5. None of this series showed any but the most negligible types of reaction. Nineteen other cases are cited in which there was such intolerance for the ārsphenamines that that type of arsenical was impossible to use. These 19 patients were able to take mapharsen in doses ranging from one-half to the full therapeutic equivalent of arsphenamine without mishap.

6. The results obtained in these cases indicate that mapharsen will gain and retain a high place among antisyphilitic agents.

Acknowledgment.—The writer wishes to express his high appreciation for assistance by Lt. H. J. Cokely (Medical Corps), United States Navy, in the Women's Syphilis Clinic, and to the following naval medical officers for their cooperation in carrying on the treatment during periods when the patients were away from the San Diego area: Commanders F. H. Haigler, E. A. M. Gendreau, V. H. Carson, J. R. White, W. J. Pennell, L. B. Marshall, S. R. Mills, J. A. Brown, and L. D. Arbuckle; Lt. Comdrs. W. D. Davis, and M. S. Mathis; Lts. J. D. Boone, A. F. Gardner, J. T. Miser, and R. C. Douthat.

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THE APPLICATION OF MEASUREMENTS OF NITROGEN ELIMINATION TO THE PROBLEM OF DECOMPRESSING DIVERS[1][2]

By Albert R. Behnke, Lieutenant, Medical Corps, United States Navy

For the purpose of gaining a better understanding of the physiologic aspects underlying the decompression of deep-sea divers quantitative studies have been made in this laboratory in cooperation with the Bureau of Medicine and Surgery. The purpose of this paper is to present the results of measurements of nitrogen absorption and elimination in dogs and in man over a period of 2 years, and to apply

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[2] Received for publication Oct. 13, 1936.

these results to the problem of decompressing workers in compressed air.

The prevention of compressed-air illness depends upon the elimination from the blood without bubble formation of the excess nitrogen absorbed during exposure to increased barometric pressure. The formulation of decompression tables for this purpose requires a knowledge of the rate of nitrogen absorption and elimination with changes in barometric pressure, the nitrogen content of the body, the substances in which the nitrogen is dissolved, and the degree to which these substances can hold nitrogen in supersaturation.

The fundamental studies of Paul Bert (1878), Heller, Mager, and von Schrotter (1900), and Boycott, Damant, and Haldane (1908) led to a better understanding of the cause, prevention, and treatment of compressed-air illness. Deep-sea diving has been made comparatively safe by the adoption of the decompression tables formulated by Boycott, Damant, and Haldane, and the hazards of work in compressed air have been minimized as a result of a practice of decompression evolved from extensive tunneling projects in New York State (Levy, 1922). Empirical rather than quantitative data, however, formed the basis for the formulation of decompression tables. Thus, two of the basic assumptions underlying the diving tables are that the absolute pressure can be safely halved during the first stage of decompression, and that about 5 hours are necessary for the complete aborption or elimination of nitrogen from the body. While these assumptions were derived from and their accuracy tested by animal experimentation and by work in compressed air, there were no actual determinations of the ability of the tissues to hold nitrogen in supersaturation, or of the time required for nitrogen elimination in man.

Fifty-three years after proof had been adduced by Bert that nitrogen bubbles cause compressed-air illness, Campbell and Hill (1931) measured the nitrogen eliminated by man when oxygen was breathed for short periods of time at normal barometric pressure, and later (1933) contributed valuable quantitative data with reference to nitrogen absorption and solubility in the brain, liver, and bone marrow of the goat. The necessity for these studies is indicated by the occurrence of occasional accidents when the standard diving tables have been followed, particularly after prolonged exposures to high pressures. An inquiry into the cause of these accidents revealed the need for additional quantitative data with reference to nitrogen absorption by and elimination from the body during exposure to and decompression from high air pressures respectively.

Definition of terms.—Saturation implies a condition of equilibrium between the nitrogen absorbed by the body and that present in the lungs. Partial saturation implies that this equilibrium has not been reached, hence, the body can absorb more nitrogen. Percentage saturation is the ratio multiplied by 100 between the partial pressure of nitrogen in the body and the partial pressure of nitrogen in the lungs. The partial pressure of nitrogen is regarded as proportional to the volume (measured under standard conditions) of nitrogen in the body; 50 percent saturation implies, therefore, that one-half of the equilibrium pressure has been reached, since one-half of the volume of nitrogen corresponding to saturation has been absorbed. The excess pressure in the body refers to the increase in the nitrogen tension above that which normally exists at atmospheric pressure, and is approximately 79 percent of the gage pressure. The absolute pressure is gage pressure plus 14.7 pounds (1 atmosphere). Difference in pressure refers to the difference between the average partial pressure of nitrogen in the body and in the lungs. It is a measure of the pressure head at which nitrogen diffuses from the body into the lungs or vice versa.

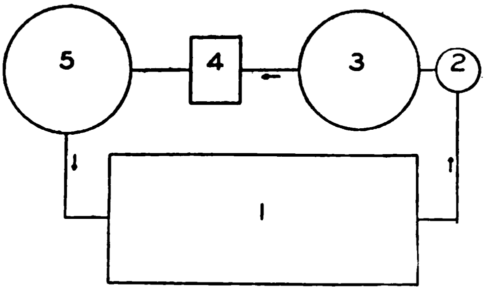


FIGURE 1.—Diagram of a closed system devised by Shaw et al. (1935) in which the nitrogen dissolved in the body can be removed by breathing pure, circulating oxygen. (1) metal box with mercury seal, (2) soda lime canister, (3) spirometer, (4) blower, and (5) cooling coil.

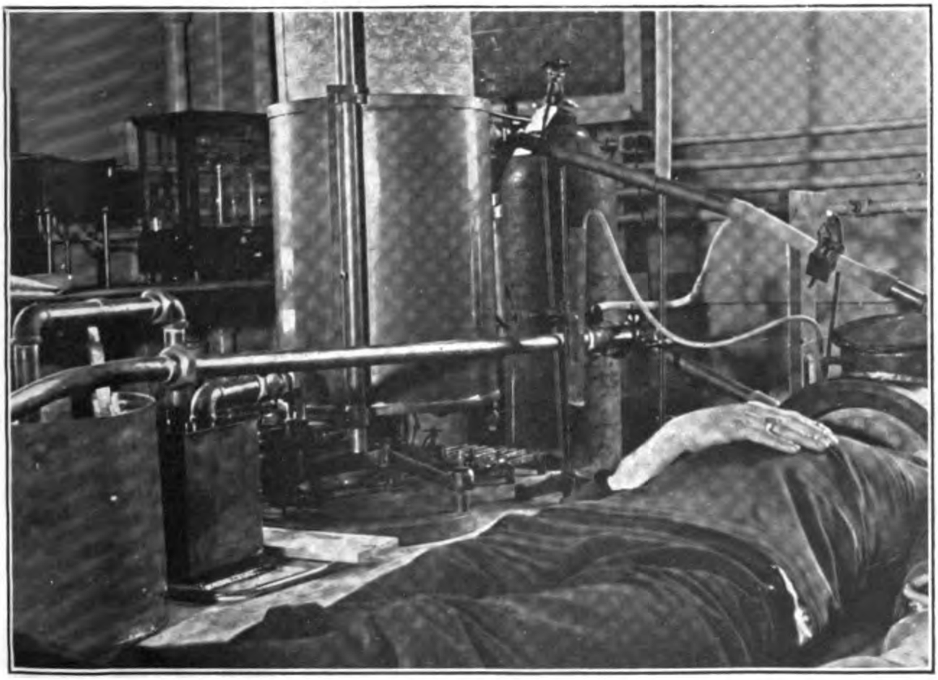
Fundamental principles.—The nitrogen dissolved in the body can be removed by oxygen inhalation, which reduces the partial pressure of nitrogen in the lungs to a value approaching zero. For this purpose Shaw and his associates (Shaw, Behnke, Messer, Thomson, and Motley, 1935) used a closed 100-liter system (fig. 1) consisting of a metal box (1), soda lime canister (2), spirometer (3), blower (4), and a cooling coil (5). In a typical experiment an anesthetized dog (dial-urethane solution introduced intraperitoneally) was placed in the metal box (1) through which oxygen circulated. Since the concentration of oxygen did not fall below 99 percent, practically complete nitrogen elimination was assured over a period of hours. During all but the first 7 minutes the eliminated nitrogen could be measured by analyzing periodic gas samples and multiplying the nitrogen percentage by the volume of the system. During the first 7 minutes the air in the apparatus and in the dog's lungs was replaced by oxygen. With this procedure it was found that about 95 percent of the total nitrogen was eliminated in 2 hours, and 100 percent in 3 hours (lean dogs). The normal nitrogen content of a lean dog was approximately 14 cc per kilogram of body weight.

Three generalizations were now subjected to quantitative test: (1) The quantity of nitrogen absorbed by the body when equilibrium is reached is proportional to the partial pressure of nitrogen in the lungs—an application of Henry's law; (2) with the same pressure head the rate of nitrogen absorption is equal to the rate of nitrogen elimination; and (3) the time required for the complete desaturation of the body and the percentage rate of elimination are the same irrespective of the initial quantity of nitrogen in the body.

The application of Henry's law to the absorption of nitrogen by the body was tested by subjecting the dog to pressures of 3 and 4 atmospheres for a period of 4 hours, respectively, in order to make certain of complete saturation. The dog was then placed in the metal box at atmospheric pressure, and the nitrogen which had been absorbed at the high pressures was measured. A comparison of the results showed that within the limits of experimental error nitrogen absorption is proportional to the partial pressure of nitrogen in the lungs.

Rate of saturation compared with the rate of desaturation.—A dog rendered completely nitrogen free by long exposure to oxygen alone was exposed for 67 minutes in air at a pressure of 4 atmospheres. The nitrogen absorbed at this pressure was found to be equal to the nitrogen eliminated by the dog during the same period of time when the pressure head of nitrogen was reversed, i. e., nitrogen tension in the dog's body equivalent to 4 atmospheres, and in the lungs 0.

Nitrogen elimination in relation to the quantity of nitrogen absorbed.—In figure 2, curve A represents the nitrogen eliminated from a dog which had been exposed to a pressure of 4 atmospheres for 120 minutes after having been previously rendered nitrogen free; curve B follows an exposure to a pressure of 4 atmospheres for 37 minutes; and curve C follows complete saturation (240 minutes) at a pressure of 1 atmosphere. All of the nitrogen measurements were obtained from the same dog. It will be observed that not only is the time for nitrogen elimination practically the same following complete (C) or partial (A and B) saturation, but also the percentage rate of nitrogen elimination for corresponding periods of time is the same within the limits of experimental error as shown by the slope of the lines A, B, and C. Thus, the nitrogen absorbed after an exposure of 37 minutes to a pressure of 4 atmospheres is not eliminated any faster than the nitrogen absorbed after a 2-hour exposure to the same pressure although the total amount given up is less.



APPARATUS FOR THE MEASUREMENT OF NITROGEN ELIMINATION FROM THE BODY.

The units are designated in Fig. 1. For man, a helmet has replaced the box (1).

The nitrogen solvents of the body, and the fat and lipoid content of the brain, spinal cord, and bone marrow.—It has been generally assumed that the chief nitrogen solvents of the body are fat and water. The correctness of this assumption was checked by determining the fat and water content of a dog and by multiplying the results by the solubility coefficients of nitrogen in fat and in water, respectively. The nitrogen content computed in this manner agreed with the quantity of nitrogen previously determined in vivo during the breathing of oxygen. The fat and lipoids were then extracted with carbon tetrachloride from the brains and spinal cords of five dogs. In table 1 the results are tabulated. In the calculation of the nitrogen content a solubility coefficient of 0.00954 was used for water, and 0.055 for fat. The solubility coefficient represents the number of cc of nitrogen dissolved per gram of water or fat at 38° C. and 570 mm. For water, the computation of the coefficient is based upon the measurements of Van Slyke, Dillon, and Margaria (1934), and for fat, upon the measurements of Campbell and Hill (1931).

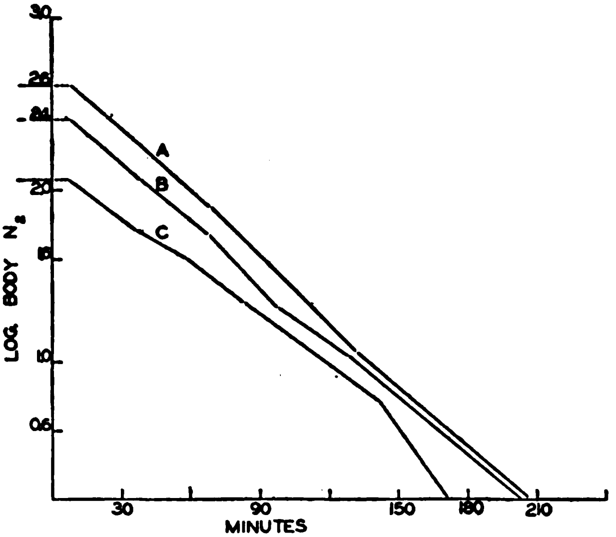


FIGURE 2.—Decrease in the nitrogen content of the dog's body during oxygen breathing in (1) figure 1, at atmospheric pressure. A, after exposure to a pressure of 4 atmospheres absolute for 120 minutes; B, after exposure to 4 atmospheres for 37 minutes; and C, after exposure to 1 atmosphere for 240 minutes (complete saturation). Ordinates represent the logarithms of the values in cc of the nitrogen content of the body.

Summary of fundamental principles.—The nitrogen dissolved in the body can be removed by breathing pure oxygen. Using this method to measure the nitrogen elimination in dogs exposed to pressures as high as 5 atmospheres absolute, it was found: (1) that nitrogen absorption is proportional to the partial pressure of nitrogen in the lungs; (2) that with the same pressure head the rate of nitrogen absorption is equal to the rate of nitrogen elimination; and (3) that the time for complete nitrogen elimination and the percentage rate of nitrogen elimination for corresponding periods of time are the same irrespective of the quantity of nitrogen absorbed by the body. Additional data were advanced to show that the body nitrogen is soluble in fat, lipoids, and water; that the brain contains about 5 grams of fatty material compared with 28 grains in the spinal cord. It was also shown that the quantity of nitrogen in a lean dog is about 14 cc per kilogram, and that this nitrogen is eliminated in about 3 hours when oxygen alone is breathed by the anesthetized dog. With these basic facts in mind we can consider the next phase of the problem.

Measurements of nitrogen elimination in man.—Measurements of nitrogen elimination on men were conducted at atmospheric pressure with apparatus similar in construction to that used for dogs as shown in the photograph. The results from seven young men who breathed oxygen for periods of 4 to 6 hours are summarized in tables 2 and 3. The data in table 2 show that 6 men of approximately the same weight eliminated from 12.3 to 14 cc of nitrogen per kilogram. In appearance these men were lean but well developed. The seventh man was moderately fat and the high value of 18.6 cc of nitrogen per kilogram reflects this condition.

The nitrogen eliminated by subjects B. U. R., R. O. M., and T. H. O. during the first 5 minutes while oxygen was replacing the air in the apparatus was calculated by extrapolating the experimental curve to the left for the corresponding period of time (Behnke, Thomson, and Shaw, 1935). In calculating the percentage of the total nitrogen eliminated by these subjects it was assumed that 95 percent of the total nitrogen is eliminated in 4 hours. This assumption is supported by the fact that in dogs 95 percent desaturation requires 2 hours and that 99 desaturation requires about 3 hours. Since the circulatory rate of the dog is about twice that of man per kilogram of body weight, it is not unreasonable to assume that 95 and 99 percent saturation will take twice as long for man. This assumption is further supported by experiments with subjects B. I. L., M. U. R., and F. A. H., in whom complete nitrogen elimination was effected within the limits of experimental error in 6 hours. The experimental errors caused a variation of ±7.5 cc so that the elimination of quantities of nitrogen of less than 7.5 cc per hour could not be accurately measured. Although the precise end-point for nitrogen elimination cannot be determined, a value of 95±2 percent can be used with reasonable certainty as the percentage of nitrogen eliminated by the body at the end of 4 hours, and 98±2 percent for the amount given up at the end of 6 hours.

Analysis of a nitrogen elimination curve.—Figure 3 shows graphically the way in which nitrogen is eliminated by lean, well-developed men while breathing pure oxygen for a period of 6 hours. The experimental values which determine the total nitrogen curve (A) are the average of the values from subjects B. I. L., M. U. R., and F. A. H. (see table 4). If the blood flow throughout the body was distributed uniformly with respect to the nitrogen content of the tissues, the values of curve A could be derived from an exponential equation of the form,

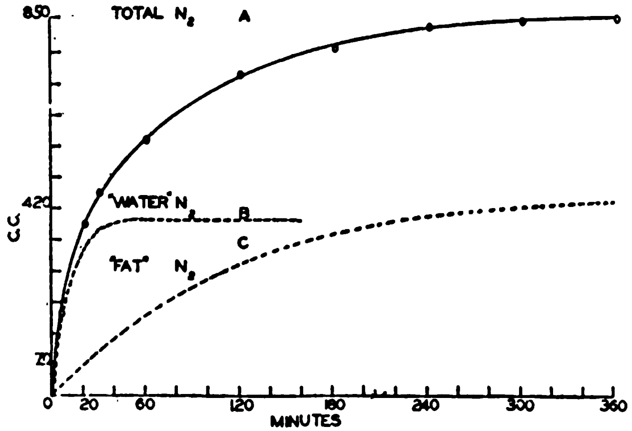


FIGURE 3.—Total N_2, A, represents the average of the values for nitrogen elimination from 3 men (average weight 64 k) who breathed pure oxygen at atmospheric pressure. "Water" N_2 (B) and "Fat" N_2 (C) are hypothetical curves showing the absorption or elimination of nitrogen by the body solvents. The values for nitrogen on A are approximately the sum of corresponding values on B and C, see table 4.

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

which states the relationship that the quantity of nitrogen eliminated from the body at any instant is proportional to the nitrogen content of the body at the given instant. In the equation, Y = the amount of nitrogen eliminated during the time interval t; A = the initial nitrogen content of the body; k = the rate of change in the slope of the curve; and e, the natural base of logarithms. The expression, $1 - e^{-kt}$,[8] gives the percentage decrease of nitrogen in the body during the time interval t. If the experimental values for nitrogen elimination on curve A be substituted in equation (1), the value of k does not remain constant but progressively decreases, as shown by table 3, columns 9 and 18. This is explained by the fact that the blood flow is not distributed uniformly in relation to the distribution of nitrogen in the body particularly with reference to fat which has a high nitrogen capacity and a poor blood supply.

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[8] For values of 0.05 or less, k and $(1 - e^{-k})$ are almost the same, so that k may also be considered as the percentage rate of nitrogen elimination per unit of time.

Thus, at the start of oxygen breathing the average nitrogen tension in the blood is equal to the nitrogen tension (partial pressure) in the different tissues of the body, and a maximum load of nitrogen is eliminated per unit of time. As the experiment progresses, the average nitrogen tension in the blood tends to fall below the nitrogen tension in the slowly saturating or fatty tissues. Consequently the percentage rate of nitrogen elimination decreases.

If the total nitrogen of the body is divided according to its solubility in water and in fat, then equation (1) with a constant value for k can be conveniently employed to represent nitrogen absorption by or elimination from water and fat, respectively.

Thus, if the elimination of nitrogen from fat is assumed to proceed at a uniform percentage rate (constant value for k), the approximate quantity of nitrogen given up by fat can be calculated in the following manner: since 98±2 percent nitrogen elimination requires 6 hours, and since fat per unit volume contains five times more nitrogen than water, it should take fat at least five times longer to eliminate its nitrogen. The nitrogen, therefore, eliminated after the first hour (curve A), 275 cc, was initially present in fat. The nitrogen eliminated from fat during the first hour (182 cc) can now be calculated from equation (1), in which $t=-60$, $A=275$, and $k=0.0085$—a value computed from an experimental curve similar to A, figure 3, by Behnke, Thomson, and Shaw (1935). Total nitrogen from fat is equal to (182+275) 458 cc. Subtracting 458 from 850 (the total nitrogen content of the body), a value of 392 cc is obtained for the nitrogen in the body fluids. The absorption or elimination of nitrogen by the body can now be represented by an equation consisting of two components, one for water, and the other for fat:

$$Y=392(1-e^{-0.098t})+458(1-e^{-0.0085t}) \qquad (2)$$

in which the value of k for water is also obtained from the calculations of Behnke et al. The curves representing the water and the fat components of equation (2) are drawn in figure 3 as B and C, respectively. In table 4 the experimental values for the elimination of body nitrogen are compared with the values calculated by equation (2); the agreement appears to be satisfactory.

The interpretation placed upon the "fat" and "water" curves.—The curves B and C are only approximations of the manner in which nitrogen is absorbed by or eliminated from its chief body solvents. They should not be interpreted to mean that fat and water exist as separated entities in the body, but rather that the fat, lipoids, and water are so distributed that during saturation a large part of the nitrogen absorbed by fat and lipoids diffuses from the body fluid. On decompression the reverse process is thought to occur. Thus during decompression following partial saturation the diffusion of nitrogen from the rapidly saturating body fluids into the slowly saturating lipoids and fat tends to equalize the partial pressure of nitrogen in the different tissues of the body. With the exception of tissues with a high fat content (fat deposits, bone marrow, and spinal cord) the division of the body into tissues which saturate or desaturate at different rates is largely arbitrary, and the body can be regarded essentially as a unit. This fundamental concept can be made more clear by comparing the body to a beaker of water in which is distributed fat, with a greater concentration of fat in the lower portion. If the beaker is now exposed to a high nitrogen pressure for a short period of time and then quickly returned to atmospheric pressure, diffusion of nitrogen will take place from the water into the surrounding air and also into the unsaturated water and fat present in the beaker. In the body after short exposures (up to 30 minutes) to high pressures the fat acts as a nitrogen absorbent during decompression and serves as a buffer against bubble formation in the blood stream. Fat men, consequently, with adequate blood circulation should be better suited for short exposures in compressed air than lean men.

APPLICATION OF THE EXPERIMENTAL RESULTS

Duration of exposure to increased pressure followed by immediate decompression to atmospheric pressure.—It is important not only in diving but also in submarine escape drills to know the duration of exposure to various depths which can be followed safely by immediate ascent to the surface, i. e., without decompression stops. In the dog experiments it was observed that the percentage rate of nitrogen elimnation for corresponding periods of time did not vary with the quantity of nitrogen absorbed, since the slope of the curve following saturation (fig. 2) was the same as the slope of the curve following incomplete saturation. It follows as a corollary that the same curve will represent the elimination of a given quantity of nitrogen irrespective of whether the nitrogen is absorbed at a low pressure over a long period of time or at a high pressure for a short period of time. If use is made of the well-established fact that compressed-air illness (excessive nitrogen bubble formation) rarely occurs with rapid decompression, even after prolonged exposures to an excess pressure of 19 pounds (Haldane, 1927), then the safe exposure time to excess pressures followed by rapid decompression can be calculated from the nitrogen elimination curve, figure 3, A, a segment of which is reproduced in figure 4 (the values of the ordinates have been expressed in terms of percentage saturation instead of cc of nitrogen). Thus, if a prolonged exposure (100 percent saturation) at an excess pressure of 19 pounds followed by immediate decompression is safe, then rapid decompression after 50 percent saturation at 38 pounds, or 25 percent saturation at a pressure of 76 pounds, will also be safe, since after each exposure the same quantity of nitrogen has been absorbed. In tabular form:

$$\begin{array}{l} P\times R\ =K \\ 19\times 100=19 \\ 38\times\ 50=19 \\ 57\times\ 33\quad 19 \\ 76\times\ 25\quad 19 \end{array}$$

where P represents the excess pressure in pounds, R, the percentage saturation of the body, and K, a value determined empirically which represents the level from which rapid decompression is safe following prolonged exposure. Figure 4 illustrates graphically the principle underlying the calculations. Thus, for men with nitrogen elimination curves similar to figure 3, 50 percent saturation requires 29 minutes and 32 percent saturation 11 minutes. It would be safe, therefore, to remain at a depth of 85 feet for a period of 29 minutes and at a depth of 133 feet for 11 minutes. The results of these calculations have been confirmed for depths between 25 and 55 meters, as reported by Kagiyama (1934), whose results follow:

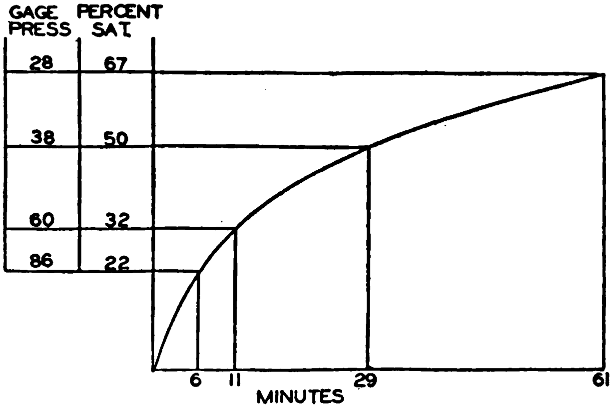

FIGURE 4.—Graphic method for calculating the duration of exposure to different gage pressures followed by immediate decompression to 0 lb. The curve is a segment adapted from A, figure 3, in which the ordinate values are expressed in terms of percentage saturation instead of cc of nitrogen.

Gage pressure	Feet	Time
36. 5	82	30
46. 8	105	20
58. 4	131	20
65. 9	148	15
73. 1	164	15
80. 2	180	10

Undoubtedly somewhat higher values for K may be used in the calculations in view of the experience of Japp (1909).

Decompression of compressed-air workers.—The stage method of decompression devised by Boycott, Damant, and Haldane (1908) for the purpose of bringing divers safely to the surface has been so extensively adopted that the term "standard" is applicable to the tables formulated by these authors. The standard practice of decompression, however, does not prevent compressed-air illness in every case when exposures at high pressures are prolonged. There is urgent need for a modification of the standard table or for a new table which will prevent this trouble. In table 5 are listed the reactions of A. R. B. which are typical of the symptoms following prolonged exposure at a pressure of 45 pounds when decompression is governed by the standard table. (See Haldane (1927) and the United States Naval Diving Manual (1924).) The pulmonary symptoms (table 5) are thought to arise from nitrogen bubbles in the pulmonary vessels, while pain in the extremities is probably the result of intravascular bubble formation in the bone marrow. The question arises, what is the cause of bubble formation under these conditions?

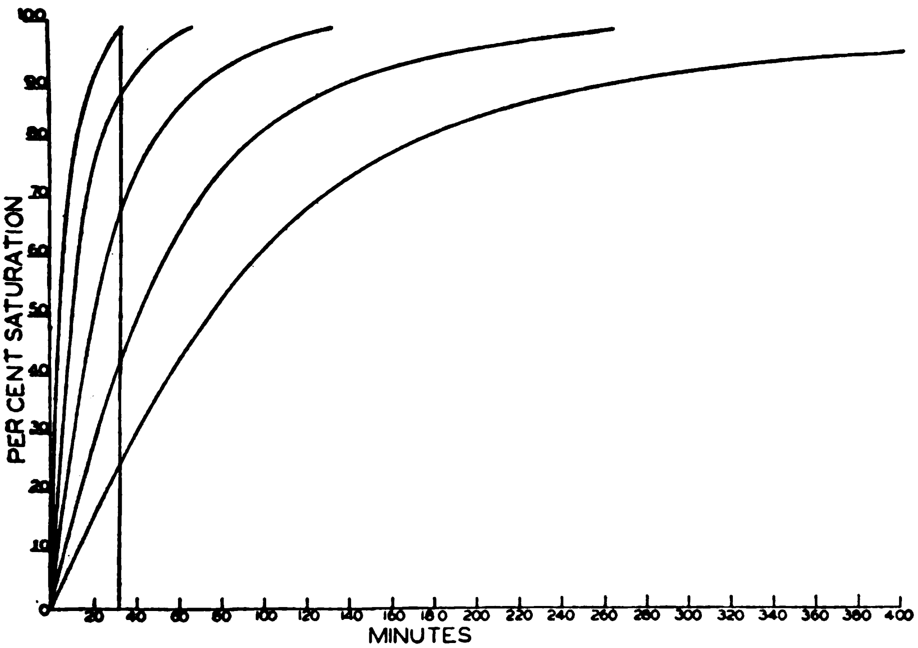

FIGURE 5.—The division of the body into 5 tissues which half saturate in 5, 10, 20, 40, and 75 minutes, respectively, is represented by the curves. This division forms the basis for calculating the standard decompression table for divers. For example, after an exposure to any gage pressure for 31 minutes the percentage saturation of each tissue is determined from the point of intersection of the perpendicular line with the curve representing the saturation of the tissue. Compare with figure 8.

The analysis of this problem requires a consideration of the correctness of the two fundamental assumptions upon which the standard table is based, namely, that about 4 hours are required for that part of the body with the lowest rate of nitrogen elimination to give up 94 percent of its nitrogen, and that the absolute pressure in the most rapidly saturating part of the body can be immediately halved. In the calculations of the standard table the body is arbitrarily divided into five tissues which half-saturate in 5, 10, 20, 40, and 75 minutes, respectively, as shown in figure 5. For example, after a diver has been exposed to any excess pressure for 31 minutes, the percentage saturation of each of the five tissues would be computed from the points of intersection where the line perpendicular to the abscissa crosses the curves. During the first stage of decompression the air pressure is abruptly decreased until a ratio of 2 to 1 exists between the absolute pressure in the most rapidly saturating tissue and the absolute pressure in the lungs. Subsequent decompression is then carried out in slower stages so that the 2 to 1 or 2.3 to 1 ratio is not exceeded in any of the five tissues.

Decompression on this arbitrary basis does not take into consideration the diffusion of nitrogen from a high pressure level in the rapidly saturating tissues to a low pressure level represented by the slowly saturating tissues, or actually from the body fluids into the body fat. Decompression, therefore, may be unnecessarily prolonged following short exposures in compressed air. This, however, is not an adverse criticism since the wide margin of safety has prevented diving accidents following the usual time limits of exposure to excess pressures. The division of the body into five tissues forms a comprehensive classification, and in part receives experimental confirmation from the fact that the rate of change in the slope of the nitrogen elimination curve progressively diminishes as shown by the *k* values in table 3, columns 8 and 17. Moreover, the assumption that the slowest desaturating tissue in figure 5 gives up 50 percent of its excess nitrogen in 75 minutes (94 percent in 4 hours, and about 97 percent in 7 hours) is supported by the experimental finding that the body as a whole is 98.2 percent desaturated in 6 hours. It is indeed remarkable that the quantitative data have so precisely confirmed the brilliant analysis of Boycott, Damant, and Haldane with respect to the desaturation time for that part of the body with the lowest rate of nitrogen elimination.[1] It is therefore unlikely that compressed-air illness following long exposures to high pressures results from an underestimation of the time required for nitrogen elimination.

With regard to the second assumption it would appear that the safety with which the absolute pressure can be halved depends entirely upon the degree of saturation of the body as a whole when decompression starts. Figure 6 represents the first stages of decompression after a dive has been made to a depth of 100 feet. The curve is adapted from A, figure 3, and shows the manner in which the body as a whole comes into equilibrium with a gage pressure corresponding to a depth of 100 feet. The first stop, for example, in decompression according to the standard method after an exposure of 15 minutes to a depth of 100 feet is at a depth of 20 feet and corresponds to approximately one-half the absolute pressure in the most rapidly saturating tissue in the classification of figure 5. From 15 to 60 minutes the first stop is at 30 feet, and after the first hour at 40 feet. It will be observed that as the time of exposure increases, the degree of saturation, and consequently, the average nitrogen pressure in the body also increases so that the difference between the pressure in the body and the lungs at the first stop becomes progressively greater.

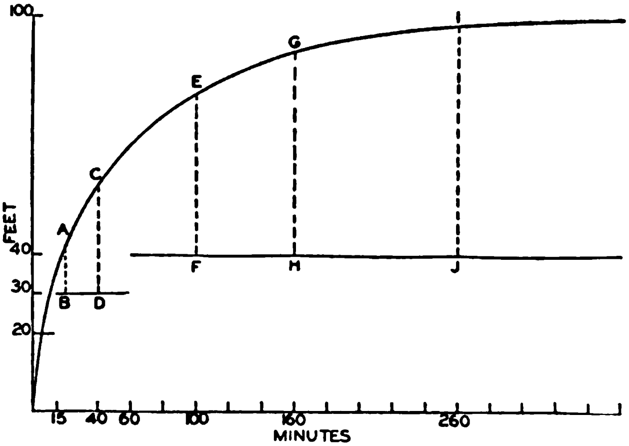

Figure 6.—The curve is adapted from A, figure 3, and represents the rate at which the pressure in the body approaches equilibrium with the gage pressure corresponding to a depth of 100 feet. The relative difference in pressure at the first state in decompression (standard procedure) between the body and the lungs is represented by the broken lines for corresponding periods of exposure.

Thus, while a difference in pressure represented by A–B or C–D may be safe, the difference in pressure E–F or G–H may result in bubble formation especially if such pressure is maintained for a considerable period of time. The proof that the absolute pressure can be safely halved is not demonstrable by short exposures up to 20 or 30 minutes since during so short an exposure the body is only partly saturated with the fat containing less nitrogen than the water, and on decompression, diffusion of nitrogen will take place into the unsaturated fat as well as to the air. Tests for the validity of the assumption that the absolute pressure can be abruptly halved must therefore be made after the nitrogen tension in the body has come into equilibrium with the nitrogen tension in the lungs.

It should be stressed that the rapid decrease in pressure from 2.3 atmospheres absolute, or even 2.8 atmospheres (Japp, 1909) to 1 atmosphere without the development of serious symptoms of compressed-air illness does not mean that the same difference in pressure can be maintained for prolonged periods of time during decompression from higher pressure levels. The bubbles of nitrogen which might be tolerated by the body after rapid decompression from 2 to 1 atmospheres would lead to serious symptoms when formed after immediate reduction of the pressure from 6 to 3 atmospheres. This is due to the fact that nitrogen bubble formation retards the elimination of nitrogen from the blood since the nitrogen tension in a bubble is only slightly higher than the nitrogen tension in the lungs (Behnke and Shaw, 1935). As a result the nitrogen from the tissues accumulates in the blood stream in bubble form instead of being eliminated into the lungs. The seriousness of bubble formation is, therefore, proportional to the pressure head of nitrogen in the tissues at the time of bubble development.

Even under ideal conditions the supersaturated state of gases in liquids is extremely unstable and bubble formation consequently unpredictable. Any assumption that the blood in a state of continual motion or any other part of the body can hold nitrogen in supersaturation at a ratio of 2 to 1 in atmospheres absolute for prolonged periods of time should be subjected to rigid tests. In the meantime, it would appear advisable to produce in diving a constant difference in pressure expressed in pounds per square inch (10 to 15) between the average nitrogen tension in the body as determined from figure 3 or from similar curves, and the tension in the lungs. While a difference in nitrogen pressure between 10 and 15 pounds (represented by an air-pressure difference of 12 to 19 pounds) may appear too low particularly in the early stages of decompression, too much stress cannot be laid on the necessity of avoiding bubble formation when a high pressure head of nitrogen is present in the tissues. A low difference in pressure in the early part of decompression allows a necessary wide margin of safety, since, if subsequent decompression is too rapid, a considerable part of the body nitrogen will have been eliminated before bubbles form.

Decompression according to the New York State regulations.—As a result of 1,360,000 decompressions up to 1822 (Levy, 1922) and over 3,000,000 at the present time attended by a negligible number of accidents (6 cases per 100,000 decompressions), the decompression schedule of New York State serves as an excellent criterion for the evaluation of conclusions drawn from laboratory results. This schedule differs from that of the standard diving table in that the gage and not the absolute pressure is halved rapidly during the first stage of decompression and then more slowly at a uniform rate during the remainder of decompression. The duration of exposure, moreover, to excess pressures from 22 to 50 pounds is so reduced that when the gage pressure is halved a fairly constant difference not exceeding 13 pounds exists between the nitrogen tension in the body and the nitrogen tension in the lungs. In figure 7 (an adaptation of curve A, fig. 3), for example, at a gage pressure (F) of 22 pounds the first work-shift lasts 4 hours during which time the body becomes 97 percent saturated with excess nitrogen. When the gage pressure is rapidly halved in the first stage of decompression a difference (F′) of 10.3 pounds exists between the nitrogen tension in the body and in the lungs. It is observed that as the gage pressure is increased (E, D, C, B, and A) the work-shift is decreased so that the difference in pressure in pounds at the first stop (E′, D′, C′, B′, and A′) remains about the same or decreases. It is believed that this comparatively low difference in pressure between the nitrogen tension in the body and in the lungs is an important factor in preventing compressed-air illness.

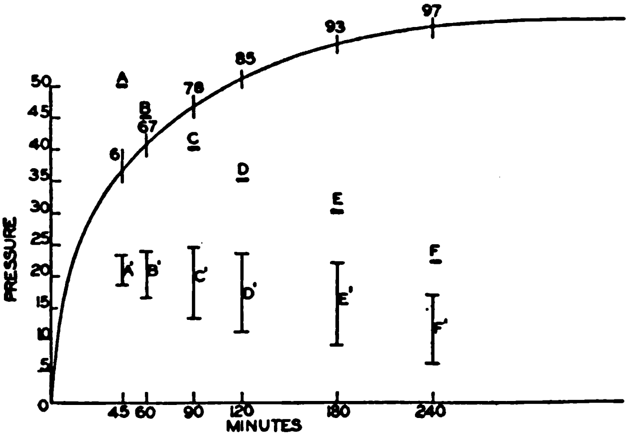

FIGURE 7.—The figures on the curve (adapted from A, figure 3) represent the percentage saturation of the body with excess pressure (A, B, C, D, E, and F) for corresponding work shifts (45, 60, 90, 120, 180, and 240 minutes) governed by the New York State regulations. A′, B′, C′, D′, E′, and F′ represent the relative differences in pressure between body and lungs at the first stage in decompression. Compare with figure 6.

Proposed method of decompression.—In the formulation of a decompression schedule from the laboratory data, the body is regarded not as five tissues with varying nitrogen tensions but essentially as a unit composed of fat and water in which the process of diffusion from water into fat or vice versa tends to equalize the nitrogen tension during saturation and desaturation. The nitrogen elimination curve, figure 3 and reproduced in figure 8 with the ordinate values changed to read in terms of percentage saturation, serves as the basis for the calculation of a decompression table for lean, well-developed men.

Decompression can be conveniently divided into two stages. During the first stage the pressure is lowered rapidly (15 pounds per minute) until a designated difference is created between the average nitrogen tension in the body and the nitrogen tension in the lungs. During the second stage the gage pressure is lowered at a uniform rate so that this pressure difference is maintained at a constant value during the remainder of decompression.

The average nitrogen tension in the body is calculated by multiplying the percentage saturation by the partial pressure of nitrogen corresponding with the gage pressure. For example, after complete saturation during an exposure to a gage pressure of 100 pounds, the average nitrogen tension is (0.79×100) 79 pounds. After incomplete saturation, say 53 percent (31-minute exposure), the average nitrogen tension is (0.53×79) 41.8 pounds. Partial saturation at a high pressure is regarded as equivalent to complete saturation at a lower pressure. Thus, the same curve (B, fig. 8; B is adapted from curve A by reducing the ordinate values of A 47 percent) represents nitrogen elimination, when the pressure is dropped to 1 atmosphere, following either complete saturation with nitrogen at a pressure of 41.8 pounds, or 53 percent saturation at a pressure of 79 pounds. The basis for this concept is the experimental finding that the slope of the lines A, B, and C representing nitrogen elimination after different degrees of saturation (fig. 2) is the same for corresponding periods of time.

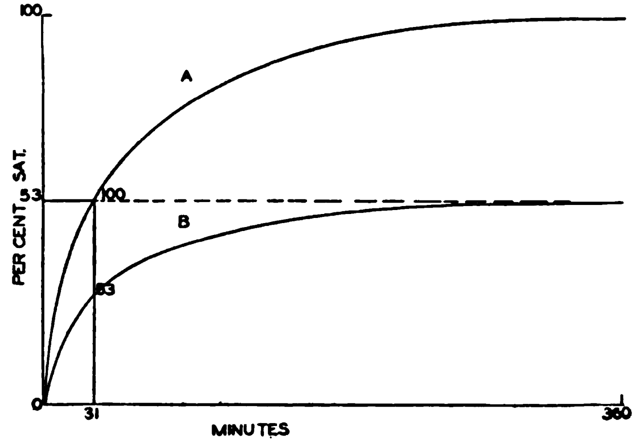

FIGURE 8.—Illustrates the proposed method of calculation for decompression of divers. After a dive of 31 minutes, for example, the percentage saturation of the body is 53 as shown on curve A (adapted from A, figure 3). If the gage pressure were lowered to 0 lb., the excess nitrogen would be eliminated according to curve B, the ordinates of which lie along the line perpendicular to the abscissa at 31 minutes. Compare with figure 5.

The safe difference in nitrogen tension that can be maintained between the body and the lungs during decompression depends upon the degree that nitrogen can be held in supersaturation by the blood and other tissues of the body. For the present this value must be estimated from empirical data with the provision that it may be modified as a result of diving or other tests. If rapid decompression from 19 to 0 pounds is safe (Haldane, 1927) then a difference in nitrogen tension between the body and lungs of (0.79×19) 15 pounds will certainly be safe at any pressure level. From the analysis of the New York State Regulations a difference in nitrogen pressure of 10 pounds (air pressure 12.5 pounds) may be regarded as a probable minimum for maintenance during decompression. The probable value, therefore, which will not unduly delay decompression or produce bubble formation, lies between 10 and 15 pounds (12 to 19 pounds air pressure).

The rate at which the nitrogen tension in the body will decrease with a given difference in pressure between body and lungs depends upon the slope of the nitrogen elimination curve. The rate of decrease (k) diminishes during the progressive desaturation of the body as shown by the values in columns 9 and 18, table 3. For example, during the first 6 minutes the body eliminates an average of 4 percent per minute of the excess nitrogen. Over a period of 21 minutes the percentage rate decreases to 3, and over a period of 121 minutes the average percentage rate drops to 1.5. This decrease in the percentage rate of nitrogen elimination is undoubtedly due to the presence of tissues which have a poor blood supply in relation to their nitrogen content. In this respect the important tissues that particularly concern us are the bone marrow and the spinal cord. Bubble formation in the bone marrow probably gives rise to "bends" while bubble formation in the spinal cord certainly is responsible for the paralysis of compressed-air illness. These tissues with their high nitrogen capacities (table 1) are enclosed in bone thus preventing the free diffusion of nitrogen into contiguous tissues, and are consequently dependent for their nitrogen absorption or elimination on their blood supply which is relatively poor. The concept that partial saturation at a high pressure is equivalent to complete saturation at a lower pressure is accordingly modified by excepting the spinal cord and the bone marrow. Allowance will be made for the desaturation of these tissues by selecting from the nitrogen elimination curve the average percentage rate for the period of time corresponding to the duration of exposure to excess pressure. Thus, after a dive of 21 minutes duration, a rate of 3 percent per minute is selected as the rate of excess nitrogen elimination. It is observed that as the duration of exposure increases, the percentage rate selected for nitrogen elimination decreases—a decrease which is arbitrarily employed in order to prevent bubble formation in the spinal cord and bone marrow.

The following example will illustrate the method of calculating decompression time. Since the partial pressure of nitrogen is 79 percent of the gage pressure, no error will result if we speak in terms of gage pressure, and the calculations will be simplified.

Example: A diver is exposed to a pressure of 100 pounds gage for a period of 21 minutes.

(1) Percentage saturation of the body from figure 3 and table 6........ 45
(2) Air pressure in the lungs........pounds.. 100
(3) Average pressure in the body (0.45×100)........pounds.. 45
(4) With a difference in pressure of 15 pounds between the body and the lungs, decompression must relieve (45–15)........pounds.. 30
(5) With a constant difference in pressure of 15 pounds the pressure in the body will decrease at the rate (table 6) of (0.03×15) 0.45 pound per minute.
(6) Time required for the second stage of decompression $\frac{(30)}{0.45}$..minutes.. 67
(7) During the first stage in decompression the gage pressure is lowered over a period of 5 minutes to 30 pounds at a uniform rate.
(8) During the second stage in decompression the pressure is lowered at the rate of 0.45 pound per minute from 30 to 0 pounds.
Total time for decompression (67+5)........minutes.. 72

The data for calculating a decompression table applicable to men with nitrogen elimination curves similar to figure 3 are presented in table 6. In comparison with the standard table these computations will shorten the decompression time for short exposures, and will lengthen the early part of decompression after long exposures. The difference in the method of calculation between the proposed and the standard method for the first stage of decompression is shown graphically by figures 5 and 8. The advantage of the proposed method lies chiefly in the fact that a decompression table can be formulated for the individual or for a group of men of similar build on the basis of previously determined curves representing actual nitrogen elimination from the body. In the experimental diving unit in the Washington Navy Yard, it is possible to obtain a nitrogen elimination curve similar to figure 3 on every first-class diver, and to make quantitative measurements of nitrogen elimination in many of the diving tests. Such procedures should result in more rapid progress as a result of a better understanding of the physiologic principles underlying work in compressed air.

The interpretation placed upon the quantitative data in this paper should not be regarded as rigid or final, and any conclusions are subject to modification or revision as a result of diving tests. The data in table 6 may serve then as an outline for experimental diving work. That the standard table can be shortened with reference to decompression time for short exposures is indicated by the modification of the table as reported by Kagiyama (1934) and by Hawkins, Shilling, and Hansen (1935). Whether the proposed method of decompression will prevent compressed-air illness after long exposures remains to be proved.

SUMMARY

The results of measurements of nitrogen elimination in man are presented, and their application to the problem of decompressing divers is discussed.

Although decompression governed by the standard procedure is safe for short exposures in compressed air, decompression after prolonged exposures (over 75 minutes) may be followed by compressed-air illness. In an analysis of this problem it was concluded that the practice of abruptly halving the absolute pressure and the comparatively rapid lowering of pressure in the early part of decompression might result in nitrogen bubble formation.

The retardation of nitrogen elimination from the body when bubbles are present in the blood was pointed out, and the danger of this condition while the pressure head of nitrogen in the tissues is high, was emphasized.

The proposed method of decompression is based on the use of a single curve which represents the rate and quantity of nitrogen eliminated from the body as a whole. To minimize the possibility of bubble formation in the early part of decompression the practice was suggested of maintaining a constant relative difference (i. e., air pressure of 12 to 19 pounds, nitrogen pressure of 10 to 15 pounds) between the pressure in the body and the pressure in the lungs.

The adoption of the proposed method of decompression in comparison with the standard procedure will shorten the time for short exposures in compressed air and lengthen the early stages of decompression after prolonged exposures to excess pressures.

The author wishes to express his thanks and appreciation to Profs. Cecil K. Drinker and Louis A. Shaw under whose direction this research was conducted. For technical assistance the writer is indebted to Miss Anne C. Messer, Mr. Robert M. Thomson, and to Mr. E. Preble Motley.

TABLE 1.—*The percentage of water and fat, and the nitrogen content of the whole body, the brain, the spinal cord, and the bone marrow of the dog*

	Percentage of fat	Percentage of water	Nitrogen content, cc per 100 g
Body as a whole	15.4	59	1.4
Brain	4.8	[1] 70	.94
Spinal cord	27.8	[1] 70	2.20
Bone marrow	[1] 90.0	----------	5.00

[1] Estimated.

TABLE 2.—*Relationship between the body weight, height, age, surface area, and the nitrogen content*

Subject	Weight (kilos)	Height (inches)	Age (years)	Surface area (square miles)	Total nitrogen (cc)	Cc per kilo
B. I. L.	62.3	69	28	1.75	[1] 786	12.6
M. U. R.	62.7	67	27	1.71	[1] 770	12.3
F. A. H.	67.7	67	33	1.77	[1] 1,002	14.8
B. U. R.	60.0	63	32	1.62	[2] 761	12.7
R. O. M.	56.4	63	30	1.57	[2] 776	13.8
T. H. O.	65.0	68	33	1.77	[2] 799	12.3
N. O. R.	76.4	71	22	1.95	[2] 1,426	18.7

[1] Nitrogen eliminated at the end of 6 hours. Oxygen percentage at the end of the experiment above 99. First minute of nitrogen elimination (rinsing period) calculated by multiplying the cardiac output by the solubility coefficient of nitrogen in blood.

[2] Nitrogen eliminated at the end of 4 hours. Oxygen percentage at the end of the experiment between 97 and 97.5. First 5 minutes of nitrogen elimination (rinsing period) calculated on the basis of subsequent experimental values.

TABLE 3.—*Nitrogen elimination during the breathing of pure oxygen at atmospheric pressure*

Minutes	B. L. L. (1 exposure)		M. U. R. (2 exposures)		F. A. H. (1 exposure)		Average percent of total	K
	Cc	Percent of total	Cc	Percent of total	Cc	Percent of total		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
5[1][2]	155	19	173	22.4	239	24	22	0.04
11	264	34	236	30.6	-------	-------	32	.035
21	366	46.6	317	41.0	474	47	45	.030
31	442	56.0	376	49.0	548	55	53	.024
41	486	62.0	425	55.0	-------	-------	59	.021
61	552	70.0	501	65.0	673	67	67	.018
91	624	79.0	593	77.0	-------	-------	78	.017
121	671	85.4	656	85.0	845	85	85	.015
181	740	94.0	707	92.0	899	90	93	.019
241	743	94.5	753	98.0	996	99	97	.015
301	751	95.5	770	100.0	1,002	100	99	.014
361	786	-------	765	-------	998	-------	-------	-------

Minutes	B. U. R. (7 exposures)		R. O. M. (8 exposures)		T. H. O. (6 exposures)		Average percent of total	K
	Cc	Percent of total [3]	Cc	Percent of total [3]	Cc	Percent of total [3]		
(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
5[1][2]	187	23	142	18	165	20	20	0.044
10	305	38	225	28	271	33	33	.040
15	374	47	284	36	349	43	42	.036
25	441	55	345	44	434	53	51	.028
45	529	66	435	55	559	68	63	.022
65	586	73	563	71	617	75	73	.020
85	606	76	609	77	662	81	78	.018
125	661	82	623	79	734	90	84	.014
185	697	87	705	89	774	95	90	.012
245	761	95	755	95	777	95	95	.012
540	-------	-------	-------	-------	-------	99	-------	.0085

[1] First minute calculated (42 cc).

[2] First 5 minutes calculated.

[3] The assumption was made that the body as a whole was 95 percent desaturated at the end of 245 minutes.

TABLE 4.—*The average of the nitrogen elimination values from 3 lean*[1] *but well-developed men who breathed oxygen at atmospheric pressure*

Time	Experimental values	Calculated values		
		Fat N_2	Water N_2	Total N_2
6 minutes	187	23	174	197
21 minutes	386	75	341	416
31 minutes	455	105	373	478
61 minutes	575	182	392	574
121 minutes	724	293	392	685
181 minutes	782	361	392	753
241 minutes	830	398	392	790
301 minutes	841	423	392	815
361 minutes	850	437	392	829

[1] Average weight 64 kilograms.

TABLE 5.—*Compressed-air illness after decompression according to the standard tables*[1] *following prolonged exposure at 45 pounds gage pressure*

Date	Exposure time (minutes)	Decompression time (minutes)	Symptoms
Feb. 13, 1933	223	122	3 hours after exposure, severe substernal irritation with deep inspiration, accompanied and aggravated by coughing. Pains in the extremities, fever, sweating, and malaise.
Feb. 28, 1933	150	122	20 minutes after exposure, intense pain in the left elbow, increased in severity and radiated between the shoulder and the hand. Fever, (1 chill), malaise.
Mar. 20, 1933	110	84	3 hours after exposure, substernal irritation, pain in the right knee and right hip.
May 15, 1933	120	84	Vigorous exercise during decompression. Immediately following decompression, pruritus and petechial rash over the chest. Fatigue particularly in the lower extremities.
May 24, 1933	90	84	Vigorous exercise during decompression. 1 hour following decompression pain in left elbow and knee. Pain in the chest on deep inspiration.
Oct. 23, 1933	120	84	Vigorous exercise at the beginning of decompression. 1 hour following decompression, deep-seated pain in the deltoid area (right arm) which radiated to the hand. Mild substernal discomfort.

[1] See Navy Diving Manual (1924), sec. X11, 3670.

TABLE 6.—*Data for the calculation of a decompression table for men with nitrogen elimination curves similar to figure 3–A*

Duration of exposure (1)	Percentage saturation of the body (2)	Percentage rate per minute of excess N_2 absorbed or eliminated $(l-e^{-k})$ [1] (3)	Rate at which the gage pressure can be lowered to maintain a constant difference in air pressure between body and lungs of—		
			12 pounds (4)	15 pounds (5)	19 pounds (6)
			Pounds per minute	*Pounds per minute*	*Pounds per minute*
21 minutes	45	3.0	0.36	0.45	0.57
31 minutes	53	2.4	.29	.36	.46
41 minutes	59	2.1	.25	.32	.40
61 minutes	67	1.8	.22	.27	.34
91 minutes	78	1.7	.20	.25	.32
121 minutes [2]	85	1.5	.18	.22	.28

[1] For values of k (see table 3) less than 0.05, k and $(l-e^{-k})$ may be considered equivalent.

[2] In excess of 2 hours the values for k in column 18, table 3, may be tentatively used. The minimum value for k can be taken as 0.0085 from the "fat" equation.

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AN ANALYSIS OF 18 SYPHILITIC REINFECTIONS

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Two hundred and fifty-eight health records in the syphilitic file at the dispensary, naval air station, Pensacola, Fla., were reviewed. Of these 18 were found to contain a distinct entry for reinfection with syphilis. The bulk of the data hereinafter to follow was derived from the now obsolete syphilitic abstracts, though each case was interviewed by the writer. For one reason or another many of these records were incomplete. Significant information was frequently not recorded. Confrontation of the patient elicited admissions in the nature of confessions that would probably not have been vouchsafed at a past more precarious time. Several patients firmly declared they had had official treatment not recorded; others were convinced the alleged reinfection was a relapse of the original infection. Pay, all important to the sailor, and time are lost because of the misconduct status imposed by venereal infection. Statements in rebuttal to syphilitic reinfection are frequent and oft absurd. Cases submitting statements in rebuttal are reviewed by competent authority and decision as to misconduct is decided by the Comptroller General. This observation is worthy of attention in deciding as to the accuracy of diagnosis in luetic reinfection. However, the records stand as