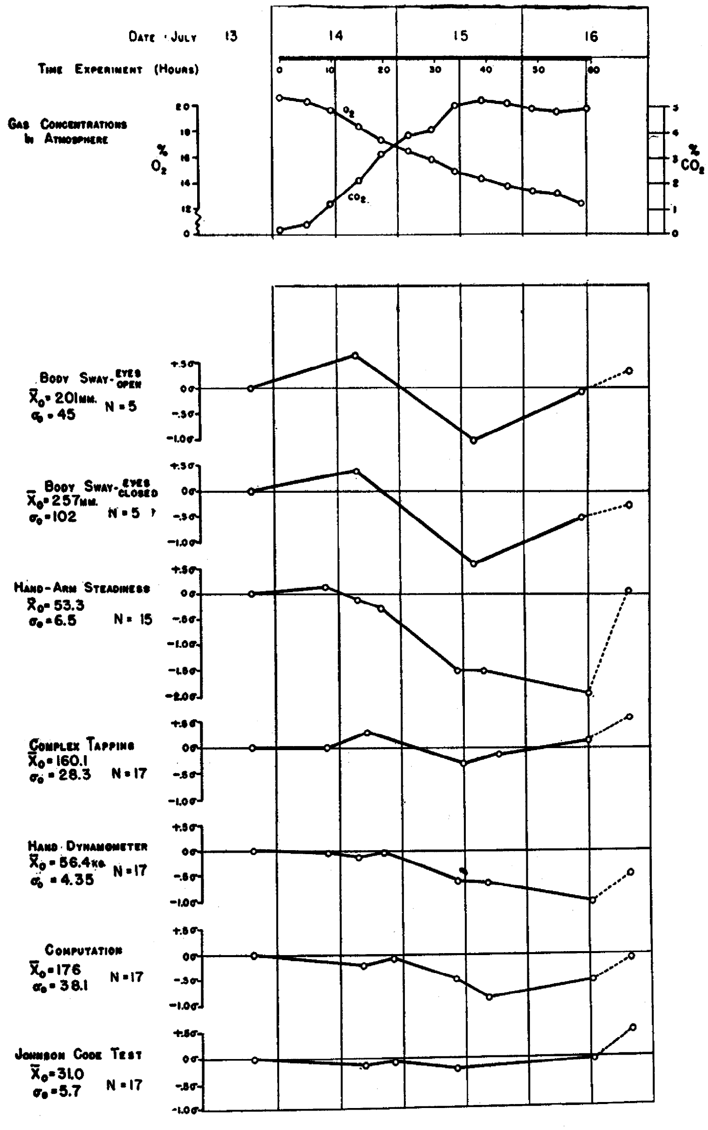


FIG. 12. Effects of increasing ambient carbon dioxide and decreasing ambient oxygen concentrations on psychomotor performance (experiment 5). All ordinates are given in standard deviation units of the score distribution in the last practice period. All scores are plotted so that positive deviation indicates improvement in performance, regardless of the raw score magnitude.

Graphs based on the data obtained from seven of the tests used in experiment 5 are shown in figure 12. All scores are plotted in comparable units, based on the standard deviation of the score distribution of the last practice session, taking

TABLE 7. *Extent and significance of the differences in performance between the last test during rebreathing and the 'recovery test'*

Each column presents the data for one experiment. Description of the conditions compared is at the head of each column. Group means of performance during the last test in the closed chamber are in the lines labeled (1); those for the 'recovery test' are labeled (2).

		EXPERIMENTS				
		1	2	3	4	5
Time of starting test in recovery period		9 hr.	2 hr.	9 hr.	2 hr.	$4\frac{1}{2}$ hr.
Highest per cent CO_2 reached		5.95	6.54	6.75	5±	5±
Lowest per cent O_2 reached		14.18	13.45	19.22	10.45	12.21
Number of subjects		4	3	4	4	[2]
Critical flicker frequency	(1)	40.7	40.4		39.0	
(flashes per sec.)	(2)	41.5	46.3		42.9	
	t	1.90	3.53		2.26	
Pitch discrimination (decile	(1)	4.5	6.3	5.5		
rank)[3]	(2)	3.8	8.3	2.2		
	t	<1.0	3.52	2.18		
Loudness discrimination	(1)	8.2	6.3	4.2		
(decile rank)[3]	(2)	5.2	7.3	1.5		
	t	1.73	<1.0	1.62		
Audiometer, 128 dv. (decibles)[3]	(1)				13.8	
	(2)				9.4	
	t				2.34	
Audiometer, 1024 dv. (decibels)[3]	(1)				18.1	
	(2)				13.8	
	t				2.74	
Audiometer, 8192 dv. (decibels)[3]	(1)				3.1	
	(2)				−1.8	
	t				1.63	
Body sway, eyes open (mm. in	(1)	390	865	294	394	204
2 min.)[3]	(2)	293	218	115	214	190
	t	1.75	1.78	2.89	4.92[1]	<1.0
Body sway, eyes closed (mm.	(1)	566	1214	754	550	308
in 2 min.)[3]	(2)	505	502	282	244	288
	t	<1.0	1.36	5.55[1]	2.49	<1.0
Railwalking (feet walked in 10	(1)	36	51	50		
trials)	(2)	35	58	62		
	t	<1.0	<1.0	1.66		

TABLE 7—*Continued*

		EXPERIMENTS				
		1	2	3	4	5
Hand-arm steadiness (contacts per min.)[3]	(1)	133.8	87.8	105.8	98.7	100.2
	(2)	23.8	14.8	38.2	41.5	49.4
	t	13.56[1]	4.16	12.26[1]	2.54	6.37[1]
Complex tapping (contacts per min.)	(1)	148	143	187	163	164
	(2)	182	167	209	213	178
	t	2.43	1.73	1.38	2.38	2.96[1]
Pursuit rotor (contact during 30 sec.)	(1)	22.08	25.34	25.85	24.79	
	(2)	25.12	25.49	27.83	26.44	
	t	1.85	<1.0	3.10	2.12	
Hand dynamometer (kgm.)	(1)	49.2	52.0	53.9	49.0	51.8
	(2)	52.6	55.0	55.0	50.4	54.0
	t	2.64	1.71	1.10	<1.0	2.24[1]
Computation (problems in 6 min.)	(1)	69.2	78.7	111		
	(2)	82.2	74.3	129		
	t	5.73[1]	<1.0	1.74		
Computation (problems in 10 min.)	(1)				154	155
	(2)				184	173
	t				1.73	3.41[1]
Code test—15 min. (letters per 90 sec.)	(1)	25.1	27.7	33.2		
	(2)	28.7	30.2	38.6		
	t	4.92[1]	2.19	2.17		
Code test—30 min. (letters per 90 sec.)	(1)				27.7	29.7
	(2)				31.8	33.7
	t				2.36	6.35[1]
Number checking (number correct in 3 min.)	(1)	47.2	55.3	65.8		
	(2)	53.5	51.7	80.8		
	t	1.58	1.00	6.12[1]		

[1] Values for t and N show that the difference between these means is significant at the .05 level of confidence, or lower.

[2] Number of subjects in experiment 5 was 17, except as follows: body sway, 5; hand-arm steadiness, 15.

[3] A lower score indicates better performance.

the average of this distribution as zero. It will be noted that only hand dynamometer and steadiness scores continued the downward trend during the last 20 hours of rebreathing. For the other tests, the lowest scores occurred between the 30th and 40th hours and subsequently improved.

Is there any advantage in the maintenance of ambient oxygen at approximately 20% if carbon dioxide is allowed to increase to 5%? This question was answered by comparing the data of the third experiment with those of experiments 1, 2, and 4. Changes in performance between the time the chamber was closed and the time, about 35 hours later, when the carbon dioxide concentration had reached about 5%, were compared under the two conditions of oxygen concentration. The conclusion of this analysis is that 19 to 21% ambient oxygen offers no advantages over oxygen reduced to 15% if the carbon dioxide concentration is concomitantly increased to 5%. In 14 comparisons of changes in test performance, 6 favored conditions of decreased oxygen; no difference was significant at the .05 level of confidence.

TABLE 8. *Improvement with practice on the hand dynamometer test during 50 hours' rebreathing, carbon dioxide concentration being 5% during the last 15 hours*

	EXP. 6	CONTROL GROUP A	CONTROL GROUP B
Number of subjects	12	18	10
First practice score (kgm.)	56.6	52.6	46.5
Sixth practice score (kgm.)	56.8	54.2	49.2
Difference	.2	1.6	2.7
Difference from Experiment 6 group in improvement		+1.4	+2.5
t		<1.0	1.52

TABLE 9. *Improvement with practice on the Johnson Code Test during 50 hours' rebreathing, carbon dioxide concentration being 5% during the last 15 hours*

	EXP. 6	CONTROL GROUP
Number of subjects	15	18
First test score (letters per 90 sec.)	26.6	26.7
Fourth test score (letters per 90 sec.)	29.8	30.9
Improvement	3.2	4.2
Difference from Experiment 6 group in improvement		+1.0
t		1.18

To what extent does performance improve on return to normal air? This is an important question since there is a decrement in some tests, (table 5) and it is important to know whether the unfavorable reactions persist. Table 7 compares performance in the last test period during rebreathing with that in the recovery period (fourth to fifth hour). Of 57 differences, 52 show some average improvement in performance during the recovery period and 12 are significant at the .05 level of confidence or lower.

What is the effect of the experimental conditions on expected improvements from practice (tables 8, 9, and fig. 13)? In experiment 5 the subjects had only two practice sessions with the pursuit rotor before closing the experimental chamber. They had four more practice periods while the chamber was closed, and one in the recovery test period. The learning curve for the group, compared with three other groups tested with the same apparatus and procedure (fig. 13), suggests that the effect on pursuit rotor learning when living in an atmosphere where concentration of carbon dioxide builds up to 5%, is roughly equivalent to that of living in an atmosphere where the Effective Temperature is above the comfort zone (22). The subjects in experiment 6 had no previous practice on the hand dynamometer or the code test. Their improvement (tables 8, 9) is slightly but not significantly less than that of groups learning under normal conditions. Although there is some indication in these data of interference or inhibition imposed by the experimental conditions during the learning period, the effect is not

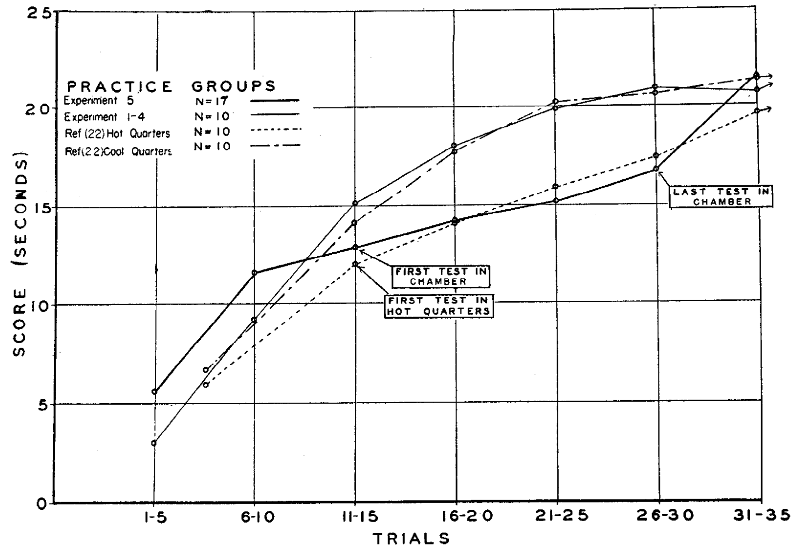


FIG. 13. Pursuit rotor learning under several experimental conditions. Each curve covers a period of four days, with two, five-trial practice periods each day in most cases. The subjects of experiments 1—4 and the 'cool quarters' group were learning under essentially normal conditions. The 'hot quarters' group lived in an environment where the Effective Temperature remained above 85°.

greater than that found in well-practiced performance, when judged by the critical ratio of the changes.

SUMMARY

1. In six experiments men breathed recirculated air for periods of 35 to 72 hours in sealed spaces of such size as to provide 500 cu. ft. of air volume per man.

2. Exposure in atmospheres of carbon dioxide concentrations up to 5% and reduced oxygen concentrations as low as 12% did not seriously impair the physical condition and efficiency of the subjects as evaluated by biochemical, physiological, and psychological tests. Minor symptoms of headache, nasal congestion, and dryness of the throat quickly disappeared when outside air was breathed.

3. In an atmosphere of 5% carbon dioxide and 12% oxygen, healthy men are able to maintain an adequate oxygen pressure in the lungs, blood and tissues because an increase in respiratory minute volume (hyperventilation) and an increase in pulse rate (circulation) prevent a corresponding reduction in oxygen concentration in lungs and blood despite the decrease in ambient oxygen from 21 to 12%. Consequently, in long exposures to atmospheres of high carbon dioxide content (5%) it is not necessary to maintain the oxygen concentration of the recirculated air at the normal value.

4. Concentrations of carbon dioxide much above 5% are not well tolerated. This value appears to be a limiting level for healthy young men if exposures are prolonged.

5. Under these conditions the carbon dioxide output was found to be 0.326 l/min. STP (0.69 cu. ft. per man hour) and the oxygen consumption was 0.387 l/min. STP (0.82 cu. ft. per man hour).

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