Whiteley, A. H. & McElroy, W. D. (1946). Denitrogenation of muscle and fat tissues of the anaesthetized cat. *Am. J. Physiol.* **146**, 229–240.
Whiteley, A. H., McElroy, W. D., Warren, G. H. & Harvey, E. N. (1944). Bubble formation in animals. V. Denitrogenation. *J. Cell. comp. Physiol.* **24**, 257–271.
Widdowson, E. M., McCance, R. A. & Spray, C. M. (1951). Chemical composition of the human body. *Clin. Sic.* **10**, 113–125.
Willard, G. (1953). Ultrasonically induced cavitation in water. *J. acoust. Soc. Amer.* **25**, 669–686.
Wismer, K. (1922). Supersaturated solutions of gases. *Trans. roy. Soc. Canad.* **16**, 217–227.
Yarbrough, O. D. & Behnke, A. R. (1939). The treatment of compressed air illness utilizing O_2. *J. ind. Hyg. Tox.* **21**, 213–218.

15

The Use of Multiple Inert Gas Mixtures in Decompression

A. A. BÜHLMANN

In collaboration with Keller it was demonstrated in Switzerland, France and the United States, between 1960 and 1962, that it is possible, both in the sea as well as in dry pressure chambers, for divers to attain depths of at least 1000 ft (31·2 ATA). Physical work was shown possible and unusually short decompression times were used (Keller & Bühlmann 1965). These experiments were based on limited theoretical and diving experience. In spite of the fact that some of the assumptions were false, the experiments were successful and the physical differences of the inert gases were exploited by using multiple gas mixtures to shorten the time of decompression. Controversy as to the cause of inert gas narcosis, as well as the unknown effect of ambient pressures on respiration and circulation, provided additional impetus at that time. Yet only five years later experimental diving to great depths has become a common practice in suitably equipped laboratories in many parts of the world.

At present the main interest is in exposures of long duration or saturation diving, which is necessary for the exploitation of the continental shelf. Whereas initially, experiments were made only to ascertain if man could reach depths of 650 to 1000 ft (20·7 to 31·2 ATA) with safe return to the surface, it has subsequently been demonstrated that it is also possible for him to live at these depths for several days. These prolonged exposures, in which the body becomes saturated with inert gases, have amplified our knowledge of the use of multiple gas mixtures for decompression and have permitted the more accurate application of theoretical concepts (Bond 1963; Hamilton, MacInnis, Noble & Schreiner 1966; Hartmann, Weiner, Fust & Seifert 1966; Cabarrou, Hartmann, Weiner, Alinat & Fust 1966; Krasberg 1966; Schreiner 1967; Bühlmann, Frey & Keller 1967; Waldvogel & Bühlmann 1968).

There are limits to the use of nitrogen as an inert gas for diving. An increased pressure of nitrogen above 230 to 300 ft (8 to 10 ATA) causes symptoms of euphoria and reduced mental and physical function and above 630 ft (20 ATA) loss of consciousness results. Individual tolerance varies considerably and may depend in some cases on the extent of muscular activity. The symptoms are often most marked at the beginning of the exposure and decrease gradually with time at depth. In resting conditions 10 to 14 ATA of nitrogen can be tolerated in a pressure chamber but in the sea the self-reliant diver should not breathe a partial pressure of nitrogen higher than 5 to 6 ATA (Carpenter 1955; Alvis 1960; Miller 1963; Hesser 1963; Bennett 1963, 1966).

A second limitation in the use of nitrogen is respiration itself. With the presence of turbulent flow, the resistance in the airways of the body and the valves of the diving apparatus increases with the higher pressures. For a given flow rate the onset of turbulence depends on the molecular weight of the gas. With helium, turbulence occurs at much higher pressures than with nitrogen or argon. According to our experiments, the flow resistance in the airways at 330 to 500 ft (11 to 16 ATA) with 90% helium amounts only to 60 to 70% of the flow resistance with 90% nitrogen (Spiegel 1963; Bühlmann 1963). Hence it follows that ventilation is considerably reduced when nitrogen-rich mixtures are breathed during deep diving. This is particularly noticeable during physical work, although in the resting state, carbon-dioxide retention is unlikely with normal lungs.

The use of oxygen, although ideal for decompression, must also be limited at high pressures due to the dangers of oxygen intoxication (Alvis 1960; Lambertsen 1963; Thomas & Neptune 1963). An oxygen partial pressure of 50 ft (2·5 ATS) can normally be tolerated for 2 to 3 hours but for prolonged exposures to pressure and with decompression times lasting for many hours or some days, the partial pressure of oxygen has to be reduced, on average, to less than 1 Atmosphere, and often to less than 0·7 ATS.

Dives to depths of 330 ft (11 ATA) or more and with bottom times of several hours or days can therefore only be achieved with the weak or non-narcotic helium as the inert gas and a reduced oxygen partial pressure. Hydrogen has a few advantages compared with helium but is used only in exceptional circumstances due to the risk of explosion when it is mixed with oxygen. Helium was used formerly, mainly in the United States Navy for diving to medium depths, when it was observed that after helium dives with short bottom times, longer decompression was required than when diving with nitrogen (Webster 1955; Workman 1963, 1966; Workman & Reynolds 1965; *USN Diving Manual* 1965).It was therefore concluded that the saturation of the body, and of some tissues in particular, occurred faster with helium than with nitrogen. This has since been confirmed by

measurements of the longest half-times (Bühlmann, Frey & Keller 1967).

The assumption of different saturation speeds suggests the possibility of shortening decompression time by advantageously combining these differences between helium and nitrogen. After saturation diving experiments it was found that the longest part of the decompression was above 300 ft (10 ATA), so nitrogen could be inhaled in a pressure chamber without risk. Theoretically the elimination of helium is accelerated because the helium gradient between tissue and blood is increased when breathing oxygen–nitrogen mixtures, while the uptake of nitrogen occurs more slowly. By gradually increasing the oxygen partial pressure after substituting nitrogen for helium, the nitrogen gradient can be kept low thereby further delaying the entry of nitrogen.

MOLECULAR WEIGHT AND SOLUBILITY RATIOS OF THE INERT GASES AND OXYGEN

In Tables 15.1 and 2 are shown the molecular weights and solubility factors in whole blood, water and olive oil. The different solubilities imply considerable differences in the mass of the dissolved gases with full saturation of all tissues. This is of significance both in regard to their toxic effects as well as for decompression.

In the case of decompression sickness, the available mass of gas controls both the volume and surface area of bubbles formed and this in turn determines the degree of tissue deformation. The size of the bubbles is also

TABLE 15.1
Molecular weights and solubility coefficients of various gases at 37 to 38°C (Dittmar & Grebe 1958, 1957)

	H_2	He	Ne	N_2	Ar	O_2
Molecular weight	2·016	4·003	20·183	28·016	39·444	32·00
Solubility, ml/ml at 760 mm Hg 37°C						
Water	0·0162	0·0087	0·0096	0·0127	0·028	0·02413
Whole blood	0·0149	0·0087	0·0093	0·0122	0·026	0·02356
Olive oil	0·0502	0·0150	0·0199*	0·0670	0·148	0·122

* Approximate

TABLE 15.2
Relationship of solubility coefficients

	N_2/H_2	H_2/He	N_2/Ne	N_2/Ar	H_2/He	Ar/H_2	Ar/He	Ar/Ne	Ar/N_2
Whole blood and watery tissues	0·819	1·402	1·312	0·469	1·71	1·745	2·988	2·796	2·131
Pure fat as oil	1·301	4·467	3·367	0·453	3·43	2·874	9·867	7·438	2·209

dependent on the gas volume due to the diffusion of oxygen, carbon dioxide and other inert gases. In this connection, helium, as a light gas, is preferable to hydrogen and with a heavy gas, nitrogen is preferable to argon. Neon would be as suitable as helium.

The great variation in the solubility ratios of these gases in oil and water (Table 15.3) influences the speed of saturation and desaturation of the fatty

TABLE 15.3
Partition coefficients at 37 to 38°C oil/water

	H_2 3·100	He 1·724	Ne 2·073	N_2 5·275	Ar 5·286	O_2 4·641	
Relationship	N_2/H_2 1·70	N_2/He 3·06	N_2/Ne 2·54	N_2/Ar 0·998	Ne/He 1·20	H_2/He 1·80	O_2/He 2·69

tissues during compression and decompression. The partition coefficient is practically identical for nitrogen and argon. For hydrogen the coefficient is smaller than for either of these gases but larger than the values for helium and neon. Due to these ratios, the rate of saturation of helium in a purely fat tissue is approximately three times faster than nitrogen. This would therefore apply to the subcutaneous fat. The pressure equilibration for hydrogen in a fatty tissue is however only 1·7 times more rapid than nitrogen. With neon, nitrogen and argon there are no significant differences. For very fatty tissues hydrogen with a slightly slower saturation speed, would have certain advantages over helium.

The different solubility coefficients of these inert gases in oil and water, as far as the speed of the pressure equilibration in watery tissues is concerned, are however of no importance. With virtually equal solubility in blood and tissue the conditions correspond to a diffusion limited system. This would be the case for very poorly perfused and capillarized tissues with long diffusion routes. Under these conditions the rate of pressure equilibration depends on diffusion, which is governed by the molecular weights of the gases. The saturation speed of two gases are in inverse proportion to the square roots of their molecular weights (Table 15.4). Thus an approximately 3·7 times faster saturation and desaturation will occur with hydrogen compared with nitrogen for watery and poorly perfused

TABLE 15.4
Square roots of molecular weights

	H_2 1·42	He 2·00	Ne 4·495	N_2 5·29	Ar 6·32	O_2 5·66	
Relationship	N_2/H_2 3·727	N_2/He 2·645	N_2/Ne 1·178	N_2/Ar 0·837	Ne/He 2·246	He/H_2 1·409	N_2/O_2 0·935

tissues. Helium will be approximately 2·6 times faster than nitrogen and no significant differences may be expected between neon, nitrogen and argon.

The physico-chemical conditions show that helium is preferable to hydrogen due to its low solubility ratio in watery and fatty tissues. The saturation rate of the watery tissues is faster with hydrogen, while that of fatty tissues is faster with helium but for the whole body this difference should not be very significant. Neon would be similar to helium with regard to the dissolved gas quantities, however, the saturation speed of the watery tissues would not be any faster than with nitrogen. Argon is the worst selection for decompression because of its fast solubility and because it shows, so far as the saturation rate is concerned, little difference from nitrogen. It may therefore be concluded that a practical advantage by using different inert gases may probably be obtained using helium and nitrogen but that no great advantage may be expected from the use of neon or argon. The gases suitable for multiple inert gas decompression techniques are therefore reduced to helium and nitrogen.

Saturation and desaturation occur according to an exponential curve and the inert gas uptake and elimination is calculated, in the main, with the aid of a spectrum of various half-time tissues. Based on the above

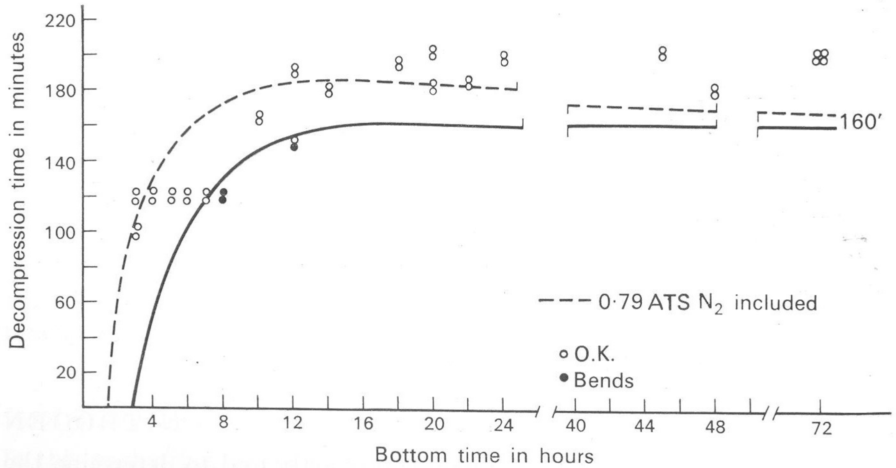

FIG. 15.1. The results of 40 experiments are presented. Bottom times with 80% helium, 20% oxygen at 100 ft (4 ATA) varied from 3 to 72 hours (abscissa). Decompression times breathing 100% oxygen are given in minutes on the ordinate. The line in dashes represents the minimum decompression times for a half-time of 160 min starting with a normal nitrogen partial pressure of 0·79 ATS. This nitrogen pressure in the tissue decreases with a half-time of 420 min during exposure on the bottom. The unbroken line represents the true minimum decompression time for a half-time of 160 min in the absence of nitrogen throughout the entire experiment

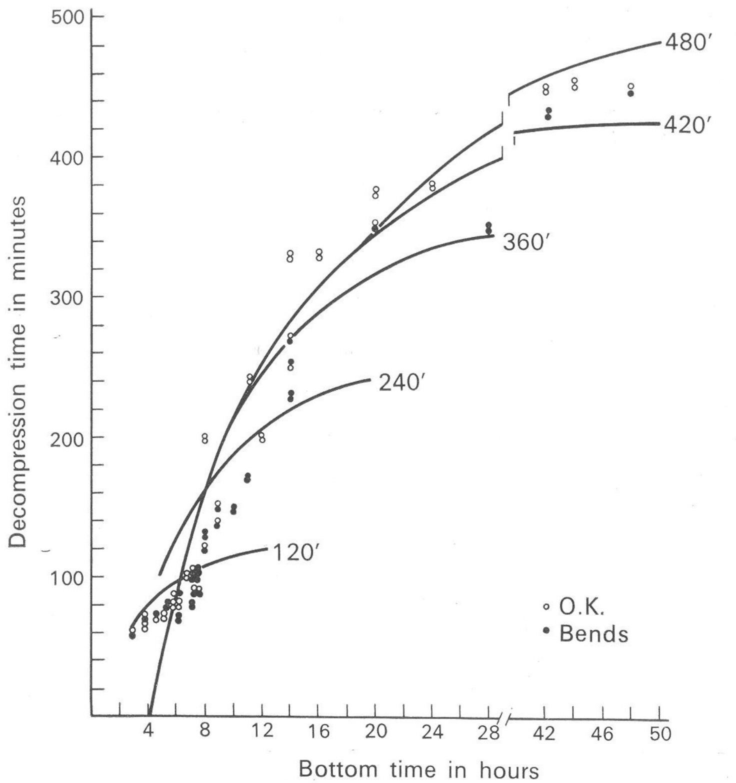

FIG. 15.2. The results of 80 experiments are presented. Bottom times with compressed air at 100 ft (4 ATA) varied from 3 to 48 hours (abscissa). Decompression times breathing to 100% oxygen are given in minutes on the ordinate. The lines represent the minimum decompression times for half-times ($t_{1/2}$) of 120 to 480 min calculated with a surfacing ratio of 1·6 to 1·0

physico-chemical differences of the inert gases it may be expected that the tissue of longest half-time would be two to three times longer for nitrogen than for helium, both in the case of a very fatty or a rather watery and poorly diffused tissue.

HALF-TIME SPECTRUM FOR HELIUM AND NITROGEN

In order to calculate the decompression exactly and to determine the optimal time for the change of inert gas, it is essential to know the longest existing half-time. Assuming that the same half-times are valid for saturation and desaturation the longest half-times were determined by finding the minimal decompression time when breathing 100% oxygen after bottom times of hours and days at 100 ft (4 ATA) breathing either 20/80 oxygen–helium or alternatively oxygen–nitrogen (Figs. 15.1, 2). In Fig. 15.1 is shown that no bends occur after an exposure to a helium partial pressure of 3·2 ATS, provided the decompression is performed on the basis of 160 to 180 min as the longest half-time, the initial nitrogen pressure of 0·8 ATS is considered in all tissues and assuming, in accordance with Haldane and Priestly (1935), that the supersaturation factor is 1·6. The longest half-time of 160 to 180 min can be explained because after an exposure of 24 hours a saturation of more than 99% is reached, and so far as is known no longer times are required for decompression after longer exposures.

The corresponding experiments with air indicated that 64 to 72 hours were required for complete saturation and the longest half-times for nitrogen were 420 to 480 min. This difference between helium and nitrogen is in agreement with the theoretical predictions for a diffusion-limited system with equal gas solubility in blood and tissue and a delayed saturation and desaturation of very fatty tissues due to the different partition coefficients of the gases. These experiments are, however, only representative of the slowest tissues and do not answer the question of whether the varying saturation rate of helium and nitrogen are due to their different solubility rates in blood and fat tissues or to their different molecular weights.

The predilection of the bends for the knee and ankle joints, with either helium or nitrogen, as the tissues in ligaments, joint capsules and menisci are mainly water (Hempleman 1963; Bühlmann, Frey & Keller 1967; Bühlmann & Waldvogel 1967), suggests involvement of a diffusion-limited system. Whether saturation and desaturation of a 'fast' tissue with helium also takes place two to three times more rapidly than with nitrogen cannot be determined from these experiments. In practice this is not so important for deep diving as for prolonged exposures since the decompression is mainly determined by the tissues of longest half-time. Therefore, the use of nitrogen results approximately in a threefold prolongation of the half-time spectrum.

THE USE OF OXYGEN, HELIUM AND NITROGEN FOR SHORT AND LONG EXPERIMENTS AT MEDIUM AND GREAT DEPTHS

General principles

In this evaluation, exposure times of up to 2 hours are designated short experiments whereas exposure times of at least 6 hours (i.e. a 75% saturation of the slowest tissues with helium) are termed long experiments. This definition does not refer to the duration of the whole dive but only to the time at maximum pressure. Exposures to pressures up to 330 ft (11 ATA) are considered as shallow or medium depths.

For short decompression times from shallow depths, the change of inert gas from helium to nitrogen has no practical advantage, as far as decompression is concerned, over performing the whole dive with air. However, the different saturation and desaturation times of helium and nitrogen do permit a considerable reduction of decompression time for exposure times exceeding 1 hour. This also applies to all dives to great depths.

The most suitable time for the change from helium to nitrogen varies according to the type of exposure. The higher the helium saturation of the slow tissues, the later occurs the change to nitrogen. In this way is avoided the absorption of further nitrogen by the slow tissues. The progressive increase during the decompression of the nitrogen partial pressure of the breathing mixture has particular advantages after dives for short periods to great depths, but it requires special equipment or an increased risk of operational errors may result.

The progressive increase of the oxygen partial pressure of the breathing mixture also shortens decompression time. With long exposures at great depths the oxygen partial pressure has to be markedly reduced and this therefore needs to be increased during ascent or hypoxia will occur. If the entire dive lasts but a few hours, the diver may breathe the prepared breathing mixture through a mask, or better, through a mouthpiece. It has proved convenient, experimentally, to simplify the procedure for long exposures by not mixing gases in prepared cylinders but carry out the entire procedure in a pressure chamber directly supplied with helium, oxygen and compressed air. Thus it is possible to reduce the oxygen partial pressure to the desired value by compressing with helium and to increase it again during decompression by direct addition of oxygen.

The change from helium to nitrogen is made quite easily by flushing the system with air. For excursions into the sea the diver only requires a supply of pre-mixed gases for his breathing apparatus or a hookah system can be employed in which the diver breathes the habitat or chamber gas through hoses. For safety reasons, a maximum oxygen partial pressure of 50% was used in the pressure chamber during the following examples of decompression from long exposures. In this way a certain reserve is available for emergency in which the final decompression can be reduced by using 100% oxygen. In order to be quite safe 100% oxygen should only be given through a mask while the chamber is filled with either oxygen–helium or oxygen–nitrogen mixtures.

Calculation of the saturation and decompression

Descent time. For the calculation of the inert gas absorption in different tissues, the descent time must also be taken into account, especially in dives to great depths for short bottom times. The descent time should therefore be as short as possible. If this is technically difficult, the descent may be made with 100% oxygen to 50 ft (2·5 ATA) followed by air to about 300 ft (10 ATA) at which occurs the change to the oxygen–helium mixture with a reduced oxygen partial pressure. For very long exposures, however, the descent time may be disregarded. Thus in all the experiments to be described the descent time is *not* included in the exposure time indicated. The descent time for short experiments amounted to only a few minutes but in those involving at least 6 hours at depth, descent times of 20 min for exposures to 330 ft (11 ATA) and 30 min for exposures to 720 ft (23 ATA) were taken into account in computation of inert gas uptake.

Summation of helium and nitrogen. In the following examples an initial nitrogen partial pressure of 0·8 ATS was assumed for all tissues, because of their saturation with normal atmospheric air. Since the pressure chamber is filled with air and, from the start, the pressure is increased with helium, this nitrogen partial pressure remains constant until the decompression is started. A partial elimination of nitrogen during the exposure to the oxygen–helium mixture occurs only when this mixture is given through breathing apparatus, as with the short exposures, or when the pressure chamber is flushed first with oxygen or oxygen–helium mixture.

For the remaining experiments, the constant nitrogen partial pressure of 0·8 ATS must be added for all tissues to the helium partial pressure which is accumulating during the exposure. We assume, according to the results of the saturation experiments at 100 ft (4 ATA), a 2·6 times faster saturation and desaturation with helium for all tissues. The summation of both inert gases occurs in a tissue with a helium half-time of 180 min and a nitrogen half-time of 480 min. Whether this summation is also correct for tissues of shorter half-time remains doubtful. However, in practice, it is of secondary importance for decompression from prolonged exposures. During the decompression with oxygen–helium, the 0·8 ATS nitrogen partial pressure is reduced but this is only of quantitative importance for slow tissues and an oxygen–helium decompression lasting for several hours or even days.

Variation of the half-time with physical activity. For dives with a total duration of 12 hours, including decompression time, a longest half-time is used of 180 min for helium and 480 min for nitrogen. However, there is little doubt that muscular activity with an increase of cardiac output would bring about a variation of the perfusion ratios and, consequently, a reduction of the half-times for certain tissues. This does not necessarily mean that the longest half-time would decrease and that the spectrum would remain limited. On the contrary, it is probable that during sleep, with a reduction of the cardiac output (in our experiments the pulse sank at night to a value of 40 to 50/min), the longest half-times increase. During the first decompression stages, as well as after the change from helium to nitrogen, an approximate adjustment may be achieved by reducing the inert gas elimination by 10%, until the fast tissues, with a helium half-time up to 15 min, are approximately equilibrated with the respiratory gas pressure. In experiments of more than 12 hours' duration this possibility was taken into consideration and at night the longest half-times were taken as 240 min for helium and 640 min for nitrogen. During the day, with the start of physical activity, the half-time spectrum was reduced again to 180 min and 480 min respectively.

Variation of the supersaturation factors. It has been learned by experience that the supersaturation factor of 1·6 by Haldane is too large for very deep dives (Hamilton, MacInnis, Noble & Schreiner 1966; Workman 1966; Schreiner 1967; Bühlmann & Waldvogel 1967). It is probable that, under such conditions, the same factor does not apply for all tissues. The supersaturation factor has to be drastically reduced, especially for the slow tissues in which decompression sickness occurs most easily, such as muscles and joints. In the following experiments for dives to great depths with an exposure of at least 1 hour, the decompression corresponds to the supersaturation factor given in Fig. 15.3. For example, the first step is reached

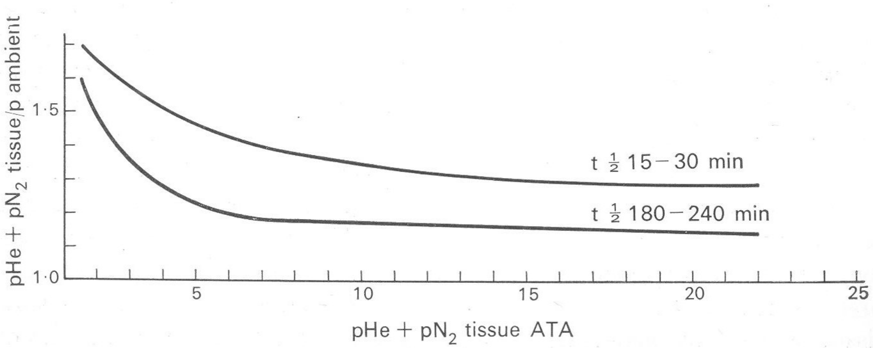

FIG. 15.3. Tolerated supersaturation factor (ordinate) for fast tissues with helium half-times to 30 min and for slow tissues from 180 to 240 min depending on the inert gas pressure added up in the respective tissues (abscissa). The stages of the decompressions after exposures of 6 to 72 hours were calculated according to these supersaturation factors

after adding the inert gas partial pressures of helium and nitrogen and dividing the sum by 1·3 in cases where the fast tissues only are saturated. This factor is reduced to 1·15 for fully saturated tissues with the longest half-times. At lower tissue pressures the supersaturation factor may again be increased. Thus in experiments to be discussed the final decompression was calculated on an approximate factor of 1·5.

Corrections for possible differences between respiratory, alveolar and

arterial inert gas pressures. As a rule, the arterial inert gas pressure, which is the determining factor for saturation and desaturation of the tissues, is considered equal to that in the inspired air. Obviously, the contamination of the breathing apparatus and pressure chamber caused by a change of inert gas for example from helium to nitrogen has to be measured and taken into account for the calculation. In spite of flushing after the change at 200 ft (7 ATA) from oxygen–helium to air, it is hardly possible to decrease the remaining helium concentration to less than 4 or 5%. Underestimation of such contamination may result in a considerable miscalculation of the decompression required. Since physiologically there is a venous admixture with the cardiac output of 3 to 6%, it should also be theoretically considered that, at the beginning of a decompression stage, the arterial inert gas pressure is rather higher than that of the inspired gas mixture. This especially applies after saturation of the fast tissues on the first decompression stop. The difference between the alveolar and arterial helium pressure diminishes rapidly as the greater part of the venous return comes from the well-perfused tissues with corresponding short half-times, the inert gas pressure of which is assimilated rapidly with the alveolar.

Similar conditions result from the change from helium to nitrogen, in the course of which the mixing time, lasting several minutes in the lungs, also causes a rather higher arterial helium pressure than that inspired. These factors may cause a temporary delay in the effects of the full pressure gradient. Experiments with 16 divers working hard on a bicycle ergometer during a 3 hours' exposure at 115 ft (4·5 ATA), while breathing 11% oxygen, 71% helium, 18% nitrogen, caused no decompression sickness after a decompression time calculated using a longest helium half-time of 180 min. The same results were found in additional experiments with 18 divers, who worked both during exposure and decompression time (Bühlmann & Matthys, in press). With the rapid decrease of inert gas pressure in the fast tissues, these factors, however, soon become quantitatively insignificant. If the effect of the venous admixture on the arterial inert gas pressure is not included, the calculation of the decompression is incorrect only for short periods and in certain phases, but has no cumulative effect on the total decompression.

A further adjustment should theoretically be necessary where the inert gas equilibrium between alveolar gases and capillary blood of the lungs is not complete. This could happen at great pressure differences in the beginning of a decompression stop but this has yet to be proved. However, as with the venous admixture, the effect of an incomplete pressure equilibration decreases more and more with the lowering of the inert gas pressure in the fast times. Consequently, this miscalculation, possible in theory, can in practice be disregarded.

Summary of the principles used in the calculations. Unless otherwise indicated, the nitrogen pressure in all tissues at the start of the dive, as well as in the breathing mixtures throughout the exposure, remains constant at 0·8 ATA. This pressure is added to the helium pressure in all tissues. The contamination of the oxygen–nitrogen mixture with helium during the inert gas change from helium to nitrogen is measured and taken into consideration when calculating the effective pressure gradient for helium. The half-time spectrum for dives with a total duration of more than 12 hours is changed during the night to 240 min for helium and to 640 min for nitrogen. It is shortened again to 180 min and 480 min respectively in the morning with the start of physical activity. The effects of venous admixture are taken into account by reducing the helium elimination by

TABLE 15.5

Mixed gas decompression after helium dives

Bottom times up to 120 min

ATA	*Bottom time (min)*	*Decompression (min)*	*No. decompressions*	*No. subjects*
5	120	20	7	7
11	60	a 105	9	9
		b 385	4	4
16	30	220	6	6
16	60	1200	6	6
21	20*	230	5	5
26	10	270	2	2
31	5*	270	4	2
31	120	3000	2	2
			45	16 different subjects

Bottom times from 4 to 72 hours

ATA	*Bottom time (hours)*	*Decompression time (hours)*	*No. decompressions*	*No. subjects*
4	72*	a 3	8	5
		b 4	—	—
		c 6	8	8
11	6	22	6	5
16	6	40	6	5
16	72	49	—	—
23	6*	52	22	12
23	2 × 6†	60	6	5
23	68*	64 & 68	7	4
31	4	64	2	2
			65	33 different subjects

* Carried out in the pressure chamber as well as with swimming excursions.
† Carried out twice for 6 hours within 48 hours, partly in the water.

10% on the first decompression stop and again at the start of the inert gas change. The supersaturation factor is reduced according to the degree of saturation of the fast and slow tissues and is increased again during decompression when lower inert gas pressures are reached. The return to atmospheric pressure occurs with a factor of approximately 1·5. The decompression is carried out continuously only for short exposures and in stages or stops during long dives, each stop lasting from 15 to 120 min.

Practical examples of inert gas changing during decompression

Dives with exposure times to 120 min. All the decompressions to be described, with the exception of two experiments, were carried out successfully by at least 4 divers without serious symptoms of oxygen poisoning or decompression sickness (Table 15.5). These decompression schedules contained a safety factor, being in excess of the minimal times calculated. Decompressions with shorter times occurred without accident, even after exposures lasting for several hours to pressures of 720 ft (23 ATA).

Exposures to 330 ft (11 ATA). Dives with a total duration of a few hours can be made with prepared gas mixtures and open or semi-closed respiratory apparatus. With this technique, the inert gas change can take place at once. In addition, the short decompression times after short exposures permit the combination of the change from helium to nitrogen with high oxygen concentrations. If the oxygen is given through a mouthpiece, the concentration can be increased to 100% without any great risk provided the decompression is performed in a pressure chamber filled with inert gas. This combination permits the shortest decompression times.

In Fig. 15.4 is illustrated such a combination for an exposure of 120 min at 130 ft (5 ATA). The oxygen partial pressure amounts to 2 ATS during the exposure and also during the decompression. The change of inert gas from helium to nitrogen takes place during the exposure to 5 ATA. This is because nitrogen can be breathed without difficulties at 130 ft and this permits elimination of helium. The nitrogen partial pressure in a tissue with, say, a 50 min half-time, decreases during the helium phase of the exposure from 0·8 ATS to approximately 0·3 ATS and increases during the nitrogen phase to 1·65 ATS. The helium partial pressure in the corresponding tissue with a helium half-time of 20 min increases to 2·7 ATS during the first phase and decreases again to approximately 0·4 ATS during the nitrogen phase. This results in a total inert gas pressure of only 2 ATS. By breathing oxygen for 15 min the helium and nitrogen pressures are decreased to the critical value of 1·6.

If the experiment was performed with 60% nitrogen as the inert gas, a nitrogen partial pressure of approximately 2·6 ATS would occur in the same tissue after 120 min and this pressure would only decrease to the

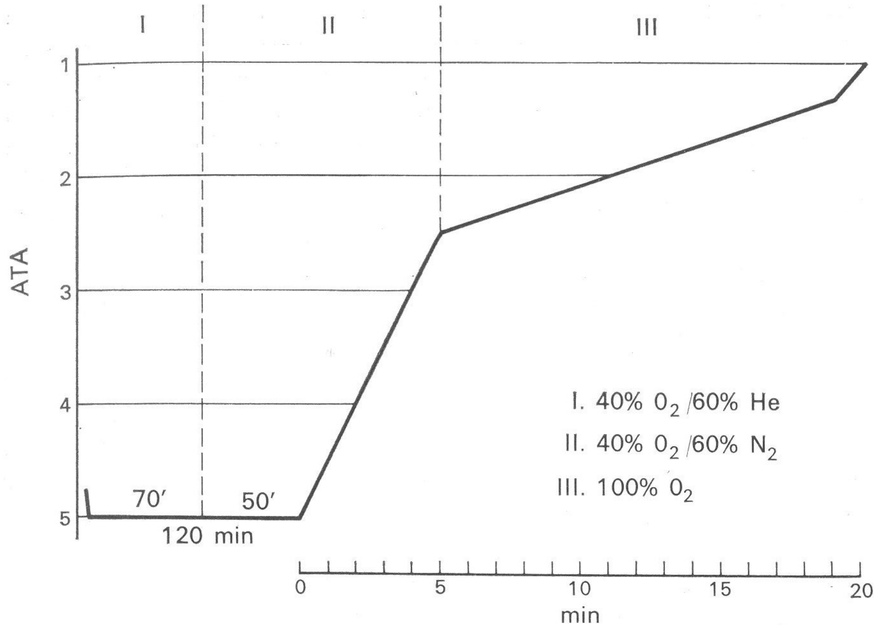

FIG. 15.4. Bottom time 120 min at 130 ft (5 ATA) with 40% oxygen, 60% helium (P_{He} = 3 ATS). Inert gas change from helium to nitrogen after 70 min. Decompression time 20 min with inhalation of 100% oxygen from 50 ft to surface (2·5 to 1·0 ATA).

critical value after breathing oxygen for 40 min. Owing to the use of the inert gas change, there is a 25-min saving of decompression time.

However, if the diver breathes 60% helium during the whole exposure, the 20-min tissue is almost saturated after 120 min which, together with the remaining nitrogen, results in a total inert gas pressure of some 3·2 ATS in this tissue. In this case breathing oxygen for 20 to 25 min would be sufficient to decrease the inert gas pressure in the tissue to 1·6 ATS.

Compared with the use of helium alone, the saving of decompression time by the inert gas change amounts to 10 to 15 min. If a mixture of 40% oxygen, 44% helium and 16% nitrogen is breathed during the first phase (in order to keep the nitrogen pressure constant at 0·8 ATA), the decompression using 100% oxygen lasts 20 min and is not much longer than in the experiment illustrated.

The differences described in the experiments above show that the change of inert gas from helium to nitrogen for exposures to shallow depths is of advantage in shortening the decompression time only after short bottom times to approximate 120 min. For longer exposures, at greater depths, the inert gas change takes place only during the decompression and is moved more and more towards the final phase of decompression.

For safety, the oxygen concentration should be reduced at medium depths, which results in higher values for the inert gas partial pressure. In Fig. 15.5 are shown two possibilities of decompression for an exposure of 60 min at 330 ft (11 ATA). The oxygen partial pressure amounts to 1·65 ATS during the period at depth and also increases for a short time to over 2 ATS during decompression. In version (a) with prepared gas mixtures and the use of breathing apparatus, the diver breathes air between 200 to 115 ft (7 to 4·5 ATA), 50% oxygen and 50% nitrogen between 115 to 50 ft (4·5 to 2·5 ATA) and thereafter 100% oxygen. In this experiment the decompression amounts to 105 min and it could be carried out in the sea.

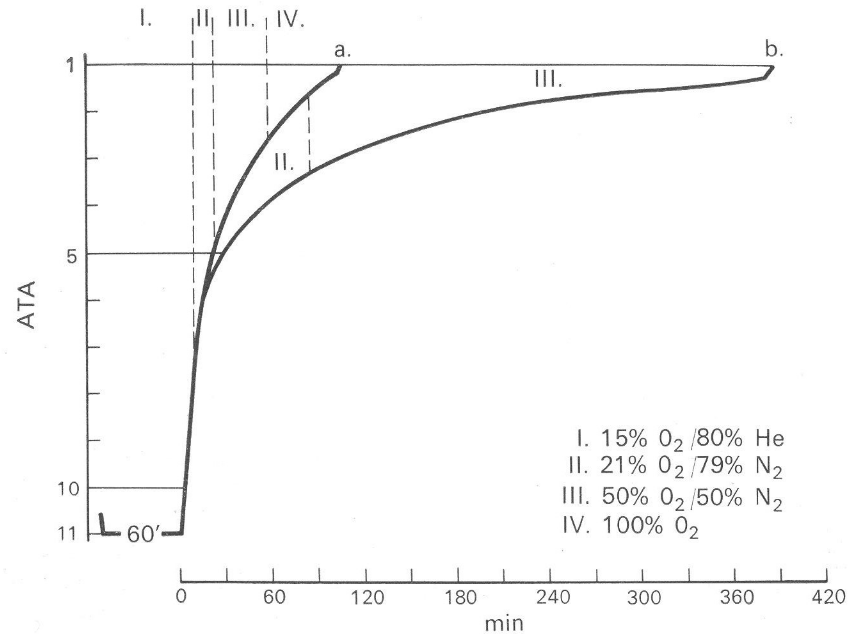

FIG. 15.5. Bottom time 60 min at 330 ft (11 ATA) with 15% oxygen, 85% helium (P_{He} = 9·35 ATS). Version (a)—inert gas change from helium to nitrogen with different oxygen partial pressures and 100% oxygen at pressures less than 50 ft (2·5 ATA). Total decompression time 105 min. Version (b)—air breathing from 120 to 35 ft (6 to 2·5 ATA) following 50% oxygen/50% nitrogen. Total decompression time 385 min

If decompressing in a pressure chamber, version (b) is preferable. The phase in which air is breathed is extended to 82 ft (3·5 ATA) after which the oxygen concentration is increased to 50%. In this version the oxygen partial pressure never exceeds 2 ATS and the total decompression time amounts to 385 min.

Exposures from 500 to 1000 ft (16 to 31 ATA). In Fig. 15.6 is shown an

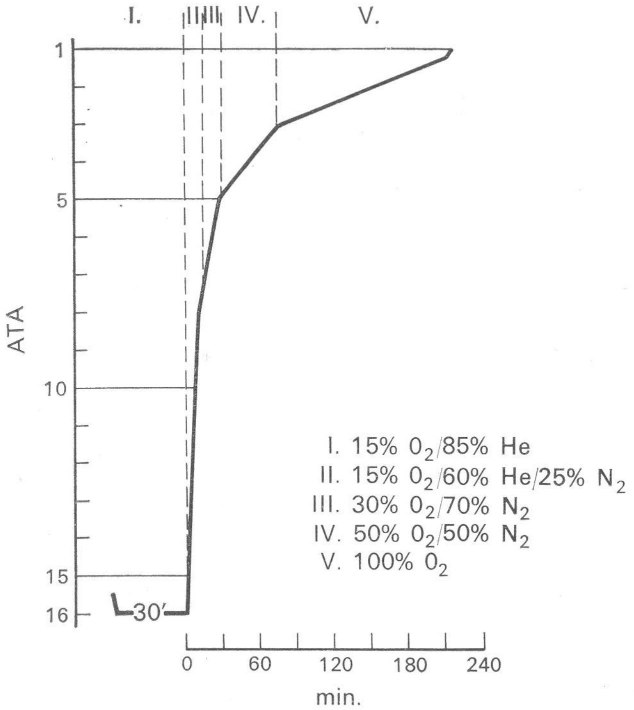

FIG. 15.6. Bottom time 30 min at 500 ft (16 ATA) with 15% oxygen, 85% helium (P_{He} = 13·6 ATS). Carried out in the pressure chamber with prepared gas mixtures and breathing apparatus. Adding stepwise oxygen and nitrogen, final stage of decompression with oxygen. Total decompression time 220 min

example of a short decompression for a 30-min exposure at 500 ft (16 ATA) with prepared gas mixtures in which the oxygen partial pressure amounts to 2·4 to 2·5 ATS. The final part of the decompression from 66 ft (3·0 ATA) is carried out breathing 100% oxygen, the entire decompression time being 220 min. With longer exposure times, however, the oxygen partial pressure must be reduced.

In Fig. 15.7 is shown an example of decompression from an exposure of 60 min at 500 ft (16 ATA) with a descent time of 20 min. The ascent, with the change from oxygen–helium to air and later to 50% oxygen and 50% nitrogen, in principle corresponds to version (b) of Fig. 15.5; the decompression being carried out in a pressure chamber without the divers wearing breathing apparatus. The oxygen pressure then amounts to less than 1 ATS during the maximum pressure exposure and remains below 2 ATS during the decompression. However, the total decompression time is 1200 min, and this is too long for an exposure of 60 min with a descent

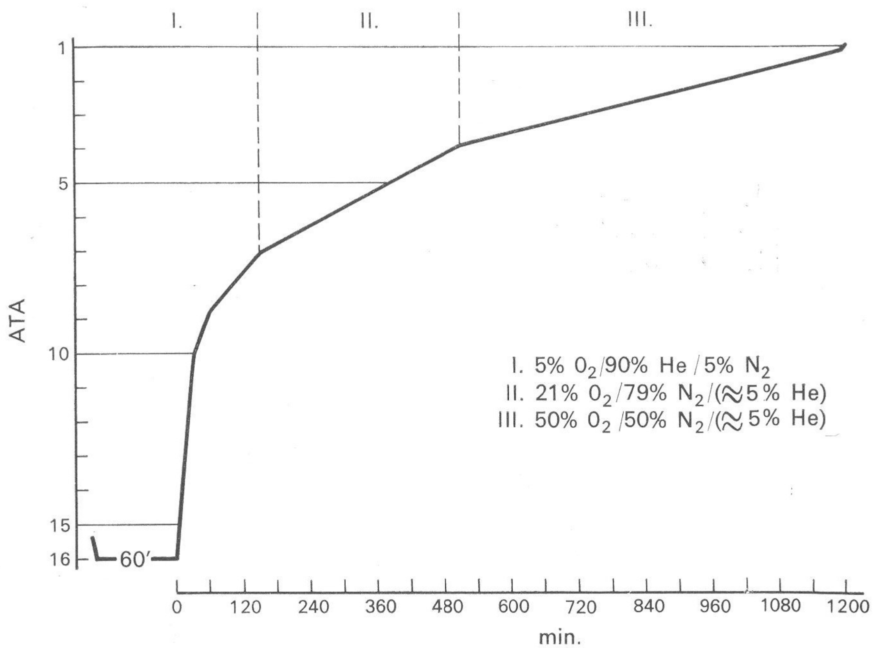

FIG. 15.7. Bottom time 60 min at 500 ft (16 ATA) with 5% oxygen, 90% helium, 5% nitrogen (P_{He} 14·4 ATS, P_{N2} = 0·8 ATS). Carried out in the pressure chamber without prepared gas mixtures and without breathing apparatus. Inert gas change from helium to nitrogen at 200 ft (7 ATA) under air breathing, 50% oxygen at pressures less than 100 ft (4 ATA). Total decompression time 1200 min (20 hours)

time of 20 min. Such a long decompression can in practice only be performed in a comfortably equipped pressure chamber. Some shortening of the decompression could be obtained by using higher oxygen partial pressures as in Fig. 15.7 but even then a decompression time of 600 to 800 min must be accepted with the risk of oxygen intoxication.

The above examples demonstrate that dives to great depths with decompressions of a few hours, to permit diving during daylight, are only possible with exposures of less than 60 min and the divers breathing relatively high oxygen pressures. Nevertheless, such experiments are of historical interest for as early as 1960 to 1962 similar dives were actually carried out, not only in pressure chambers but also in the sea (Keller & Bühlmann 1965). The oxygen pressure in such experiments was always greater than 2 ATS, the breathing gases were inhaled through mouthpieces and the decompression was a continuous ascent rather than in stages. Using the same gas mixtures almost the same decompression time of 270 min was sufficient for a 10-min exposure at 825 ft (26 ATA) (Figs. 15.8, 9).

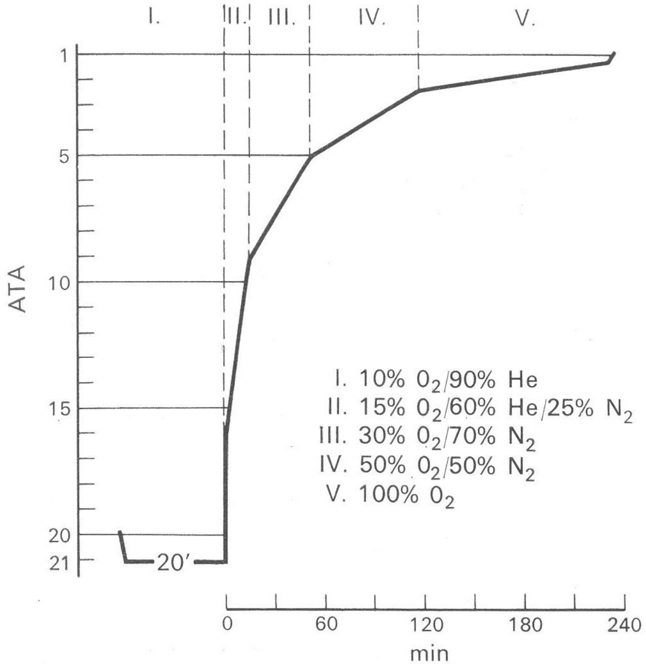

FIG. 15.8. Bottom time 20 min at 660 ft (21 ATA) with 10% oxygen, 90% helium (P_{He} = 18·9 ATS). Carried out in the pressure chamber and in water with prepared gas mixtures and breathing apparatus. Stepwise increase of oxygen to 100%. From 500 to 260 ft (16 to 9 ATA) helium as well as nitrogen in the gas mixture, thereafter nitrogen only. Total decompression time 230 min

These deep diving experiments show that for exposures longer than 60 min, as would be required for significant practical work to be done, the decompression would be uneconomic in length and require expensive equipment such as submersible pressure chambers. Using such equipment, however, even longer decompression times are feasible. For practical requirements the results of such long duration exposures to great depths, as have been carried out by various groups in the past years, are of significant interest.

Exposure times of 4 to 72 hours

At depths equivalent to 330 ft (11 ATA). In Fig. 15.10 are illustrated various possibilities of diving to 100 ft (4 ATA) for several days. In version (a) the nitrogen is eliminated from the pressure chamber by flushing and the divers breathe 20% oxygen and 60% helium permitting a helium saturation of 3·2 ATS. In version (b) the normal nitrogen pressure

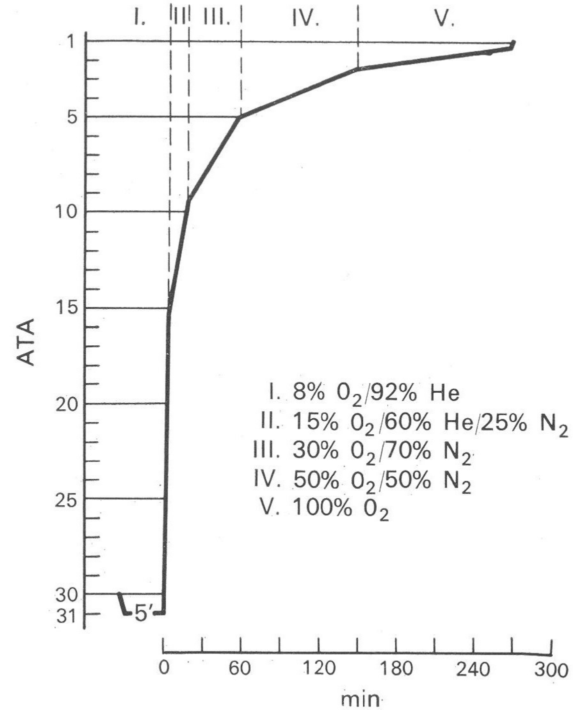

FIG. 15.9. Bottom time 5 min at 1000 ft (31 ATA) with 8% oxygen, 92% helium (P_{He} = 28·5 ATS). Carried out in the pressure chamber and in water with prepared gas mixtures and breathing apparatus. Identical procedure as in Fig. 15.8. Total decompression time 270 min

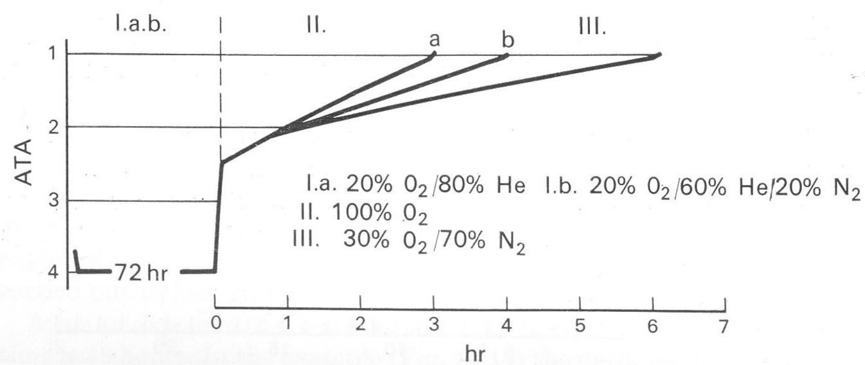

FIG. 15.10. Decompression after complete saturation at 100 ft (4 ATA). Version (a)—the divers breathe 20% oxygen, 80% helium (P_{He} = 3·2 ATS) and, during decompression, 100% oxygen. Decompression time with 100% oxygen is 3 hours. Version (b)—the normal nitrogen pressure remains constant at 0·8 ATA during the exposure. Decompression time with 100% oxygen is 4 hours. With 30% oxygen, 70% nitrogen the decompression requires 6 hours in both versions

of 0·8 ATS remains constant throughout the exposure and together with a helium partial pressure of 2·4 ATS, amounts to the same inert gas pressure in all tissues of 3·2 ATS. The decompression, using 100% oxygen, amounts to 3 hours and 4 hours respectively. If the decompression is performed with 30% oxygen and 70% nitrogen, 6 hours are necessary which is economic in relation to the long exposure.

After full saturation of the body with a nitrogen pressure of 3·2 ATS, 8 hours are required for the decompression breathing 100% oxygen (Fig. 15.2). The decompression with 30% oxygen and 70% nitrogen would take 17 hours. Such a dive, with complete helium saturation was carried out in the dry chamber as well as in the sea. This example illustrates, for long exposures at shallow depths, the decompression advantages of the use of helium as well as changing the inert gas.

Shown in Fig. 15.11 is the decompression for a 6-hour exposure at 330 ft (11 ATA) using an 83% helium mixture. In contrast to the decompression from an exposure of only 1 hour (Fig. 15.5) it is no longer economical during decompression to change to air after 6 hours and then to 50% oxygen and 50% nitrogen. It is better to increase only the oxygen pressure, by

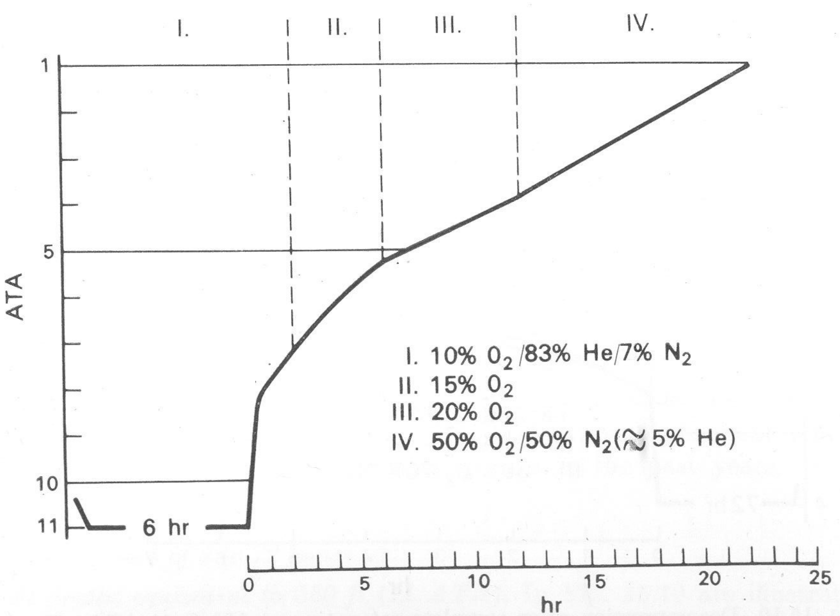

FIG. 15.11. Bottom time 6 hours at 330 ft (11 ATA) with 10% oxygen, 83% helium, 7% nitrogen (P_{He} = 9·1 ATS, P_{N2} = 0·8 ATS). Stepwise increase of oxygen concentration, inert gas change from helium to nitrogen only during the final phase at pressures less than 100 ft (4 ATA). Total decompression time 22 hours

stages, and to substitute nitrogen for helium only during the terminal phase. Decompression then takes 22 hours. As this example demonstrates, a dive of less than 24 hours with a bottom time of several hours is only possible to about 330 ft (11 ATA).

At depths equivalent to 500 to 1000 ft (16 to 31 ATA). After 6 hours at 500 ft (16 ATA) with 91% helium, the decompression with a stepwise increase of the oxygen partial pressure and a change from helium to nitrogen during the final phase requires 40 hours decompression (Fig. 15.12). Decompression after full saturation at 16 ATA does not take much longer but only 49 hours (Fig. 15.13).

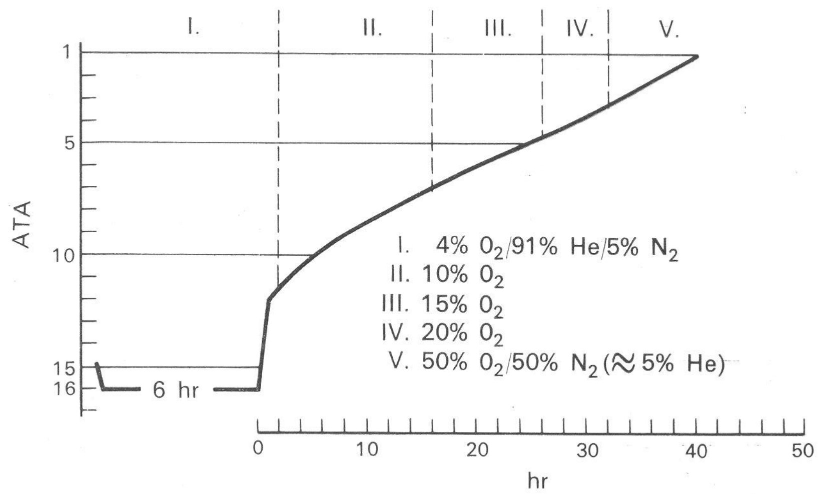

FIG. 15.12. Bottom time 6 hours at 500 ft (16 ATA) with 4% oxygen, 91% helium, 5% nitrogen (P_{He}, 14·6 ATS, P_{N2} = 0·8 ATS). Stepwise increase of oxygen concentration, inert gas change from helium to nitrogen only during the final phase at pressures less than 75 ft (3·3 ATA). Total decompression time 40 hours

Knowledge of the behaviour of the diver during long exposures in the pressure range from 20 to 23 ATA is of great practical importance for exploitation of the continental shelf. Various experiments were therefore carried out by our group in this pressure range (Table 15.5).

After an exposure of 6 hours at 23 ATA, the minimal safe decompression time is 43 hours. In the example (Fig. 15.14) the decompression, which was also carried out after swimming excursions from depths of 720 ft (23 ATA), contains a safety factor. With 52 hours decompression it amounts to almost ninefold the bottom time. It is therefore more advantageous not to decompress completely after each work period but only after completion

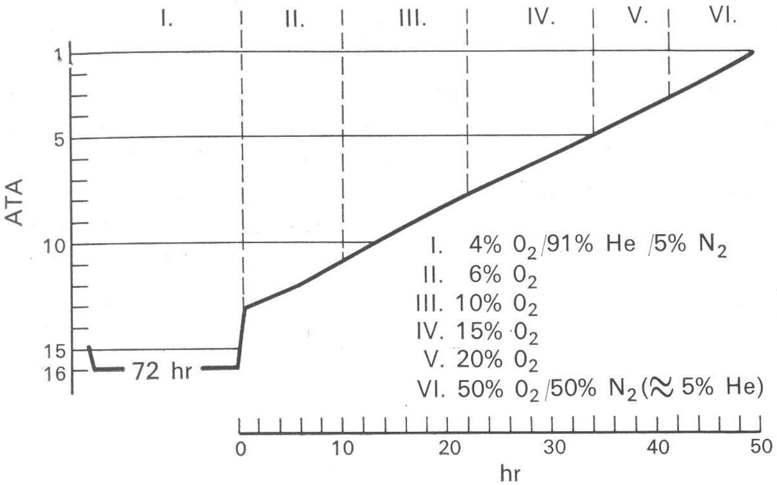

FIG. 15.13. Decompression after full saturation at 500 ft (16 ATA) with 4% oxygen, 91% helium, 5% nitrogen (P_{He} = 14·6 ATS, P_{N2} = 0·8 ATS). Identical procedure as in Fig. 15.12 with a somewhat delayed reduction of pressure at the beginning. Total decompression time 49 hours

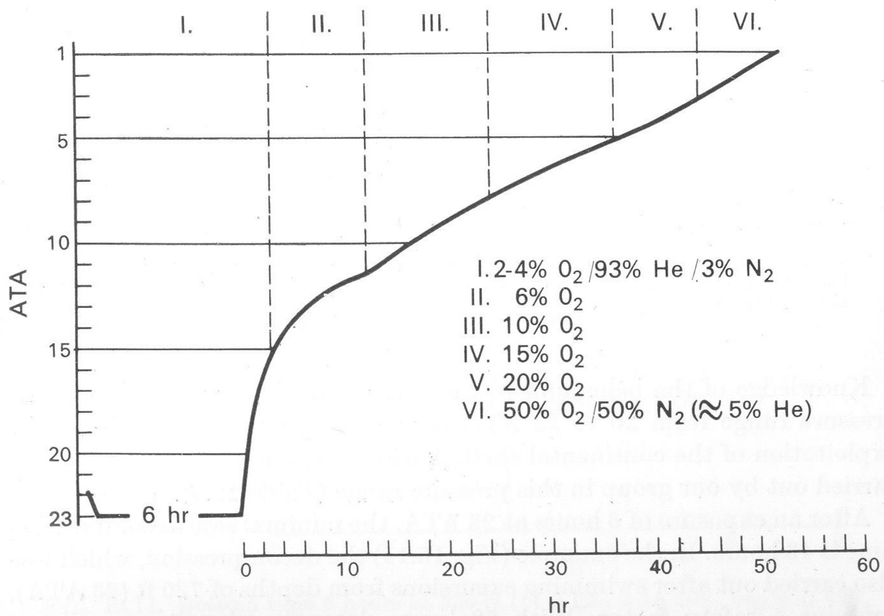

FIG. 15.14. Bottom time 6 hours at 720 ft (23 ATA) with 4% oxygen, 93% helium, 3% nitrogen (P_{He} = 21·4 ATS, P_{N2} = 0·8 ATS). Identical procedure as in Fig. 15.11. Total decompression time 52 hours

of the task, which may take several days. However, this requires knowledge of the exact time required for decompression after full saturation at this pressure.

Experiments to determine such data were carried out in the United States of America, Germany and Switzerland (Hamilton *et al.* 1966; Cabarrou *et al.* 1966; Bühlmann & Waldvogel 1967). Hamilton *et al.* (1966) required 146 hours decompression for an exposure of 48 hours at 660 ft (21 ATA). Cabarrou *et al.* (1966) decompressed two divers safely after 100 hours at 23 ATA in 86 hours. Our schedule required 64 hours for a decompression with no bends or subjective symptoms of oxygen toxicity. In contrast to the American and French-German experiments we did not use 100% oxygen at any time (Fig. 15.15). A shortening of the decom-

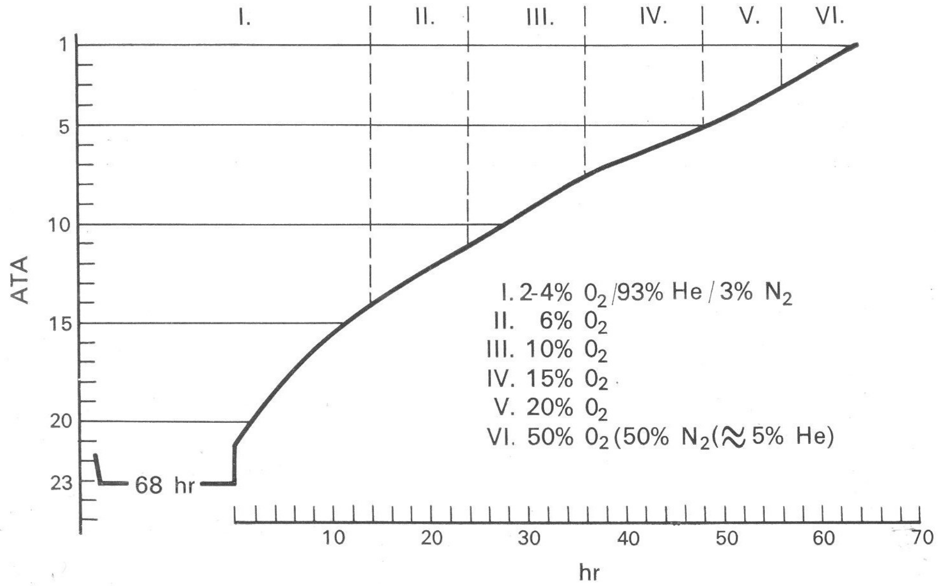

FIG. 15.15. Decompression after full saturation at 725 ft (23 ATA) with 4% oxygen, 93% helium, 3% nitrogen (P_{He} = 21·4 ATS, P_{N2} = 0·8 ATS). Identical procedure as in Figs. 15.12, 13 and 14, but with delayed reduction of the pressure during the initial phase. Total decompression time 64 hours, or 68 hours if breathing air at pressures less than 4 ATA.

pression by 4 to 5 hours in an emergency would be possible using 50% oxygen at pressures less than 130 ft (5 ATA) and 100% oxygen for pressures less than 50 ft (2·5 ATA).

Differences in the first decompression phases after complete and incomplete saturation of the slowest tissues point to the varying supersaturation factors for fast and very slow tissues (Fig. 15.3). The time saved by changing the inert gas during the final phase is not very significant. The

TABLE 15.6

Various possibilities of final decompression from saturation dives of 720 ft (23 ATA) using 2 to 4% O_2, 95% He and 3% N_2 with maximum 50% O_2 below 100 ft (4·0 ATA) or later

Inert gas pressure in tissues with longest half-times

		half-time He	180·00	240·00	270·00 min
		half-time N_2	480·00	640·00	720·00 min
A	21% O_2/79% He	P_{He}	1·13	1·26	1·31
	below 4·9 ATA	P_{N2}	0·35	0·35	0·35
	31 hours, total 79 hours	$P_{He} + P_{N2}$	1·38	1·51	1·66
B	50% O_2/50% N_2	P_{He}	0·46	0·82	0·99
	below 4·0 ATA	P_{N2}	0·74	0·67	0·65
	10 hours, total 62 hours	$P_{He} + P_{N2}$	1·20	1·49	1·64
C	50% O_2/50% N_2	P_{He}	0·58	0·95	1·12
	below 3·3 ATA	P_{N2}	0·62	0·56	0·55
	8 hours, total 64 hours	$P_{He} + P_{N2}$	1·20	1·51	1·67
D	21% O_2/79% N_2	P_{He}	0·18	0·36	0·46
	below 4 ATA	P_{N2}	1·26	1·15	1·12
	16 hours, total 68 hours	$P_{He} + P_{N2}$	1·44	1·53	1·58

Versions B and C were carried out in practice, and no symptoms of insufficient decompression resulted. In version B both subjects showed some symptoms of O_2 intoxication with paraesthesia in the finger tips.

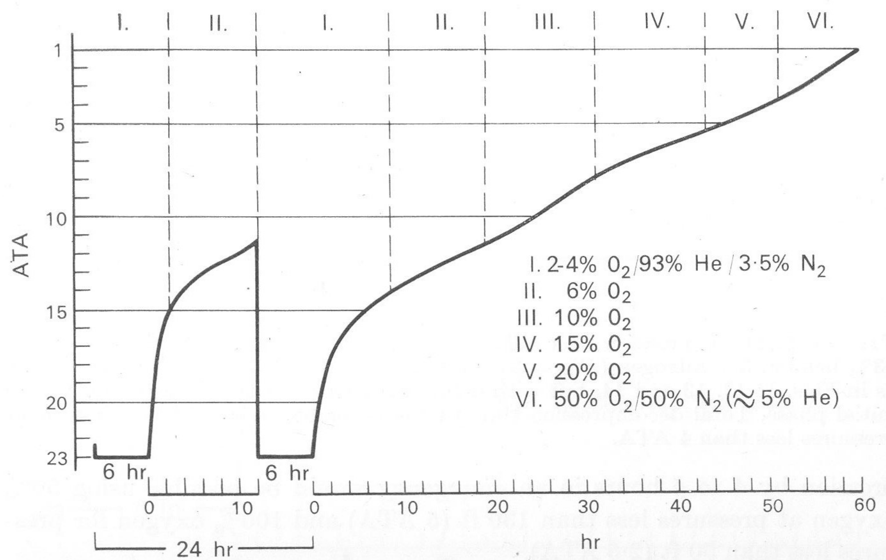

FIG. 15.16. Two descents to 720 ft (23 ATA), 6 hours each during 24 hours, with 4% oxygen, 93% helium, 3% nitrogen (P_{He} = 21·4 ATS, P_{N2} = 0·8 ATS). At night decompression to 340 ft (11·4 ATA) under increase of the oxygen concentration to 6% below 460 ft (15 ATA). After the second exposure of 6 hours decompression according to the procedure in Figs. 15.11 to 14. Decompression time 60 hours

final decompression with 50% oxygen and 50% helium, for pressures less than 75 ft (3·3 ATA) would last 2 more hours, until, at the time of ascent, the tissues with a helium half-time of 180 to 240 min have reached approximately the same inert gas pressure. If the change to 50% oxygen and 50% nitrogen is made at 100 ft (4 ATA) a decompression time of 62 hours results with the disadvantage of a slightly higher oxygen pressure. We have also performed such a schedule successfully.

The above example represents an optimum in decompression time and oxygen pressure (Table 15.6). If the daily exposure amounts to 6 hours at 23 ATA, with partial decompression between, almost complete saturation is attained after the second exposure of 6 hours. Thus the full decompression with the same procedure requires 60 hours (Fig. 15.16). This experiment, which was carried out several times, show that intermittent partial decompression (e.g. at night) is economical in regard to the duration of the

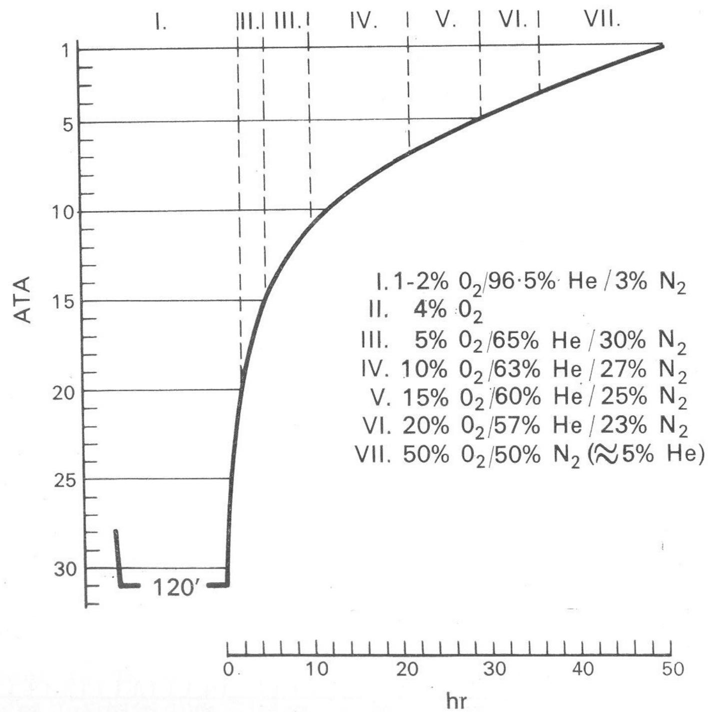

FIG. 15.17. Bottom time 120 min at 1000 ft (31 ATA) with 1 to 2% oxygen, 96·5% helium, 3% nitrogen (P_{He} = 30·0 ATS). Carried out in the pressure chamber adding 30% nitrogen at 480 ft (15·5 ATA) and stepwise increase of oxygen. Final decompression with 50% oxygen, 50% nitrogen below 100 ft 3·8 ATA). The 30-min compression time from 1 to 31 ATA is not included in the bottom time of 120 min

final decompression only if daily exposure times are less than 4 hours. In the example shown, the second exposure occurs within 24 hours. However, extending decompression by 6 hours after the first exposure would not bring about a significant reduction of the final decompression.

In Fig. 15.17 is demonstrated the decompression schedule after an exposure of 120 min at 1000 ft (31 ATA). Without adding 30% nitrogen at 480 ft (15·5 ATA) the decompression time would require 59 hours. The effect of an inert gas exchange in reducing decompression time is more and more reduced as bottom times become longer. After an exposure of 4 hours at 1000 ft (31 ATA) (Fig. 15.18) the time saved by adding nitrogen is small. It is preferable to increase only the oxygen percentage and to change from helium to nitrogen only during the final phase. The decompression time after complete saturation at 1000 ft (31 ATA) will be about 90 hours.

All the long exposure experiments described were carried out without using prepared gas mixtures or breathing apparatus. The oxygen partial pressure was always below one ATA during the exposure and the nitrogen

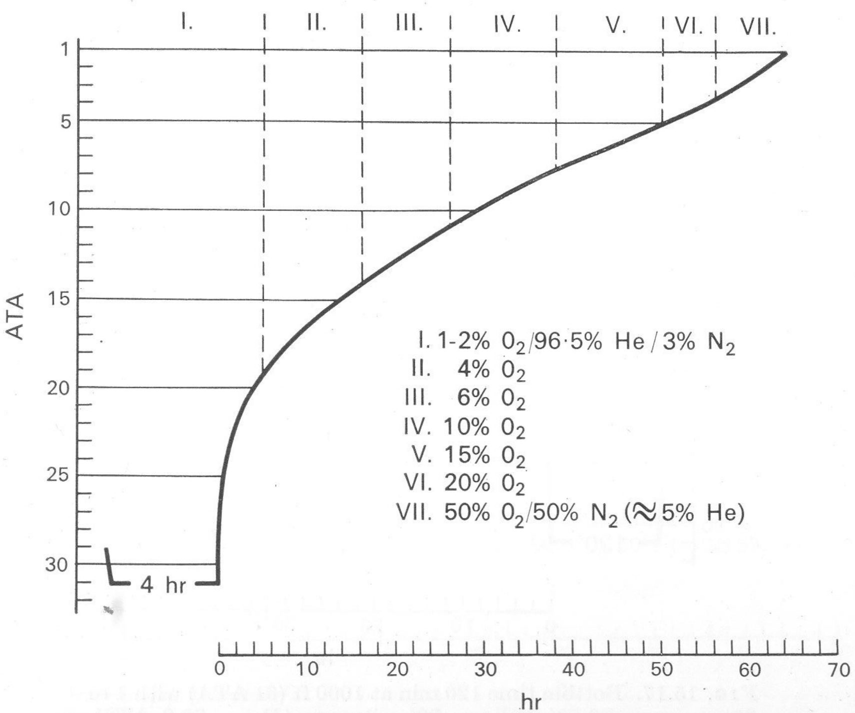

FIG. 15.18. Bottom time 4 hours at 1000 ft (31 ATA) with 1 to 2% oxygen, 96·5% helium, 3% nitrogen (P_{He} = 30·0 ATS). Stepwise increase of oxygen concentration. Inert gas change from helium to nitrogen only during the final phase of the decompression at less than 80 ft (3·5 ATA). The compression time of 30 min is not included in the 4-hour bottom time

partial pressure remained constant at 0·8 ATS. All decompressions after exposures of several hours at 11 to 23 ATA were done according to the same scheme. This involved a stepwise increase of the oxygen percentage to 50% in the final phase of decompression and, at this time, an inert gas change from helium to nitrogen. As soon as the same inert gas pressure was reached in the tissues with a helium half-time of 180 to 240 min, the decompression was the same.

The rationale

The use of the technique of changing inert gases to shorten the decompression time is based on the concept that saturation and desaturation, especially in poorly perfused and fatty tissues, proceeds two to three times faster with helium than with nitrogen. This is due to the low molecular weight of helium and its different solubility ratio in blood and fat. This theoretical difference in saturation speed was confirmed by saturation experiments at 3·2 ATA helium and 3·2 ATA nitrogen. The application of the inert gas change from helium to nitrogen depends on the depth and time of exposure. This was demonstrated experimentally for exposures from 100 to 1000 ft (4 to 31 ATA).

The use of helium permits the shortening of decompression from shallow depths after both short and long exposures lasting either several hours to days. The combination of the inert gas change and high oxygen concentration (oxygen partial pressure at 2·5 ATS) permits very short decompression times after exposures at 330 ft (11 ATA) with bottom times to 60 min and for exposures of shorter duration to pressures of 1000 ft (31 ATA).

With an exposure time of 6 hours at 330 ft (11 ATA), in spite of changing the inert gas, the decompression time amounts to as much as 20 hours. The long duration also necessitates a reduction in the oxygen concentration so as to keep the oxygen partial pressure below an average of 1 ATS during the exposure at maximum pressure and with a short and transient increase above 2 ATS during decompression. However, the inert gas change from helium to nitrogen allows the final decompression to be shortened between 100 ft (4 ATA) and 1 ATA (surface), even after full saturation at great depths.

The decompressions from long exposures are simplified by giving oxygen, helium and air in a pressure chamber without preliminary preparations of gas mixtures and without breathing apparatus. Although bottom times varied from a few hours to full saturation at pressures from 330 to 720 ft (11 to 23 ATA), the examples were designed to result in identical decompression procedures once the same inert gas pressures of helium and nitrogen were reached in the tissues with a helium half-time of 180 to 240 min.

REFERENCES

ALVIS, H. J. (1960). Diving and submarine operations. In *Clinical Cardiopulmonary Physiology*, p. 961. New York & London: Grune & Stratton.

BENNETT, P. B. (1963). Neuropharmacologic and neurophysiologic changes in inert gas narcosis. In *Proc. 2nd Underwater Physiology Symposium*, Publication 1181. Ed. Lambertsen, C. J. & Greenbaum, L. J. Washington: Nat. Res. Council, Nat. Acad. Sci.

BENNETT, P. B. (1966). *The Aetiology of Compressed Air Intoxication and Inert Gas Narcosis*. International Series of Monographs in Pure and Applied Biology; Zoology Division; Vol. 31. Oxford & New York: Pergamon.

BOND, G. F. (1963). Prolonged exposure to high ambient pressure. In *Proc. 2nd Underwater Physiology Symposium*. Publication 1181. Ed. Lambertsen, C. J. & Greenbaum, L. J. Washington: Nat. Res. Council, Nat. Acad. Sci.

BÜHLMANN, A. A. (1963). Respiratory resistance with hyperbaric gas mixtures. In *Proc. 2nd Underwater Physiology Symposium*. Publication 1181. Ed. Lambertsen, C. J. & Greenbaum, L. J. Washington: Nat. Res. Council, Nat. Acad. Sci.

BÜHLMANN, A. A., FREY, P. & KELLER, H. (1967). Saturation and desaturation with nitrogen and helium at 4 ATA. *J. appl. Physiol.* **23**, 458–462.

BÜHLMANN, A. A. & WALDVOGEL, W. (1967a). The treatment of decompression accidents. *Helv. med. Acta*, **33**, 487.

CABARROU, P., HARTMANN, H., WEINER, K. H., ALINAT, P. & FUST, H. D. (1966). Introduction à la physiologie de 'Homo Aquaticus'. *Presse méd.* **74**, 2771.

CARPENTER, F. G. (1955). Inert gas narcosis. In *Proc. 1st Underwater Physiology Symposium*, Publication 377. Ed. Goff, L. G. Washington: Nat. Res. Council, Nat. Acad. Sci.

DITTMER, S. D. & GREBE, R. M. (1958). *Handbook of Respiration*. London & Philadelphia: Saunders.

DITTMER, S. D. & GREBE, R. M. (1959). *Handbook of Circulation*. London & Philadelphia: Saunders.

HALDANE, J. B. S. & PRIESTLEY, J. G. (1935). *Respiration*. New Haven: Yale Univ. Press.

HAMILTON, R. W. Jr., MACINNIS, J. B., NOBLE, A. D. & SCHREINER, H. R. (1966). *Saturation Diving to 650 Feet*. Tonawanda, New York: Ocean Systems Inc. Tonawanda Research Lab. Report.

HARTMANN, H., WEINER, K. H., FUST, H. D. & SEIFERT, R. (1966). Ueber einen Dauerversuch von 100 Stunden bei einem Druck von 11 ATA. *Intern. Z. Physiol. einschl. Arbeits physiol.* **22**, 30.

HEMPLEMAN, H. V. (1963). Tissue inert gas exchange and decompression sickness. In *Proc. 2nd Underwater Physiology Symposium*, Publication 1181. Ed. Lambertsen, C. J. & Greenbaum, L. J. Washington: Nat. Res. Council, Nat. Acad. Sci.

HESSER, C. M. (1963). Measurement of inert gas narcosis. In *Proc. 2nd Underwater Physiology Symposium*, Publication 1181. Ed. Lambertsen, C. J. & Greenbaum, L. J. Washington: Nat. Res. Council, Nat. Acad. Sci.

KELLER, H. & BÜHLMANN, A. A. (1965). Deep diving and short decompression by breathing mixed gases. *J. appl. Physiol.* **20**, 1267

KRASBERG, A. R. (1966). Saturation diving techniques. *4th Intern. Congr. Biometerology*. Rutgers Univ., New Brunswick, New Jersey.

LAMBERTSEN, C. J. (1963). Physiological effects of oxygen. In *Proc. 2nd Underwater Physiology Symposium*, Publication 1181. Ed. Lambertsen, C. J. & Greenbaum, L. J. Washington: Nat. Res. Council, Nat. Acad. Sci.

LANPHIER, E. H. (1963). Influence of increased ambient pressure upon alveolar ventilation. In *Proc. 2nd Underwater Physiology Symposium*, Publication 1181. Ed. Lambertsen, C. J. & Greenbaum, L. J. Washington: Nat. Res. Council, Nat. Acad. Sci.

MILLER, S. (1963). A theory of inert gas narcosis. In *Proc. 2nd Underwater Physiology Symposium*, Publication 1181. Ed. Lambertsen, C. J. & Greenbaum, L. J. Washington: Nat. Res. Council, Nat. Acad. Sci.

SCHREINER, H. R. (1967). Safe ascent after deep dives. *Journées Internationales d'Hyperbarie et de Physiologie Subaquatique*. Marseille.

SPIEGEL, M. V. (1963). Die bronchialen Strömungswiderstande bei Ueberdruck. *Z. klin. Med.* **157**, 405.

THOMAS, J. J. & NEPTUNE, E. M. Jr. (1963). Chemical mechanisms of oxygen toxicity. In *Proc. 2nd Underwater Physiology Symposium*, Publication 1181. Ed. Lambertsen, C. J. & Greenbaum, L. J. Washington: Nat. Res. Council, Nat. Acad. Sci.

WALDVOGEL, W. & BÜHLMANN, A. A. (1968). Man's reaction to long-lasting overpressure exposure. Examination of the saturated organism at a helium pressure of 21–22 ATA. *Helv. med. Acta*, **34**, 130.

WEBSTER, A. P. (1955). Some theoretical aspects on the use of multiple gas mixtures for deep-sea diving. In *Proc. 1st Underwater Physiology Symposium*, Publication 377. Ed. Goff, L. G. Washington: Nat. Res. Council, Nat. Acad. Sci.

WORKMAN, R. D. (1963). Studies of decompression and inert gas–oxygen mixtures in the U.S. Navy. In *Proc. 2nd Underwater Physiology Symposium*, Publication 1181. Ed. Lambertsen, C. J. & Greenbaum, L. J. Washington: Nat. Res. Council, Nat. Acad. Sci.

WORKMAN, R. D. (1966). Recent Navy experiences in decompression. *4th Intern. Congr. Biometerology*. Rutgers University, New Brunswick, New Jersey.

WORKMAN, R. D. & REYNOLDS, J. L. (1965). In *U.S. Navy Diving Manual*. Washington: U.S. Navy.