Prolonged Exposure in the Navy Full Pressure Suit at "Space Equivalent" Altitudes

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MUCH TIME, effort, and money is being spent to provide a vehicle and a suitable environment to carry man on flights into space. While some attention has been devoted to those human factors with which the pilot will have to contend, many of the experiments conducted in this field have not been at space-simulating altitudes. Strughold[11] and Strughold, Haber, Buettner and Haber[12] have stated that "space equivalent" altitude occurs at 50,000 feet and above as regards breathing properties of the atmosphere. At this altitude, the total alveolar space is occupied by carbon dioxide and water vapor so that no significant oxygen can enter into contact with the alveolar membranes from the inhaled gas. The consciousness time, survival time and revival time are therefore the same at 50,000 feet or 50,000 miles. To be realistic in testing man for space flight, it would appear that the human subject should be exposed to simulated altitudes in excess of 50,000 feet.

Since useful consciousness time is about thirteen seconds at 50,000 feet or higher, the man in space must be protected by a pressure suit in case of loss of cabin pressure. Even though continuous exposure of the man to complete vacuum might be undesirable, it would be of utmost importance that he be protected while corrective action was taken. It would be desirable that the suit be capable of maintaining life in a near vacuum for many hours in case of emergency.

The problem of extended breathing of 100 per cent oxygen at altitude has not been studied adequately. Becker-Freyseng and Clamann[1] exposed themselves to 90 per cent oxygen for sixty-five hours at sea level pressures. One of the subjects developed fever, leukocytosis, nausea, vomiting and malaise, and bronchitis. Comroe, Dripps, Dumke and Deming[3] exposed human subjects to 100 per cent oxygen at 1 atmosphere for twenty-four hours. Twenty-eight of thirty subjects experienced a substernal ache which was accentuated during inspiration. Eight of the subjects complained of aggravation of the pain following termination of the experiment. The substernal distress was diagnosed as being either tracheobronchial or pulmonary parenchymal damage. A reduction in vital capacity, which did not correlate with chest pain, occurred in sixty-three of

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eighty subjects.[3] Ohlsson[10] found a reduction in vital capacity of 400 to 1600 cc in five of six subjects in a similar experiment. Behnke, Johnson, Poppen and Motley[2] reported one subject with substernal discomfort and a white blood count of 21,200 after an exposure of four hours while breathing oxygen.

Mullinax and Beischer[9] have concluded that "it would seem inadvisable to breathe pure oxygen at 1 atmosphere for greater than eight to twelve hours. At tensions less than 425 mm Hg. oxygen can be breathed indefinitely."

Structural weight saving is a prime interest of design engineers. If man can tolerate 100 per cent oxygen at 35,000 feet (178.6 mm Hg) for indefinite time periods as Mullinax and Beischer indicate, it would be an advantage to the engineers of space cabins to be able to stress the cabins for a maximum internal pressure of 3.46 pounds per square inch (psi) (35,000 feet) rather than 7.34 psi (18,000 feet) or 14.7 psi (sea level). Man can tolerate 100 per cent oxygen at 35,000 feet as far as tissue oxygenation is concerned. Thirty-five thousand feet on pure oxygen is nearly the same oxygen tension as in air at sea level pressure. Adequate oxygen supply in a space cabin would be much simpler than an adequate air supply. Therefore, if man can tolerate 100 per cent oxygen at 35,000 feet without oxygen toxicity or hypoxia, it would seem most desirable from an engineering standpoint to consider a cabin pressure schedule to withstand a maximum of 3.46 psi.

The psychophysiologic aspects of man in space have been studied by Strughold and his group. These studies include weightlessness,[6] closed cabin systems and isolation of a man therein,[13] and balanced systems.[4,5] Mayo[8] has given theoretical requirements for space cabin flight including likelihood of meteorite and space trash impact on the cabin. He estimates that the chance of the cabin being hit by small particles might make self-sealing characteristics desirable in the cabin walls.

This paper is concerned with the following questions:

1. Can man tolerate 35,000 feet body pressure in a full pressure suit for seventy-two hours?
2. Can man tolerate 100 per cent oxygen for this period?
3. Can man function adequately in the pressure suit when the ambient pressure is space equivalent (above 50,000 feet)?
4. What psychologic and physiologic changes occur as a result of this exposure?

METHODS AND PROCEDURE

A thirty-six-year-old male naval aviator and flight surgeon was selected as the subject for the experiment. Being an active naval aviator, proficient in the newer jet aircraft, as well as being a flight surgeon proficient in aviation physiology, it was thought that this subject could give cognizant subjective data and correlate the objective data gathered by outside observers.

He was fitted with the Mark III, Mod II Navy lightweight full pressure suit designed by the U. S. Navy Air Crew Equipment Laboratory. He was given a pre-exposure aviation physical examination which included chest x-ray and ECG. The subject was then given a four-hour exposure at simulated altitudes of up to 170,000 feet.

After a twenty-four-hour rest period, the subject was prepared for a seventy-two hour exposure. He was advised as to low bulk diet for the rest period; the night before the exposure he was given a high cleansing enema; the morning of the exposure he was given another high cleansing enema. ECG limb leads were attached by means of collodion and adhesive tape (Fig. 1). No precordial leads were used. The pressure suit used had a front zipper to facilitate urination at altitudes of 40,000 feet or below. The subject's weight with the ventilation garment was 198 pounds. He was 70 inches in height. Routine blood studies, as well as blood chemistry studies, urine samples and lung physiology studies were performed before suiting for basal levels. In addition, he was pre-evaluated by psychologic battery tests.

After suiting, he entered the low pressure chamber and was preoxygenated for one hour prior to ascent. He was taken to simulated altitudes (Fig. 2) and remained at the various altitudes as follows:

Altitude	20-50,000 feet	60,000 feet	80,000 feet	90-140,000 feet
Time	22 hrs. 09 min.	0 hrs. 55 min.	13 hrs. 43 min.	33 hrs. 25 min.

The subject was in the suit a total of seventy-six hours and forty-eight minutes, of which seventy-two hours were spent at altitudes greater than sea level. Discrepancy between time at altitude and total time in the low pressure chamber is due to time spent ascending and descending.

A record was maintained during the exposure of food and water intake, oxygen expenditures and subjective symptoms. Routine urine studies and continual ECG tracings were made throughout the exposure.

Fig. 1. Method used for attachment of ECG limb leads under the Navy full pressure suit.

RESULTS

Total water input, including that from food but not from metabolism, was 12,476 cc. Water recovered in the urine was exactly 2,000 cc. Total caloric input was 5,550 calories, with weight loss 6.5 pounds. No desire to defecate was expressed by the subject during the experiment and a defecation (small) did not occur until twenty-one hours and fifteen minutes after the termination of the experiment.

Oxygen expenditures averaged, over

one hour test periods, 10.58, 11.24, 11.90 and 11.55 liters per minute, standard temperature and pressure, dry (STPD). While this is a greater oxygen expenditure than would be normally expected, it can be accounted for by face-seal leakage since the subject purposely permitted face seal leakage for head ventilation.

Fig. 2. Subject at simulated altitude wearing the Navy Mark III full pressure suit.

The post-exposure physical condition of the subject was excellent except for several pressure points over both shoulders and at the back of the neck over seventh cervical vertebra. A pustular dermatitis was present over the dorsum of the back and the lateral and anterior thorax. These probably were due to unsanitary skin conditions inherent in the experiment. Skin pustules and erythema were present at the sites of the ECG electrodes. Ear canals were normal. Nasopharyngeal mucous membranes were moderately red and injected but without edema. The tongue and cervical glands remained normal. The abdomen was normal except for slight liver tenderness on deep inspiration. Reflexes were normal. The subject had a minus 2 Schneider index immediately following the experiment but returned to normal (plus 12) within a few days. All weight loss was regained within a week post-exposure.

Subjective reaction to the Navy Mark III, Mod II suit was essentially favorable. The suit was a good fit for the subject. However, he stated that the exhalation valve was hard to open when the suit was in the unpressurized state (35,000 feet or below), requiring several inches of positive respiratory pressure to open it. Complaints of a pressure point on the foot were noted after thirty-six hours and on the back of his neck after forty-three hours. After sixty-seven hours the subject complained of cramped muscles in his legs. Irritated eyes at this same time were relieved by self-application of boric acid ophthalmic ointment. Noise level of the suit controller on high ventilation flow was annoying.

Examination of the laboratory findings showed no loss of pulmonary function. Vital capacity was actually increased a little. ECG records showed "that the variations are of a minor character and might be explained by such factors as over-ventilation, changes in body position, and change in position of the heart in the thorax. The only heart rates over 100 are associated with the beginning and end of the experiment. Some of the T-wave variations were clearly due to changes in direction of the mean T vector in the frontal plane. Some of the variations involved all of the T-waves and in some instances the changes may have resulted from errors in standardization. . . . All of these variations were of a nonspecific character and were of physiological rather than of pathological significance. In all other respects the records were not only within limits but showed relatively little change."[7] Post-flight blood and urine laboratory tests indicated a moderate stress situation (eosinophil count up from 222 to 244 per cc. 17 ketosteroids from .70 to .88 mgm per cent). Normal transaminase values (increased from 16 to 23 GOT units/ml) indicated no detectable muscle or organ pathology (Table I).

DISCUSSION

This experiment exposed the subject to most severe conditions. Forty-eight hours and three minutes at altitudes of 50,000 feet and above (forty-seven hours above 80,000 feet) would simulate loss of cabin pressure for this period of time. One would expect short periods of cabin pressure loss in emergencies only. Theoretically, small leaks could be repaired, and the man would be exposed to space conditions in the suit only for the time required to repair the leak in the cabin.

The fact that the subject had to keep his visor closed at 35,000 feet would be also unnecessarily severe. In a cabin with 100 per cent oxygen at cabin pressure of 3.4 psi, there would be no need to keep the visor closed. In the event of loss of cabin pressure, the visor could be closed in one or two seconds. The subject breathes aviator's oxygen in this suit. This oxygen is dry and has a dehydrating effect systemically and locally on the eyes, nose, throat, and lungs. For actual space cabin use, the oxygen would be recirculated and the moisture content would be increased to ameliorate the drying effects. Physical examination following the exposure showed moderately red and injected pharynx and nasal membranes. The subject complained of irritation of the eyes. These symptoms were probably due to the dry oxygen. While not severe, these symptoms would show the desirability of a higher moisture content in the oxygen.

The subject could walk, move his arms and hands and head at extreme altitudes (140,000 feet). His fine finger movements were restricted under this maximum pressurization. Even though he could function adequately at all altitudes, it would appear that a crew of at least two would be required for extended space flight. The

TABLE I. URINE, BLOOD, BLOOD CHEMISTRY AND RESPIRATORY MEASUREMENTS BEFORE AND AFTER 72-HOUR EXPOSURE TO SIMULATED "SPACE EQUIVALENT" ALTITUDES

		Pre-Chamber	Post-Chamher
Urinalysis*	Color	Straw hazy	Straw—clear
	Reaction	Acid	Acid
	Sp. gr.	1.013	1.020
	Alb.	Neg.	Neg.
	Sugar	Neg.	Neg.
	Acetone	Neg.	Neg.
	Bile	Neg.	Neg.
	Micro:	Few amorphous crystals	Rare uric acid crystals. Some amorphous crystals. Few yeast cells.
24 hour specimens	Volume	360 cc	450 cc
	WBC	160,000	200,000
	RBC	120,000	100,000
	Casts	0	700
	Urobilinogen	1-10	1-10
	17 Keto-steroids		
	Total volume	300 cc	320 cc
	17 Keto-steroids	0.70 mgm %	0.88 mgm %
	Total 17 Keto-steroids	2.13 mgm T.V.	2.82 mgm T.V.
Hematology	WBC	8,400	8,750
	Diff:		
	Neutrophils	38	28
	Lymphs	55	68
	Monos	5	1
	Eos	2	3
	Hemoglobin	14. gms/97%	14.5 gms/100%
	Sed. rate	1 mm	9 mm
	Total circulating eos.	222 per cc	244 per cc
	Hematocrit	48 mm	50 mm
Blood chemistry	BUN	10.8	15.4
	Glucose	108 mgm %	123 mgm %
	Total protein	6.6	8.5
	Albumin	4.9	6.3
	Glohulin	1.7	2.2
	Icterus index	3.4	Not done
	Thymol turbidity	2.6	3.6
	Cephalin floc.	Neg.	Neg.
	Serum transaminase	16. GOT	23. GOT
	Sodium	139 meq	139 meq
	Potassium	4.7 meq	4.85 meq
	Inorganic phos.	1.7 mgm per 100 cc	Not done
	Calcium	5.8 mgm per 100 cc	Not done
	Chlorides	630 or 107.7 meq	620 or 105.9 meq
	CO_2 comhining power	4.9 (250%) or 22.0 meq	56 vol. per cent 25.2 meq
Results of pulmonary function studies	Max. breath. cap.	Not done	192/1pm
	Predicted (80)	Not done	117%
	Vital cap.	5.2 L	5.819 L
	Predicted (80)	122%	137%
	Insp. cap.	Not done	3879 cc
	Exp. res.	Not done	2292 cc
	Air vel. index	Not done	0.9
	Tidal air	Not done	711 cc
	Breath res. hasal	Not done	94%
	Min. vent. basal	Not done	5.1 L/min/BS
	Timed vit. cap.		
	1st sec.	4.5/5.2 87%	4.6/5.7 81%
	2nd sec.	5.0/5.2 96%	5.4/5.7 95%
	3rd sec.	5.1/5.2 98%	5.6/5.7 98%

*Specimens secured during the exposure showed no significant change from pre-exposure specimen.

Pre-Chamber Remarks: Values for timed vital capacity done 9/5/58 prior to entry into the chamber reveal normal values for all the tests. The actual vital capacity was 122% of the predicted.

Post-Chamber Remarks: Pulmonary function studies done 9/8/58 after 72 hours in the chamher breathing 100% oxygen revealed all the results to be within normal limits. The actual vital capacity on this occasion was 134% of normal. The tidal air was 711 cc, which was slightly above the usual observed basal values (usually about 500 cc). The resting minute ventilation was at the upper limits of normal with a value of 5.1 L/min./M^2 (Normal values 2.5 to 5.0).

Save for the volume of tidal air, the results for the tests as noted ahove from the chart are completely normal. It is likely that the slight increase in tidal air was due to environmental factors.

fact that the one subject has to sleep would necessitate a fellow crewman. For flights in excess of four days and nights, defecation becomes a problem. With two or more crewmen, the suit of one could be lowered for defecation with the calculated risk that if cabin pressure loss occurred during this interval, one of the other crewmen could repair the leak or get the suit back on the unprotected man before death occurred. It would appear from data gathered in this experiment that the ideal crew would be a flight surgeon-aviator and an aeronautical engineer-aviator, so that the specialties of human physiology and flight control could be covered by the former and mechanics and flight control would be in the cognizance of the latter.

SUMMARY

A naval aviator-flight surgeon was fitted with a Navy Mark III, Mod II full pressure suit. He was exposed to simulated altitudes between 30,000 and 170,000 feet for a period of seventy-two hours. Results of the experiment showed that (1) man can tolerate 100 per cent oxygen at 35,000 feet for seventy-two hours; (2) the Navy Mark III, Mod II full pressure suit is tolerable at extremely high altitudes for extended time intervals; and (3) he can function adequately with negligible physiologic or psychologic deterioration.

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REFERENCES

1. Becker-Freyseng, H., and Clamann, H. G.: Zur Frageder Saurstaffvergiftung. *Klin. Wchnschr.*, 18:1382, 1939
2. Behnke, A. R., Johnson, F. S., Poppen, J. R., and Motley, E. P.: Effect of oxygen on man at pressures from 1 to 4 atmospheres. *Amer. J. Physiol.*, 110:565, 1935.
3. Comroe, J. H., Jr., Dripps, R. D., Dumke, P. R., and Deming, M.: Oxygen toxicity. Effects of inhalation of high concentrations of oxygen for twenty-four hours on normal man at sea level and at a simulated altitude of 18,000 feet. *J.A.M.A.*, 128: 710, 1945.
4. Gafford, R. D., Bitter, H. L., and Adams, R. M.: Provisions of respiratory gas exchange for small primates by use of a photo-synthetic gas exchanger. USAF Sch. Aviation Med., Report 58-126, Oct., 1958.
5. Gaume, J. G.: Design of an algae culture chamber adaptable to space ship cabin. USAF Sch. Aviation Med., Report 58-61, May, 1958.
6. Gerathewohl, S. J.: Comparative studies on animals and human subjects in the gravity-free state. *J. Aviation Med.*, 25:412, 1954.
7. Graybiel, A.: Personal communication.
8. Mayo, A. M.: Space cabin design, Douglas Aircraft Co., Tech. Paper No. 555, AAS Preprint 57-30, 1957.
9. Mullinax, P. F., Jr., and Beischer, D. E.: Oxygen toxicity in aviation medicine; a review. USN Sch. Aviation Med. Proj. NM 12 01 11, Subtask 1, Report 2, Feb., 1958.
10. Ohlsson, W. T.: Study on oxygen toxicity at atmospheric pressure. *Acta med. scandinav.*, 128: Suppl. 190, 1-93, 1947.
11. Strughold, H.: Atmospheric space equivalence. In *Epitome of Space Medicine*, USAF Sch. Aviation Med., 1958.
12. Strughold, H., Haber, H., Buettner, K., and Haber, F.: Where does space begin? *J. Aviation Med.*, 22:342, 1951.
13. Strughold, H.: United States Air Force experimental sealed cabin. *J. Aviation Med.*, 27:50, 1956.