Ramifications in and around the world of hyperbaria

Albert R. Behnke, Jr., M. D.

It is a privilege to relate some elementary experiments conducted in altitude and hyperbaric environments with the hope that with your sophisticated technology you will finalize the early, incomplete, and largely neglected but highly promising studies. These center in the effects of hyperbaric oxygen (HBO) and in the quantification of inert gas transport. A new world was revealed to me in hyperbaria and I soon developed a working relationship with such ethereal substances as oxygen, nitrogen, carbon dioxide, and helium.

Preliminary Statement in Regard to Pressure. It is a remarkable phenomenon that the body can adapt rapidly to a range of pressure from 0.1 ATA to 10 ATA without any effects from equalized pressure *per se*. Thus, if there is no obstruction in auditory tubes or sinal ingress, a descent can be made to 91.4m (300ft) within 3 minutes, and to a simulated altitude of 15,849m (52,000ft) at a rate of 1,524m (5,000ft) per minute. Prior to the altitude ascent, a period of ground level denitrogenation by four hours of oxygen inhalation, is required to prevent altitude decompression sickness (DCS) **(Fig. 1, 2)**.

One may ask, how can man subsist for any length of time at the peak altitude, if alveolar CO_2 and water vapor approach the ambient pressure of 79 torr. The answer is *pressure breathing* to maintain an expiratory force of 20–30 torr. The lung volume at all times is maintained close to maximal volume and the respiratory rate is limited to 2–3 cycles per minute. As a subject in these tests (whom I shall designate hereafter as 'Subject Z'), I can state that there were no hypoxic manifestations such as cyanosis and headache. The usual aftermath was a feeling of well being probably due to the enforced elevation of systolic blood pressure incident to the high intrapulmonic tensions of oxygen.

Submarine Escape Drills. In 1927, there was no procedure to escape from submerged submarines at those depths where personnel can be expected to survive and where rescue or escape is at least possible. The loss of two submarines, the S-51 in 1925, and the S-4 in 1927, intensified efforts to develop escape and rescue procedures. In the S-4 disaster, divers tapping on the submerged hull at the relatively shallow depth of submergence (31m), detected signs of life as long as 22 hours after the accident. However, there were no escape hatches to permit even 'free ascent' which subsequently has become routine from this depth.

In 1928, the Momsen 'lung' (a rebreathing device with CO_2-absorbent canister) became available and drills were initiated in the use of this appliance. Although trainees were instructed to exhale during ascent, and above all, to avoid breath-holding, there were occasional fatalities in training at depth of only 0.46 meters. Having deduced the cause of these accidents as an overexpansion of the lungs and consequent rupture of pulmonary vessels leading to air embolism, I was afforded an opportunity to become a research fellow in

of cumulative hypercarbia.

Apart from the high extraction rate of heart muscle for oxygen and a relatively low oxygen pressure in cardiac tissue compared with pulmonary O_2 tension, I have never been able to ascertain from investigators engaged in basic cardiac research, the nature of the protective mechanism which sustains heart function in the high HBO environment.

2) Tests on Man. Some aspects of the animal tests (e. g., loss of vision, incapacitation following a second daily seizure) were of concern and did not encourage naval application. Favorable to human exposure were complete functional reversibility of adverse effects on initial appearance when a switch to air was made.

Three of the early human exposures to HBO (4 ATA) merit recall. In the first test, Subject Z inhaled oxygen (4 ATA) during the course of a symptomless period of 43 minutes. This quiescent period, however, was abruptly terminated by syncope (an unusual response) associated with blanching of the face, palmar sweating, absence of radial pulse, and fall in brachial blood pressure. Immediate recovery attended inhalation of air. The test was again repeated the following day with similar termination except that the symptom-free latent period was shortened to 20 minutes. These two tests raised the possibility that man, in contrast to lower animals, might lose consciousness without onset of seizures.

In a third test on another suject, there occurred without warning what subsequently proved to be a typical oxygen-induced seizure without detrimental sequelae. At the time, however, the violent tonic contractions and clonic movements in the unconscious subject were of serious import. Follow-up examination of this subject who experienced the first experimentally-induced seizure in man, over a two-year period revealed no latent injury nor abnormal EEG tracings.

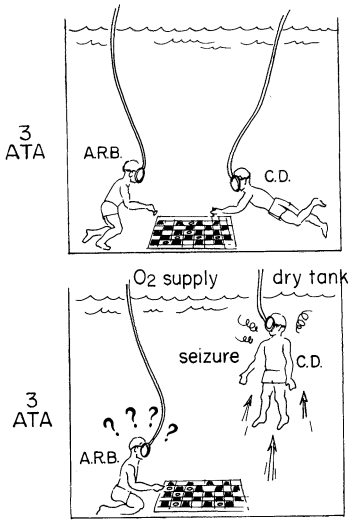
Subsequently, during the course of decompression following a helium-oxygen chamber dive (91.4m, 300ft), Subject Z was switched to pure oxygen instead of air at 40.2m (132ft, 5 ATA). The error was discovered during ensuing paralysis of respiration. Recovery of normal breathing followed within minutes after shift to air. With the exception of a few punctuated admonitions, there were no sequelae.

In a diver subject, HBO (3 ATA), prominent responses were narrowing of the visual fields which terminated in amblyopia during the fourth hour, bradycardia, and periodic waves of nausea. Noteworthy and indicative of the end of the latent period of tolerance was an abrupt rise in systolic and diastolic blood pressure, an upswing in pulse rate, and extreme facial pallor.

Of prime concern was the effect on vision. A collateral visual test was to time the appearance of the negative after-image which was thought to be an indicator of HBO catalysis of the rod pigment, rhodopsin. In execution of the test, the subject, in a temporarily darkened chamber, viewed an illuminated red and green miniature cross bar. After a period of 5 or 10 seconds, the subject closed his eyes and held up his hand when the negative after-image appeared. The delay in appearance of the after-image was concomitant with a decrease in visual acuity. The opportunity to conduct *in vitro* studies of HBO interaction with rhodopsin was never realized.

2. OXYGEN AND EXERCISE

1) Dry Chamber Tests. Bornstein and Stroink (1912), during the course of inhalation of oxygen (3 ATA) while exercising on a bicycle ergometer, developed spasms in the arms and legs after 51 minutes. Behnke and White (1945) repeated these tests as subjects together with 11 divers. It was found that moderate bicycle exercise (307kg/m/min) shortened the



A GAME OF CHECKERS

Fig. 3. Upper: A game of checkers underwater. Both subjects breathing oxygen (3ATA). Lower: After one hour, one subject vanishes upward.

time of oxygen tolerance at 2.82 ATA to a range of 6 to 18 minutes. Two subjects developed seizures. The inability to perform leg exercise was striking.

Subsequently, Banister et al. (1970) showed that maximal exercise could be performed at 2 ATA (HBO) following two hours of oxygen inhalation at rest. This type of exercise test remains to be implemented together with measurements of oxygen uptake and carbon dioxide elimination, as a prime procedure to define the gray zone of intolerance to HBO at 2 to 3 ATA during the course of exercise.

2) **Wet Chamber Tests.** Even more dramatic is the markedly decreased tolerance to oxygen inhalation underwater with subjects wearing self-contained breathing apparatus. Retention of carbon dioxide is the striking feature, in part attributable to equipment-induced breathing resistance, disturbed CO_2 transport from tissues, and impaired chemoreceptor response to CO_2, factors which require further evaluation.

Casket Rule

Try On Yourself First That Which You Would Have Others Do
And
Errors Will Not Be Repeated

Fig. 4.

One experiment at 3 ATA in a wet tank in water 3.7m (12ft) deep, involved the Officer-in-Charge of the Experimental Diving Unit and Subject Z. The O-in-C had a penchant for the innocuous game of checkers played underwater with iron'men on delineated fabric. It is a game that Subject Z always endeavored to avoid playing. During the course of one hour of oxygen inhalation (3 ATA), having lost the first two games badly, Subject Z in the third game was amazingly successful when he became aware in the aqueous medium that he had no partner. He had floated to the surface unconscious while Subject Z, although able to play checkers, was mildly stuporous. The Golden Rule has limitations with respect to trying on yourself first that which you would have others do! **(Fig. 3, 4).**

3) **Potentiation of Oxygen Effects.** The wide individual response to HBO, notably in the pressure range of 2.5 to 3.0 ATA is a disturbing characteristic of hyperbaric exposures. It is my experience that phlegmatic individuals, not subject to apprehension and in the fasting state, consistently have a stable tolerance to elevated oxygen pressures. On the other hand, the following factors create disturbing inroads on HBO tolerance, namely, elevated pulmonary and tissue CO_2 levels; exercise at levels higher than 2 ATA and markedly underwater; endocrine factors involving adrenal, pituitary,

and thyroid glands; and stimulation of sympathetic ganglia and pathways. Early, we characterized oxygen as 'adrenergic'. This may be manifest even at one ATA in the hyperpneic respiration attending the effort to achieve a perfect score in response to light and sound signals, e. g., in operation of a 'pursuit meter'.

4) **Role of CO_2.** Apart from the adrenergic stimulus, elevated CO_2 tensions appear to be the chief factor responsible for individual and intra-individual variability. Specifically, cerebral circulation is augmented. In experiments in which a Forbes window was inserted into the cranium of an anesthetized cat, the vessels of the pia mater were dilated when CO_2 was added to inhaled oxygen at 4 ATA. With substitution of air for CO_2-enriched oxygen, the caliber of the pial vessels decreased to their initial diameter. A constrictive action of oxygen *per se* was not noted in contrast to the marked vasoconstriction of retinal and peripheral vasculature.

The augmentation of cerebral blood flow as a result of CO_2 elevation is a well-established phenomenon. In the anesthetized dog (4 ATA O_2), the tension of oxygen in mixed venous blood from the right ventricle (withdrawn by intra-jugular canula) may vary from 90 torr to over 1,000 torr in response to variable CO_2 tensions.

3. OXYGEN APPLICATION IN DIVING

The results of the HBO tolerance tests (+ 2hrs at 3 ATA) without residual or other complications, supported the rationale of O_2 iuhalation at stages of 18.3m (60ft), 15.2m (50ft), and 12.2m (40ft) during the course of decompression from deeper depths. Important is the fact that stages were not programmed for less than 12.2m unless an occasional diver showed idiosyncrasy to oxygen.

When symptoms referable to pulmonary irritation were reported, there was immediate relief on switch to air, or to lower partial pressures of oxygen. Subject Z, for example, became sensitive to oxygen after inhalation of dry gas at one ATA over a period of four hours. He was then placed in a helmet oxygen recirculating system and taken to a simulated altitude of 10,363m (~0.25 ATA), where he remained on oxygen for an additional 24 hours. At the end of this test, he was completely relieved of all symptoms.

It is my firm impression over the years that despite pulmonary irritation sufficient to restrict vital capacity, divers remain remarkably free from pulmonary infection and respiratory ailments in general.

An outline was prepared in 1937 for the treatment of decompression sickness. Currently, this schedule with some modification (saturation exposure to normoxic nitrogen, or to 50-50 N_2-O_2 at 30m (98ft) is currently employed or under trial.

In regard to Type I ('mild') cases of DCS, Behnke and Shaw (1937) recommended that "……recompression to a pressure of 30 pounds (psig) with inhalation of oxygen for one hour, followed by a 30-min decompression, should be sufficient". Air 'breaks' for the relatively short period of oxygen inhalation were not recommended.

4. OXYGEN APPLICATION IN CAISSON WORK

Nashimoto (1967) and Nashimoto and Mano (1973) demonstrated the vaule of oxygen in decompression of caisson workers. It is of interest to recall a letter from the Manager of the Cunningham Sanitarium, David Thomas, written to me in 1935. He had inquired previously in regard to proper decompression following saturation exposure in air at 30 psig, and he was advised to follow a Haldane-type procedure. He wisely made a test on himself, and after a sojourn of some 4 days at 30 psig (3.24 ATA), (the first saturation experience) He developed DCS during the last stages of the

Table II. Prototype oxygen decompression table

Tunnel Pressure		*Work Shift*	*Calculated Decompression Time (min.)*	
psig	*kg/cm²*	*hrs*	*Total*	*per hr. of work**
20	1.38	6	64	10
30	2.07	6	105	18
36	2.48	6	117	20
40	2.76	4	120	30

* For a continuous or intermittent work shift (Jones & Behnke)

recommended schedule.

The unfavorable results suggested that although halving the absolute pressure for the first stop was symptomless, 'silent bubbles' had formed which gave rise to symptoms subsequently. Our interest in the requirement for saturation exposures in evaluation of decompression tables and for the requirement of oxygen inhalation was stimulated immeasurably.

Saturation air tests (60-90ft, 18.3-27.4m) were conducted at the Experimental Diving Unit in 1940 to test the value of oxygen decompression (63-111min) but Type I DCS occurred. It was not until the Bay Area Rapid Transit Project (BART) that Subject Z was able to conduct a series of tests on himself over a period of three months. The result was the following prototype table **(Table II)**.

1) **"No-Stop" Decompression of Caisson Workers in a Pressurized Habitat.** In 1934, Surg. Lt Cdr. Shunroku Kagiyama published the first 'No-Stop' decompression schedule which markedly influenced our thinking at the time. His schedule (later proof-tested on divers) was developed from observation of "the time after surfacing at which a diver's urine liberated gas bubbles only under 2cmHg negative pressure, was regarded as the time required for complete recovery of the diver's state with regard to gas content of the body". Kagiyama's formula may be stated as,

$$Y_{\text{time min}} = \frac{922}{X^{1.0739}}$$ where x is depth in meters.

At a depth of 30m, for example, duration of stay followed by 'No-Stop' decompression was 24 minutes. The accuracy of Kagiyama's table was verified by test dives between 25 and 55 meters.

In 1942 (Behnke), it was proposed "that caisson workers work on a job continually living under pressure". Although the pressurized habitat has been highly effective in diving operations, it has never been implemented in the propitious dry environment. Nevertheless, as an extension of Kagiyama's principle underlying 'No-Stop' decompression procedure, and from a basic (1 ATA) formula of Hempleman, $\sqrt{\text{Time(min)}} = \frac{500}{\text{Depth(ft)}}$ one can project a 'No-Stop' decompression table for tunnel workers living at welltolerated pressures in a habit. **(Table III)**.

2) **Résumé Comments.** The experience of David Thomas and our own difflculties following too rapid decompression to the first stop from 4 ATA (1932-1935) emphasized the importance of relatively slow ascent initially, and a deeper first stop. The lesser circulation (venous reservoir) is limited in capacity to accommodate rapid infusion of gas from tissues, or gas injected rapidly intravenously as demonstrated by experiments of Richardson et al. (1937) **(Fig. 5)**.

5. NITROGEN NARCOSIS

In the 1932-1935 period, experiments conducted in air at 4 ATA, revealed that even at

Table III. Excursions followed by "No-Stop" decompression for various workshifts.

Habitat Pressure					*Work Shifts(hrs.)*			
ATA	*psig*	*ft.*	*Equiv. K**1		*2*	*4*	*6*	*8*
				Factor*2	24.62	34.83	42.65	49.25
1.0	0	0	500	Excursion	14.4	11.7	10.2	
1.606	8.9	20	634	Pressure*3	34.7	27.1	23.8	21.8
1.909	13.4	30	691		41.5	33.2	29.6	27.4
2.212	17.8	40	744		48.0	39.2	35.2	32.9
2.515	22.3	50	793		54.5	45.1	40.9	38.4

*1. Equivalent $K=\sqrt{ATA\times 500}$

*2. Factor$=\sqrt{\text{work shift time(min)}}\times 2.248$

*3. Excursion Pressure = Habitat(psig) + $\frac{\text{Equiv. K}}{\text{Factor}}$

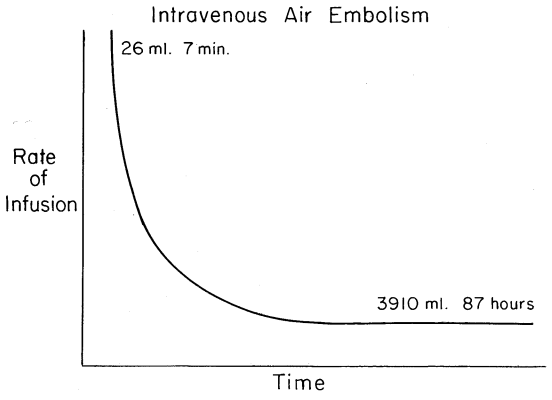


Fig. 5. Critical relationship between the rate of infused air (intravenously in the dog) and mortality. (from Richardson et al. 1937)

this relatively low pressure, the investigators experienced varying degrees of euphoria, fixation of ideas, and some impairment in neuromuscular coordination. Behnke et al. (1934) attributed the untoward subjective responses and reactions to the narcotic effect of nitrogen. Attention was focussed on the molar concentration of nitrogen at pressures in excess of 10 ATA, to that of ether under conditions of light anesthesia. Nitrogen was classified with chemically-inert, anesthetic substances generally, in accord with the Meyer-Overton hypothesis.

That nitrogen in air at increased pressures possessed a narcotic action appeared to be an original observation of some merit. Subsequently, literature search revealed the following arresting statement of Meyer and Hopff (1923), "The experiments prove that nitrogen under high pressure induces narcosis, a fact which is not generally known". Specifically, these authors stated that the chemically inert inhalation anesthetics have a narcotic effect on mice, when they are inhaled in such concentrations as to ensure a content of 0.06mols per liter in the fat-like brain lipoids.

This is proof that to protect discoveries made within circumscribed boundaries, one should not read foreign literature.

Tests by Behnke and Yarbrough (1939) revealed that the chemically inactive gas, argon, brought about an even greater degree of stupefaction than nitrogen in a wet chamber test to 39.6m (Subject Z) and in the dry chamber to 91.4m (300ft).

Nitrogen Narcosis and Ethanol Intoxication. Implicit credence must be accorded the affirmative statements of Navy divers that the effects of nitrogen narcosis and ethanol intoxication are similar. Nevertheless, the results of the following test by Dr. Blanch (MC) USN, circa 1945 at the Experimental Diving Unit, are in the direction of confirmation. "The Subject's usual response to increased air pressure was first noted in a routine dry chamber dive to 68.6m (225ft). While other members of his

section showed some degree of release of inhibitions, the Subject's behavior was entirely different in that he appeared to be like a person under the influence of alcohol with laughing, singing, slurring of speech and incoordination".

"As a test, the Subject and a control diver were given 4 equal doses of alcoholic beverage (52ml of 86proof whiskey, per dose, on a fasting stomach) at intervals of 15 minutes. At the end of 45 additional minutes following alcohol ingestion, the time required by the Subject to solve arithmetical problems was trebled. At the end of one hour, it was only twice the initial time, and at the end of 1.5 hours, the time required to solve problems had returned to the pre-alcohol ingestion level. The time required by the control diver to solve problems did not change appreciably throughout. His behavior indicated that he was only slightly intoxicated but in control of his emotions".

6. HELIUM-ABOLITION OF NARCOTIC EFFECT

In 1869, the British astronomer, Lockyer, identified helium (from helios (Gr.) meaning the sun) in the vapors surrounding the sun as a yellow spectral line near the two yellow lines of sodium. In 1895, Ramsay found helium in the mineral cleavite. The discovery of helium in natural gases was made in Kansas.

In 1925, preliminary tests were conducted at the Bureau of Mines with impetus from Professor Hildebrand, independently but in accord with earlier considerations of Elihu Thomson, that helium possessed the physical properties of a diving gas. It remained for systematic studies at the Experimental Diving Unit, Washington, D. C., to establish the value of helium as non-narcotic, 'light' gas for routine use in diving.

In 1938, diver Nohl under the supervision of Dr. Edgar End, made a dive in Lake Michigan to a depth of 122m (400ft). In 1938 and early 1939, systematic 'wet' chamber tests were carried out to depths of 152.4m (500ft). A drawback to employment of helium was rapid loss of body heat in a cool environment. This resulted in the development of an electrically-heated suit. In regard to decompression, it was necessary to come to the first stop more slowly (and at a relatively deeper depth) than with nitrogen. Overall, the experimental dives were satisfactory and preparations were made to conduct sea tests when of May 23, 1939, a message from Naval Headquarters, "Squalus is down off the Isles of Shoals (New England Coast), depth between 200 and 400 ft, have your divers and equipment ready to leave immediately".

By means of the McCann rescue chamber and diver support, 33 survivors in the forward compartments of the submarine were rescued within 20 hours of report of disaster. Crew members in the flooded compartments aft in the submarine, were dead.

Salvage operations were then begun. During initial helium dives to a depth of 73.1m (240ft), divers lost consciousness and it appeared that a critical sea trial to confirm the value of helium diving, was a failure. Air diving proved to be impractical because nitrogen narcosis prevented effective work at 240 feet. Open circuit supply of helium-oxygen was impractical because of the large volume of gas required at bottom depth.

What was the source of failure not previously encountered at the Experimental Diving Unit? Carbon dioxide was the likely offender as a result of inadequate circulation through the CO_2-absorbent canister attached to the back of the diver's helmet. Within two days the problem was solved when we conducted tests and had available the indispensable help of Professor Yaglou at Harvard. The cause of diving failure was a substandard size injector nozzle of the venturi device in the recirculating system. Increasing nozzle size by 50 percent rendered helium-oxygen circulation in the

helmet adequate for all subsequent 248 dives.

1) **Decompression Procedure.** After a fifteen to twenty minute working period at depths of 220 to 240 ft (66 to 72m), a diver was brought to the surface in 15 minutes, because of the cold water, stopping only at the 80, 60, and 50 foot (24, 18, and 14m) levels. He was then taken to the recompression chamber, where oxygen was administered at 50–40 foot levels for 45 minutes or longer. After completion of oxygen inhalation at the 50 to 40 foot levels it was safe to return to normal atmospheric pressure within 5 to 10 minutes. This procedure, termed 'surface decompression', permits the elimination of excess gas dissolved in body tissues under ideal conditions ; the body being warm and the diver at rest, under observation. The danger of the method lies in the formation of extensive bubbles during the interval between the rapid ascent to the surface and subsequent recompression. That the procedure served its purpose is evident from 628 dives, including 302 dives in excess of 200 feet, with only two cases of decompression sickness.

2) **Absence of Injury.** Commendable was the absence of injury during both rescue and salvage operations conducted over a period of three and one-half months of arduous task performance. Each diving procedure was rehearsed aboard the salvage tender, and there was no urgency that divers expedite their tasks. The fitness of each diver before a dive was assessed by a short but systematic examination, the results of which were recorded.

I desire to emphasize that there was sustained group concentration and determination to maintain the momentum required to accomplish objectives.

7. MEASUREMENT OF TISSUE NITROGEN TRANSPORT

Some of the most rewarding experiments at Harvard were in collaboration with Louis Agassiz Shaw, a master in execution of meticulous physiologic procedures. The measurement of molecular tissue nitrogen was simple in concept but tedious in execution. It involved respiration of pure (99.5%) oxygen circulated in a closed system over the course of many hours. My contribution was to analyze (using the Van Slyke apparatus) the amount of tissue nitrogen collected in a 30-liter spirometer which was of the order of 1,000ml or less. The analysis of samples of gas as large as 35ml involved absorption of oxygen during the course of reduction of the initial sample volume to either the 0.5ml or 0.25ml level of the Van Slyke burette, dependlng upon the amount of nitrogen present. Although tedious, it was possible to achieve an accuracy of ± 1 part per 100,000 of nitrogen. In a lean man (10%fat) it appeared that after about 6 hours of oxygen inhalation, nitrogen recovery attained a plateau and an end-point in our ability to determine less than 15ml of N_2 per hour in the large spirometer system. Initially we were unaware that percutaneous diffusion of nitrogen from ambient air precluded a complete washout of tissue nitrogen (**Fig. 6**).

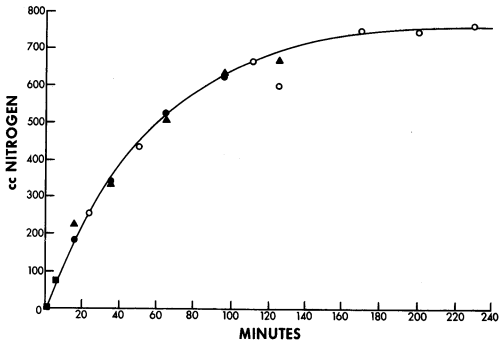


Fig. 6. Curve representing tissue nitrogen dlearance during the course of oxygen inhalation in a lean subject over a period of 240 minutes. Triangles, open and closed circles represent separate experiments. (Data from Shaw, unpublished)

Percutaneous Diffusion of Nitrogen. From the anesthetized dog, surrounded by air and breathing oxygen through a tracheal can-

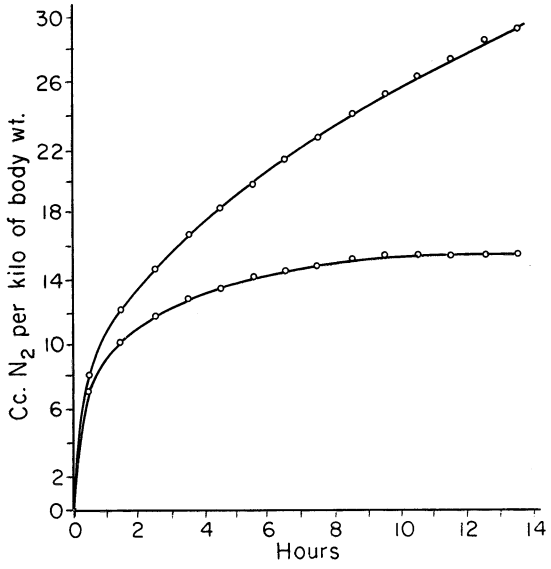


Fig. 7. The upper curve represents the elimination of N_2 via the lungs of anesthetized dogs with open incisions over the trachea and the femoral artery of one leg. The lower curve reprenents the elimination of N_2 under the same conditions with the exception that the incisions were closed by suture. (data from Shaw and Behnke, 1934)

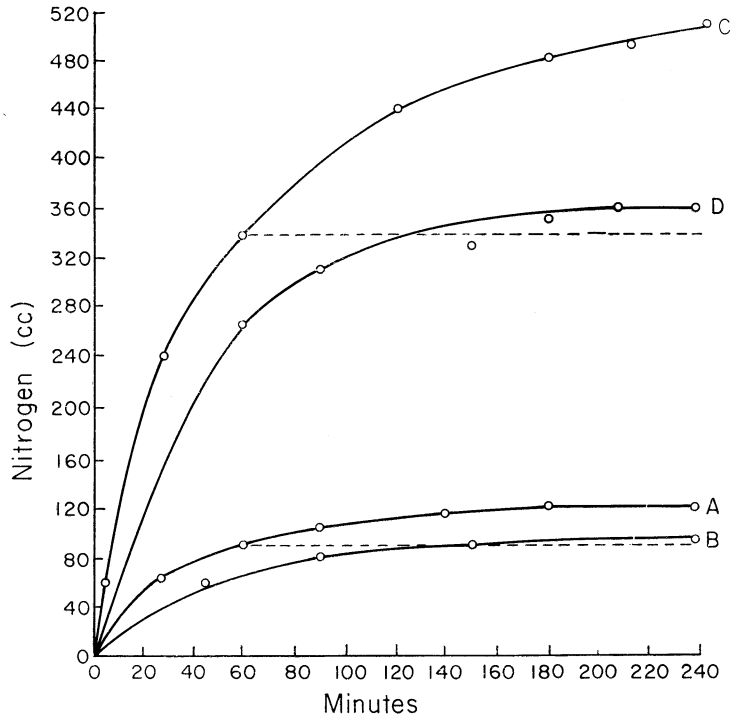


Fig. 8. Nitrogen saturation time compared with desaturation time (anesthetized dog D) determined on different days. The N_2 eliminated during the first 7 minutes (pulmonary N_2 washout) was not measured. Curve A follows complete desaturation at 1 ATA. Curve B represents N_2 desaturation following resaturation over a period of 67 minutes of the dog's N_2-free body. Likewise, curve C represents N_2 desaturation after N_2 equilibration of dog D at 4 ATA. Curve D represents N_2 desaturation following 67 minutes equilibration of the dog's tissue at 4 ATA, previously free of nitrogen. (Shaw et al. 1935)

nula, we obtained after 14 hours, a remarkable combination of exponential-linear curves. What was the source of nitrogen collected at a constant linear rate from the 4th through the 14th hour of oxygen inhalation? Since skin incisions at the tracheal and femoral sites were not sutrured, we were chagrined by the thought that we were measuring nitrogen in the atmosphere which had diffused into the dog's tissues, and subsequently collected in the spirometer.

To obviate the probability also of small amounts of atmospheric N_2 diffusing through intact skin, we placed the anesthetized dog on a wooden support and then into a metal container integrated into the closed recirculating oxygen system. The wooden support was introduced to diminish heat loss when the dog's body was in contact with the bottom of the metal container **(Fig. 7)**.

In our first experiment, presumably with an ideal system (dog enveloped in oxygen and supported by a wooden frame), an exciting and apparently fundamental discovery was made. Twice as much N_2 was collected from the dog's tissues in the closed system compared with the amount recovered from the dog's body when in air. This momentary discovery held promise of a laureate voyage to Sweden. But all in vain!

Removal of the dog and leaving only the old wooden support in the oxygen system (after it had been exposed to air for 24 hrs), resulted in an exponential N_2 elimination curve for the dog board! The quantity of N_2 collected from the board, fortuitously approximated the N_2 eliminated solely from the tissues of the dog in the absence of the beguiling wooden support.

The most informative N_2 transport experiments in the series with Louis Shaw were those in which N_2 elimination was followed in the same dog on different days. All measurements were made at one ATA so that in the hyperbaric exposures, the dog was decompressed to normal pressure and placed in the oxygen collection system. During the first 7 min (lung rinsing period) N_2 was not recovered. At one ATA, the lean dog was rendered N_2-free in the closed oxygen system, and then re-exposed to air for 67 minutes. Following this period of 67 min resaturation in air, the dog was placed again in the oxygen system and rendered N_2-free. In a similar manner, the hyperbaric re-exposures in air and N_2 recovery in the oxygen system, were performed **(Fig. 8)**.

The conclusion from these experiments was that the time required for desaturation following partial (67min) saturation was the same within the limits of experimental error, as the time required for desaturation following complete saturation of the dog's tissues. In confirmation of this 'isotemporal' principle are the subsequent experiments of Tobias et. al., (1949) who employed the refined ^{85}Kr technique to demonstrate similar half-time clearances for krypton when the previous inhalation periods varied as widely as 20 and 310 minutes.

8. PERCUTANEOUS DIFFUSION OF HELIUM AND NITROGEN IN MAN

Diffusion as a fundamental property of gases would lead one to expect some movement of gaseous molecules through the skin. This can be demonstrated by an arrangement to permit the inhalation of oxygen while the body is surrounded by the same or an indifferent gas. Following 9 hrs of oxygen inhalation when air in the bag surrounded the body, a subject eliminated 47ml of N_2 per hour during the spirometric recovery. When oxygen replaced air in the bag, the hourly collection of N_2 was reduced one-half (24ml). This quantity of N_2, however, is less than the amount one expect to recover if diffusion were sufficiently rapid to establish equality between the pressure of ambient nitrogen and its pressure in skin and subcutaneous vessels **(Fig. 9)**.

By contrast, if the subject breathes air or oxygen, and the body is surrounded by helium,

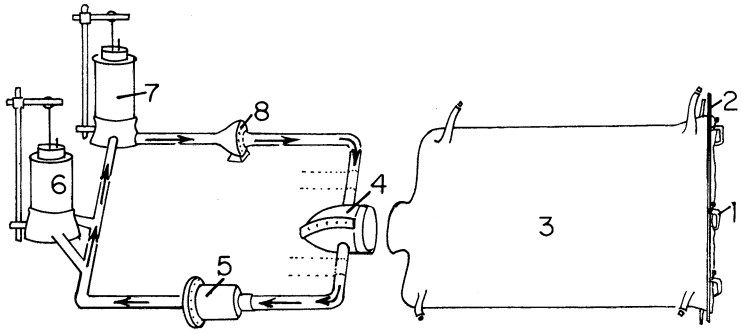


Fig. 9. Diagram of apparatus used to measure percutaneous diffusion of inert gases. When the clamps (2) are removed, subject enters rubber bag ; head protrudes into helmet (4). Oxygen is recirculated by means of blower (8), carbon dioxide is absorbed in canister (5). Technique : Body is surrounded by inert gas which is collected in spirometers during oxygen inhalation (inward percutaneous diffusion). When inert gas is recirculated instead of oxygen which now envelopes the body (3), *outward* percutaneous diffusion is measured. (from Behnke and Willmon, 1941)

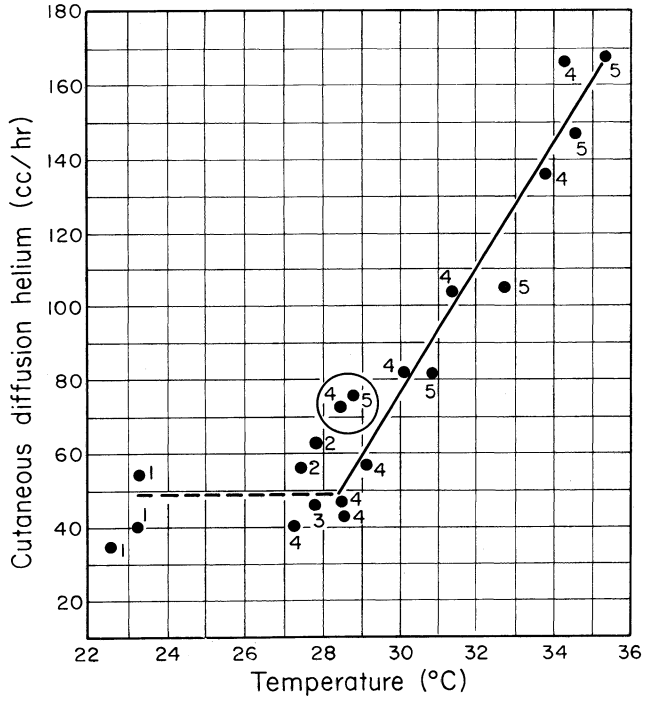


Fig. 10. Cutaneous diffusion of helium in relation to temperature, measured as ml He recovered from the lungs per hour in the spirometer system when the body is immersed in a helium atmosphere (pHe 700torr). The numbers 1 to 5, refer to different subjects. The encircled values were obtained after the previously heated ambient helium had been cooled to 20°C . (Behnke and Willmon, 1941)

then a constant volume of helium will be excreted by the lungs after 30 to 60min provided that the ambient temperature is constant. The abrupt linear rise in the amount of gas diffusing through the skin in the range of 20°C and upward is explained chiefly on the basis of increased subcutaneous blood flow. Compared with nitrogen, the diffusion of helium is so much greater that equality appears to be established rapidly between ambient helium and helium diffusing into the skin and underlying vessels **(Fig. 10)**.

At the time of the studies of percutaneous gas transfer, control of ambient temperature was not rigid and analysis of helium (extraction in the Cady apparatus at N_2 liquefaction temperature) was cumbersome. Today, these difficulties no longer exist; helium can be measured ± one part in a million, and ambient temperature is subject to rigid control. Amazingly, only limited investigation in man has been made of inert gas transfer across the skin, and that only of the forearm. It is for this reason that I present the early and admittedly incomplete studies in the hope that such investigative endeavor will be implemented by the advanced technology of Japan.

Importance of Percutaneous Helium in Decompression of Divers. Consider the following example of percutaneous helium transfer (PHT) in a euthermic environment:

Potential PHT in a diver (height 174cm; weight 72.5 kg; surface area 1.87 m^2) is $1.87 \times 22 = 41$ ml/hr of helium per ATA, as a conservative estimate. At 31ATA(308.8m, 1000 ft) the potential PHT is 1271 ml/hr. Isobaric pulmonary elimination of helium during the course of decompression should be approximately 170 ml/hr (O_2 window, 0.3 ATA). It is apparent that it is necessary by some procedure (e.g., water immersion) to exclude counter-diffusion of helium during the course of decompression. The problem remains an important one for investigation and subsequent applications **(Table IV)**.

9. BODY COMPOSITION: GASOMETRIC AND DENSITOMETRIC TECHNIQUES

1) Partition of the Human Nitrogen Elimination Curve. Total body N_2 recovered during the course of oxygen inhalation can be separated into 'fluid' and 'fat' solvents. If total body water (TBW) is determined, then an estimate of body fat can be made from the simple procedure of N_2 recovery after several hours of oxygen inhalation **(Table V)**.

2) Absorption of Lipophilic Gases. Lesser and Zak (1963) combined krypton (another lipophilic gas) with cyclopropane. The results of an 8-hr test on Subject Z (w 96.4kg) follow:

Body fat (krypton uptake)……20.9kg

Body fat (cyclopropane)……23.3kg

The hourly metabolic rate which served to monitor the integrity of the closed system for recirculation of the lipophilic gases was: 14.7, 14.8, 15.2, 14.8, 15.2, and 14.9 liters/hr (STP). **(Fig. 11)**.

3) The Specific Gravity of the Body. In 1939, following rescue and salvage operations at the time of the U.S.S. Squalus disaster, there was renewed interest in development of a practical method to assess body fat in divers who were then engaged in test dives to 152.4m (500ft). Since volume displacement of a submarine and buoyancy were matters of daily discussion, it was a 'serendipic' application to measure the volume of the body in diving tanks, and to re-introduce the basic anthropometric parameter of volume as a third 'dimension' in addition to stature and weight (Behnke, Feen, and Welham, 1942).

We are indebted to Archimedes some 2000years earlier for Proposition 7 (from T.L. Heath's classic text), namely, "A solid heavier than a fluid, will if placed in it, descend to the bottom of the fluid, and the solid will, when weighed in the fluid, be lighter than its true weight by the weight of the fluid displaced".

Table IV. Estimated potential percutaneous diffusion of helium into helium-free tissues at pressures of 2 to 50 ATA. Pulmonary loss of helium is estimated at 170 ml/hr.

Pressure ATA	*50*	*40*	*30*	*20*	*10*	*2*
Diffusion (ml/hr)	2,000	1,600	1,200	800	400	80
PA loss* (ml/hr)	170	170	170	170	170	170

* pulmonary isobaric He elimination, O_2 window 0.3 ATA

Table V. Diffusion of nitrogen percutaneously (ml N_2 hr.) during the course of prolonged oxygen inhalation. When the subject's body is surrounded by oxygen, N_2 recovery from tissues via the lungs, decreases. (Behnke and Willmon)

Time(hrs.)	*Subject* I		*Subject* II	
7.5	53	Body in air	—	
8.5	52		—	
9.5	47		—	
11.0	46	Body in O_2	49	
12.0	33		47	
13.0	34		46	
14.0	24		41	
15.0	48	air	60	air

Subjects breathed 99%O_2 during test period

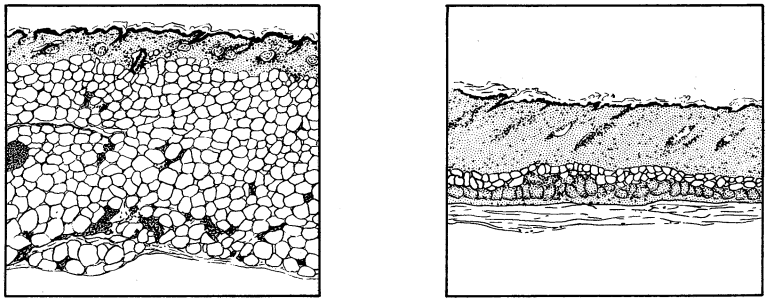


Fig. 11. Subcutaneous fat in a fat (A) and a lean (B) rat. (after Hausberger, F., Anat. Record, **135**: 113, 1939) The importance of percutaneous diffusion of lipophilic gases in obese subjects is apparent.

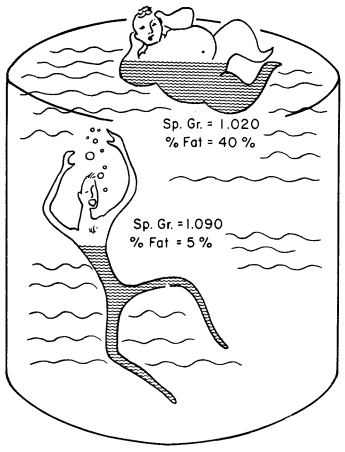


Fig. 12. The technique of underwater weighing (Principle of Archimedes),provides an assessment of body fat which is inversely proportional to the specific gravity of the body. (Original drawing by Dr. E. F. Osserman)

We may determine either loss of weight of the submerged body to assess volume, or measure the volume of the water displaced by the immersed body. Both techniques are now standard for determination of body volume. Since density is the quotient, W/V, it has been determined in thousands of examinations that body fat is inversely proportional to the density of the body as a whole. With assessment of body fat, accurate methods to determine TBW, and with radioisotopes to expedite knowledge of inert gas transport, we are in a new era of intriguing, scientific investigation **(Fig. 12)**.

10. SUMMARY : APPLICATIONS AND SUGGESTIONS FOR FOLLOW-UP STUDIES

1) Pressure *per se* can be applied for mass screening of individuals to ascertain patency of auditory tubes, sinal openings, as a presumptive test for prevalence of subclinical, upper respiratory tract infection.
2) Nitrogen in compressed air serves as a benign stress to elicit psychic instability and compensatory reserve to accomplish given tasks. Chamber confinement serves to elicit latent claustrophobia.
3) Exercise tolerance tests remain to be conducted in the 'gray' zone of 2 to 3 ATA and entail measurements of oxygen comsumption, carbon dioxide output and/or storage.
4) In tests of oxygen tolerance, pulmonary function is to be supplemented by a standard test of cardiovascular function.
5) Diffusion of helium, nitrogen, and other gases are to be investigated systematically, outward from subcutaneous tissues, and inward from a gas envelope enclosing the body.
6) The advantage during decompression of body immersion in water with appropriate garment protection, or of an oxygen envelope (2.82 ATA/or less), remains to be investigated. Higher ambient oxygen pressures are projected pending to tolerance tests of skin and subcutaneous tissues to high oxygen pressures.
7) Quantitative data referable to nitrogen, helium, and hydrogen transport are required to improve current decompression practice.
8) Determinations of body fat and water are complementary to studies of gas transport.
9) Clinical application of the colosed air cabinet is projected to detect trace substances eliminated from the body, and to determine basal metabolic rate under conditions that are truly basal.

REFERENCES

1) Banister, E. W., J. E. Taunton, T. Patrick, P. Oforsagd, and W. R. Duncan : Effect of oxygen at high pressure at rest and during severe exercise. Resp. Physiol. **10** : 74-84, 1970
2) Behnke, A. R., R. M. Thomson, and E. P. Motley : Psychologic effects from breathing air at 4 atomospheres pressure. Amer. J. Physiol. **112** : 554-558, 1935
3) Behnke, A. R., and L. A. Shaw : The use of

oxygen in the treatment of compressed-air illness. Nav. med. Bull. Washington. **35**: 61-73, 1937

4) Behnke, A. R., and T. L. Willmon: Cutaneous diffusion of helium in relation to peripheral blood flow and the absorption of atmospheric nitrogen through the skin. Amer. J. Physiol. **131**: 627-632, 1941

5) Behnke, A. R., B. J. Feen, and W. C. Welham: The specific gravity of hedlthy men. J. Amer. med. Assn. **118**: 495-498, 1942

6) Behnke, A. R: Effects of high pressures; Prevention and treatment of compressed-air illness. The Med. Clin. North America. pp. 1213-1237, (July) 1942

7) Bornstein, A., and Stroink: Über Sauerstoffvergiftung. Dtsch. med. Wschr. **38** 1495-1497, 1912

8) Fitzgerald, L. A: Cutaneous respiration in man. Physiol. Rev. **37**. 325-336, (July) 1957

9) Heath, T. H: *The works of Archimedes.* New York. Dover Publ. 1953, p. 258.

10) Jones, J. P., Jr., and A. R. Behnke: Prevention of dysbaric osteonecrosis. Clin. Orthoped. & Related Res. **130**: 118-128, (Jan-Feb., 1978)

11) Kagiyama, S: Studies on the prevention of caisson disease, on diving depth, resting time, and safe time allowable for stay on the bottom. J. Kumamoto Med. Soc. **X**(4): 1-18, 1934

12) Lesser, G. T., and G. Zak: Measurement of total body fat in man by simultaneous absorption of two inert gases. N. Y. Acad. Sci. **110**: 40-54, 1963

13) Meyer, K. H., and H. Hopff: Narkose durch indifferente Gase unter Druck. Physiol. Chem. **126**: 281-298, 1923

14) Nashimoto, I: The use of oxygen during decompression of caisson workers. In: *Decompression of Compressed Air Workers in Civil Engineering*. Ed. R. I. McCallum. Newcastle Upon Tyne, Oriel Press, 1967, pp. 217-227

15) Nashimoto, I., and Y. Mano: Experimental studies on oxygen decompression. In: 5th Int. Hyperbaric Conference. Eds. W. G. Trapp, E. W. Banister, A. J. Davison, and P. A. Trapp. Burnaby 2, Canada. Simon Fraser Univ. 1973, pp. 909-904

16) Richardson, H. F., B. C. Coles, and G. E. Hall: Experimental gas embolisom. I. Intravenous air embolism. Canad. med. Assn. J. **36**: 584, 1967

17) Shaw, L. A., A. C. Messer, and S. Weiss: Cutaneous respiration in man. Amer. J. Physiol. **90**: 107-118, 1929

18) Shaw, L. A., A. R. Behnke, A. C. Messer, R. M. Thomson, and E. P. Motley: The equilibrium time of gaseous nitrogen in the dog's body following changes in nitrogen tension in the lungs. Amer. J. Physiol. **112**: 545-553, 1935

（本稿は，昭和55年10月16日，名古屋にて開催されたOne Day Symposium「高気圧酸素治療の最近の進歩」における特別講演を基に寄稿されたものである。）

'he Good Old Days — Training Required = Turn Valve On or Off !!

この図は，Dr. Behnke が好んで引用される Illustration です。本稿の特定の部分を説明するためのものではありません。The Good Old Days!むかしは，装置の操作も人間も単純でした。Dr. Behnke のユーモアを十分にお楽しみください。（編集委註）