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PHYSIOLOGIC STUDIES PERTAINING TO DEEP SEA DIVING AND AVIATION, ESPECIALLY IN RELATION TO THE FAT CONTENT AND COMPOSITION OF THE BODY

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THE environment again concerns the investigator. Beginning with the studies of Paul Bert, Heller, Mager, von Schrötter, and Haldane knowledge has accumulated slowly upon the effect of high pressures on the diver and caisson worker. The investigations conducted in the physiology laboratory of the Harvard School of Public Health in collaboration with the late Louis A. Shaw, and then at the Experimental Diving Unit, Navy Yard, Washington, D. C., have served to make possible rescue and salvage operations incident to a submarine disaster.

Recently these studies have clarified some of the puzzling phenomena observed in high altitude flight. In this lecture I shall outline the physiologic factors that enable divers and aviators to work in a pressure environment of 16 atmospheres or in a rarefied medium of 0.20 of an atmosphere, respectively. Of especial interest are the quantitative studies

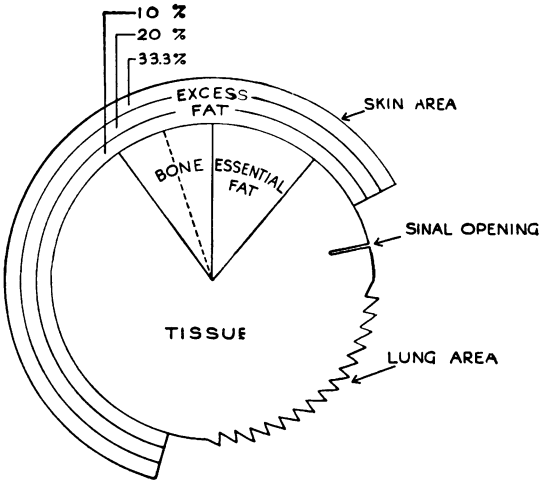

Fig. 1—Schematic representation of the body showing the volumetric relationship between the excess fat and the true body mass.

These data form the basis for the diagram—

Analysis of the true body mass, specific gravity=1.099

Substance	*Specific Gravity*	*Weight % Total mass*	*Volume % Total mass*
Bone	1.560	15	10.5
Essential Fat	0.940	10	11.7
Tissue	1.060	75	77.8

The addition of excess fat amounting to 10 per cent of total body weight reduces the specific gravity of the true body mass from 1.099 to 1.080; 20 per cent additional fat lowers the specific gravity to 1.062; and 33.3 per cent additional fat lowers the specific gravity to 1.036.

pertaining to the absorption or elimination of gaseous nitrogen which in turn have permitted estimates of fat content and composition of the body of the healthy, adult male.

With reference to the schematic diagram, Figure 1, protoplasm can be compressed or placed in a rarefied atmosphere without demonstrable effect provided that the pressure is equally distributed. Since air or other gaseous media are necessary for compression, interference with the free movement of gas, particularly in the channels leading to sinal and aural spaces, dilates blood vessels and produces hemorrhage into the occluded spaces. These painful but circumscribed effects of pressure are of minor importance, however, compared with the physiologic response brought about by the disturbance in gaseous equilibria whenever pressure fluctuates.

I. The Major Effects of High Barometric Pressure

1. *Nitrogen Narcosis.*—As the pressure is raised in an air atmosphere the ambient gases are absorbed by the circulating blood and transported to the other tissues of the body. Apart from the possible difficulty in opening the normally closed auditory tubes, it is perceived that as the air is warmed by the heat of compression, its increased weight calls forth greater respiratory effort which may interfere temporarily with the normal elimination of carbon dioxide. The outstanding phenomenon is that the previously normal individual loses his ability to function efficiently.[1,2]

Thus, the individual subjected to a pressure of 4 atmospheres, equivalent to a diving depth of 100 feet, begins to experience symptoms not unlike those elicited by altitude anoxia or alcoholic intoxication. Experienced divers, for example, are able to estimate diving depth within a range of 25 feet "by the way they feel." This feeling manifests itself as an impairment in neuromuscular coördination as well as a slowness and unreliability in cerebration. Essentially greater effort is required to perform work.

The agent responsible for the narcosis is "atmospheric nitrogen" including argon. When pure oxygen instead of air was breathed at a depth of 100 feet, the retardation, at least for short periods of time and prior to the onset of the symptoms of oxygen poisoning, was minimized. The employment of helium, moreover, to replace atmospheric nitrogen abolished or rendered negligible the adverse effect and proved that a rather ideal atmosphere could be created compatible with efficient work at depths up to 500 feet, and at a pressure not supporting consciousness were air breathed. By contrast, when argon was substituted for atmospheric nitrogen, the inhaled mixture at high pressures elicited reactions similar in type but more intense than those manifest in compressed air. Elementary gases, therefore, that are wholly innocuous at normal pressures may render an individual completely helpless in a high pressure atmosphere.

The explanation of the action of nitrogen and argon is to be sought in some physical property since argon does not possess valence and hence like helium, is incapable of entering into any stable chemical combination. Of the obvious physical properties solubility in oil and molecular weight may be important.

TABLE I

ARGON, HELIUM, NITROGEN, AND OXYGEN SOLUBILITY IN WATER AND IN OLIVE OIL AT 38° C., AND THE RESPECTIVE OIL WATER SOLUBILITY RATIOS

Water			
Argon	Helium	Nitrogen	Oxygen*
0.0262	0.0087	0.0127	0.023
Olive Oil			
Argon	Helium	Nitrogen	Oxygen
0.1395	0.0148	0.0667	0.112
Oil Water Solubility Ratios			
Argon	Nitrogen	Helium	Oxygen
5.32: 1	5.24: 1	1.7: 1	4.9: 1

* Sendroy, J., Jr., Dillon, R. T. and Van Slyke, D. D. *J. Biol. Chem.*, 1934, *105*:597.

The data in Table I are in accord with the Meyer-Overton hypothesis relating anesthetic effectiveness to fat solubility. The consideration that the higher molecular weights of nitrogen and argon might interfere with cellular gaseous metabolism particularly with carbon dioxide diffusion and transport has not yet been supported by experimental data.

The employment of hydrogen with a solubility coefficient in oil considerably higher than that of helium, may lead to the solution of the problem, or at least to an evaluation of the role that fat solubility in comparison with molecular weight assumes in the etiology of this type of narcosis.[3]

2. *Phenomena of Oxygen Poisoning.*—The increased partial pressure of oxygen in the air at great depths, the employment of oxygen as the basis for the decompression of divers and the treatment of compressed air illness, have necessitated extensive tests of oxygen tolerance.

At a pressure of 1 atmosphere pure oxygen has been inhaled by healthy men for periods as long as 17 hours without injurious effects. On the other hand, some individuals have complained of substernal distress and irritability following the inhalation of pure oxygen for periods of 7 hours. In one individual sensitivity to oxygen was manifest by the formation of wheals, dermatographia, flushing of the face, and later by

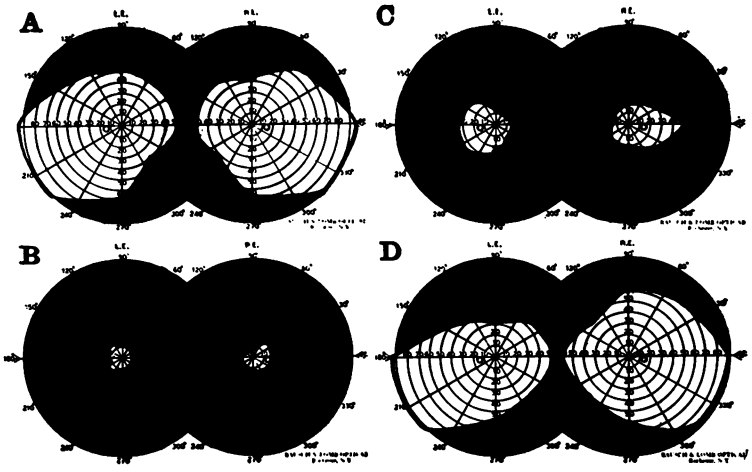

Fig. 2—Perimetric measurements made before and after 3½ hours' oxygen breathing at 3 atmospheres' pressure (30-lb. gauge). A, normal field limits; determinations made with the Ferree-Rand perimeter and exposure method with 7 foot-candles illumination. B, C, and D, field limits 5, 25, and 50 minutes, respectively, following 3½ hours' oxygen breathing; observations made at atmospheric pressure with a black perimeter of 25 cm. radius illuminated by a blue bulb placed behind and above the observer's head; moving stick stimuli were used and checked by the exposure method; test object was a white disc 6 mm. in diameter. From Behnke, Forbes, and Motley, *Am. J. Physiol.*, 1935-36, *114*:436.

the development of dermatitis. Remission of symptoms was hastened by the administration of histaminase. The action of a histamine-like substance, as postulated by Campbell,[4] explains many of the toxic symptoms associated with the inhalation of oxygen and suggests an approach to the solution of the problem.

At a pressure of 3 atmospheres the oxygen taken up by the blood in physical solution is sufficient to meet tissue requirements so that hemoglobin is not reduced.[5] Periodic waves of nausea constitute the most frequent symptom at this pressure together with the appearance of facial pallor. Progressive contraction of the visual fields terminating in a transient amblyopia has been repeatedly observed during the fourth hour of exposure.[6] Although vision is temporarily lost, a measure of consciousness is retained and recovery begins immediately upon the substitution of air for oxygen as illustrated by Figure 2.

Whenever doubt arises as to the habitability of a given environment, the decisive criterion is ability to work. An excellent test therefore of

resistance to the toxic effects of oxygen at a pressure of 3 atmospheres consists in having subjects exercise on a bicycle at a rate sufficient to increase oxygen consumption fourfold over the basal state. Test runs of this character are usually terminated after 15 to 20 minutes by extreme fatigue, numbness of the lower extremities, and in one instance by an abortive convulsive seizure. In control runs this type of exercise can be maintained without undue fatigue for a period of one hour.

In man, at a pressure of 4 atmospheres severe convulsive seizures occur after about 45 minutes of oxygen inhalation. Perhaps no other induced physiologic disturbance of comparable severity is followed by such prompt and complete functional recovery. Essentially oxygen induces transient idiopathic epilepsy in the apparently normal individual.

For periods of 27 minutes men have repeatedly inhaled oxygen at 4 atmospheres pressure with no other symptoms than a sensation of cerebral fulness and some degree of mental torpidity. Under these circumstances the excess quantity of oxygen taken up by the blood stream and held in solution in the tissues during a period of 17 minutes may augment oxygen absorption by 159 cc. per minute, a 55 per cent increase compared with the consumption during a control period. In the circulating blood of dogs exposed to 4 atmospheres pressure the oxygen in physical solution in arterial blood was 7 volumes per cent while the oxygen dissolved in the mixed venous blood was at times as high as 3.6 volumes per cent.

In the dog repeated daily seizures over a period of 21 days do not exert a detrimental effect on the well-being of the animal in that weight remains constant, appetite and muscular activity are unchanged. The tests indicate that tolerance for high oxygen pressure is developed because the exposure time necessary to produce the seizure is increased. Of particular interest are the recurrent strychnine-like seizures indicative of involvement of the spinal cord. During these attacks which are particularly apt to occur during the second diurnal exposure, the eyes turn outward, the whole body becomes rigid, the extremities spread apart, and opisthotonus supervenes. Tetanic contractions of the diaphragm stop respiration. These attacks may recur from four to twelve times per minute. The reflex excitability of the nervous system is greatly heightened since tactile, auditory, and visual stimuli serve to initiate the tetanic seizures.

Although these disturbances are severe, in view of the rapid recovery and the considerable latent period preceding onset of the symptoms, it has been possible to utilize oxygen in the prevention and treatment of compressed air illness.

3. *Field Application.*—The observations made in the laboratory soon governed field practice during diving operations in submarine disasters.

In 1939, divers breathing air at a depth of 240 feet in salvage work on the U.S.S. *Squalus*, suffered lapses of memory, mental confusion, and occasionally loss of consciousness. It proved to be not only dangerous but futile to work within a maze of hose and cables at a depth of 240 feet in an atmosphere of air.[7]

As in the laboratory, so also in the field, the substitution of helium for nitrogen rendered negligible the impairment in neuromuscular coördination and enabled divers to work efficiently when under 7 atmospheres of pressure. The successful termination of the salvage operations was made possible only by the employment of helium.

In 1940 a second submarine disaster occurred in water 440 feet deep. Although the pressure at this depth was sufficient to crush the hull of the disabled craft, divers breathing a mixture of helium and oxygen reached the bottom and were able to survey the sunken vessel. These divers, in spite of subjection to a pressure of 14 atmospheres, felt well and had little difficulty in performing the work required in descent and ascent to a depth corresponding closely to the height of the Washington monument.

II. Manner of Absorption or Elimination of Inert Gas

1. *Animal Experiments.*—The basic consideration concerned with existence in an abnormal pressure environment is the absorption and subsequent removal of inert gas. In this connection all of the gaseous nitrogen appears to be dissolved in fluids and fat in the ratio of 1 to 5 except for a small additional amount due to the presence of hemoglobin in solution. This molecular nitrogen can be removed from the tissues and measured if the body is placed in an oxygen atmosphere. Knowing the volume of the system and taking periodic samples it is not difficult to ascertain the quantity of nitrogen originally present in the tissues.

Dogs anesthetized by the injection of a suitable drug serve well for such experiments. If the first 7 minutes of an experiment be utilized to

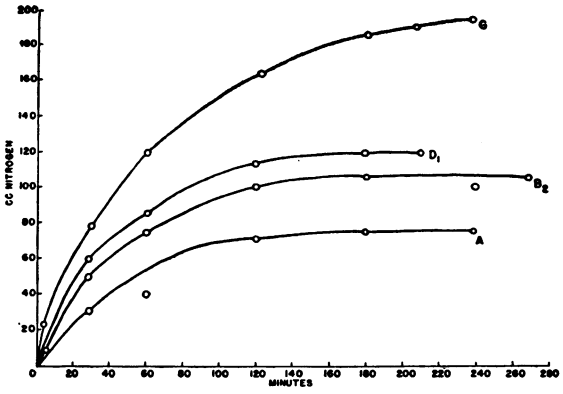

Fig. 3—Nitrogen elimination from 4 dogs placed in an oxygen atmosphere at normal pressure. During the first 7 minutes of oxygen inhalation the lungs and apparatus were rinsed free from nitrogen. (From Shaw, Behnke, Messer, Thomson, and Motley, *Am. J. Physiol.*, 1935, *112*:545.)

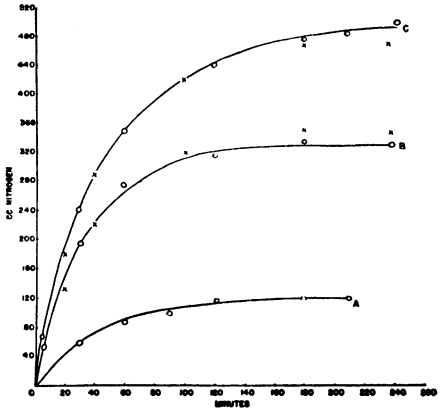

Fig. 4—The nitrogen elimination of dog "D" following equilibrium exposures in air at 1, 3, and 4 atmospheres of pressure. The nitrogen eliminated during the first 8 minutes of oxygen inhalation was not collected. Curve A, desaturation from 1 atmosphere; curve B, desaturation from 3 atmospheres; curve C, desaturation from 4 atmospheres. O, experimental values; ×, theoretical values. (From Shaw, Behnke, Messer, Thomson, and Motley, *Am. J. Physiol.*, 1935, *112*:545.)

rinse the lungs and apparatus free from nitrogen, then during a subsequent period of 3 to 4 hours the dog's body becomes nitrogen free.[8] Figure 3 represents a number of nitrogen elimination curves obtained on several dogs subjected to such a procedure at normal barometric

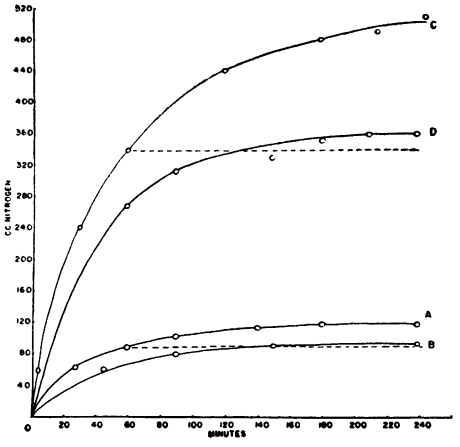

Fig. 5—Saturation time compared with desaturation time. Dog "D." The nitrogen eliminated during the first 7 minutes of oxygen inhalation was not collected. Curve A, follows complete saturation at 1 atmosphere; curve B, follows 67 minutes' saturation at 1 atmosphere; curve C, follows complete saturation at 4 atmospheres; curve D, follows 67 minutes' saturation at 4 atmospheres. (From Shaw, Behnke, Messer, Thomson, and Motley, *Am. J. Physiol.*, 1935, *112*:545.)

pressure. The fact that dog "G" was fat and dog "A" was lean is reflected by the large difference in the nitrogen content of the dogs in proportion to body weight.

If the dog is now placed in compressed air until saturation with ambient nitrogen has been attained, the nitrogen absorbed can be collected in the manner previously described. From a series of exposures in compressed air, utilizing the same dog "D," it was observed from the plotted data of Figure 4 that the amounts of nitrogen recovered following decompression from 3 and 4 atmospheres respectively, were proportional to the pressure. These results are in accord with Henry's law.

In another series of tests the rate of nitrogen absorption was compared with that of nitrogen elimination. Dog "D" was first rendered completely nitrogen free in the manner represented by curve A, Figure 5. For a period of 60 minutes the dog breathed air and following the air inhalation it was again placed in an atmosphere of oxygen. The amount of nitrogen absorbed during the 60-minute period of air inhalation, curve B, Figure 5, is equal to the quantity originally eliminated during the same period of time.

The same type of experiment was repeated at a pressure of 4 atmos-

pheres and again it was demonstrated that within the limits of experimental error, the manner of nitrogen transport is the same either to or from tissues.

Gaseous Nitrogen in Relation to Fluid and Fat Content of the Body.—If the body of dog "D" be subjected to analysis for the quantity of water, fat, and solid constituents, these values are obtained, body weight = 12.234 K., weight of fat* = 1.889 K., weight of dry solids = 3.117 K., weight of water (by difference) = 7.228 K. If these weights are multiplied by the appropriate solubility coefficients, the total nitrogen content of the body can be computed. Corrected for a pressure of 570 mm., for the density of fat, and for the decreased solubility of gas in body fluids when other dissolved substances such as salts are present, the coefficients adapted from Table I, are 52 cc.** per kilo of fat and 9 cc.† per kilo of fluid.

The nitrogen dissolved in the fat therefore is equal to 1.89×52, or 98 cc., and in fluids, 7.23×9, or 65 cc. The total nitrogen is 163 cc. or 1.3 cc. per kilo of body weight.

The quantity of nitrogen recovered from dog "D" was 124 cc. The difference between 163 and 124 cc. represents the estimated quantity of nitrogen given up during the first 7 minutes or rinsing period, and is in agreement with values based upon extrapolation of the experimental curve, that is 30 ± 5 per cent of the body total.

In practice, in order to avoid the use of extrapolated values, the quantity of nitrogen for the 7-minute period is taken as equal to the measured quantity obtained from the seventh to the twentieth minute as shown in columns 5 and 6, Table II.

The total nitrogen content of the body as measured by our technique, is distributed between fluid and lipid constituents of tissues.

Estimation of the Fat Content of the Body on the Basis of Measurements of Nitrogen Elimination.—In laboratory studies of gas absorption or elimination, it is of great importance to obtain an accurate estimate of the fat content of the body. From the discussion in the previous paragraph it is apparent this estimate can be made on the basis of meas-

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* Substances soluble in carbon tetrachloride.

** In the original paper a value of 55.7 cc. was used on the basis of analysis of omental dog fat. In all subsequent analyses we have used olive oil as a more convenient solvent since it has an absorbing capacity similar to that of body fat for nitrogen.

† In the original paper the value of 9.54 was used as the nitrogen solubility coefficient in water. It is more appropriate for body fluids, however, to use a coefficient approaching the solubility of nitrogen in serum. In urine analyses there is a decrease of 0.01 volume per cent of nitrogen for every two units increase in specific gravity. The value of 9 is closer to the true value than 9.54.

TABLE II

ESTIMATION OF THE FAT CONTENT OF THE DOG'S BODY ON THE BASIS OF THE MEASUREMENTS OF THE NITROGEN DISSOLVED IN THE TISSUES

Dog	*Weight* (1)	*Weight of fluids* (60% *body wt.*) (2)	*Nitrogen capacity of fluids* (3)	*Nitrogen capacity of fat* (4)	Total nitrogen capacity of body			*Weight of fat* (8)	*Weight of excess fat* (9)	*True body weight* (10)	*Fluid percentage of true body weight* (11)
					0-7′ (5)	7′-20′ (6)	Total (7)				
	kilos	*kilos*	*cc.*	*cc.*				*kilos*	*kilos*	*kilos*	
"D" lean	12.23	7.23	65	98	39	39	163	1.89	0.70	11.5	62
"A" very lean	8.8	5.28	48(+3)*	50(—3)	24	24	98	0.96	0.09	8.71	61
"B-2" lean	11.3	6.78	61	81	38	38	142	1.56	0.48	10.8	63
"D-1" lean	11.9	7.14	64	104	50	50	168	2 00	0.90	11.0	64
"G" fat	13.8	8.28	75(—5)*	183(+5)	65	65	258	3.52	2.38	11.4	71

* Optional correction to make fluid percentage of the true body weight a constant value of 63.

urement of nitrogen recovered from tissues and a knowledge of the water content of the body. The variability, however, in the amount of fat in different individuals renders invalid the employment of fixed percentages to denote the relative amounts of such body constituents as water.

This difficulty can be overcome by dividing the fat into an essential portion comprising such substances as myelin in the spinal cord, fat in bone marrow, lecithin, cholesterol and other lipid or lipoid matter essential in body economy, and a portion consisting of excess adipose tissue.

If one considers then that there is a basic body structure exclusive of excess fat as constant in composition as blood, which constitutes the true body weight, this weight can be divided into the following relatively fixed percentages: for the dog, water=63, solid substances=27, and essential lipids=10; for man, reflecting in part the difference in integument, water=66, solid substance=24, and essential lipids=10.

For the percentage of water in the body a tentative value of 60 may be used based on the analysis of dog "D."

The true body weights then of a series of dogs as well as the amounts of excess fat can be computed in the following manner using the data from dog "D" as an example:

Body weight—$12.23 \times 60 = 7.23$ weight of fluids.

$7.23 \times 9 = 65$ cc. nitrogen in the fluids.

$163 - 65 = 98$ cc. nitrogen dissolved in fat.

$98 \div 52 = 1.89$ kilos, weight of body fat.

$10/9\ (12.23 - 1.89) = 11.5$, true body weight.

$189 - 0.10\ (11.5) = 0.70$, excess fat.

$7.23 \div 11.5 \times 100 = 63$, percentage of water in true body weight.

The analytical data for the series of dogs are presented in Table II.

An initial value for water content of 60 per cent of the gross body weight may require some correction if the percentage of fluids in relation to true body weight is to be maintained at 63. With reference to dog "G," for example, a value of 60 per cent of total body weight for water content results in a final percentage of water of 71 in the true body weight, column 11 (Table II). Having determined the gross amount of body fat, it is not difficult to make the minor corrections in the division of nitrogen so that the water percentage in relation

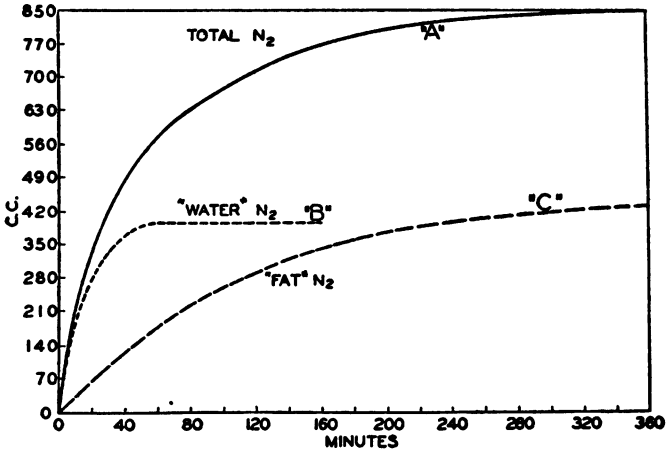

Fig. 6—Total N_2, A, represents the average of the values for nitrogen elimination from 3 men (average weight 64 k) who breathed pure oxygen at atmospheric pressure. "Water" N_2 (B) and "Fat" N_2 (C) are hypothetical curves showing the absorption or elimination of nitrogen by the body solvents. The values for nitrogen on A are approximately the sum of corresponding values on B and C. (From Behnke, *U. S. Nav. M. Bull.*, 1937, *35*:219.)

to true body weight is 63. The large difference between the solubility coefficients of nitrogen in water and in fat permit this correction without invalidating the estimate for fat. Of primary interest is the method of analysis rather than the attempt to maintain any given, fixed percentages in the calculations.

2. *Measurements in Man.*—If a human subject is placed in an enlarged oxygen recirculating system similar to that devised for the dog,[10] the gaseous nitrogen can also be removed from the tissues. Figure 6 shows the manner in which nitrogen is eliminated by lean men of comparatively small stature, average weight 64.2 kilos, if 99 per cent oxygen is inhaled for a period of 6 hours. It is observed that the rate of nitrogen output is about one-half of the corresponding rate for the dog, an anticipated finding in view of the comparative circulatory rates in relation to body weight.

If blood flow throughout the body were distributed uniformly with respect to the nitrogen content of tissues, the values of curve A could be derived from an exponential equation of the form $-Y = (1-e^{-kt})$ which expresses the relationship that a constant percentage of the nitro-

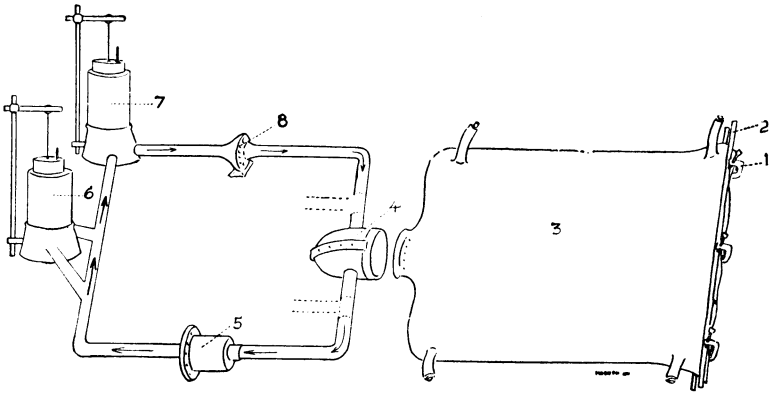

Fig. 7—Diagram of apparatus used to measure gas eliminated from the lungs and gas diffusing through the skin.

1, clamp on iron bars; 2, used to seal open end of rubber bag; 3, designed to fit around the body serving as a gas-tight seal; 4, rubber helmet and collar secured with adhesive tape around the subject's neck; 5, canister with absorbent for water and CO_2 cooled with ice; 6, spirometer for measuring added oxygen; 7, spirometer; 8, fan to circulate oxygen, bearing encased in oil to exclude air. Dotted lines indicate connections to a second similar system. (From Behnke and Willmon, *Am. J. Physiol.*, 1940-41, *131:* 627.)

gen present in the body is being eliminated throughout the entire period of oxygen inhalation. 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 is the base of the natural logarithms. The expression, $1-e^{-kt}$, gives the percentage decrease of nitrogen in the body during the time interval, t.

If the experimental values plotted on curve A, Figure 6, be substituted in the equation, the value for k is found to decrease progressively; a decrease that indicates that blood flow is not distributed uniformly in relation to the nitrogen content of tissues particularly in relation to fat which has a high nitrogen capacity and a poor blood supply. Thus, at the start of oxygen inhalation the average nitrogen pressure in the blood tends to fall below the nitrogen pressure in the fatty tissues which desaturate slowly. Consequently, the percentage rate of nitrogen elimination decreases.

However, if the total nitrogen content of the body is divided according to its solubility in water and in fat, then an equation can be applied similar to the one discussed in the previous paragraph but con-

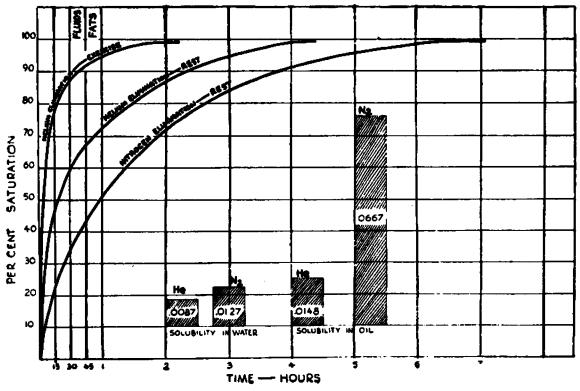

Fig. 8—Desaturation rate for man, comparing nitrogen with helium. During the first 45 minutes, gaseous removal takes place from the body fluids, and subsequently from the body fat. The solubility coefficients for helium and nitrogen are expressed as cubic centimeters of gas, reduced to standard conditions, dissolved per cubic centimeter of solvent, temperature 38° C.

sisting of two component parts, one for fat and the other for the body fluids. . . .

"Fluids" "Fat"

$$Y = 364\ (1-e^{-0.098\,t})\ \text{plus}\ 500\ (1-e^{-0.0085\,t})$$

The values for k will vary for different individuals on the basis of elimination rate and division of nitrogen between water and fat.

The previously described tests were terminated at the end of 6 hours so that the endpoint for nitrogen elimination was not known with certainty. Several years later, by means of the system outlined in Figure 7, it was possible to collect nitrogen from the tissues for periods as long as 17 hours. Table III gives the results of a test in which the subject, a diver weighing 70 kilos, breathed oxygen for a period of 15 hours. The data plotted in Figure 8 agree well with those obtained in the earlier tests if allowance is made for the difference in fat content of the subjects.

2. *Cutaneous Diffusion of Gases.*—Diffusion as a fundamental property of gases would lead one to expect some movement of gaseous molecules through skin.[11] This can be demonstrated by the arrangement, Figure 7, to permit the inhalation of oxygen in a hood while the body is surrounded by the same or an indifferent gas. In a representative ex-

TABLE III

NITROGEN ELIMINATION FOR A DEEP SEA DIVER, AGE 32, WEIGHT 154 POUNDS, HEIGHT 69 INCHES

Time	*Total eliminated*	*Nitrogen† diffusion into system*	*Net nitrogen*
min.	*cc.*		
0–5*	(150)		(150)
5–65	481	47	434
65–70‡	(25)		(25)
70–130	228	47	181
130–135‡	(12)		(12)
135–195	158	47	111
195–200‡	(7)		(7)
200–260	122	47	75
260–265‡	(5)		(5)
265–325	85	47	38
325–330‡	(2)		(2)
330–390	72	47	25
390–395‡			(–)
395–455	53	47	6
460–520	52	47	5
525–585	47	47	
			Total 1076
Body surrounded by oxygen			
595-655	46		
660–720	33		
725–785	34		
790–850	24		
Body surrounded by air			
855–905	48		

* Lung rinsing period. Estimated value of nitrogen elimination for this period.
† Diffusion of nitrogen into system includes atmospheric nitrogen diffusing through rubber tubing, helmet, spirometer water seal, and nitrogen diffusing through the skin.
‡ Represents a period of lung rinsing whenever a shift was made in spirometer systems. Nitrogen elimination values estimated for these periods.

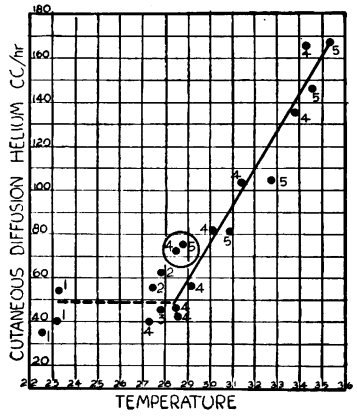

Fig. 9—Cutaneous diffusion of helium in relation to temperature, measured as cubic centimeters of helium recovered from the lungs per hour when the body is immersed in a helium atmosphere, pressure 700 mm. The numbers 1 to 5, refer to different subjects. The encircled values were obtained after the previously heated ambient helium had been cooled to 29° C. (From Behnke and Willmon, *Am. J. Physiol.*, 1940-41, *131*:627.)

periment following the prolonged inhalation of oxygen and when the body appeared to be nitrogen free, the substitution of oxygen for the ambient air in the bag brought about a sharp reduction in the quantity of nitrogen recovered from the lungs amounting to about 10 to 20 cc. per hour, Table III. This quantity of nitrogen, however, is only one-third to one-fifth the amount that one would expect to recover were diffusion sufficiently rapid to establish equality between the pressure of ambient nitrogen and its pressure in the skin and subcutaneous vessels.

The rapid diffusion of helium indicates the cutaneous penetration of gas. In experiments when helium was breathed, it was possible to recover from the lungs only about two-thirds of the helium, estimated on the basis of solubility in fluid and lipid constituents, to be present in the body following saturation in a helium atmosphere. Further, the demonstration that helium diffuses rapidly from the urine contained within the bladder walls of divers subjected to rapid decompression from high pressure, suggested that the outward diffusion of helium through the skin accounted for the one-third or greater discrepancy between the pulmonary measurements and the estimated helium content of the body.

If the subject breathes air or oxygen in a hood and the body is surrounded with helium, then a constant volume of helium will be excreted by the lungs after 30 to 60 minutes, provided that the temperature of the gas in contact with the skin is controlled.

In Figure 9, the relationship is apparent between the helium collected in the spirometer and the temperature of the ambient helium in the bag surrounding the subject's body. The abrupt linear rise in the amount of gas diffusing through the skin in the range of 28° C., and upward is explained chiefly on the basis of increased cutaneous blood flow. There is in fact a close correspondence between the computation of peripheral blood flow on the basis of heat loss from the body as demonstrated in the calorimeter, and on the basis of diffusion of helium through the skin. In contrast with nitrogen, the diffusion of helium is so much greater that equality appears to be established promptly between the pressure of the ambient helium and its pressure in the skin and underlying blood vessels.

3. *The Helium Elimination Curves.*—If the nitrogen that is carried away from the tissues after the first 40 to 60 minutes of oxygen inhalation has its depot in fatty tissue then helium possessing a low fat solubility coefficient should be eliminated faster and in smaller quantities during a corresponding period of time.[12] Following exposure in a helium-oxygen atmosphere it is observed that the absorbed gas leaves the body in about one-half of the time required for nitrogen removal and that the plotted data, Figure 8, resemble the nitrogen curves characteristic of the dog. The amount of helium both in percentage of the body total and the actual quantity eliminated after the first hour are small compared with nitrogen. During exercise sufficient to increase oxygen consumption threefold, almost all of the helium was eliminated during the first 15 minutes, and after 40 minutes 90 per cent of the helium had left the body.

4. *The Field Test of Decompression.*—There is yet a better way to demonstrate the difference in the capacity of fat to absorb nitrogen compared with helium. In diving operations and caisson work the length of time required for decompression is a good index of the quantity and rate of removal of gas absorbed in the tissues.

Although about 75 per cent of the total body nitrogen is given off at a comparatively rapid rate in depths up to 100 feet, and hence does not usually contribute to the development of "bends," there appears

TABLE IV

COMPARISON OF TOTAL DECOMPRESSION TIME FOLLOWING EXPOSURE IN COMPRESSED AIR AND EXPOSURE IN A HELIUM-OXYGEN ATMOSPHERE

Depth	*Exposure*	*Recompression**	
		Air	*Helium-oxygen*
ft.	*min.*		
90	100	50	75
90	180	...	77
90	360	...	79
90	540	638	79
150	80	141	121
150	180	...	126
150	360	...	128
200	65	217	154
200	90	...	164

* Time in minutes.

to be a relatively small amount of gas dissolved in the fat of bone marrow and in the spinal cord that requires many hours for removal. Following an exposure of 9 hours (probable saturation) in compressed air simulating a depth of 90 feet, a period of 10½ hours was required for decompression. On the other hand, a 2-hour exposure (75 per cent saturation) at the same depth required only 60 minutes for decompression. In tissues other than bone marrow and the spinal cord, gaseous diffusion and a greater circulation of blood tend to equalize nitrogen pressure throughout the body. Are the greater nitrogen uptake, the limitation of diffusion by bony walls, and the sluggish, sinusoidal circulation the factors responsible for the slow decompression necessary after long exposures in compressed air?

By contrast, the properties of helium render this gas ideal for diving and the decompression time following saturation in a compressed helium-oxygen atmosphere is not only greatly reduced but no appreciable decompression is required in excess of one hundred minutes' exposure as shown in Table IV. With reference to helium, the period of

decompression of 79 minutes stands in contrast with the corresponding period of 10½ hours required for air. Thus, the test data obtained from rapid decompressions corroborate the laboratory analysis as to the contrasting behavior of nitrogen and helium.

III. Physical Qualifications for Work in Abnormal Pressures

1. *The Altitude Tolerance Test.*—The selection of individuals resistant to "bends" and other ills incident upon decompression has been difficult. *A priori*, one might select men devoid of excess fat since every kilogram of adipose tissue absorbs 52 cc. of nitrogen per atmosphere of pressure. A second important consideration, in view of the manner of gas transport, would be circulatory efficiency in the sense of good cardiac output and adequacy of collateral circulation. Degree of cardiovascular tone and age therefore would appear to be important criteria. Yet susceptibility to "bends" could not be predicated on the basis of these qualifications alone. Essentially it was necessary to know for each individual his resistance to the ill-effects of decompression by means of a specific test.

To meet this practical need, individuals were exposed to an atmosphere equivalent to a depth of 100 feet for a period of 28 minutes. The subsequent rapid decrease in pressure to normal during a period of 2 minutes induced symptoms in susceptible individuals but the test had obvious disadvantages in that, not only was an undetermined quantity of nitrogen absorbed during the 28-minute period of exposure that fell far short of saturation, but symptoms elicited by the test required recompression treatment.

These disadvantages were overcome by an experiment in which the normal barometric pressure was decreased rapidly in what may be termed an altitude tolerance test.[13] The simulated altitudes to be reached range from 30,000 to 40,000 feet at a rate of ascent of 5,000 feet per minute, and the duration of stay at the designated altitude is one hour unless aeroembolism supervenes. Oxygen was breathed continuously in these tests.

The results of sixty tests indicated that twenty-eight divers and aviators were able to remain free from symptoms at or above an altitude of 34,000 feet. On the other hand, thirty-two divers and aviators developed "bends" and occasionally incipient asphyxia. The lowest altitude at which symptoms occurred was 27,000 feet. Areas of old injury

proved to be frequent sites for the location of the characteristic pain associated with "bends." This test has served to classify aviators as to their ability to remain free from symptoms at altitudes above 30,000 feet, and deep sea divers as to their resistance to compressed air illness. The divers, for example, who descended to depths of 440 feet in search of a disabled submarine, and ascended safely to the surface, were men who were able to remain free from symptoms for a period of one hour at a simulated altitude of 40,000 feet.

2. *The Specific Gravity of the Body as an Index of Obesity.*—Our problems as analyzed in this lecture are intimately concerned with the amount of fat in the body. Measurements of the nitrogen dissolved in the tissues yield data which may be used to estimate fat content but the procedure is too tedious for routine determinations.

A direct method that serves effectively is the measurement of the specific gravity of the body as a whole, essentially a determination of the density of corporeal tissue in relation to unit volume.[14,15] This objective is attained by weighing an individual in air and in water. The relationship between the loss of weight in water and the weight in air is an index of the density of the tissues. The influence of fat, possessing as it does the lowest density of any body constituent, is apparent.

It is not necessary to go into details as to procedures. It suffices to state that the proper method, taking due care to measure the residual air volume, has enabled us to classify men as to their degree of obesity on the basis of the outlined principles. Fat men tend to float in water and values in the range of 1.030 for specific gravity are characteristic of these individuals. On the other hand, for a group of lean men in the Naval Service, average weight 150 pounds, the mean specific gravity was 1.080. For a group of professional football players, although their weight was 200 pounds, the mean specific gravity was also 1.080 ± 0.001. This fact tends to show that it is the inherent composition of tissue rather than the absolute weight that governs specific gravity.

3. *The Composition of the Human Body.*—It has been helpful in the study of the effect of the abnormal pressure environment on the individual to consider the body as a mass of essential tissue separate from the excess fat. In the completion of our analysis various fragments of knowledge can be assembled into a mosaic that reveals the composition of the true body mass as relatively constant under controlled conditions for individuals of the same sex and age groups, realizing that eventually

TABLE V

COMPOSITION OF THE BODY

Substance	*Specific gravity*	*Water*	*Solid constituents*		*Basic body composition equivalent combinations sp. gr.* 1.099+0.001	
			Percentage	*Specific gravity*	*Substance*	*Percentage*
		Per Cent				
Blood	1.060	80	20	1.4		
Tissue	1.060	80	20	1.4	Tissue Bone Fat	75.0 15.0 10.0
Bone	1.56	30	70	1.68		
0.5 Calcium salts	3.00			3.0	Tissue Bone salts Fat	82.5 7.5 10.0
0.5 Tissue	1.060	80	20	1.4		
Fat	0.94				Water Solids Bone salts Fat	66.0 16.5 7.5 10.0
Body as a whole	1.099	66	16.5 7.5*	1.4 3.0	Water Solids Fat	66.0 24.0 10.0

* Calcium salts in bone.

quantitative analyses will define the range in variation of such constituents as bone and fluids.

The true weight of the body, therefore, as represented by Figure 1, is assumed to consist of 15 per cent bone, 10 per cent essential lipids, and 75 per cent tissue. The specific gravity of this mass then can be computed on the basis of the following data:

Bone is frequently analyzed as containing 50 per cent mineral substance, largely calcium salts to which a specific gravity value of 3 may be assigned. The other half of bone amounting to 7.5 per cent of the body weight may be classed as tissue.

The specific gravity of the lipids is of the order of body fat, 0.94, a value obtained experimentally on the basis of actual fat loss in relation to specific gravity.

For tissues a value for specific gravity of 1.060 is the same as that obtained by repeated determinations of whole blood withdrawn from the above mentioned test subjects. Analyses for individual tissues ac-

TABLE VI

EFFECT OF EXCESS FAT ON THE SPECIFIC GRAVITY OF THE BODY

Basic composition	*Weight units*	*Volume units*	*Specific gravity*	*Specific gravity determinations of 174 Naval personnel*		
				No. men	*Range of specific gravity*	*Difference thoracic, abdominal circumference*
Tissue	75.0	70.75				
Bone	15.0	9.62				
Essential lipids	10.0	10.70				
	100.0	91.07	1.099	21	1.090—1.099	7.2
10 per cent	100.0	91.07				
excess fat	11.1	11.82		30	1.080—1.089	6.3
	111.1	102.89	1.080	41	1.070–1.079	5.5
20 per cent	100.0	91.07				
excess fat	25.0	26.60		41	1.060–1.069	5.2
	125.0	117.67	1.062	31	1.050–1.059	4.3
				5	1.040–1.049	4.2
33.3 per cent	100.0	91.07		3	1.030–1.039	0.9
excess fat	50.0	53.76		2	1.020–1.029	–0.1
	150.0	144.83	1.036			

cording to Vierordt,[16] give values of the order of 1.014 for pericardium to 1.1219 for tendon; e.g., muscle, 1.051, brain, 1.040, liver, 1.057. For tissue it may be assumed that the distribution of water and solid constituents is in the ratio of 80 to 20. In accord with this distribution the specific gravity of the solid residuum is 1.40.

The analysis of the composition of the body is summarized in Table V, showing the values used for blood, tissue, bone, fat, and solid constituents. The basic composition of the body can be analyzed in several ways as long as the ratios of the constituent substances or their equivalents are not altered with respect to body weight. The same value for specific gravity of 1.099, representing the true body mass, is therefore applicable to any group arrangement of constituent substances, as shown in the table.

If to the true corporeal structure, excess adipose tissue be added in percentages of 10, 20 and 33.3 of the total body weight, the respective values for specific gravity will be 1.080, 1.062, and 1.036 corresponding

TABLE VII

BODY COMPOSITION AND SPECIFIC GRAVITY OF A DEEP SEA DIVER COMPUTED FROM THE GASEOUS NITROGEN CONTENT OF THE BODY
(See Table III, Page 576)

Body weight	= 70 kg.	Total nitrogen	= 1,076 cc.
Weight fluids	= 70 × 0.60		= 42 kg.
"Water" nitrogen	= 42 × 9		= 378 cc.
"Fat" nitrogen	= 1076 — 378		= 698 cc.
Weight fat	= 698 ÷ 52		= 13.4 kg.
True body weight	= 10/9 (70 — 13.4)		= 63 kg.
Excess fat	= 70 — 63		= 7 kg.
Ratio $\frac{\text{Weight water}}{\text{True body weight}}$			= 66.6

Corrections—

Water, 0.66 × true body weight	= 41.58 kg.
"Water" nitrogen = 4.58 × 9	= 374 cc.
"Fat" nitrogen = 1076 — 374	= 702 cc.

Specific gravity of the body, computed—

True body weight	*Weight (units)*	*Volume (units)*
Water	41.58	41.58
Fat	6.30	6.77
Solid constituents	15.12	9.00
	63.00	57.35

SPECIFIC GRAVITY = 63 ÷ 57.35 = 1.098

True body weight plus excess fat = 63 + 7 ÷ 57.35 + 7.53 = 1.079

Specific gravity of the diver's body as determined by the method of water displacement = 1.060

to the division of Naval personnel into three groups on the basis of high, intermediate, and low specific gravity measurements.

On the basis of determinations of specific gravity the value of 1.099 is higher by two units than the top figure obtained in a series of 200 tests in which healthy individuals between the ages of 20 and 40 served as subjects. Men possessing the highest values therefore have no excess fat and their bodies contain only about 10 per cent by weight of lipid matter that is regarded as essential. A reading for specific gravity of 1.080, or approximately the average for the high group, is indicative of the presence of 10 per cent *excess* fat, a figure of 1.062 indicates the presence of 20 per cent *excess* fat, while a value of 1.036 obtained on several fat men denotes that 33.3 per cent of the body weight consists of *excess* fat, Table VI.

The analysis applicable to the diver whose nitrogen measurements extended over a period of 15 hours, Table VII, summarizes the results with reference to the estimation of the fat content of the body both on the basis of measurements of nitrogen elimination and determination of specific gravity. In this particular example some discrepancy exists between the specific gravity as measured, and the specific gravity as computed on the basis of excess fat in relation to basic body structure. But undoubtedly quantitative data obtained in the future as to the relative amounts of the constituents in the true body mass will diminish the difference.

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