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PRELIMINARY REPORT ON AEROEMBOLISM AND EQUIPMENT FOR OXYGEN INH--ETC(U)
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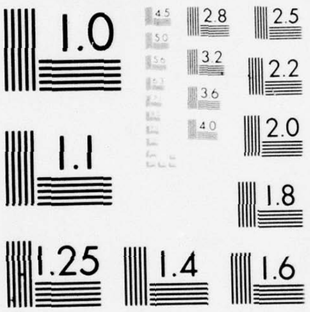

MICROCOPY RESOLUTION TEST CHART
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# NAVY EXPERIMENTAL DIVING UNIT

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# PRELIMINARY REPORT ON AEROEMBOLISM AND EQUIPMENT FOR OXYGEN INHALATION.

⑪ 26 DECEMBER 1940

⑫ 39p.

RESEARCH REPORT 1-40

⑩ A. R. Behnke
T. L. Willmon

⑭ NFDU-RR-1-40

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# FOREWORD

The Experimental Diving Unit is essentially an Engineering-medical organization under the cognizance of the Bureau of Ships, and manned by personnel from the Bureau of Navigation and the Bureau of Medicine and Surgery.

During the past 13 years systematic test and research projects have centered mainly in submarine problems dealing essentially with deep sea diving and the effects on personnel of abnormal barometric pressures.

From the medical point of view the Experimental Diving Unit serves to make the individual more capable of handling the machine by bringing into field practice the advanced ideas and methods developed in the laboratory.

The feature that distinguishes the Experimental Diving Unit from other test and research organizations is the presence of a group of intelligent, courageous and rugged divers who serve as subjects to make possible immediate application of new procedures for the benefit of the whole Naval Service.

For these men there is no distinction between ordinary endeavor and endeavor beyond the ordinary call of duty, Typical of the group are C. F. Pugh, E.M.1c., J. E. Duncan, C.T.M., who made the rubber helmets and Douglas bags, H. H. Frye, C.S.F., who adapted the venturi aspirator for the recirculation of oxygen, F. L. Westbrook, C. Ph.M., who measured body nitrogen elimination at a simulated altitude of 30,000 feet, and L. B. Lewis, Ph.M.1c., and H.H. Snider, Ph.M.2c., who over a period of several years carried out the essential physiological procedures.

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# PRELIMINARY REPORT ON AEROEMBOLISM
# AND EQUIPMENT FOR OXYGEN INHALATION

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## INDEX (Continued)

EXPERIMENTAL DIVING UNIT
NAVY YARD, WASHINGTON, D.C.

26 December 1940.

From: Lieutenants A. R. Behnke, B. G. Feen and T. L. Willmon, Medical Corps, U. S. Navy.
To: The Officer in Charge, Experimental Diving Unit, Navy Yard, Washington, D.C.

Subject: Preliminary report on AEROEMBOLISM and EQUIPMENT FOR OXYGEN INHALATION.

Reference: (a) Report from Behnke and Willmon dated 11 July 1940, entitled "Physiological Investigation at the Experimental Diving Unit Pertaining to Aviation Medicine".
(b) BuShips Ltr. S94-(3)-(4) (Mz) of Nov. 1, 1940, authorizing investigation at the Experimental Diving Unit of effects on personnel rapidly decompressed to simulated high altitudes.

Enclosure: (A) Report of Lieut.Comdr. C. A. Swanson (MC) USN - "Decompression Effects On Vision".

I - INTRODUCTION: Two serious problems in aviation are; (1) Aeroembolism or the evolution of gas bubbles in the blood of aviators subjected to rapid, high altitude ascents, and (2), Lack of adequate facilities for oxygen inhalation.

The results of tests conducted during the past 8 weeks, although not complete, have been so conclusive with respect to aeroembolism as to warrant a report at this time in the hope of aiding other investigators at work on the problem.

With respect to oxygen inhalation it is believed that the equipment designed and made at this Unit for the simulated altitude test runs and for the measurement of nitrogen elimination can be adapted for actual flight conditions.

## II - SUMMARY AND CONCLUSIONS:

1. Deep Sea Divers develop bends following rapid ascent to simulated altitudes.

2. Bends, consisting essentially of pains in the extremities usually in the region of the joints, are caused by the evolution in the blood of bubbles consisting of nitrogen, carbon dioxide, water vapor, and oxygen as integral parts. In aviation medicine the term "Aeroembolism" is used to designate "bends".

3. Removal of nitrogen dissolved in the body tissues by the inhalation of oxygen at the ground level or at altitudes up to 20,000 feet, eliminates all symptoms incident to simulated high altitude flight.

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4. Men decompressed or "conditioned" by oxygen inhalation for the purpose of nitrogen elimination are able to ascend from the ground level at the rate of 5,000 feet per minute to an altitude of 37,000 feet for a duration of at least 4 hours. These men are found to be in excellent condition at the ceiling altitude and after return to the ground level.

5. If the body nitrogen is replaced by helium, the period of decompression or oxygen inhalation prior to high altitude flight is reduced by about 66 per cent, or from 300 minutes to 90 minutes for an ascent to 37,000 feet at the rate of 5,000 feet per minute, duration at altitude, 4 hours.

6. Debilitating fatigue following simulated altitude exposure is regarded as a delayed manifestation of aeroembolism.

7. Age and physical condition appear to be the important factors enabling individuals to tolerate rapid ascent to high altitudes without the development of aeroembolism.

8. A test of physical fitness consisting of an ascent at the rate of 5,000 feet per minute to an altitude of 28,000 feet for a duration of 1 hour is outlined.

## OXYGEN INHALATION EQUIPMENT

9. An air-tight closed system used in the simulated altitude tests and consisting essentially of a rubber helmet, oxygen reservoir, motor blower, and carbon dioxide absorbent, enables men to breathe oxygen comfortably for prolonged time periods. With this system oxygen exposures have been made for periods of 17 hrs. at the ground level. At simulated altitudes oxygen exposures have been maintained for 5 hours at 20,000 feet and then continuing at 37,000 feet for a period of 4 hours.

10. An open-circuit valveless system consisting of a mask, a small oxygen reservoir, and an exhalation tube, has proved to be satisfactory at simulated altitudes of 37,000 feet for at least 2 hours duration.

11. A semi-open system consisting of a mask, oxygen reservoir, carbon dioxide absorbent, and featured by an aspirator based on the venturi principle for the recirculation of gas, provides an economical, automatic, and self-rinsing method of supplying essentially pure oxygen.

12. These types of equipment fabricated by personnel of the Experimental Diving Unit out of materials at hand have met some rather stringent requirements incident to our investigations. Tests of the appliances at low temperatures are now in progress.

## DETAILED PRELIMINARY REPORT - AEROEMBOLISM

III - INTRODUCTION: The deep sea divers attached to the Experimental Diving Unit, Photograph 1, represent a well trained group of men who last year accomplished the successful rescue and salvage operations incident to the U.S.S. SQUALUS disaster. These men have experienced bends repeatedly in diving operations employing air or helium-oxygen mixtures.

During the past year the divers were exposed to air pressures up to 4 atmospheres for periods of 9 to 24 hours. Under these conditions bends following decompression were frequent. It was of interest therefore to subject these same men to a decreased pressure of 1/4 of an atmosphere or lower, and to compare their reactions with those manifested following exposure in the high pressure environment.

1. Definition of Terms: Aeroembolism is the term used in aviation medicine to denote bubble formation in the blood stream induced by a rapid reduction of barometric pressure.

Bends constitute a clinical entity. The term established by usage, refers to pains in the extremities usually in the area of the joints. The term, although of lay origin, cannot be conveniently replaced. Bends may be regarded as the most frequent manifestation of aeroembolism or compressed air illness in contrast with the incidence of asphyxia or paralysis. With reference to high or low pressures it will be convenient to refer to divers' bends or altitude bends respectively.

Decompression refers to the reduction of nitrogen pressure in the body tissues as a result of oxygen inhalation or by barometric pressure decrease. Since the purpose of oxygen inhalation prior to an altitude ascent is nitrogen removal, the term decompression is preferable to pre-oxygenation. Decompression can also be effected by the breathing of helium-oxygen mixtures.

Decompression Embolism refers to all gas emboli generated by too rapid reduction of pressure, occurring either from increased pressures to normal atmosphere or from normal atmosphere to decreased pressures.

Altitude refers to the simulated altitude brought about by lowering the barometric pressure in a chamber.

Rapid Ascent as employed in this paper means 5,000 feet per minute.

2. The problem. If the symptoms elicited by rapid exposure of individuals to high altitudes are due to aeroembolism, then the problem resolves itself into the removal of gaseous nitrogen dissolved in the tissues of the body. We are dealing with the following gas pressures in the capillary and venous blood contributing to bubble formation:

| | | |
|---|---|---|
| Nitrogen----------------- | 573 mm. | |
| Carbon Dioxide----------- | 47 mm. | |
| Water vapor-------------- | 47 mm. | |
| Oxygen------------------- | 40 mm. | (Variable) |
| | 707 mm. | |

As long as the ambient pressure is 707 mm. the respective gases will remain in solution. At some external pressure below 707 mm. evolution of gas in bubble form may be anticipated. Of the four gases it is feasible to eliminate only nitrogen and this can be accomplished in one way simply by oxygen inhalation. The problem then resolves itself into maintaining the nitrogen pressure at a sufficiently low level so that bubble formation will not be initiated irrespective of the rapidity of ascent.

## IV - METHOD OF PROCEDURE.

The subjects were principally deep sea divers, average age 33, range 29 to 42 years; average height 71 inches; and average weight 184 pounds, range 149 to 205 pounds. Test runs were conducted in the pressure chamber of the Experimental Diving Unit. Evacuation of the chamber was accomplished by reversing one of the air compressers.

In all tests the rate of ascent and of descent was maintained constant at 5,000 feet per minute.

In a typical experiment a diver in the sitting position at rest breathed 99 per cent oxygen from the time that the ascent was started until the termination of the run. Prior to an ascent a period of 3 minutes was allowed for washing out the residual nitrogen in the lungs. The diver was then locked in and placed "on his own" until the termination of the run either at the end of 6 hours or earlier if symptoms supervened. Glass ports allowed a close watch to be maintained on the subject.

At the ceiling altitude a series of recordings were made by the subject in order to ascertain his state of well being and his ability to carry out assigned tasks.

The temperature in the chamber was fairly constant at 79° F. dry bulb, and 72° F. dry bulb.

Since the onset of divers' bends may be delayed as long as 12 hours following a decompression, short altitude runs are of no significance in the formulation of a decompression table.

Test runs were normally of six hours duration with a minimum time of two hours at the ceiling altitude. Under these conditions it is anticipated on the basis of diving experience that the presence of aeroembolism will become manifest within these time periods in at least 3 out of 4 exposures.

Altitude-pressure was computed from the table for the United States standard atmosphere. The pressure in the chamber was recorded by a U mercury manometer, one arm opening into the chamber, the other remaining open to the ambient atmosphere. In measuring the difference between the two columns of mercury in the manometer and computing constant altitude, corrections were made for variations in barometric pressure.

1. Scope of the physical examination. All observations on the subjects were made before and after test exposures. Because of the possibility of increased intracranial pressure at low barometric pressures, the visual examination was considered to be expecially important. Lieutenant Commander Swanson (MC) USN, conducted the visual tests and his separate report is appended to this paper.

The otologic examination was made with particular care since pressure trauma to the middle ear is a long established diving ailment.

In the neurological examination particular attention was paid to signs indicative of spinal cord injury, in view of the susceptibility of this tissue to injury by air emboli.

A circulatory fitness test served to evaluate the effect of exercise before and after exposures.

A study of blood gravimetry was carried out by means of the falling drop method in view of the high degree of hemoconcentration previously observed in dogs as a result of extensive air embolism.

2. Facilities for Oxygen Inhalation. The second part of this paper reports in detail the means provided for oxygen breathing. The usual system employed consisted of a rubber helmet, bag reservoir, canister containing a carbon dioxide absorbent, and a motor blower to provide gas circulation. These parts formed a closed circuit which rinsed at 30 minute interval to ensure a 99 per cent oxygen concentration.

The open circuit type of apparatus consisted of a mask-system without valves featuring three-fourths to one inch rubber tubing on the exhalation outlet.

The photographs appended to this report illustrate some of the equipment used.

## V - EXPERIMENTAL RESULTS.

The essential data are recorded in Tables 1 and 2. The decompression chart, Figure 1, outlined from these data serves as the basis for the following presentation.

1. Presumptive test for Nascent Bubbles. From diving experience it is inferred that rapid ascents to high altitudes not attended by symptoms, may or may not signify the generation of air

emboli. For it appears that considerable quantities of gas bubbles may exist in the peripheral and even pulmonary capillary beds without inducing immediate symptoms, provided that blood supply to tissues is not seriously impaired.

Gas in bubble form however, is eliminated slowly compared with gas in solution if one considers the results of treatment of compressed air illness.

If the blood is comparatively free from bubbles after rapid ascent to, for instance, 20,000 feet, then a four hour period of decompression at this or lower levels will permit rapid ascent to 35,000 feet. On the other hand, if the blood contains an appreciable number of bubbles at the end of four hours at 20,000 feet, ascent to 35,000 feet may elicit symptoms indicative of aeroembolism brought about by rapid expansion of residual or nascent bubbles.

2. Altitudes Attainable Without Decompression. Figure 1, Column 1. Up to a level of about 20,000 feet rapid ascents do not appear to induce aeroembolism since a subsequent rapid increase in altitude to 35,000 feet is not attended by ill effects within a period of 2 hours.

Rapid ascents to between 20,000 and 25,000 feet, however, have led us to designate this altitude range indicated by the dotted area on the chart, as one of "silent" bubble formation, although elevation subsequently to an altitude of 35,000 feet did not elicit pain.

The assumption of the presence of bubbles is supported by the occasional debilitating fatigue developing after return to the ground level; also by the fact that oxygen inhalation in this range of altitude is less effective in preventing symptoms than is oxygen inhalation at or below 20,000 feet, followed in each instance by a sudden increase in altitude to great heights.

Ascents can be made to altitude levels between 25,000 and 28,000 feet where men may remain for a period of 4 hours to reach ultimately an altitude of 35,000 feet for a stay of 2 hours.

Mild bends, indicated by the heavy lines running crosswise, may appear either between 25,000 and 28,000 feet during the stay of four hours or subsequently when the altitude is increased to 35,000 feet. The symptoms, however, are usually not of sufficient severity to terminate the test run.

3. Forty-five Minutes of Decompression at Ground Level Followed by Rapid Ascent. Figure 1, Column 2.

Breathing oxygen for a period of 45 minutes at the ground level enables individuals to reach altitudes of 29,000 to 30,000 feet for a stay of 3 hours and thence to 35,000 feet for 2 hours.

4. Ninety Minutes of Decompression at Ground Level Followed By Rapid Ascent. Figure 1, Column 4.

Oxygen inhalation at the ground level for a period of 90 minutes permits an ascent to an altitude of 34,000 feet for a stay of 2 1/2 hours and then to 35,000 feet for the duration of 2 hours.

5. One Hundred Eighty Minutes of Decompression At Ground Level Followed by Rapid Ascent, Figure 1, Column 5, will prevent bends during a period of 2 hours at 37,000 feet. Bends, however, may occur during the third or fourth hour of exposure.

6. Three Hundred Minutes of Decompression at Ground Level will enable men to remain at an altitude of 37,000 feet for at least 4 hours. Upon return to the ground level the men should continue to remain in good physical condition.

Column 6, Figure 1, has not been completed at this time but it is anticipated that a period of 300 minutes for decompression is ample for an exposure of 2 hours at 40,000 feet. In this preliminary study it did not appear desirable to complicate the picture by symptoms attributable to anoxemia. However, the state of well being at 37,000 feet is better than one would infer from a theoretical consideration of alveolar oxygen pressure.

7. The Value of Oxygen Inhalation for the Purpose of Decompression at Altitudes Above Sea Level. If equal protection against the development of aeroembolism could be afforded by oxygen inhalation at higher altitudes, then the feasibility of nitrogen removal is enhanced.

The tests that we have carried out, although limited in number, indicate that up to an altitude of about 20,000 feet oxygen inhalation is probably as effective in promoting decompression as oxygen breathing at the ground level. In other words ascent can be made from the ground level at a rate of 5,000 feet per minute to any altitude short of 20,000 feet in order to effect nitrogen elimination.

So important is this consideration that the following data are given: For a constant rate of ascent, 5,000 feet per minute, 300 minutes of oxygen inhalation at sea level rendered safe an ascent to 37,000 feet for 4 hours, 300 minutes of oxygen inhalation at 20,000 feet rendered safe an ascent to 37,000 feet for 4 hours, 45 minutes of oxygen inhalation either at the ground level or at altitudes up to 20,000 feet is equally effective for decompression.

With respect to the 90 minute period of oxygen inhalation, additional tests are required to determine the comparative effectiveness of decompression at 20,000 feet and at sea level.

The altitude of 20,000 feet appears to be a critical level with respect to manifest bubble formation. It must be remembered however, that variation of several thousand feet above or below 20,000 feet may be expected, depending primarily on age and physical condition of the men exposed.

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One of our divers appears to be particularly susceptible to bends, probably as a sequel to a diving injury in 1933 (See SMITH, 12/12/40, Tables 1 and 2). Following a rapid ascent to 20,000 feet for a 5 hour period of decompression at this level, he developed pain in the right knee 3 minutes after the altitude level had been increased to 37,000 feet. Our only explanation for the ineffectiveness of this long period of decompression is the assumption that embolism was induced as a result of the steep climb to 20,000 feet and that the emboli in the knee were not appreciably diminished despite the 5 hour period of oxygen inhalation.

At an altitude of 25,000 feet in contrast to the level of 20,000 feet, decompression was not as effective as at sea level for corresponding time periods. With reference to chart, Figure 1, the third column indicates a decompression period of 45 minutes at 20,000 feet and 45 minutes at 25,000 feet, total 90 minutes. The altitude reached however, was but slightly higher than the ultimate altitude attained following either the single 45 minute period of decompression at 20,000 feet or at the sea level. The effectiveness of the two 45 minute periods spent at 20,000 and 25,000 feet respectively stands in contrast with the result obtained when oxygen was inhaled for a period of 90 minutes at sea level.

From these considerations and the fact that no symptoms with the exception of late fatigue have been recorded during or following ascents to altitudes between 20,000 and 25,000 feet, it seems appropriate to designate this altitude range as an area of silent bubble formation, made manifest only by a sudden increase in altitude or by the late onset of fatigue after return to the ground level.

8. Measurements of Nitrogen Elimination at High Altitudes. Compared with sea level elimination, the quantity of nitrogen given off by the body when oxygen is breathed at 20,000 to 30,000 feet altitude is the same within limits of experimental error.

### TABLE 3

### QUANTITIES OF NITROGEN ELIMINATED AT HIGH ALTITUDES COMPARED WITH SURFACE ELIMINATION

| | | Nitrogen Elimination cc. NTP. | | |
|---|---|---|---|---|
| Time Period Minutes | Ground Level | 20,000 Feet | 25,000 Feet | 30,000 Feet |
| 3-60 | 524 | 485 | | |
| 3-60 | 524 | 544 | | |
| 3-92 | 614 | 653 | | |
| | | 44' | 45' | |
| | 215 | | | 227 |
| 90-180 | | 45' | 45' | 90'-180' |

One must not conclude however, from these tabulated values that oxygen inhalation is equivalent in effectiveness at the several altitudes. While the measured quantities of nitrogen are the same, the consideration of prime importance is the physical state of the gas remaining in the body - that is to say whether the residual gas is mainly in a state of solution or in bubble form.

Experience in the treatment of compressed air illness indicates the slowness with which bubbles are reabsorbed in contrast to the elimination of gas in the dissolved state.

We conclude, tentatively and from inference, therefore, that the lack of effectiveness of the second 45 minute period of oxygen inhalation, at 25,000 feet (Figure 1, col. 3), is brought about by bubble evolution in the circulating blood during ascent from 20,000 to 25,000 feet.

9. Value of Helium. In diving operations helium substituted for nitrogen does away with the stupefying effect associated with compressed air exposure. For dives of short duration however, decompression time is not materially shortened by the use of helium.

For long exposures, on the other hand, measurements indicated that helium desaturation (Figure 3) would require about one-half of the time compared with nitrogen removal (Figure 2). Moreover, since helium compared with nitrogen, is one-fourth as soluble in fat, the incidence of aeroembolism should be greatly reduced, if substitution of helium for nitrogen could be made.

The laboratory data showed that the nitrogen transport from the body was accomplished equally well with either the inhalation of helium-oxygen mixtures or with essentially pure oxygen.

In practice however, we had not to date completely replaced nitrogen with helium for diving. The following tests therefore, are regarded as important not only for their potential value in aviation but also in diving operations of long duration.

In the first test run a diver breathed a mixture of 49 per cent helium, 48 per cent oxygen, and 3 per cent nitrogen for a period of 9 hours at sea level pressure. Tank oxygen was than breathed for a period of 45 minutes, and an ascent was made to 37,000 feet for a stay of 4 hours. Although mild pain developed in the left ankle and knee at the end of 2 hours, it was not of sufficient intensity to terminate the run. (See Table 2, 12/17/40).

In the second test run a diver breathed a mixture of 7 per cent helium, 2 per cent nitrogen, and 21 per cent oxygen for a period of 9 hours, then 99 per cent oxygen was breathed for a period of 90 minutes. An ascent was then made to a simulated altitude of 37,000 feet for a stay of 4 hours. The diver remained in excellent condition throughout the run and after return to the ground level.

For rapid ascent to 37,000 feet the substitution of helium for body nitrogen reduced the time required for decompression from 300 minutes to 90 minutes or less.

The conclusions drawn from these tests are; (1) That the body can be made nitrogen free by the inhalation of helium-oxygen mixtures for a period of 9 hours followed by 90 minutes of oxygen inhalation, and (2) that the time required for helium decompression is about one-third of the requisite time when the body is in equilibrium with atmospheric nitrogen.

## VI - ESSENTIAL QUANTITATIVE DATA UNDERLYING THE EXPERIMENTAL PROCEDURE AND FORMULATION OF THE DECOMPRESSION CHART.

1. Quantity of nitrogen given off by the body during oxygen inhalation and the graphic representation of decompression. The nitrogen elimination curve, Figure 2, was obtained on a diver 32 years old and weighing 154 pounds. It is typical of repeated test data obtained at this Unit and some years ago at the Harvard School of Public Health.

The first 5 minute period of nitrogen elimination during lung rinsing period is not recorded. Taking the actual quantities of nitrogen measured as a guide, it is possible to ascertain accurately the percentage of nitrogen eliminated and the average reduction of nitrogen pressure in the body for given time periods.

During a 45 minute of oxygen inhalation for example, about 30 per cent of the body nitrogen is eliminated, and about 50 per cent during a period of 90 minutes.

It is observed that nitrogen is transported from the body rapidly during the first two hours and then slowly during successive hours. After about 9 hours an endpoint is reached within the limits of experimental error of +- 2.5 c.c. per hour.

The nitrogen elimination curve (Fig.2) is an exponential curve with values that can be expressed by the formula:

$$Y = A(1-e^{-kt}),$$

where A is the initial nitrogen content or percentage in the body, Y is the quantity or percentage of nitrogen elimination during the time interval t, k is the rate of change in the slope of the curve; and e, the natural base of logarithms. The value of k for the curve is 0.0067 where t is expressed in minutes. On the basis of Haldane's concept of tissue desaturation, the curve represents a tissue which is approximately 50 per cent desaturated in 90 minutes, 70 per cent desaturated in 180 minutes, and 90 per cent desaturated in 300 minutes.

2. Variation in the Elimination of Nitrogen and the Factor of Exercise. Sixty-five per cent of the body nitrogen is eliminated rather uniformly by individuals of the same age group. In fugure 3, the average helium curve obtained on our divers indicates a 4 per cent variation in the rate of gas elimination from the mean curve. Applying this variation to the nitrogen curve, (figure 2), figure 4 is plotted as a logarithm of percentage nitrogen against time. It is observed that as body desaturation progresses, the time variation among different individuals increases from a few minutes at the beginning to several hours as the end of desaturation is approached.

Exercise promotes a rapid removal of nitrogen during the first 30 minutes. A period of exercise, for example, sufficient to increase oxygen consumption two and one-half times doubles nitrogen elimination during the first ten minutes and brings about a 40 per cent increase during the first 30 minutes, compared with the resting state.

With respect to nitrogen removal the value of exercise is limited to about the first 30 minute period. We do not know whether or not exercise hastens the elimination of the small but important quantity of nitrogen dissolved in bone marrow.

The helium curve, (Figure 3), gives us an evaluation of the effect of light exercise for a period of 40 minutes. As with nitrogen we have not worked out the effect of exercise after the third hour. We infer that blood flow through bone marrow, in contrast with muscles, may not be appreciably altered by exercise.

3. The Nitrogen Slowly Eliminated is of Great Importance. During the first 2 hours of oxygen inhalation and exclusive of the first 5 minutes, about 65 per cent of the measured body nitrogen is eliminated, while during the 2 hour period between 3 and 5 hours only 15 per cent of the body nitrogen is given up.

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We have learned from diving tests that this small amount of gas which requires many hours for removal is of great importance. At a depth of 90 feet, for example, 10.5 hours of air decompression were necessary following a 9 hour or probably saturation exposure. On the other hand a 2 hour exposure bringing about at least 65 per cent tissue saturation, required a period of only 60 minutes for decompression.

Likewise one can make a contrast with reference to the chart, (Figure 1), between a decompression time of 90 minutes ensuring safety in rapid ascent to 34,000 feet and a period of 3 to 5 hours for rapid ascent to 37,000 feet, duration of stay 2 to 4 hours.

It is a small amount of nitrogen therefore, that gives us a great deal of trouble. We believe that this gas is located in the bones, principally in the marrow, with its high fat content acting as a nitrogen reservoir and that gas emboli giving rise to bends form in situ in the capillaries and sinusoids; or perhaps these vascular beds act as a trap for gas bubbles disseminated from the general circulation.

It may well be that freedom from bends in high altitude ascent may rest on the vagaries of blood circulation in bone marrow.

4. Calculations of Decompression Time Based on the Quantitative Data. A system of computation using Haldane's concept that the body tissues are able to hold nitrogen gas in supersaturation according to stated ratio, will apply to the experimental data. With reference to decompression of divers, we have found that calculations may be of some value, especially in determining intermediate points, but only after the limits of exposure have been determined by intelligent trial and error.

One may infer from the rapid changes in barometric pressure affecting divers and aviators, that the body tissues including the blood are able to hold gaseous nitrogen in a state of supersaturation. It is difficult however, to determine a precise ratio for the apparent degree of supersaturation tolerated by the body tissues in relation to ambient pressure.

The ratio derived from a single change of pressure in diving or in aviation will not hold for a series of pressure changes or decompressions. It is necessary to decrease the initial ratio either for an increase in exposure time or for an increase in diving depth, and conversely for altitude ascent.

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It may well be that bubbles form as soon as a state of supersaturation is initiated and that what appears to be a ratio of saturation tolerance is in reality an index of the degree of embolism that the body can tolerate.

This distinction will save confusion and render more useful a concept promulgated by a master physiologist. What is important clinically is that there are sharply demarcated limits of perhaps 5 feet in diving depth or about a thousand feet in altitude ascent separating injury from a state of well being.

If bubble formation is initiated in blood flowing through peripheral capillaries, the following gas pressures at 760 mm. enumerated on page 4, enter into the calculations;

| | | |
|---|---|---|
| Nitrogen ------ | 573 | |
| Carbon Dioxide- | 47 | |
| Water --------- | 47 | |
| Oxygen -------- | 40 | (Variable) |
| | 707 | |

If immediate ascent to 20,000 feet does not induce the bubble state, the ratio of gas pressure in venous blood to ambient pressure may for a short time be 707/349.1 or approximately 2 to 1.

The time required for decompression with oxygen prior to an ascent to 30,000 feet then may be computed in the following manner;

At 30,000 feet the barometric pressure is 225.6 mm.

If the total pressure of gases in venous blood can safely be doubled a value of 451 mm. (2 x 225.6 mm) is obtained.

Before rapid ascent can be made to 30,000 feet, the total gas pressure in venous blood must be reduced from 707 mm. to 451 mm., a reduction of 256 mm.

Of the total gases it is feasible only to remove nitrogen. In other words the nitrogen pressure in the body must be reduced 256 mm. If the initial nitrogen pressure is 573 mm. at sea level, the body must lose 256/573 or 45 per cent of its nitrogen. From the nitrogen elimination curve, (Figure 2), 45 per cent desaturation requires 63 minutes, or the decompression time required for immediate ascent to 30,000 feet.

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Example 2. Calculation of desaturation time prior to an ascent to 35,000 feet;

At 35,000 feet, barometric pressure 178.7 mm.

2 x 178.7 = 357.4 mm., upper limit tolerance based on 2 to 1 gas pressure ratio.

707 - 357 = 350 mm. = required pressure decrease in body.

350/573 = 61 per cent, or percentage of N2 elimination required to reduce pressure to 350 mm.

From Nitrogen curve, 61 per cent desaturation requires 105 minutes. Time required for oxygen inhalation prior to immediate ascent to 35,000 feet is 105 minutes.

For ascents above 35,000 feet however, the 2 to 1 ratio does not hold. At 37,000 feet, the altitude test runs indicated that 3 hours of oxygen inhalation was necessary for a stay of 2 hours and for a stay of 4 hours, a period of 5 hours of oxygen inhalation was required. To conform with the computations enumerated above, the tolerance ratio must be reduced from 2 to 1 to 1.6 to 1 for the 2 hour exposure and again to 1.2 to 1 for the 4 hour exposure.

## VII - SYMPTOMATOLOGY

1. Are We Dealing With "Bends"? The Symptoms Elicited by Rapid Ascent to High Altitudes Compared With Symptoms Resulting From Too Rapid Ascent From Diving Depths. In 39 test runs recorded in Table 1, bends developed 19 times, extreme fatigue was manifest twice, and temporary loss of hearing was reported in one instance at 40,000 feet.

Bends, therefore, in these tests represent the essential clinical entity incident to rapid ascent to simulated high altitudes. Asphyxia and paralysis, the more serious manifestations of aeroembolism, were not present. Moreover with adequate decompression, all symptoms except those attributable to equalization of pressure in the ear were prevented and the men remained in good condition.

The question may arise, are "altitude bends" similar to "Diving bends? In the following table the symptoms elicited by rapid ascent to high altitudes are compared with symptoms observed after too rapid ascent from diving depths.

## TABLE 4

## SYMPTOMS ELICITED BY RAPID CHANGES IN BAROMETRIC PRESSURE

| Name | Too Rapid Decompression From High Pressure Atmospheres. | Too Rapid Decompression to Low Pressure Atmospheres - Present Test Runs Tables 1&2. |
|---|---|---|
| Dr. Willmon | Jan.-May 1939. Debilitating fatigue daily several hours following rapid decompression from 4 atmospheres. | Oct. 18, 1940. Debilitating fatigue 3 hours after return to sea level following an exposure at 23,000 feet for 6 hours. |
| Dr. Behnke | Feb. 13, 1933. Under 4 Atmospheres pressure for 4 hours; 3 hours after exposure severe substernal irritation, pains in extremities, fever, sweating, malaise.<br>March 20, 1933. 4 atmospheres pressure for 110 mins. 3 hrs. following decompression, substernal irritation, pain in right knee and right hip.<br>May 15, 1933. 4 atmospheres pressure for 120 mins. 1 hr. following decompression throbbing pain deltoid area, right arm. Mild substernal discomfort. | Dec. 5, 1940. 20,000 feet for 45 mins; 25,000 feet for 45 mins; 30,000 feet for 90 mins; 37,000 feet for 49 mins. At 23 mins. at 30,000 feet and continuing at 37,000 feet, pain in left shoulder, both knees. Extreme fatigue 5 hours after return to Surface.<br>Oct. 28, 1940. 25,000 feet for 240 mins; 35,000 feet for 120 mins. After 2 hours at 25,000 feet, pain developed in left shoulder. At 35,000 feet pain felt in right knee accompanied by substernal distress. Complete relief after return to sea level. |
| Smith | 1933. Spinal cord injury, pain in right knee; residual foot drop and hyperactive reflexes followed by complete recovery.<br>May 10, 1940. 90 feet for 9 hours. 1 hour following decompression diver developed pain in right knee, relieved by 4 hours recompression. | Oct. 31, 1940. 27,000 feet for 114 mins. Developed pain in right knee, progressive. Relieved at 14,000 feet.<br>Dec. 12, 1940. 20,000 feet for 300 mins; 37,000 feet for 10 mins. Pain developed in right knee at 37,000 feet, abated at 25,000 feet. |
| Crosby | May 8, 1940. 90 ft. for 9 hours. 65 mins. following decompression, severe pain in left elbow, recompressed. | Nov. 11, 1940. Surface Oxygen inhalation 45 mins; 31,000 feet for 111 mins. After 90 minutes developed pain left elbow radiating to shoulder, pain abated at 21,000 feet. |
| Havens | April 16, 1940. 90 feet for 6 hrs. 4 hours following decompression pain in both knees accompanied by fatigue. | Dec. 6, 1940. 20,000 feet for 40 mins; 30,000 feet for 97 mins. Pain developed in left knee at 37,000 feet. Abated at 23,000 feet. |

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Data ~~Perusal of table~~ 4 reveal~~s~~ that the symptoms manifested at high altitudes are the same as divers' bends, and identical regions of the body are frequently affected as a result of exposures in high or low pressure atmospheres. It may be said perhaps that the altitude bends are milder; certainly recovery is more rapid.

However, it should be stressed that the time factor is of great importance. Were exposures prolonged at high altitudes, mild degrees of aeroembolism might develop into severe injury manifested by cerebro-spinal injury, asphyxia, and cortical involvement as a result of anoxemia.

Nevertheless the rapid recovery from symptoms frequently brought about by an altitude drop of a few thousand feet is believed to have a sound physiological basis related to the composition of the gas emboli.

A bubble of gas formed in the venous blood at atmospheric pressure approximates in composition 83 per cent nitrogen, 6 per cent carbon dioxide, 6 per cent water vapor, and 5 per cent oxygen. At one-fourth of an atmosphere corresponding to an altitude of about 34,000 feet, the composition of a nascent gas bubble will tend to approach 24 per cent carbon dioxide, 24 per cent water, variable percentage of oxygen, and a percentage of nitrogen somewhat less than 50 per cent.

Should a bubble of this composition produce an embolus capable of eliciting pain, then by increasing the barometric pressure the water vapor and carbon dioxide fractions of the bubble should be rapidly dissipated in contrast with the nitrogen fraction.

The bubble therefore, occurring in diving bends, containing 83 per cent nitrogen should require a longer period for resolution than the bubble containing about half this percentage of nitrogen.

The long period of time that may be required for the elimination of a bubble of nitrogen was observed many years ago by Boycott, Damant, and Haldane in their classic investigation. Recent observations of emboli in dogs and clinical experience with compressed air illness corroborate the older findings.

2. Fatigue and the X-Factor Described by Armstrong. During the past eight years we have been cognizant of a type of fatigue

that merits a great deal of study. It is related to exposure in compressed air and invariably follows too rapid release of pressure, usually with an interval of several hours of well being.

This type of fatigue, because of its relation to exposure in compressed air and because it constitutes a frequent prodromal or concomitant symptom of pain, is regarded by us as a manifestation of decompression embolism. Adequate decompression with oxygen administration prevents the syndrome.

Fatigue similar in character to the compressed air sequelao developed also as a result of too rapid ascent to simulated high altitudes. In these tests the factors of subnormal alveolar oxygen pressure, cold, vibration, noise, and the strain of task performance were absent.

The X-factor described by Armstrong as an anoxemia-like effect of decreased barometric pressure changes, and characterized by a profound physical and mental depression is evidently a chronic type of the same fatigue observed in divers either released too quickly from high pressure atmospheres or subjected to unduly rapid altitude ascent.

The delayed onset of the fatigue and its cumulative effect were puzzling until it was realized that following a return to normal pressure, gas elimination into the blood stream from slowly desaturating tissues might augment the size of gas bubbles to bring about a delayed embolic anoxia.

In a series of daily exposures, for example, to a pressure of 4 atmospheres, the first exposure may see the individual entirely well, the second may be accompanied by delayed fatigue, while the third might result in frank bends; or a chronic effect might develop, characterized by drowsiness, irritability, lack of volition, inability to concentrate, and a feeling of constant malaise.

The manner in which the presence of bubbles brings about fatigue has not been determined. Factors considered are possible anoxic cellular destruction with liberation of toxic substances, and impeded venous return to the right side of the heart.

The biochemical approach to the problem would seem to offer a great deal of promise and should lead to a worthwhile contribution in a remarkably obstinate field.

3. Nature of Decompression Embolism. Bubble formation in divers appears to be a common occurrence following decompression. In small quantities bubbles produce nothing more than pruritus usually more intense in the lobes of the ear and over the chest and abdoman. If the skin is chilled, the attendant vasoconstriction and slowed circulation enhance the liberation of gas in bubble form. Frequently, transient, macular abdominal rashes are observed.

The location and quantity of gas in bubble form governs the symptomatology. In the lungs large numbers of emboli filling the extensive capillary bed cause asphyxia, while bubbles in the spinal cord and brain give rise to sensory and motor disturbances. Reference already has been made to the concept that emboli or bubbles arising in situ in the capillary bed and sinusoids of bone marrow, give rise to bends. Frequently rapid recompression may temporarily intensify the pain of bends which suggests that the compression decrease in gas volume is not immediately compensated for by blood flow into the medullary area.

Bends, disregarding pruritus, rash, and fatigue are usually the first and certainly the most common manifestation of embolism. If untreated, either asphyxia, or paralysis, or both conditions may follow. Occasionally, asphyxia or paralysis appear first and are of sudden onset. One may consider that bends serve as a warning and in this manner protect the central nervous system and heart from serious injury. The following diagram may clarify the symptomatology of decompression embolism:

| | | | | |
|---|---|---|---|---|
| DECOMPRESSION EMBOLISM | From High Pressures<br>(Compressed Air Illness) | Fatigue<br>Pruritis<br>Rash | ASPHYXIA<br>BENDS<br>PARALYSIS (Sensory and/or motor). | Debilitating Fatigue 1-4 hrs. after exposure. |
| | At Low Pressures<br>(Aeroembolism)<br>Symptoms observed in current tests. | | BENDS | Debilitating Fatigue 1-4 hours after exposure. |

The statement is frequently made that gas bubbles are present in tissues. Under the conditions in which men are decompressed in contrast with the procedure in some of the older experiments on lower animals, it is doubtful if gas bubbles form extravascularly. In dogs we have observed bubbles apparently circulating through arteries and veins until blood flow was impeded. In accompanying lymphatics under the same conditions, bubbles were not seen.

It may be that gas in bubble form can escape from the circulating blood and accumulate in tendon sheaths or form in cerebrospinal fluid, but we have not observed symptoms or seen roentgenologic evidence to substantiate this statement. Further tests are required to evaluate Armstrong's finding of increased cerebrospinal fluid pressure.

The disappearance of symptoms attendant upon early recompression and the absence of demonstrable residual injury point to embolic ischemia as the underlying pathogenesis of decompression injury.

VIII - TREATMENT OF AEROEMBOLISM. The most important factor is immediate recompression at the appearance of the first symptoms. Without immediate treatment disability is to be expected. One can appreciate the importance of the time factor if tissue anoxia is accepted as the consequence of painful embolism.

Symptoms of aeroembolism may be expected to disappear before the ground level is reached. In severe injury, recompression combined with oxygen inhalation may be required as in compressed air illness.

In the treatment of compressed air illness when there is any doubt as to the elimination of the nitrogen emboli, we do not hesitate to keep men under 15 to 20 pounds of atmospheric gage pressure for periods of 24 hours or longer. Treatment by prolonged immersion in compressed air has saved us a good deal of grief.

## IX - PRESSURE TEST FOR PHYSICAL AND ALTITUDE FITNESS.

Tests for Physical Fitness Based on Rapid Changes in Barometric Pressure. In a group of divers some men will be more susceptible to bends than others. It is difficult on the basis of physical examination and cardiovascular efficiency tests to determine who are the susceptible individuals.

One diver, for example, in the group of 23, has never had bends. In appearance the immune diver is roly-poly and of Italian descent. He is not the textbook picture of the perfect diver. While cardiovascular tests indicate that he is in good condition, these tests do not rate him above other members of the group. In trial dives at deep depths and adhering to identical time periods for decompression, lean, muscular divers, following this man, even though they be Nordic in type, have been carried into the recompression chamber for treatment.

These facts have led us to the consideration of an actual pressure test as an index of physical fitness. The considerations for such test follow.

The rate of nitrogen removal is a function of cardiac output which in turn is related to metabolic mass or surface area. Small mammalian species with a comparatively large surface area in relation to body weight eliminate excess nitrogen so rapidly from their tissues that it is difficult to induce air embolism in these animals following exposure to high pressures.

The rate of nitrogen transport in the dog, for example, is double that of man. The dog also tolerates twice the drop in pressure, i.e., 4 to 1 atmospheres compared with 2 to 1 atmospheres for man.

Goats on the basis of Haldane's work fall in between dogs and man with respect to high pressure tolerance followed by an abrupt drop in pressure to normal.

It appears then that the elimination of excess nitrogen from the tissues without the development of manifest air embolism depends primarily upon the blood supply in relation to body weight, or for any given species, essentially upon effective blood flow through tissues. Both cardiac output in relation to body weight and the adequacy of collateral circulation would appear to be the important factors preventing accumulation of air emboli sufficient in number to elicit pain or fatigue.

From empirical data, age appears to be the most important factor in any given species; the tolerance of young individuals being greater than that of older individuals. Chronological age moreover, may not be so important as physiological age.

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The amount of fat in the body is also a factor differentiating individuals but it is not so important a factor as age.

Factors which tend to slow or damage the circulation increase susceptibility to air embolism. Divers engaged in test work, for example, will refrain from alcohol for several days prior to a dive. Some of the most severe injuries in the past have been associated with poor physical condition brought about by the previous ingestion of alcohol. A series of easily controlled animal tests would serve to evaluate the factor of alcohol and its after effects.

While we cannot at this time assign proper weights to the various factors that render some individuals more resistant to the development of air embolism than others, for our purpose a pressure test for fitness, at least for altitude or depth exposure, is of great practical importance.

The pressure test carried out at this Unit consists of an exposure to a simulated depth of 100 feet for 30 minutes of which 3 minutes are spent in "going to the bottom". Return to the surface is effected also in a period of 3 minutes. Susceptible individuals develop some pain or fatigue following this procedure.

The altitude test has many advantages over a pressure test principally because the quantity of gas in the body at the start of decompression, i.e., altitude ascent, is constant from day to day, except for slight fluctuations due to barometric pressure and because untoward symptoms disappear before the ground level is again contacted. The test specifically applicable to our age group and for men not in training consists of oxygen inhalation for a 3 minute period at sea level followed by an ascent to 28,000 feet at the rate of 5,000 feet per minute. The duration of stay at the ceiling altitude is one hour, but it may be necessary to increase this time. Descent to sea level is again at the rate of 5,000 feet per minute. Individuals who qualify remain free from bends and fatigue at the exposure level and following return to sea level. A rating of our divers on the basis of the principles underlying these tests is in progress. Thus far in about ten tests, one man, the oldest and most corpulent diver in the group developed bends after 48 minutes at 28,000 feet.

## X - ADDITIONAL OBSERVATIONS.

Summary With Reference to Observations Pertaining to the Ear, Blood Gravimetry, Cardiovascular Fitness, Neurological Examination, and Vision (See Table 2). With the exception of certain traumatic effects on the middle ear, no verified symptoms other than those attributable to aeroembolism were manifested by the divers.

1. The Ear. Divers may be subjected to pressure variations between 15 and 240 pounds per square inch, while aviators are exposed to pressures usually between 15 and 3 pounds per square inch. These pressure variations frequently elicit symptoms referable to the ear and sinuses in both divers and aviators. Aero-otitis media, for example, is an entity not new in the field of diving but was recognized about 100 years ago and carefully described and evaluated by Heller, Mager and von Schrotter in 1900. Impairment of hearing has not been observed in relation to this type of trauma.

With reference to the current tests, divers usually experience little difficulty in equalizing pressure on tympanic membranes. It was surprizing therefore, to note signs and symptoms of middle ear congestion appearing usually not immediately but 24 hours after exposure to high altitudes.

The explanation for this phenomenon appears to be a negative pressure effect brought about by the absorption of oxygen from the middle ear spaces during sleep when voluntary opening of the auditory tubes is not effected.

Inhalation of air following removal of the oxygen mask at about the 10,000 foot level minimizes or abolishes the symptoms.

2. Vision. A comprehensive visual examination was conducted by Lieutenant Commander C. A. Swanson (MC) USN, and his report is appended as a separate enclosure. It was considered that vision or the eye grounds would be affected by uncompensated increases in intracranial pressure, if it occurs.

Essentially, the visual findings were negative. Occasional diminution of visual acuity is ascribed to fatigue. In one man, however, a small hemorrhage was observed in an area of retinal atrophy following an altitude run. The visual field examination revealed a scotoma which almost completely disappeared after a period of 3 weeks. Evaluation of this finding depends upon its recurrence in relation to barometric pressure change. In view of the normal findings on the other subjects, the retinal injury in the one man is regarded tentatively as a coincidental observation.

3. Cardiovascular Fitness was determined by a step-up test consisting of 20 body lifts on the same leg to a height of 18 inches in a period of 30 seconds. The pulse rate was recorded after 2 minutes and then the test was repeated. Men in good condition have

a pulse rate which returns to the pre-exercise level within two minutes. Pulse rate values given in table 2, column (B) and column (A) were recorded before and after exposure to high altitudes respectively. The use of tobacco by habitual smokers after an abstinence period of only 6 hours, i.e., during oxygen inhalation at high altitude, appears to be a complicating factor bringing about in some men a rise in pulse rate of as many as 20 beats following the smoking of a single cigarette.

4. The Neurological Examination, testing reflexes, vibratory sense, and the ability to maintain balance with the subject standing on one foot, eyes closed, was directed especially toward the detection of cord injury. Some temporary unsteadiness of legs injured by bends was noted but significant positive findings were not manifest.

5. Blood Gravimetry determinations were carried out because of the high degree of hemoconcentration associated with air embolism in dogs. The falling drop method of Barbour and Hamilton was used; plasma protein was calculated according to Weech's formula, and the cell volume was measured in the Magath tube. The following relations were noted:

| | Sp.G. Whole Blood | Per Cent Cell Volume | Sp.G. Plasma and Per Cent Plasma Protein |
|---|---|---|---|
| I. CASES WITH NO BENDS. | | | |
| Increase | 4 | 5 | 4 |
| Decrease | 3 | 7 | 2 |
| No change | 12 | 7 | 13 |
| II. CASES WITH BENDS. | | | |
| Increase | 3 | 5 | 7 |
| Decrease | 3 | 5 | 3 |
| No change | 11 | 7 | 7 |

All changes fell within the normal daily variation of 0.0033 except one in which the specific gravity of plasma increased from 1.0314 to 1.0351 following a helium-oxygen run (See Table 1), 12/17/40. A recheck in 19 hours showed a return to the initial level. In a control test duplicating all conditions except the altitude-oxygen exposure, no deviation from normal was observed.

Essentially then, the findings are normal and serve as a base line for future test runs.

## XI - LIMITATIONS OF THE EXPERIMENTS CONDUCTED DURING THE PAST EIGHT WEEKS.

With reference to the test data presented in this report, it is recognized that (1) repeated daily exposure of the same individuals must be made; (2) the decompression chart serves as a guide outline and that for completion, more test runs are necessary; (3) that the decompression chart based on exposure of our divers is applicable mainly to men of the same age group and degree of fitness; younger men will require less decompression, and (4) some of our divers may be more susceptible to bends as a result of previous tissue injury; Smith, for example.

## XII - SIGNIFICANT POINTS.

Some of the concepts presented have been developed from a maze of apparently conflicting observations over a period of several years. It is our hope that certain of these ideas may be of some value as a guide to reduce a large body of inference to substantial experimental facts.

With the above mentioned limitations in mind, significant points or inferences from this report are:

1. Removal of gaseous nitrogen from the tissues of the body prevents aeroembolism and enables men to ascend at the rate of 5,000 feet per minute to a simulated altitude of 37,000 feet for a stay of 4 hours.

2. That the body can be rendered nitrogen free equally as well at an altitude somewhere in the range of 20,000 feet as at ground level.

3. That helium replacement of nitrogen in the body will reduce decompression time or pre-oxygenation time by about one-third.

4. That nitrogen must be eliminated from the body by decompression if high altitude flight is contemplated.

5. That the treatment of aeroembolism is immediate return to lower altitudes, if disability is to be prevented.

6. That the administrative problem of conditioning men for high altitude flight is considerably simplified if decompression can be effected at altitudes between 15,000 to 20,000 feet or by means of helium-oxygen inhalations.

7. That pure oxygen inhalation at an altitude of 15,000 to 20,000 feet for the purpose of decompression will greatly lessen the danger of oxygen toxicity from repeated exposures.

8. That increased cerebrospinal pressure if it occurs at high altitudes induces no immediate symptoms.

EXPERIMENTAL DIVING UNIT
NAVY YARD, WASHINGTON, D.C.

Subject: Preliminary Report on AEROEMBOLISM and EQUIPMENT FOR OXYGEN INHALATION.

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XII Introduction: Over a period of years the Experimental Diving Unit has developed or tested respiratory appliances for submarine escape and deep sea diving. Problems connected with this activity have been as arduous perhaps as the problem of supplying aviators with oxygen.

Of the developments, the submarine "lung" and a recirculating system for helium and oxygen based on the injector principle have been incorporated into submarine and diving practice.

During recent years it has been necessary to make physiological measurements of nitrogen and helium absorption and elimination incident to experimental and practical deep sea diving. The success of such endeavor frequently depends upon equipment or perhaps some innovation in design worked out by a clever craftsman.

At the Experimental Diving Unit we are fortunate in having men of unusual ability like Duncan, Frye, Westbrook and Pugh, who are able to make and assemble apparatus out of material at hand, frequently scrap parts.

Investigation of the problem of aeroembolism involved the use of such appliances devised especially for the comfortable and leak proof administration of oxygen for long periods of time at normal and abnormal barometric pressures. The equipment, although not elegant, has served its purpose well.

Although facilities for oxygen administration in aviation, particularly in Canada and in England, may be adequate, it seemed worthwhile to outline briefly the respiration units employed in the current tests in the belief that some of the equipment or the principles underlying its assemblage might be adapted for aviation.

XIII Closed Circuit Systems: For oxygen inhalation over prolonged periods of time a closed circuit system is essential. In such system a bag reservoir, a carbon dioxide absorbent, either valves or motor blower to provide circulation, and a face or head piece, are essential; see photographs 2, 3, 4, 5 and 6.

The crux of the assemblage is the contact that the individual has with the system. It is extremely difficult to find a gas-tight facepiece that can be worn comfortably. An ordinary mouthpiece induces fatigue in about one hour; masks can be worn up to 6 hours (Photograph 4), but extreme discomfort may be experienced over the bridge of the nose as a result of pressure necessary to prevent leakage of gas.

Subject: Preliminary Report on AEROEMBOLISM and EQUIPMENT FOR OXYGEN INHALATION.

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Our problem of securing a gas-tight headpiece which could be worn comfortably for a period of at least 17 hours was solved with the aid of Duncan, who fabricated a rubber helmet within a period of several hours after he was told what was needed.

TEST RUNS MADE: Employing the unit shown in photograph 3, it has been possible to make over 50 successive nitrogen elimination tests up to 17 hours duration without leakage through the helmet.

Previous test runs with masks, photograph 4, were frequently unsatisfactory because a leakage of only 10 to 20 cc. of air into the system was sufficient to invalidate an experiment. The rubber helmet made possible the results shown graphically in Figure 2, a 17 hour test run in which an endpoint for body nitrogen was measured to within an error of about 5 cc. of gas per hour.

The helmet with an oval window, photograph 5, was satisfactory for the current test exposures in which simulated altitudes of 37,000 feet were attained.

The helmet fitted with goggles and supplied with compressed air, photograph 6, was worn without discomfort for 8 hours daily by a workman engaged in chipping cement with an air hammer.

Adaptability For Aviation: This is largely a matter of test involving trial and error. Tentative suggestions are that the oxygen reservoir, the carbon dioxide absorbent, and the motor blower, could be made part of a permanent installation in aircraft. Equipped with his own fitted helmet the aviator could "plug into" the closed circuit for his oxygen supply. The problems to overcome relate to fogging of the eyepieces and to rinsing of the system.

The advantages of the system are comfort, economy, and the inhalation of essentially pure oxygen warmed by passage through the carbon dioxide absorbent.

Although aircraft may be provided with pressure cabins, it is not clear, in view of internal pressure limitations of about 5 pounds per square inch, how great heights can be attained unless individuals are supplied with oxygen. It does not appear to be feasible in view of the fire hazard and the matter of economy with reference to space and weight, to fill cabins with oxygen.

Consideration is given therefore, to a system of recirculating oxygen supply to individuals wearing hoods in a pressure cabin plane which might then be designed for any altitude, say up to 50,000 feet without exceeding an internal cabin pressure of 3 pounds per square inch.

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## XIV-OPEN CIRCUIT SYSTEMS

A system without valves and therefore offering no resistance to breathing, is potentially of great advantage. Dr. J. Kreiselman, a Washington physician called the senior author's attention to a simple, valveless mask system that he had been using for about one year. In tests conducted at this Unit, a representative alveolar oxygen percentage of 56 was maintained with an oxygen supply of 7 liters per minute. Since percentages of oxygen higher than 56 are essential at high altitudes, a modification in the system was made by attaching one inch tubing to the exhalation outlet.

With a potential rebreathing dead space of 600 cc. created by the addition of one inch tubing on the exhalation outlet, the alveolar oxygen percentage was increased from 56 to 89, oxygen supply 7 liters per minute.

Decreasing the exhalation dead space to 250 cc. by shortening the outlet tubing reduced the alveolar oxygen percentage from 89 to 73.5.

Principles Applied to "BLB" or Other Types of Masks: We have had difficulty with the earlier types of the "BLB" appliance in connection with the regulation of oxygen flow to prevent the complete emptying of the reservoir bag during inspiration. If the oxygen flow is too small, inspiration is prematurely inhibited by an empty bag. If the oxygen flow, on the other hand, is greater than the minute volume of respiration, oxygen is wasted.

Having several "BLB" appliances available, it was a simple matter to apply the principles outlined in a previous paragraph by removing the valve and attaching 4 feet of 3/4 inch tubing to the exhalation outlet, see photograph 7. A reduction in the length of the exhalation tubing to 2 1/2 feet and an increase in diameter to 1 inch, will serve the same purpose as the longer tubing.

Test Runs in Relation to Oxygen Supply: A subject at rest having a respiratory minute volume of 10 liters per minute breathed oxygen in the mask system. The following alveolar gas percentages were obtained:

| Oxygen Flow Liters Per Minute | Alveolar Oxygen | Alveolar Carbon Dioxide | Resp. Rate | Remarks |
|---|---|---|---|---|
| 10 | 90.3 | 6.02 | 13 | Comfortable. |
| 7 | 86.0 | 6.11 | 14 | Comfortable. |
| 5 | 75.5 | 6.35 | 14 | Slight increase in depth of respiration. |
| 3 | 65.0 | 6.53 | 15 | Some discomfort. |

<u>Tolerance Tests</u>: Thirty inches of 1 inch tubing on exhalation outlet of "BLB" mask, valves removed, bag retained, oxygen flow 3 liters per minute. Subjects at rest, sitting position:

| Subject | Duration of Test | Oxygen Flow, Liters Per Minute | Alveolar Dioxide. | Oxygen and Carbon Per Cent. |
|---|---|---|---|---|
| A | 1 hour | 3 | 52.23 | |
| A | 6 hours | 3 | 51.20 | NOTE: Subjects |
| B | 1 hour | 3 | 49.50 | stated that they |
| B | 4 hours | 3 | 52.36 | were comfortable; |
| C | 5 hours | 3 | 56.42 | felt well after |
| D | 6 hours | 3 | 49.04 | test runs. |

<u>Simulated Altitude Tests at 37,000 feet</u>: Three tests were made of the valveless, exhalation tube system, photograph 7. In one experiment of 2 hours duration at 37,000 feet altitude, the subject sat in a chair and received an oxygen supply equal to his tidal volume of inspiration. Alveolar samples were not taken as the experiment pertained to aeroembolism. The pulse rate, however, decreased from 78 at the beginning to 69 at the end of 2 hours of altitude exposure.

The advantages of the system are: (1) absence of respiratory resistance, (2) removal of need for continual adjustment of oxygen flow, (3) simplicity and comfort.

<u>Adaptability for Aviation</u>: The system appears to be satisfactory for short slights or where an adequate supply of oxygen is available. Resistance to breathing should not develop under any conditions including freezing.

On the other hand, a free flow of oxygen is required equal to that of any open circuit unit. Under conditions of deep inspiration some rebreathing takes place. It appears however, that some rebreathing may be a desirable feature at altitudes as high as 37,000 feet and it is not objectionable at the lower altitudes.

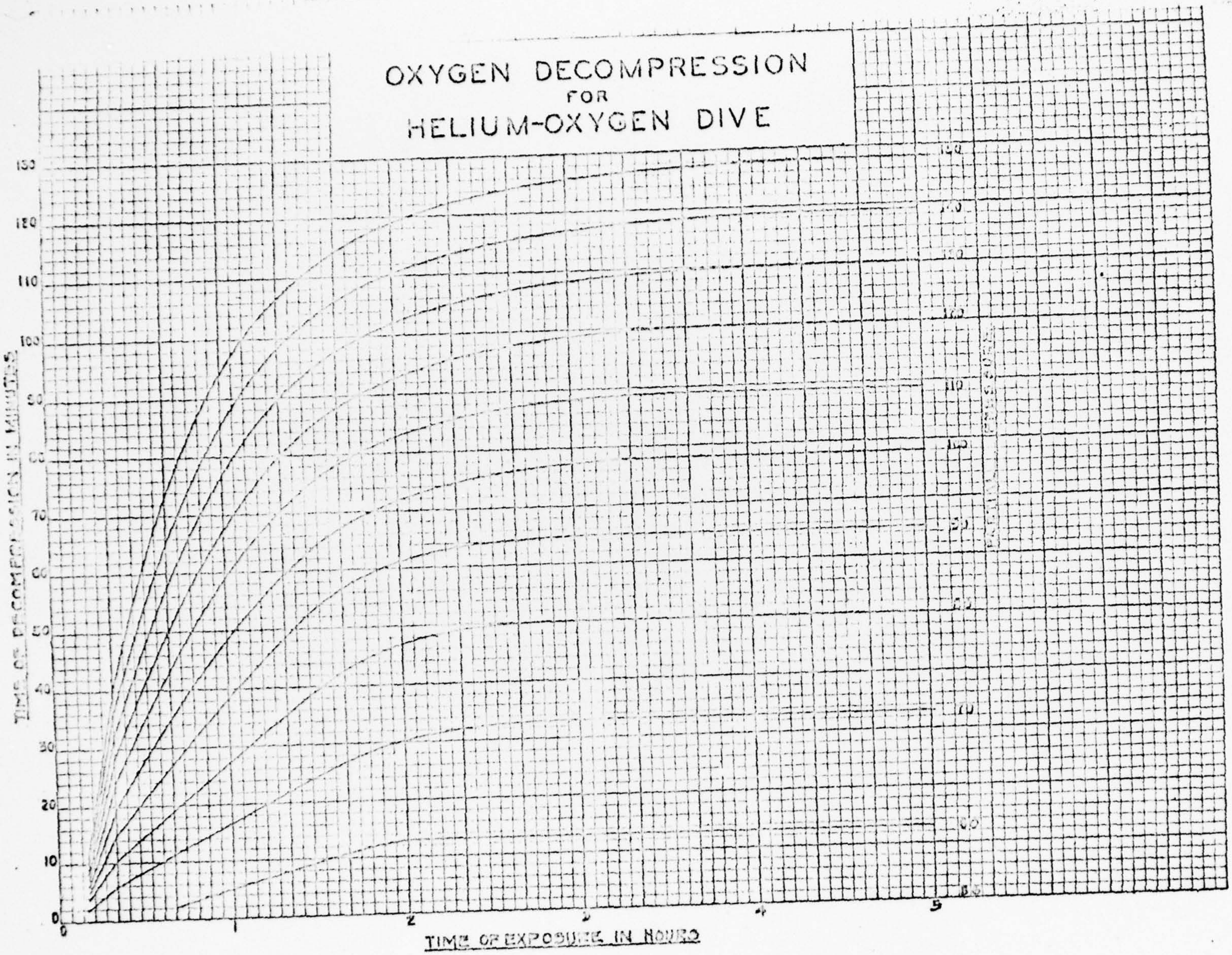
## XV -SEMI-OPEN CIRCUIT

As a result of Frye's skill and persistance in adapting the injector, a highly promising unit is now under test. It consists of a mask, reservoir, and canister for carbon dioxide absorption. The system (Photograph 8), is featured by a circulator operating on the injector principle which underlies gas circulation in the helium-oxygen diving helmet.

Test Runs at the ground level and at simulated altitudes of 20,000 and 30,000 feet for a duration of 3 hours show these advantages; (1) a comfortable system supplying warm oxygen (2) automatic, that is, it requires no regulation except the initial adjustment, (3) economical in that less than half of the oxygen necessary in the open circuit appliance, is needed (4) self rinsing and delivering 99 per cent oxygen; oxygen delivered in excess of metabolic usage escapes into the atmosphere. In the test runs 3 liters of oxygen were admitted to the system per minute when the pressure in the reducing valve was 5 pounds.

Adaptability for Aviation: For altitude flights up to 2 to 3 hours duration the unit approaches an ideal assemblage. It remains however, to be tested under cold conditions as the freezing of moisture will stop gas circulation by blocking the jet-venturi arrangement in the aspirator.

# OXYGEN DECOMPRESSION
FOR
HELIUM-OXYGEN DIVE



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13. ABSTRACT

The Experimental Diving Unit is essentially an Engineering-medical organization under the cognizance of the Bureau of Ships, and manned by personnel from the Bureau of Navigation and the Bureau of Medicine and Surgery.

During the past 13 years systematic test and research projects have centered mainly in submarine problems dealing essentially with deep sea diving and the effects on personnel of abnormal barometric pressures.

From the medical point of view the Experimental Diving Unit serves to make the individual more capable of handling the machine by bringing into field practice the advanced ideas and methods developed in the laboratory.

The feature that distinguishes the Experimental Diving Unit from other test and research organizations is the presence of a group of intelligent, courageous and rugged divers who serve as subjects to make possible immediate application of new procedures for the benefit of the whole Naval Service.

For these men there is no distinction between ordinary endeavor and endeavor beyond the ordinary call of duty, Typical of the group are C. F. Pugh, E.M.1c., J. E. Duncan,, C.T.M., who made the rubber helmets and Douglas bags, H. H. Frye, C.S.F., who adapted the venturi aspirator for the recirculation of oxygen, F.L. Westbrook, (cont. on other side)

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| 14 KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |

(cont.)

who measured body nitrogen elimination at a simulated altitude of 30,000 feet, and L. B. Lewis, Ph.M.1c., and H.H. Snider, Ph.M.2c., who over a period of several years carried out the essential physiological procedures.