put is 0.5 cubic foot per hour per man. It will then be seen that without the use of carbon dioxide absorbent a concentration of about 3 percent of carbon dioxide would be reached in 12 to 15 hours. Consequently, future plans should include the provision for each ship to carry more oxygen and more carbon dioxide absorbent. It is readily seen that this is necessary in case a submarine might be unable to come to the surface and would require a longer time than 72 hours for location by the salvage vessels.

The danger of chlorine in a submarine cannot be overestimated; in fact, all ships should be supplied with masks for such protection. It is interesting to know that in the *Squalus* rescue, the survivors reached the surface in excellent physical condition. The only untoward symptoms were headache, in about one-third of the crew, and a few showed evidence of mild shock. The temperature being between 45° and 55° was the greatest hardship that the men were called upon to withstand. All of these men were given oxygen during the period of restoring body warmth, and all symptoms cleared at a very rapid rate.

The lesson learned at this time is the value of the knowledge we now have of the nitrogen narcosis. Here is a sign that is a definite preliminary warning of impending danger from carbon dioxide concentration. When symptoms of narcosis develop the man should be immediately brought to the surface, recompressed and given oxygen therapy. With rare exceptions then, the incidents of having men blown to the surface from great depths will be minimized and possible fatal accidents avoided.

If the Navy has done anything helpful at all in the prevention of asphyxial death, I believe its outstanding contribution is the improved methods of oxygen therapy.

It is my great hope that in the coming year we will be able to present to the medical profession satisfactory evidence of the use that helium plays in the treatment of asphyxia, and also what useful part it may play in the field of anesthesia.

U. S. S. SQUALUS

MEDICAL ASPECTS OF THE RESCUE AND SALVAGE OPERATIONS AND THE USE OF OXYGEN IN DEEP-SEA DIVING

By Lieutenant A. R. Behnke, Medical Corps, United States Navy, and Lieutenant T. L. Willmon, Medical Corps, United States Navy

PART I—RESCUE OF THE SQUALUS SURVIVORS

On the morning of May 23, 1939, preliminary preparations were already under way at the experimental diving unit, Navy Yard, Washington, D. C., to conduct diving tests in the vicinity of Portsmouth, N. H., beginning about June 7.

For a period of 20 months the personnel of the diving unit under the supervision of Lieutenant Commander Momsen had been conducting laboratory experiments and tests in the pressure tank to ascertain the value of helium-oxygen mixtures in deep-sea diving.

At about 11:30 a. m., a critical experiment in a series designed to determine the level of maximum nitrogen elimination from the body during oxygen breathing was interrupted by the announcement "The *Squalus* is down off Portsmouth; stand by to leave within 2 hours."

Shortly after 2 p. m. the personnel of the unit, supplied with diving apparatus and tanks of helium left by airplane from Anacostia field for Portsmouth. Arriving at Portsmouth in the early evening, preparations were made during a cold, drizzly rain to rescue survivors of the disaster.

By means of temporary telephone communication, and then by tapping signals it was learned that the *Squalus*, flooded aft of the control room, was lying on a fairly even keel at a depth of 240 feet, 16 miles east of Portsmouth. In the control room and forward, 33 men were alive. The pressure in this part of the boat had built up to 13 pounds per square inch. Aft of the control room in the flooded portion of the ship, the fate of 26 men was unknown.

Diving operations were now contingent upon the arrival of the U. S. S. *Falcon* from New London. In the meantime, a submersible decompression chamber was sent to the scene of the disaster aboard a Coast Guard cutter to provide recompression for possible survivors escaping from the after end of the boat by means of the Momsen "lung."

Aboard the sister submarine *Sculpin*, which first sighted smoke bombs released from the sunken *Squalus*, Rear Admiral Cole and staff officers were making plans for the rescue of survivors.

Early the next morning, May 24, the *Falcon*, carrying the rescue chamber, arrived, and by 9:30 a. m. was moored over the sunken submarine.

Then occurred a series of remarkable operations, characterized by calm and faultless execution. All hands, conscious of the momentous task of rescue, worked in perfect unison.

Sibitzky, the first diver down, landed forward on the submarine, about 8 feet from the torpedo room hatch, where the downhaul cable of the diving bell was to be attached. His dive successful, the rescue chamber was started on its way to the submarine.

In the early afternoon, the first group of survivors was brought to the surface. These men appeared calm and relaxed. There was no evidence of hysteria. All were cold and some were in a condition of mild shock. About one-third of the survivors suffered from headache, undoubtedly the result of increased carbon-dioxide concentration.

The development of bends, although the survivors had been subjected to an excess pressure of 13 pounds for over 30 hours, was extremely remote. The recompression chamber, however, was utilized to supply warmth, and, if necessary, for oxygen therapy. Medical treatment was directed toward maintaining absolute rest, and supplying heat and fluids, consisting of coffee and malted milk, to which liberal amounts of sugar were added.

Particularly effective were the hot towels placed over the upper abdominal and hepatic areas. Within a few hours, the survivors had recovered sufficiently so that they could be safely transported to Portsmouth Naval Hospital.

Shortly after midnight, or about 15 hours after the start of operations, the fourth and last group of survivors was brought to the surface. This last ascent of the diving bell was marred by the jamming of the downhaul cable and for more than 4 hours the survivors were trapped at a depth of 240 feet, unable to surface.

In the meantime, strands of cable leading from the rescue chamber to the *Falcon* began to part. Two divers failed to attach a new cable, and the task now resolved itself into severing the downhaul cable leading from the chamber to the submarine.

In successfully cutting the downhaul cable, Squire, the diver, had to descend to a depth of 220 feet in cold water (39° F.), enveloped by complete darkness. Moreover, breathing air at this depth induces in divers a condition of intoxication so that coordinated activity requires intense effort.

By the time that the downhaul cable was severed, the rescue chamber was suspended by a weakened safety cable. For fear of breaking this controlling wire by hauling with power machinery, officers and men under the direction of Commander McCann and Lieutenant Commander Momsen actually pulled the rescue chamber to the surface.

Rescue operations ended on the morning of May 25, when Badders and Mihalowski, descending in the rescue chamber to the after hatch of the submarine under a pressure of 108 pounds per square inch, reported that the torpedo room was flooded.

Meanwhile all of the survivors had been sent to the hospital and with the exception of three, were in good condition. Hospitalization served not only to prevent complications, particularly the development of pneumonia, but also to keep the survivors in a single group under naval surveillance.

Of conditions in the submarine prior to rescue, Lieutenant Naquin, the commanding officer of the *Squalus*, made the following comments:

> Every effort was made to conserve the energy of the men who spent a great deal of time sleeping. The men were instructed to remain calm as excitement would increase oxygen consumption and carbon dioxide output. The oxygen

supply and available carbon dioxide absorbent were adequate for about 72 hours.[1]

The carbon dioxide concentration probably reached about 3 percent. One tank of oxygen was used in the control room (containing about one-half of the survivors) and another tank in the torpedo room. The intermediate battery compartment was not inhabited since it was feared that chlorine gas might be generated as a result of entrance of sea water into the storage batteries. After a number of hours the odor of chlorine was detected in this compartment, and the men wore "lung" appliances converted into chlorine protectors enroute from the control room to the torpedo room, where escape into the diving bell was effected.

Carbon dioxide absorption was facilitated by spreading absorbent throughout the compartments. A noticeable improvement in respirability followed each fresh addition.

Except for the men engaged in communicating with surface vessels by tapping signals, there was no activity on the part of any of the survivors, who remained in the same positions throughout the period prior to rescue (28 to 40 hours).

With respect to food, the emergency ration of beans was eaten by only a few and in small quantity. The men particularly relished and ate almost exclusively canned pineapple, tomatoes, and peaches, which were available in the commissary storeroom. Fluids were derived entirely from the canned goods, as the fresh water supply in the control and torpedo rooms, although potable, had an unpleasant taste.

The atmosphere in the submarine was dark, cold, and moist. The men suffered acutely from cold, which was only partially relieved by eating.

It is apparent that the survivors while awaiting rescue consumed a minimum amount of oxygen. The remarkable discipline present under trying conditions certainly prevented the early occurrence of oxygen lack and high carbon-dioxide increase.

The atmospheric conditions in the submarine were, however, not conducive to effort. The men existed in a dark atmosphere, saturated with moisture at a temperature between 45° and 55° F. Moreover, they were under a pressure of 13 pounds per square inch. It was impossible to keep warm even with blankets as the body heat was rapidly lost through conduction in the moist atmosphere.

The communicators especially were taxed severely in their efforts to send and to receive messages. In fact, any exertion caused great discomfort.

The maintenance of an adequate oxygen concentration and the limitation of carbon-dioxide content were so well directed by the commanding officer that life in the compartments could have been maintained for at least 72 hours.

PART II—SALVAGE OPERATIONS

The *Squalus* disaster provided a crucial test for the preparation embodied in a long period of experimentation and training incident to

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[1] An allowance roughly of 0.5 cubic foot per hour is made for the carbon-dioxide output and about 0.6 cubic foot per hour for oxygen consumption by men at rest. In this type of submarine the available air space is approximately 450 cubic feet per man. According to the manual of the Bureau of Construction and Repair, the limiting concentration of carbon dioxide is set at 3 percent, and of oxygen at 17 percent. Without adding oxygen or absorbent for carbon dioxide, such limiting concentrations would be reached in from 12 to 15 hours if the men were moderately active or in 24 to 30 hours if the men remained at rest.

submarine rescue and salvage operations. These developments have been engineering and medical in scope.

The engineering accomplishments include the raising of the submarines *S–51* and *S–4*, and the development of the rescue chamber and the submarine escape appliance (the "lung").

Coincident with these advances have been physiologic studies and experiments providing quantitative data as to the effects of pressure and of gases under pressure on personnel. These studies participated in by naval medical officers at the Harvard school of public health and at the experimental diving unit have centered in the introduction of a simple and effective method of utilizing oxygen in the decompression of divers, in the application of oxygen therapy for the treatment of compressed-air illness, and in the employment of helium-oxygen mixtures for work at depths in excess of 150 feet.

It remained, however, to test newly acquired knowledge and recently developed methods of procedure by actual deep-sea diving. A sunken submarine at a depth of 240 feet unfortunately provided the test.

Although 6 weeks of engineering and diving effort was nullified when the bow of the *Squalus* emerged from the water on July 13, nevertheless the diving operations were satisfactory. For without effective diving the involved engineering feat of placing pontoons, and of reeving chains under a submarine could not have been accomplished.

The diving record is further unique in that from May 24 to August 1, 372 dives were made without the occurrence of a single case of bends. Several accidents in which divers losing consciousness on the bottom and blown to the surface, were treated effectively by compression and oxygen therapy.

In contrast with previous diving methods, the distinguishing features of the diving technic were the successful employment of helium-oxygen mixtures for deep diving in cold water, made necessary by the failure of the standard method using air, and the effective use of oxygen permitting the decompression of divers without injury.

Of the engineering innovations relative to diving, several were especially important, namely, the fabrication of fireproof, electrically heated garments for cold-water diving, improved recirculation of gas through the diver's helmet, and the perfection of telephone communication.

Diving on air.—Since helium diving was still in the experimental stage at the beginning of salvage work, it was deemed advisable to follow the accepted method of air diving.

In previous salvage operations on the *S–51* at a depth of 132 feet and on the *S–4* at a depth of 104 feet, air diving was effective although the incidence of bends was high.

Diving in semidarkness, however, to a depth of 240 feet for the purpose of tunneling under the submarine and attaching hoses proved to be too dangerous when the divers breathed air. Two factors, the accumulation of carbon dioxide, and nitrogen narcosis impaired neuromuscular coordination to the extent that simple tasks could be carried out only with great difficulty.

The responses of the divers were marred by lapses in memory and loss of consciousness. On one occasion, the diver losing control of his air supply was blown to the surface. It was not only dangerous but futile for divers with impaired faculties to work at a depth of 240 feet in a maze of hoses and cables. The confusion of the divers is apparent from the following statements made by them:

I found the after torpedo room hatch, then went to the starboard rail and forward about 15 feet. At this time thinking became difficult. I started to tie the descending line to the rail and suddenly realized that I was just waving my arms and not accomplishing anything. Managed to steady down and tied what I believed to be two half hitches. I had a moment of blankness; when I observed the knots again, was surprised to see that I had made several turns with the line and had tied clove hitches and then half hitches. Heard order to come up. Went up on descending line outside of rail and waited to be pulled up. Was told I was fouled and to get back on submarine. Got back and faintly remember starting up again and being pulled up.

(Diver lost cable due to incoordination and asked that it be sent down to him again.) I waited for the cable to be sent down again; this time I cut it loose and made sure it was clear of the descending line, walked aft along the rail to the hatch, and put the shackle down against the pin. After feeling for the pin for some time, lying pretty close to the deck (because of poor visibility) with my air cut a little low, I saw slight moisture on my face plate (early carbon dioxide indication) and hadn't discovered the location of the pin.

I got on my feet, opened the exhaust another turn, opened my air, cleared the face plate. I looked over the shackle and saw the pin in the shackle, where I had been told it would be.

After discovering the pin, I laughed out with joy, and mumbled a few words intended for myself, but loud enough for the topside to hear. I could tell the way the topside was asking, "Was I all right," that they were worried about me. Told topside that I was O. K. and now knew what I was doing."

I made a normal descent, but as I started to get aboard the submarine I had a turn around my leg with the descending line. Had to struggle a bit to get it clear. Got on the submarine, called topside and reported. Did not hear any answer. I am not sure but I think that I asked them if they heard me, to give me the telephone signal on my life line. I must have lost consciousness for the next thing I remember is that I was jerked up off the submarine. I must have had control of myself on the way up, for when I regained consciousness I had the control valve in my hand.

As to the nature of nitrogen narcosis it may be stated that beginning at about 4 atmospheres' pressure (100 feet) and increasing progressively, nitrogen acts as a depressant to produce symptoms comparable to those manifested in alcoholic intoxication or to those associated with the excitement stage of anesthesia.[2 3 4 5]

While we were aware of the symptoms of nitrogen narcosis at a depth of 240 feet, we were surprised at their intensity. For the application of pressure in a chamber equivalent to a depth of 240 feet elicits reactions of considerably lessened severity.

Additional diving tests indicated that the difference in reactions between chamber and deep-sea diving could be attributed to the increase in carbon dioxide concentration in the diver's helmet.

The symptoms, however, were not typical of high carbon dioxide tension in the lungs but rather of air at a depth of 300 feet or more. Increased depth of respiration, for example, did not precede loss of consciousness.

Apparently the increase in carbon dioxide augmented the narcotic action of nitrogen.

As a possible explanation of this phenomenon we refer to the dilatation of cerebral vessels when the carbon dioxide tension is increased in the lungs.[6] Presumably as a result of increased vascularity more nitrogen will diffuse into brain tissue per unit of time.

It is likewise true that the toxic effects of oxygen at high pressures are intensified by raising the carbon dioxide tension in the lungs.[7] Conversely, lowering the carbon dioxide tension by hyperventilation decreases the untoward symptoms.

HELIUM-OXYGEN DIVING.—The substitution of helium for nitrogen in the air minimizes the narcotic symptoms associated with air breathing under pressure.[3 4 5] To divers accustomed to breathing air under pressure, the use of helium afforded considerable relief. The following statement from a diver was typical:

> This dive (on helium) was the best dive I have ever experienced. I did not feel deeper than 50 feet at any time; my head was clear and my mental faculties were working well at all times.

It may be of interest to record that the helium supplied to the *Falcon* was shipped from Lakehurst in cylinders containing about 1.5 cubic feet under a pressure of 2,000 pounds. At the Portsmouth Navy Yard, helium and oxygen cylinders were "split" and the gases mixed

[2] Behnke, A. R., Thomson, R. M., and Motley, E. P., Psychologic effects from breathing air at 4 atmospheres' pressure, Am. J. Physiol. 112: 554–558, July 1935.

[3] Behnke, A. R., and Yarbrough, O. D., Physiologic studies of helium, U. S. Nav. M. Bull. 36: 542–558, Oct. 1938.

[4] Behnke, A. R. and Yarbrough, O. D., Respiratory resistance, oil-water solubility, and mental effects of argon, compared with helium and nitrogen. Amer. Journ. Physiol. 126, June 1939.

[5] End, E., Rapid decompression following inhalation of helium-oxygen mixtures under pressure. Am. J. Physiol. 120: 712–718, Dec. 1937.

[6] Behnke, A. R., Forbes, H. S., and Motley, E. P., Circulatory and visual effects of oxygen at 3 atmospheres' pressure, Am. J. Physiol. 114: 436–442, Jan. 1936.

[7] Shaw, L. A., Behnke, A. R., and Messer, A. C., Role of carbon dioxide in producing symptoms of oxygen poisoning, Am. J. Physiol. 108: 652–661, June 1934.

to give cylinders containing about 75 percent helium and 25 percent oxygen. Analysis of the gas composition was performed in a laboratory set up near the dock.

After allowing several days for complete mixing, the cylinders were transported to the *Falcon* and set up in a manifold from which a hose led to the diver's helmet.

In the diving helmet the gas was recirculated through carbon dioxide absorbent by means of an aspirator. The aspirator or circulator is an ingenious mechanism working on the same principle as a water suction pump and consisting of a tiny jet facing into a venturi tube. The flow of a small volume of gas through the jet at an excess pressure of 150 pounds aspirates gas from the helmet into the container filled with carbon dioxide absorbent. The recirculating system has a high efficiency, as only about one-fifth of the gas supply is necessary compared with the open circuit.

Without an efficient method of recirculation the use of helium is not practical. On one occasion before adjustments were made in the helium supply to the helmet, a diver developed asphyxial symptoms at a depth of 240 feet and was blown to the surface. Under such conditions gas emboli rapidly form in the blood stream and accumulate in the pulmonary bed to produce a severe asphyxia known among divers and caisson workers as the chokes. Recovery followed oxygen administration in the pressure chamber.[8]

DECOMPRESSION OF DIVERS.—The problem inherent in bringing divers to the surface is to provide for the elimination of excess gas dissolved in the body tissues without bubble formation.

The history of diving, however, is marred by faulty methods of decompression giving rise to gas embolism and the resulting symptoms of pain, asphyxia, and paralysis.

If we could keep a diver under pressure and at the same time effect the removal of gas from his tissues, and if, in addition, the major part of decompression could be carried out in a pressure chamber on the surface, then our problem would be solved.

These objectives were accomplished in the decompression of divers aboard the *Falcon* by the administration of oxygen in a recompression chamber at the 50-foot level following comparatively rapid ascent to the surface.

Essentially the substitution of oxygen for air or the helium-oxygen mixture in the lungs allows excess nitrogen or helium gas to diffuse from the body at a maximum pressure head; and the maintenance of pressure at two and one-half atmospheres (50-foot level) prevents bubble formation.

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[8] Yarbrough, O. D., and Behnke, A. R., Treatment of compressed air illness utilizing oxygen, Journ. Ind. Hyg. and Toxicology 21: 213-218, June 1939.

A diver, for example, following a 20-minute working period at a depth of 240 feet, surfaced in 15 minutes, stopping only at the 80, 60, and 50-foot levels. He was then taken to the recompression chamber and given oxygen to breathe for a period of 45 minutes following which it was safe to effect his return to normal atmospheric pressure.

Bringing a diver rapidly to the surface for subsequent recompression, or surface decompression as the practice is usually designated, was forced upon diving personnel in the salvage of the *S–51* in 1925 because cold water and tides rendered decompression in the open sea impracticable. The procedure permits the elimination of excess gas from the body tissues under ideal conditions, that is, with the diver warm, at rest, and under observation. The danger of the method lies in the formation of extensive gas embolism during the interval between surfacing the diver and his subsequent recompression.

During the 15-minute period in the water, however, the high-pressure head of helium in the blood stream and body fluids is lowered to the point where it is safe to bring the diver to the surface provided recompression is applied within several minutes.

Should bubbles begin to form in the interval period, recompression to the 50-foot level with the diver breathing oxygen brings about a resolution of bubbles and promotes a maximum elimination of gas as previously determined by laboratory measurements.

In sharp contrast to the novel practice of effecting decompression by breathing oxygen at a single, optimum level, is the procedure followed in previous salvage operations (*S–51*, *S–4*) of breathing air in carefully graded stages during the diver's stay in the pressure chamber. The assumption underlying this method is that the body tissues can hold gas in supersaturation for an extended period of time to permit the pressure to be lowered in stages. Diffusion of excess dissolved gas from the body under these conditions is precarious because of the imminent probability of bubble formation as a result of the higher pressure head of gas in the body compared with the lungs.

The problem of administering oxygen economically in the recompression chamber has been solved by adopting the mask developed by Boothby and his coworkers. The divers were able to wear this appliance without discomfort, and the fractional rebreathing of oxygen prevented irritating dryness of the throat frequently complained of when oxygen is breathed in an open circuit.

By administering oxygen only to the diver by means of a mask, the fire hazard is minimized. Were it necessary to fill the chamber with oxygen under pressure, the fire hazard would preclude oxygen therapy from further consideration.

The electrically heated suit.—The hazards of decompression are greatly increased by exposure in cold water. Especially subject to cold are divers breathing and surrounded by a helium atmosphere in which presumably body heat is more rapidly dissipated through conduction than it is in an air atmosphere.

To counteract the harmful effect of cold, predisposing as it does to bends and preventing efficient manipulation of the hands, a manufacturer, carrying out suggestions from the experimental diving unit, fabricated a fireproof, electrically heated garment. The heat supply, controlled from the surface, comes from storage batteries.

Wearing these garments the divers were comfortable not only while working on the bottom but also while standing on the stage during decompression.

VOICE CHANGES.—The peculiar nasal quality imparted to the voice by helium is not improved at deep depths, indicating that the density of the helium-oxygen mixture is not responsible for the sound distortion.

So serious was the impaired audibility of the diver's conversation over the telephone that it became imperative to improve sound equipment. As a result of efforts to improve communication, sound reception from the telephone when the diver was at a depth of 240 feet was rendered as clear as at the surface.

EQUALIZATION OF PRESSURE.—For a period of 6 weeks in which over 200 dives were made, divers did not have any difficulty equalizing pressure on the tympanic membranes. About the middle of July, however, upper respiratory tract infection sealing the auditory tubes prevented as many as six divers from working in a single day. Whether air or helium mixture was breathed apparently made little difference in the ability to equalize pressure.

PART III.—PHYSIOLOGIC BASIS FOR OXYGEN ADMINISTRATION IN DEEP-SEA DIVING

In view of the increasing scope of oxygen administration, and its proved value in deep-sea diving, it may be well to review briefly some of the physiologic studies of oxygen effects at increased pressures.

In theory oxygen would be an ideal gas for deep-sea diving since bubbles forming in the body after decompression would be quickly absorbed by the tissues.

In practice, however, pure oxygen has been found to be toxic, producing symptoms referable to the lungs and the nervous system. At a pressure of one atmosphere after prolonged exposure pulmonary edema develops in rats, dogs, and rabbits. At a pressure of 4 atmospheres convulsive seizures signalize the most striking phenomenon of oxygen poisoning.[9] [10]

[9] Behnke, A. R., Johnson, F. S., Poppen, J. R., and Motley, E. P., Effect of oxygen on man at pressures from one to four atmospheres, Am. J. Physiol. 110: 565-572, Jan. 1935.

[10] Schilling, C. W., and Adams, B. H., Study of convulsive seizures caused by breathing oxygen at high pressures, U. S. Nav. M. Bull. 31: 112-121, April 1933.

While the exact nature of oxygen poisoning is a matter of conjecture, of great importance is the time elapsing before toxic symptoms appear. On the basis of animal experiments at least 24 hours were required before pulmonary edema developed, and at a pressure of 4 atmospheres about 45 minutes elapsed before convulsions were manifest.

Although the tolerance of various animals to high oxygen pressures had been established, the problem in 1932 called for tolerance tests in man. From these tests conducted by naval medical officers at the Harvard school of public health, it was found that at atmospheric pressure healthy men could breathe oxygen for a period of at least 6 hours without showing symptoms indicative of pulmonary irritation. At higher pressures the effect of oxygen on the nervous system superseded the pulmonary manifestations.

At a pressure of 3 atmospheres, for example, definite and sometimes alarming symptoms occurred during the fourth hour of oxygen inhalation.[6] Preceded by a period of normality and with fairly abrupt onset, a rise in blood pressure, increase in pulse rate, and contraction of visual fields terminating in loss of vision, pointed to the action of oxygen on the nervous system.

Although loss of vision and an epileptic type of seizure pointed to a severe functional disturbance, complete recovery invariably followed these symptoms when air was again breathed.

From these tests developed several facts worthy of emphasis, namely, that the harmful effect of oxygen on the nervous system begins to manifest itself at a pressure of 3 atmospheres, at which level the oxygen in physical solution is sufficient to take care of tissue requirements and hemoglobin is not necessary as an oxygen carrier;[11] that the nervous symptoms, therefore, are concomitant with the building up of the oxygen tension in venous blood; that 1.8 volumes percent of oxygen are dissolved in arterial blood per atmosphere of oxygen; that the acidity of the venous blood is increased by a pH change of 0.03 when pure oxygen is inhaled; and that increasing the carbon dioxide tension in the lungs greatly enhances the toxicity of oxygen.[7]

Successive daily exposures to induce convulsions were then carried out by placing dogs in a chamber and raising the pressure to 5 atmospheres. After 30 exposures residual injury could not be detected.

On the basis of these observations, although the cause of oxygen toxicity was not determined, it appeared justifiable to use high oxygen pressures for the treatment and prevention of compressed-air illness.

Oxygen therapy was then evaluated in compressed-air illness. In a series of tests on dogs rapidly decompressed from a pressure of 65 pounds, multiple emboli formed throughout the vascular system,

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[11] Behnke, A. R., and others, Studies on effects of high oxygen pressure; effect on high oxygen pressure upon carbon dioxide and oxygen content, acidity, and carbon dioxide combining power of blood, Am. J. Physiol. 107: 13-28, Jan. 1934.

blocking blood flow, and unless treatment supervened, produced death by asphyxiation, due to nitrogen bubbles obstructing blood flow through the pulmonary capillaries.

The administration of oxygen in a chamber at a pressure of 30 pounds compressed the bubbles and relieved the asphyxia.[12]

Later, at the experimental diving unit, recompression utilizing oxygen was employed to treat injured divers. Out of 50 patients suffering from bends, 49 responded to the initial treatment without recourse to additional pressure therapy.[8]

With respect to the decompression of divers, rational oxygen administration depends upon the determination of the pressure level at which maximum diffusion of nitrogen or helium takes place from the body following exposure to increased pressure.

At the present time experiments in which gas measurements were made in a pressure chamber have progressed sufficiently to indicate that the most favorable level ranges between 50 and 60 feet.

At pressures equivalent to these depths oxygen is well tolerated, at least for a period of time sufficient to eliminate excess nitrogen or helium regardless of previous depth or exposure.

Taking these facts into consideration, it has been possible in the decompression of divers to bring them rapidly to the 50-foot level where they remain breathing oxygen until the excess gas pressure in the body has decreased, as shown by experimental graphs, to the point where immediate surfacing is safe. Thus, the complicated and precarious practice of decompression has evolved into a simple and effective procedure.

OXYGEN[1]

IMPORTANCE OF OXYGEN TO THE NAVY IN AVIATION AND IN THERAPEUTICS

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The development by Boothby,[2] Lovelace[3] and Bulbulian[4] of a new inhalation apparatus for the comfortable, economical, and efficient administration of oxygen in any desired concentration up to 100 percent has opened up new fields for oxygen therapy and has increased greatly the practicability and the value of the administration of oxygen not only in the field of medical therapeutics but also in the field of aviation.

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[12] Behnke, A. R., and Shaw, L. A., Use of oxygen in treatment of compressed-air illness, U. S. Nav. M. Bull. 35: 61–73, Jan. 1937.

[1] From the Mayo Foundation, Rochester, Minnesota.

[2] Boothby, W. M., Oxygen administration: value of high concentration of oxygen for therapy, Proc. Staff Meet., Mayo Clin. 13: 641–646, Oct. 12, 1938.

[3] Lovelace, W. R., II., Oxygen for therapy and aviation: apparatus for administration of oxygen or oxygen and helium by inhalation, Proc. Staff Meet., Mayo Clin. 13: 646–654, Oct. 12, 1938.

[4] Bulbulian, A H., Design and construction of masks for oxygen inhalation apparatus, Proc. Staff Meet., Mayo Clin. 13: 654–656, Oct. 12, 1938.